Customizable Coherent Servo Demodulation for Disk Drives

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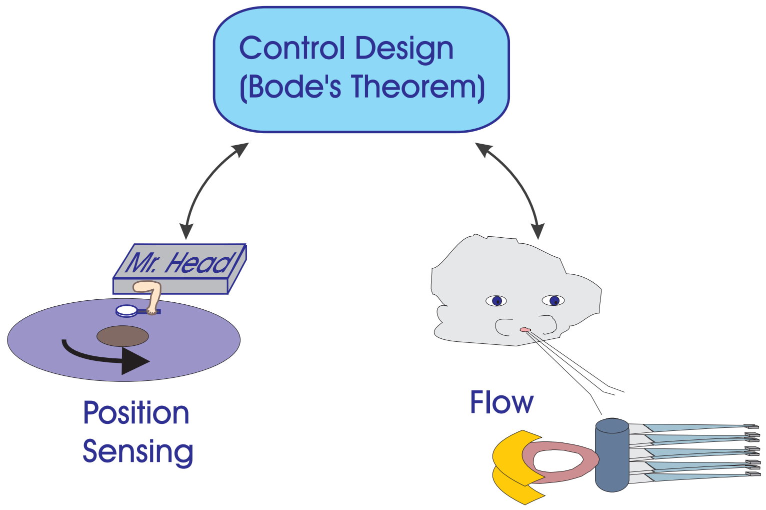
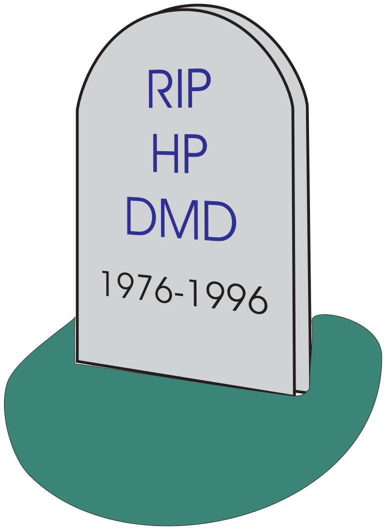
When We Last Left PES Pareto



- Position Sensing Noise (PSN) and Wind Flow (Windage) were primary sources of broadband baseline PES.
- Bode's Integral Theorem limits our abilities to deal with flow through higher bandwidth until we take care of PSN.
- PSN is largely controlled by head/media interaction and by the demodulation of the readback signal.
- Demodulation was what I got to before HP got out of the business.

Brief Status of This Work

- Patent granted, waiting for patent #.
- HP out of hard disk business.
- This work is 2 years old.
  - Last of HPL disk drive technology fire sale.
  - "Everything must go!"
- Work being extended at CMU.



Motivation

PRML channels make use of a lot more signal information than the servo channels do. There is no reason for servo channels not to use this information.

In the past, the cost of the extra circuitry was not justified by the improved signal quality. Now it is.

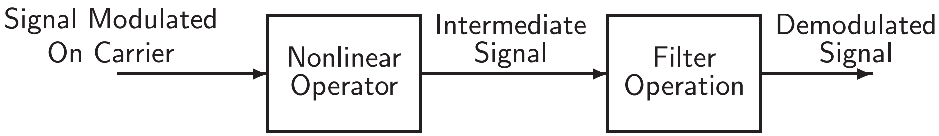
Talk Outline

- Coherent versus non-coherent demodulation
- The math behind the algorithm
- Implementation options
- Matching measured data
- Simulating various noise and non-ideal conditions
- Second harmonic measurements and timing issues

Non-Coherent Demodulation vs. Coherent Demodulation

- **Non-coherent demodulation uses memoryless nonlinearity to shift portion of signal down to baseband.**
- **Coherent demodulation uses mixing signal to shift portion of signal down to baseband.**
- **Either way, filter operation should remove higher orders.**
- **Rectifier is most common memoryless nonlinearity for non-coherent demodulation.**

Non-Coherent Demodulation


Signal Modulated On Carrier

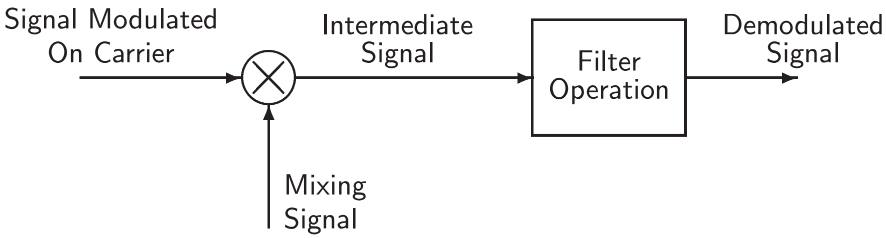
Nonlinear Operator

Intermediate Signal

Filter Operation

Demodulated Signal

Coherent Demodulation


Signal Modulated On Carrier

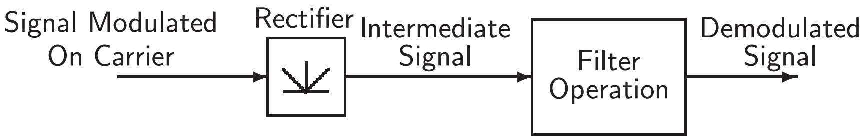
Intermediate Signal

Filter Operation

Demodulated Signal

Mixing Signal

Non-Coherent Demodulation Using a Rectifier


Signal Modulated On Carrier

Rectifier

Intermediate Signal

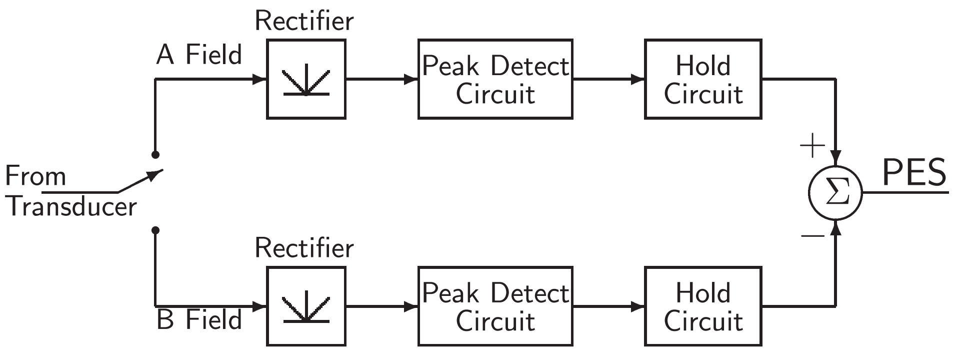
Filter Operation

Demodulated Signal

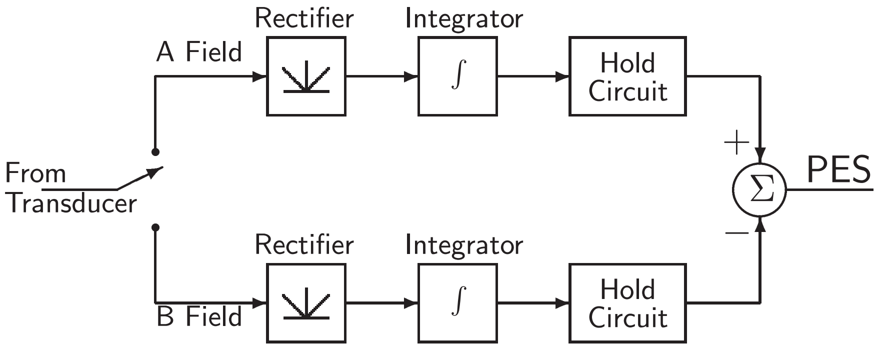
Non-Coherent Disk Drive Servo Demodulators

- Peak detection generally has simpler cicuitry.
- Rectify and integrate (commonly called area detection) generally has higher noise immunity.
- Either of these can come with prefiltering.

