Loran of the Future – On-Air Tests of Some Possible Changes

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We have been looking at "modernizing" Loran

Recent questions:

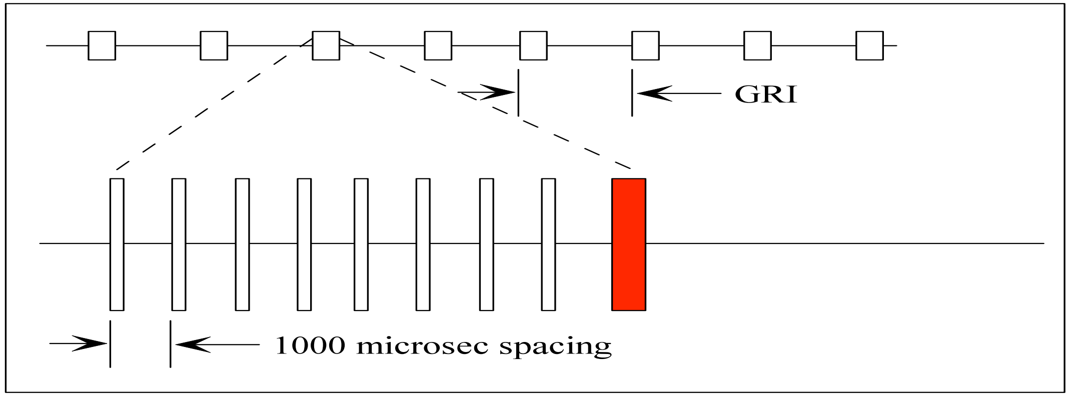
- Since LDC has limited rate (20-40 bps), **how would you increase it?**
- While phase codes allow spectral overlap between chains (CRI), **how significant is it?**

+ Serendipity of some experimental transmitter testing this year at LSU (2 papers tomorrow)

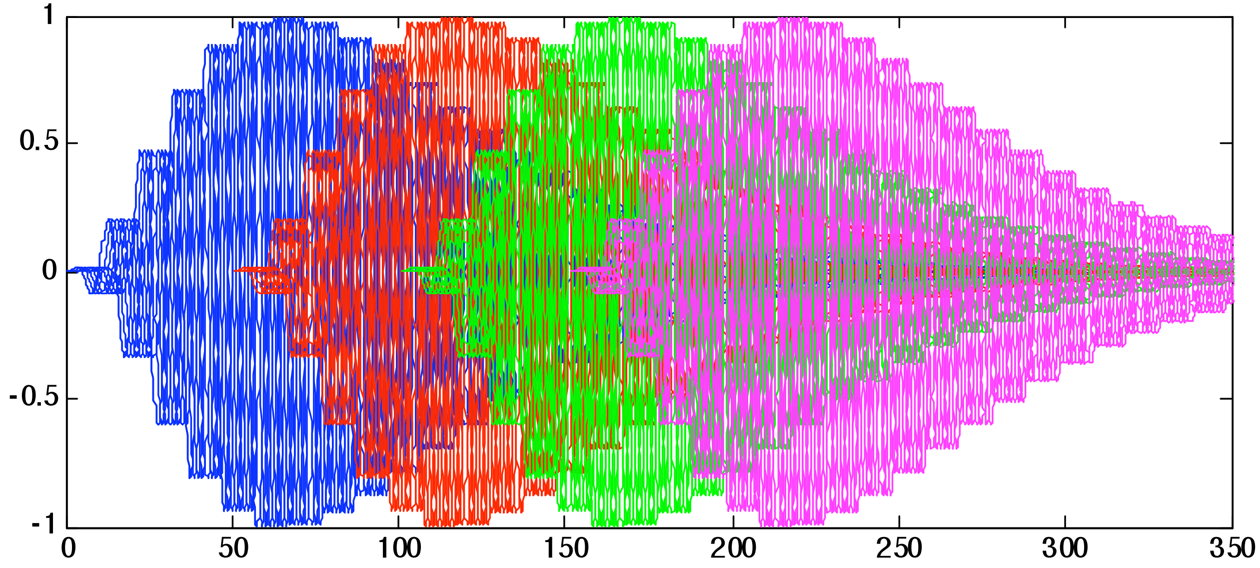
= today's paper

9^{th} Pulse LDC

- Modulation of a single extra pulse
  - 1 “symbol” per group

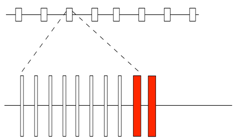


- 32-ary pulse position modulation (PPM)
  - 5 bits/pulse
    - 2 bits of coarse time delay (~50 μsec)
    - 3 bits of fine time delay (~1.25 μsec)

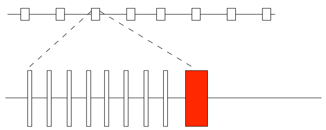


Adding Bits to 9th Pulse

- Add a 10th pulse (BP)
  - 32-ary PPM on each



- More bits on the 9th
  - 6 bits (64-ary PPM)
  - 7 bits (128-ary PPM)



10^{th} Pulse Ideas