Peak Detection Servo Demodulator



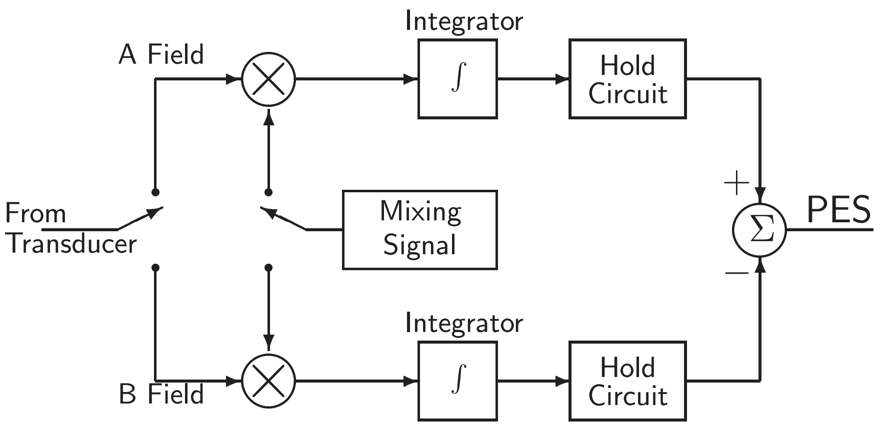
Rectify and Integrate Servo Demodulator



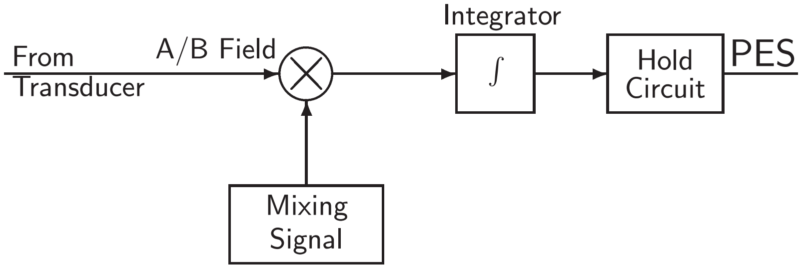
Coherent Disk Drive Servo Demodulators

- Coherent servo demodulation has a simple block diagram.
- This applies to split-field amplitude encoded servo or null pattern.
- Either of these can come with prefiltering.

Coherent Servo Demodulation



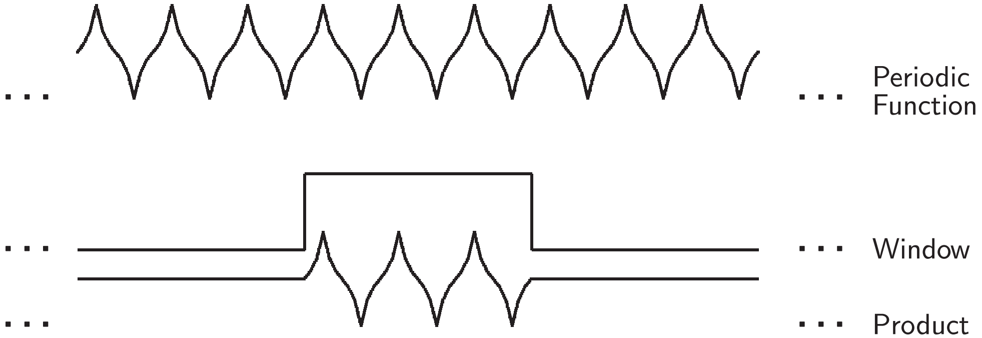
Coherent Servo Demodulation for Null Pattern Signals



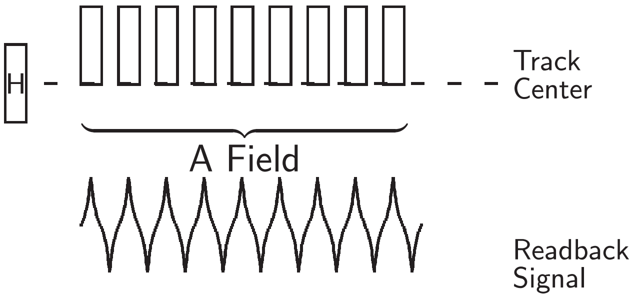
Analyzing Burst Signals

- We can analyze ideal burst as product of periodic signal and window function.
- Choose window as period of integration $= M$ signal periods. Now window is transparent, *i.e.* no leakage.
- Can analyze periodic signal as Fourier Series.

Ideal Dibit Signal can be composed of a periodic signal and a windowing operation.



Burst patterns and the resulting readback signal for a single burst.



Fourier Series

Periodic signal, $r(t)$, can be analyzed using Fourier Series analysis i.e.

$$r(t) = A_0 + \sum_{n=1}^{\infty} (A_n \cos(n\omega t) + B_n \sin(n\omega t))$$

where

$$\begin{aligned} A_n &= \frac{1}{\pi}\int_0^{2\pi} r(t)\cos(n\omega t)d(\omega t), \\ B_n &= \frac{1}{\pi}\int_0^{2\pi} r(t)\sin(n\omega t)d(\omega t), \textbf{ and} \\ A_0 &= \frac{1}{\pi}\int_0^{2\pi} r(t)d(\omega t). \end{aligned}$$

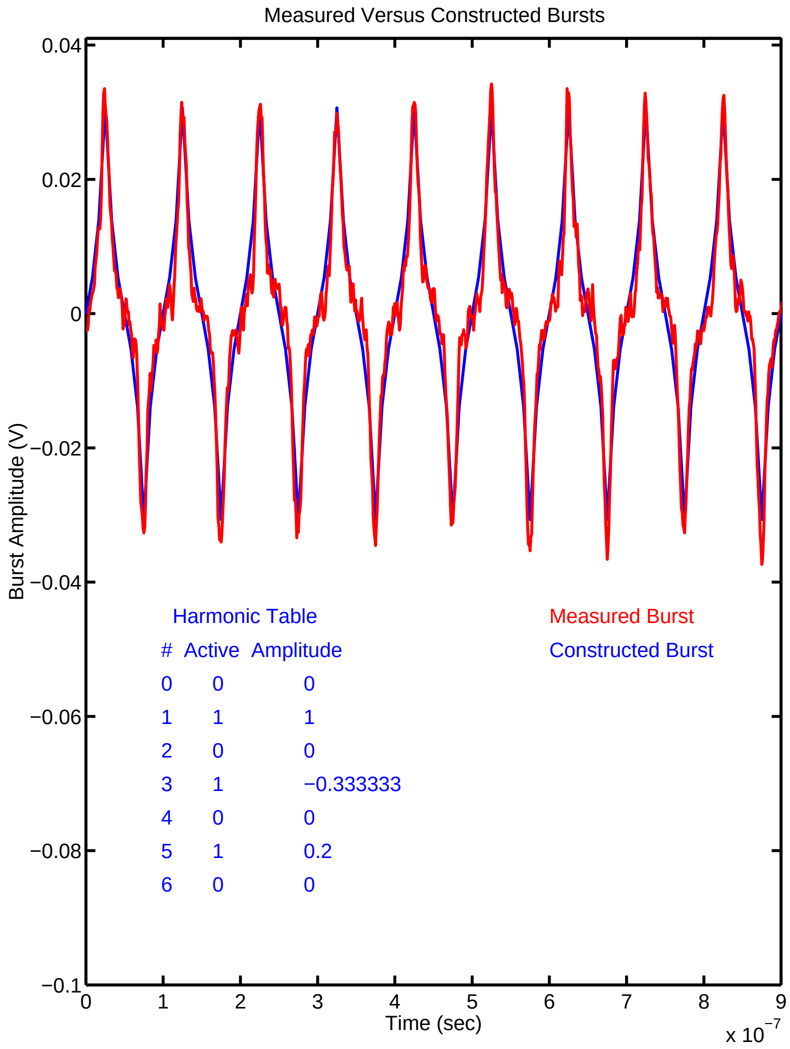
Due to the symmetry properties of DSMR burst signal:

$$r(t) = A_0 + \sum_{n=1}^{\infty} B_n \sin(n\omega t).$$

If signal has no DC and is an odd function:

$$r(t) = \sum_{\substack{\mathbf{n=1,} \\ \mathbf{n\ \ odd}}}^{\infty} B_n \sin(n\omega t).$$

Extracted Burst versus Modeled Burst



Harmonic Table

#	Active	Amplitude
0	0	0
1	1	1
2	0	0
3	1	−0.333333
4	0	0
5	1	0.2
6	0	0

Mixing Coherently With Harmonics

We matched the averaged DSMR burst by:

$$r(t) = R_0\left(r_1 \sin \omega t + r_3 \sin 3\omega t + r_5 \sin 5\omega t\right) + n(t).$$

Let's use a mixing signal

$$m_1(t) = \sin \omega t.$$

The product is

$$m_1(t) r(t) = \frac{R_0}{2}\left[r_1\left(1 - \cos 2\omega t\right) + r_3\left(\cos 2\omega t - \cos 4\omega t\right) + r_5\left(\cos 4\omega t - \cos 6\omega t\right)\right] + \left(\sin \omega t\right) n(t).$$

Use properties sinusiod and integral:

$$\frac{1}{MT}\int_0^{MT} m_1(t) r(t) dt = \frac{R_0 r_1}{2} + \frac{1}{MT}\int_0^{MT} (\sin \omega t) n(t) dt$$

and the expected value to

$$E\left\{\frac{1}{MT}\int_0^{MT} m_1(t) r(t) dt\right\} = \frac{R_0 r_1}{2}.$$

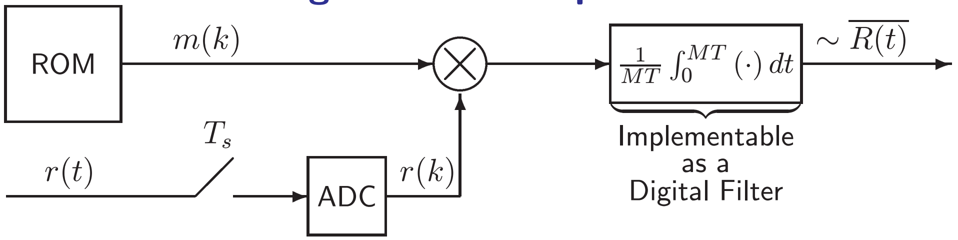
Note:

- **We can add extra harmonics that we like to improve SNR.**
- **Unlike a matched filter, we can ignore harmonics that behave badly such as second harmonic distortion:**

$$r(t) = R_0\left(r_1 \sin \omega t + r_3 \sin 3\omega t + r_5 \sin 5\omega t + k_0 - k_0 \cos 2\omega t\right) + n(t).$$

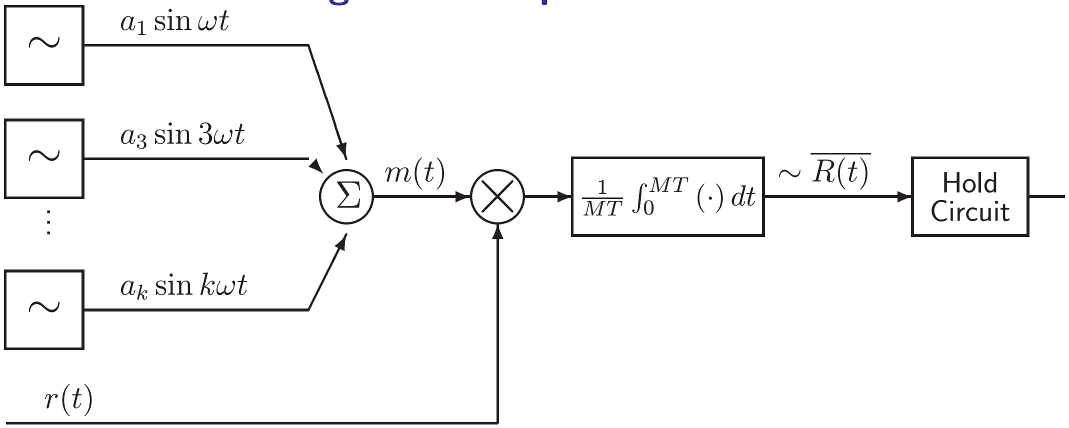
Multiple Circuit Implementations

Digital Circuit Implementation



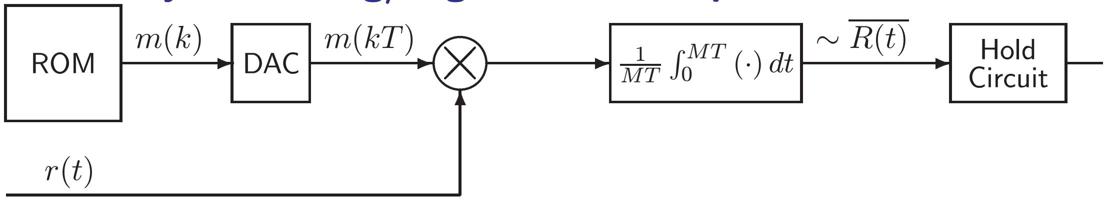
- **Simplest circuitry.**
- **Speed may be an issue.**

Analog Circuit Implementation



- **Fastest circuitry**
- **Least flexible as sine wave generators have to be chosen in advance**
- **Adding extra harmonics results in a more complicated circuit.**

Hybrid Analog/Digital Circuit Implementation



- **Perhaps the best compromise.**
- **ROM and DAC can be very fast.**
- **Analog integration can be very fast.**
- **ROM preserves waveform flexibility.**

Computing of Error Measures

- Random variable, x, with probability density function $p(x)$, expected value of x is

$$E\{x\} = \int_{-\infty}^{\infty} p(x) x dx = \mu$$

- Expected value of $f(x)$, is

$$E\{f(x)\} = \int_{-\infty}^{\infty} p(x) f(x) dx.$$

- The variance is

$$\sigma^2(x) = E\{(x-\mu)^2\}$$

- The standard deviation is given by the square root

$$\sigma(x) = E\{(x-\mu)^2\}^{\frac{1}{2}}.$$

- When a percentage is desired, the above number is multiplied by 100.

- We normailize the standard deviation by the true mean of the number.

$$\sigma_{nor}(x) = \frac{E\{(x-\mu)^2\}^{\frac{1}{2}}}{\mu}.$$

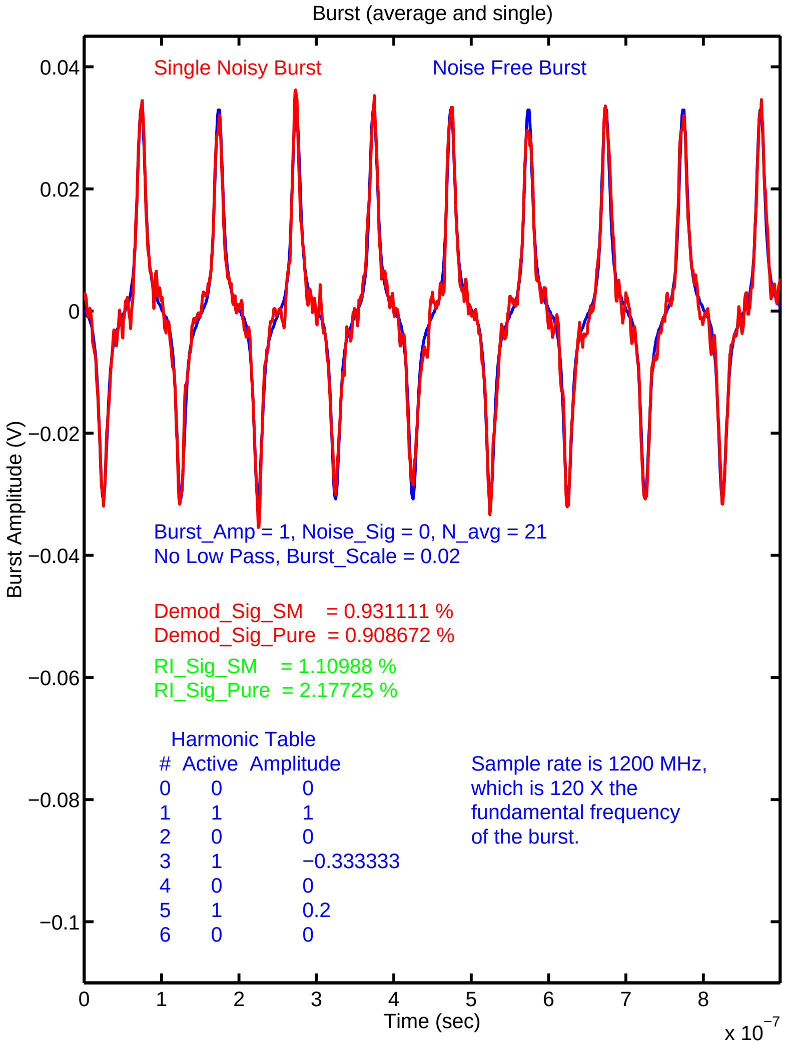
- In simulation, this true mean is the answer that one would get were there no noise or nonideality.
- For measured data, "true mean" is obtained from averaging all the dibits before demodulation and demodulating the heavily averaged burst, rather than taking average of demodulated values.
- This is important when

$$\overline{f(x)} = \frac{1}{n}\sum_{1}^{n} f(x_i) \neq f(\overline{x}) = f\left(\frac{1}{n}\sum_{1}^{n} x_i\right).$$

such as when noise is rectified.

Ideal Cougar I Burst

Demodulating Measured Burst



Harmonic Table

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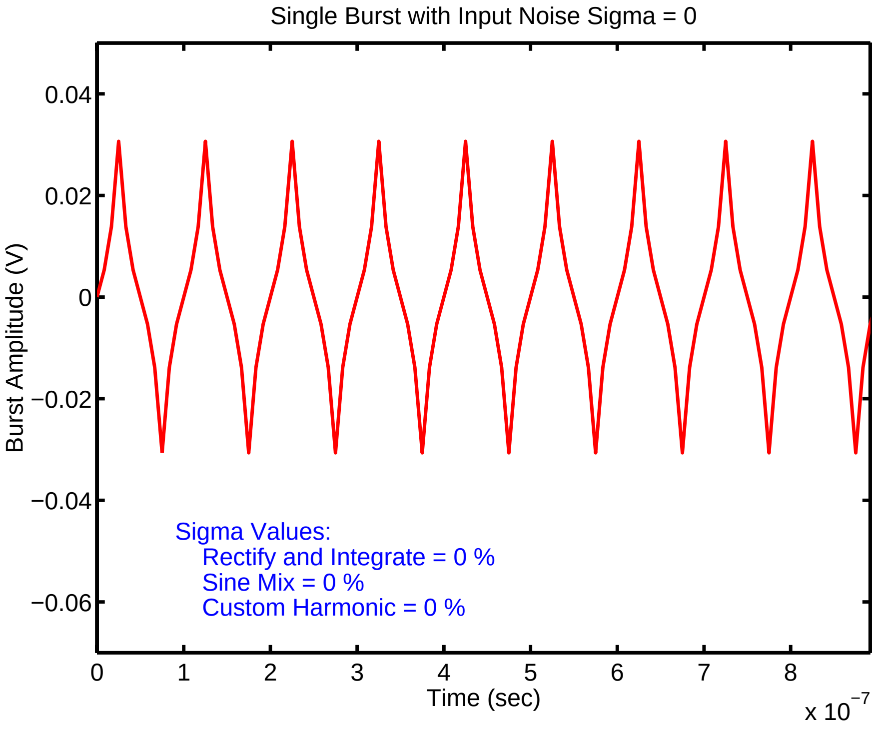
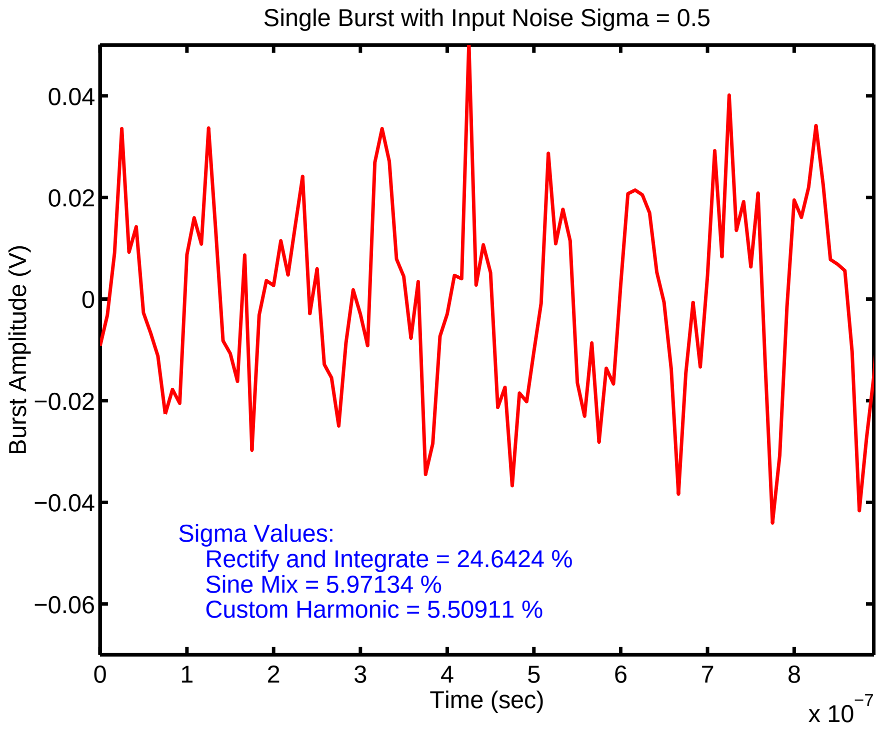
Sample rate is 1200 MHz, which is 120 X the fundamental frequency of the burst.



Sigma Values:
Rectify and Integrate = 0 %
Sine Mix = 0 %
Custom Harmonic = 0 %

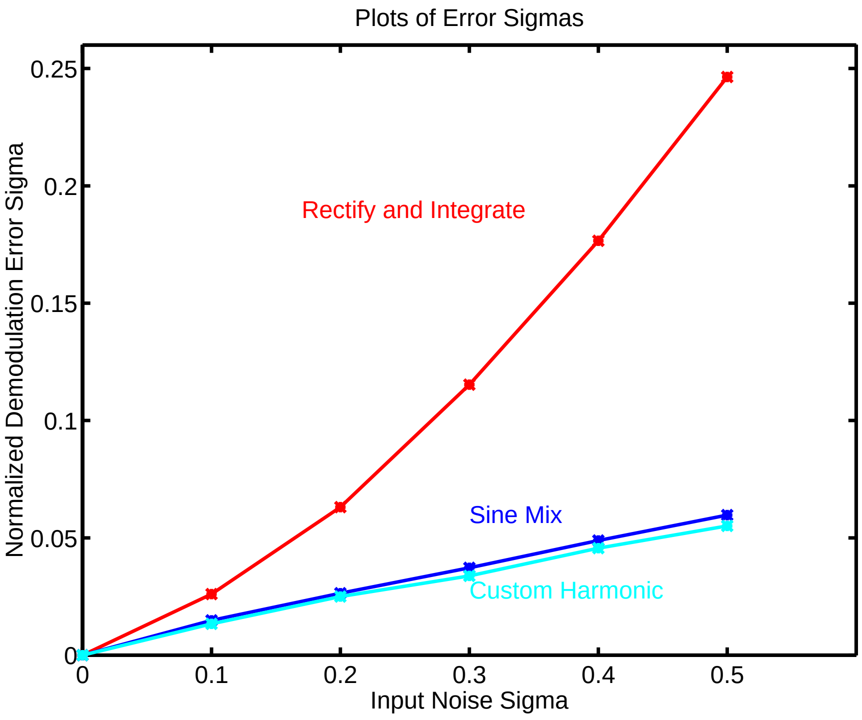
- Harmonics fit to burst data supplied by Greg Hofer (formerly of HP DMD).
- Composed of 1st, 3rd, and 5th harmonics.
- Sine components only.

Cougar I Burst with Additive White Gaussian Noise



Single Burst with Input Noise Sigma = 0.5

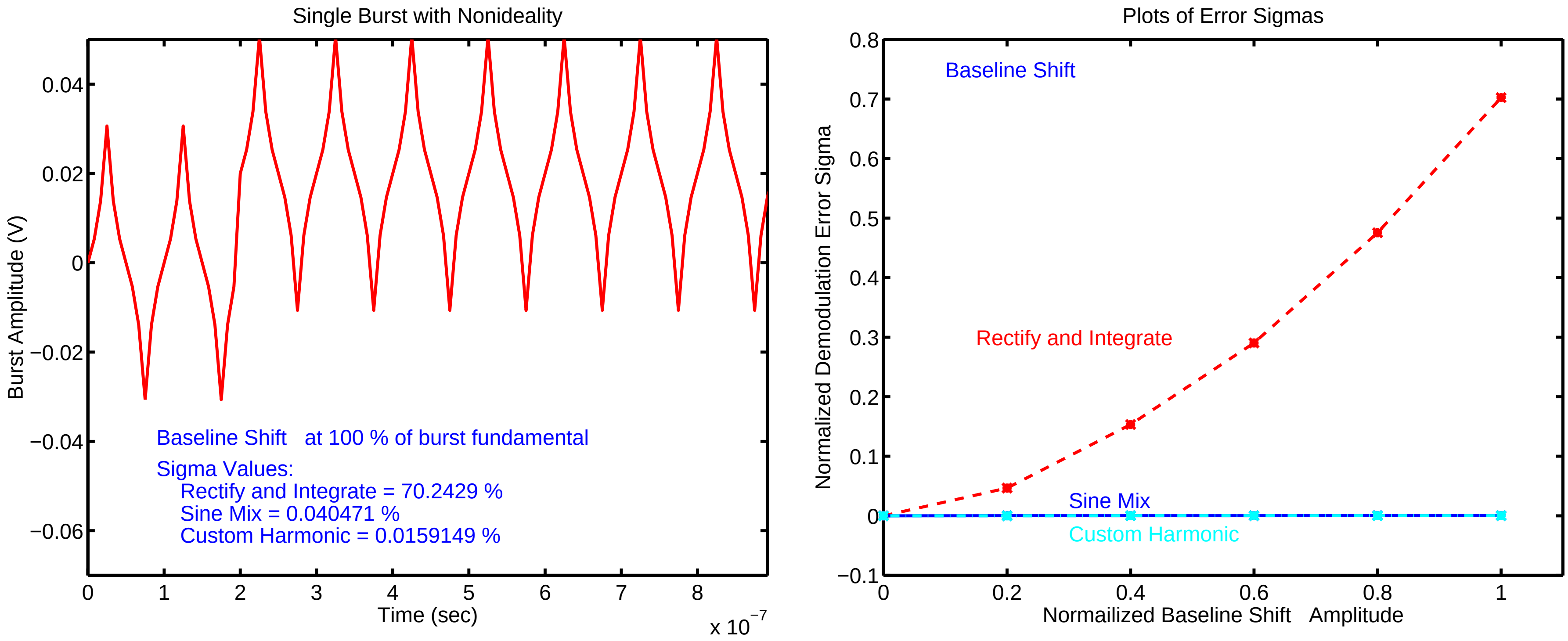
Sigma Values:
Rectify and Integrate = 24.6424 %
Sine Mix = 5.97134 %
Custom Harmonic = 5.50911 %



Plots of Error Sigmas

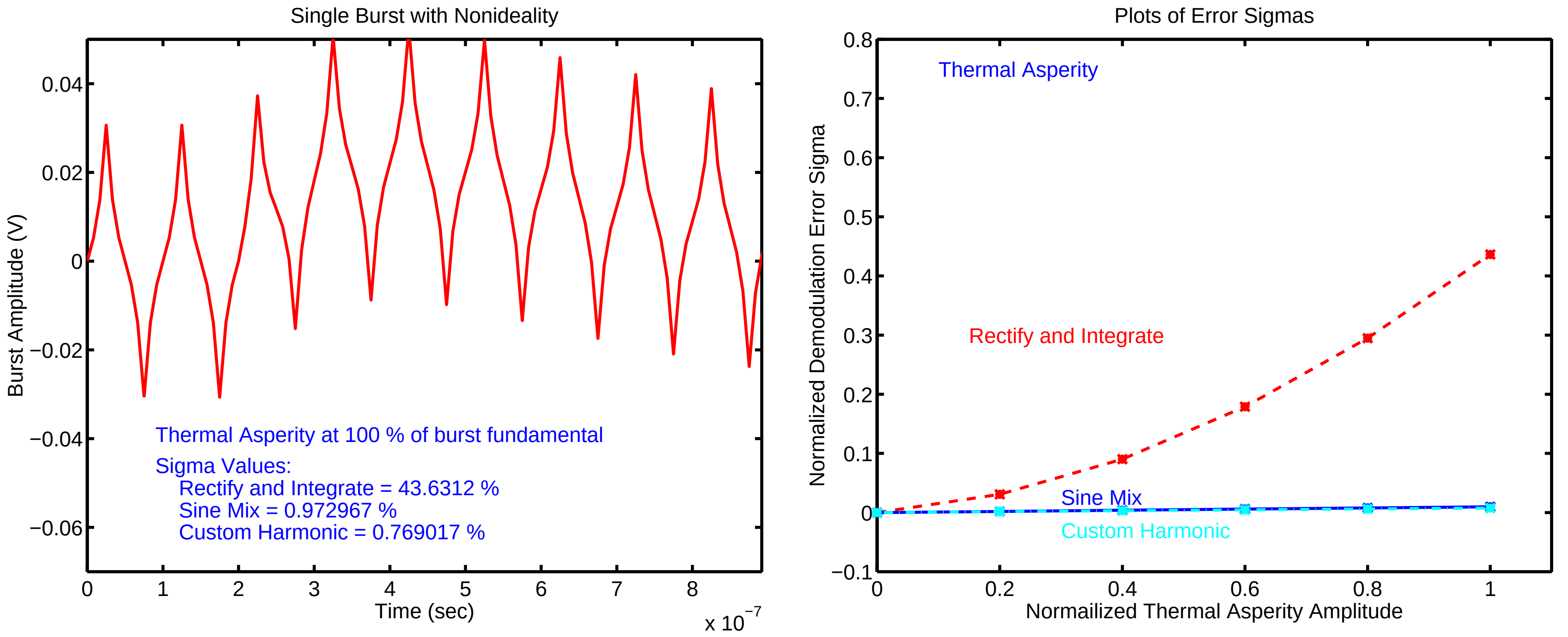
- At current noise sigmas (≈ 0.1) sine mix and custom harmonic are about a factor of 2 better.
- Advantage increases dramatically with increasing input noise.

Cougar I Burst with Baseline Shift



- Baseline shift causes severe errors in rectify & integrate.
- It is a low frequency phenomena.
- CC Demod ignores it.

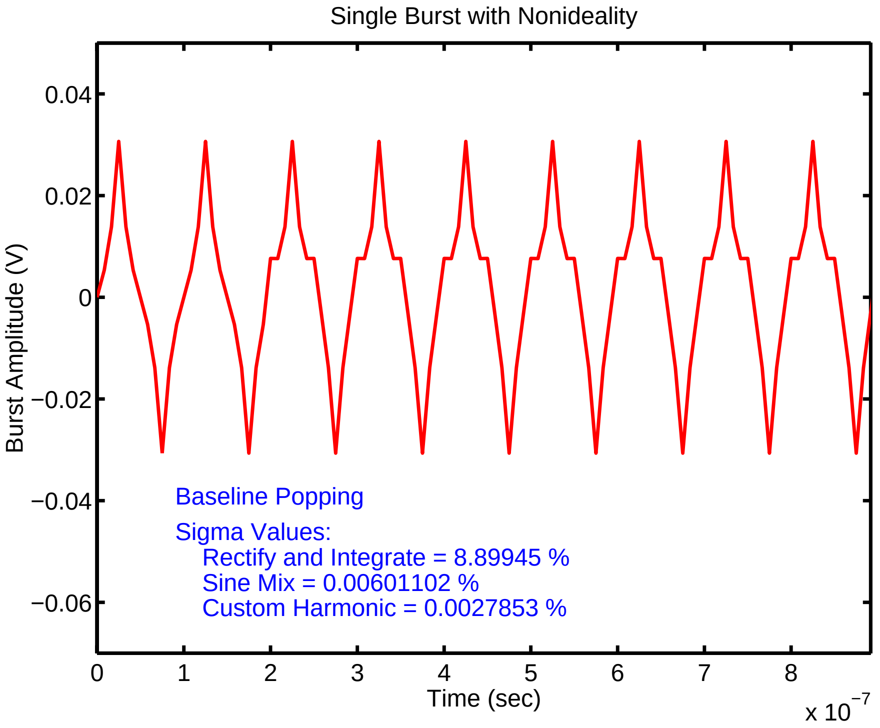
Cougar I Burst with Thermal Asperity



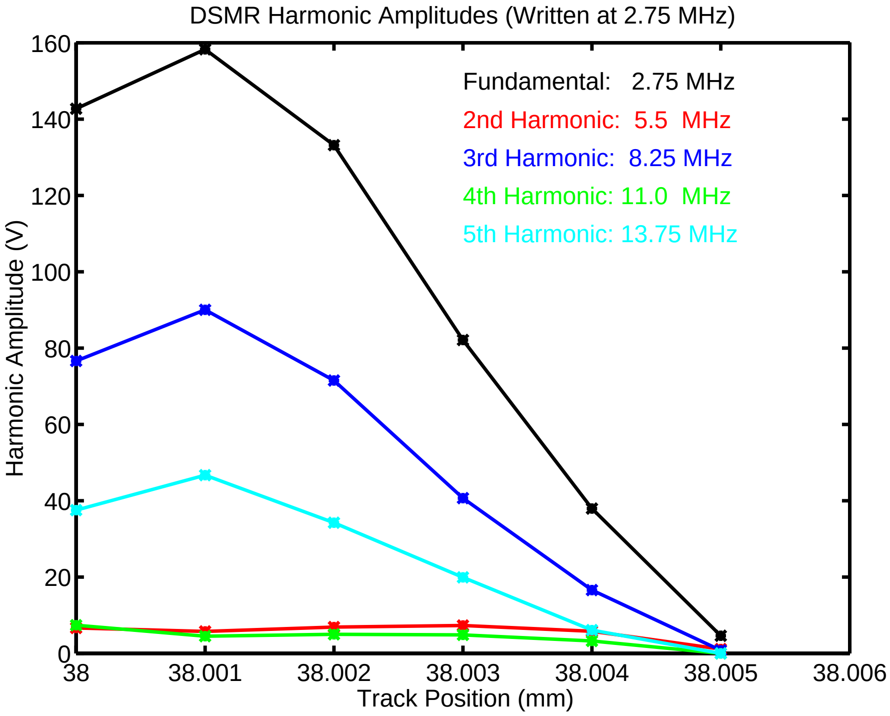
- **A thermal asperity causes severe errors in rectify & integrate.**
- **It is a low frequency phenomena.**
- **CC Demod ignores it.**

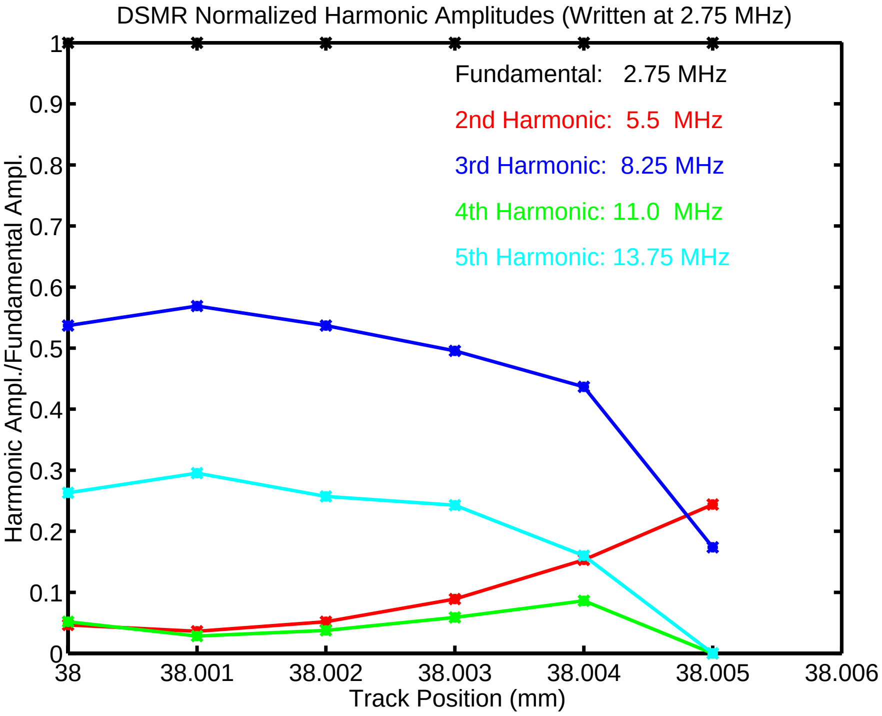
Cougar I Burst with Baseline Popping

- **Nominal quiescent value of dibit pulse returns to a nonzero value.**
- **A relatively minor problem for rectify & integrate.**
- **CC Demod ignores it.**



Offtrack Behavior of Harmonics (preliminary)

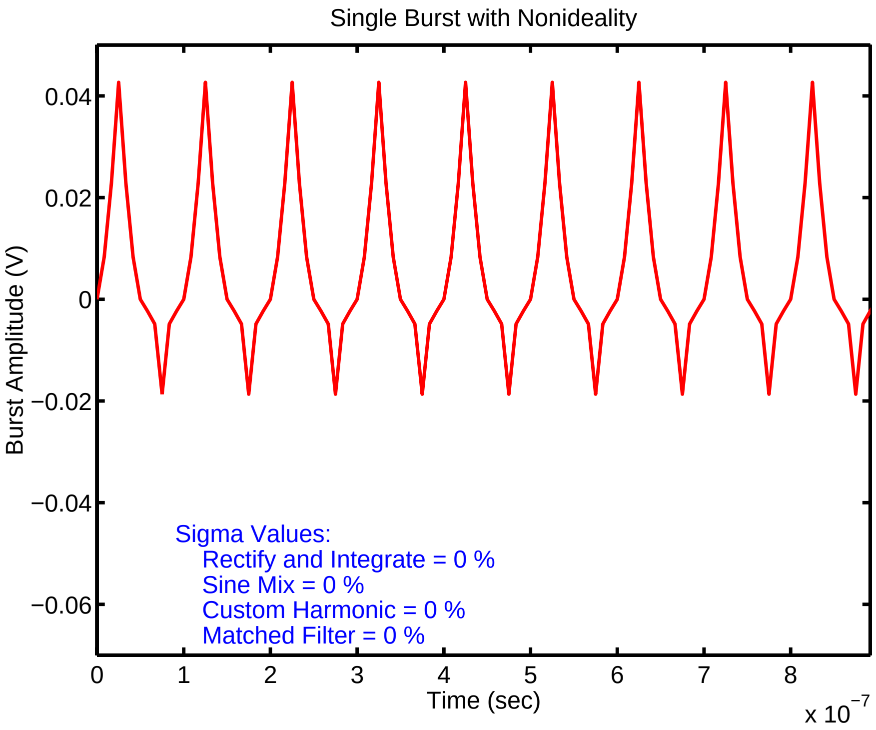

DSMR Harmonic Amplitudes (Written at 2.75 MHz)


DSMR Normalized Harmonic Amplitudes (Written at 2.75 MHz)

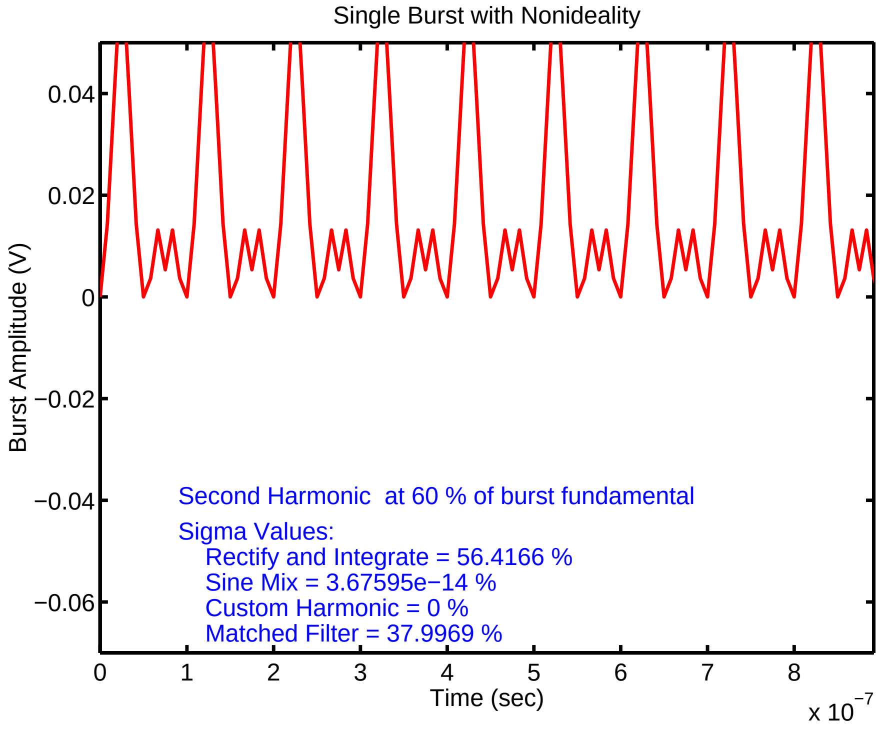
- **Measured by Dick Henze and Lung Tran (HPL).**
- **Signal written at 2.75 MHz.**
- **Averaged spectrum taken at harmonic frequencies.**
- **First, third, and fifth harmonics dominate at track center.**
- **Second and fourth harmonics get more significant at track edge.**
- **Servo track center is at track edge of dibits.**
- **Supposedly, it gets worse in SAL and GMR heads.**

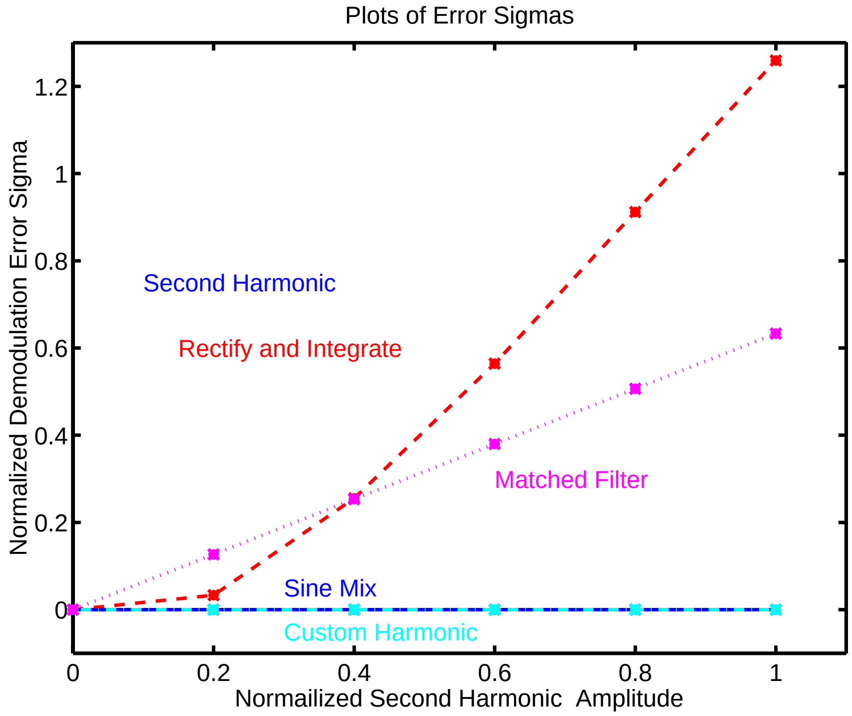
Cougar I Burst with Nominal Second Harmonic Distortion

- **Created by adding a squaring term to time response.**
- **Adds DC and $\cos 2\omega t$ harmonics.**
- **Results in asymmetric pulse shape.**



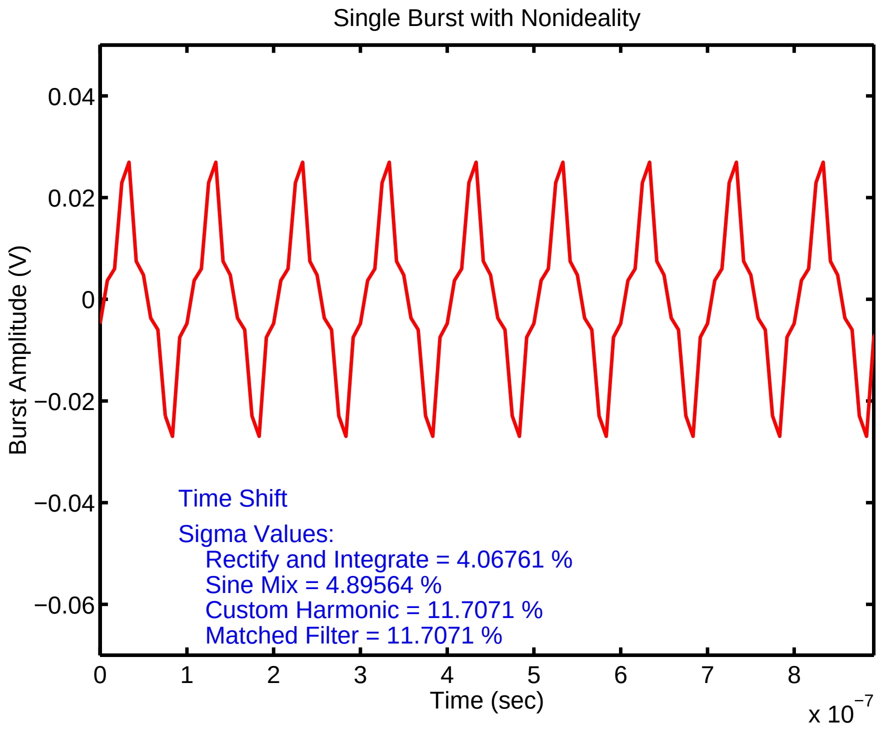
Deviations from Nominal Second Harmonic Distortion

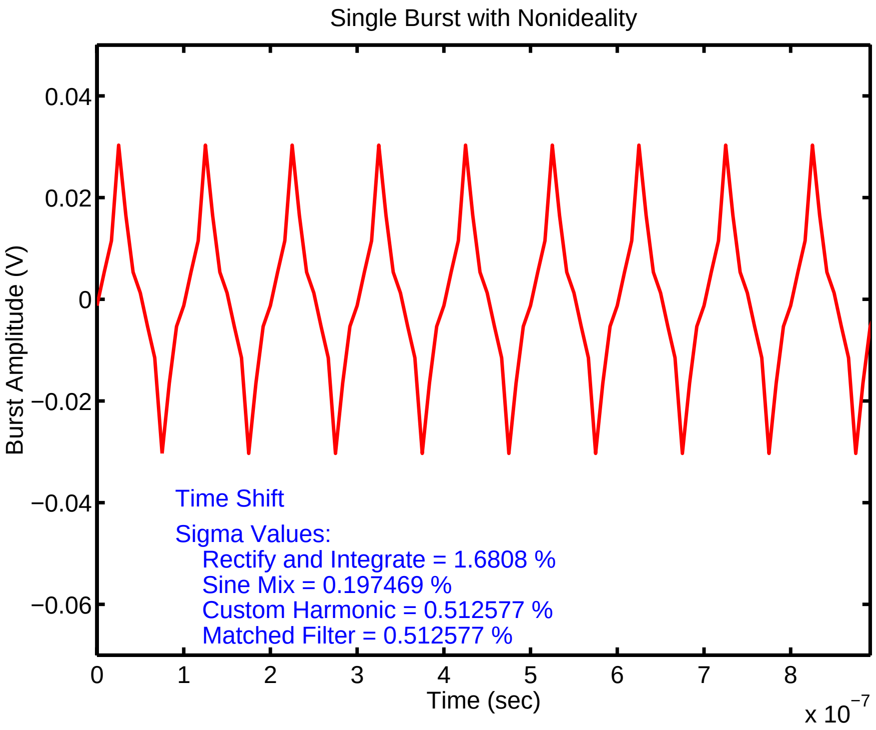




- **Deviation from the nominal second harmonic causes severe errors in rectify & integrate.**
- **Deviation from the nominal second harmonic causes severe errors in matched filter demodulation.**
- **CC Demod ignores it.**

Timing Jitter Must Be Kept Small





- **Coherent demodulation is more sensitive to large timing shifts (5–10nS) than non-coherent demodulation.**
- **Small timing shifts (1 nS) cause little trouble.**
- **Can lock a PLL to recover timing (as done in PRML channels).**
- **Note that Sine Mix is less sensitive than Custom Harmonic to this problem.**
- **In the worst case schenario it is fixable with in-phase and quadrature demodulation.**

Conclusions

- The Customizable Coherent Demodulator has several big advantages over conventional servo demodulation:
  - dramatically better noise immunity
  - immunity to several nonidealities: baseline shift, thermal asperities, and baseline popping.
  - equivalent to rectify and integrate for other nonidealities: drop in, drop out, and digital AMing.
- The cost is a more complicated servo channel design.
- Timing issues commonly dealt with in PRML channels.
- Several implementations are possible
  - fully analog circuitry,
  - fully digital circuitry, or
  - hybrid analog/digital circuitry.
- Appropriate attitude from channel folks: silicon is cheap.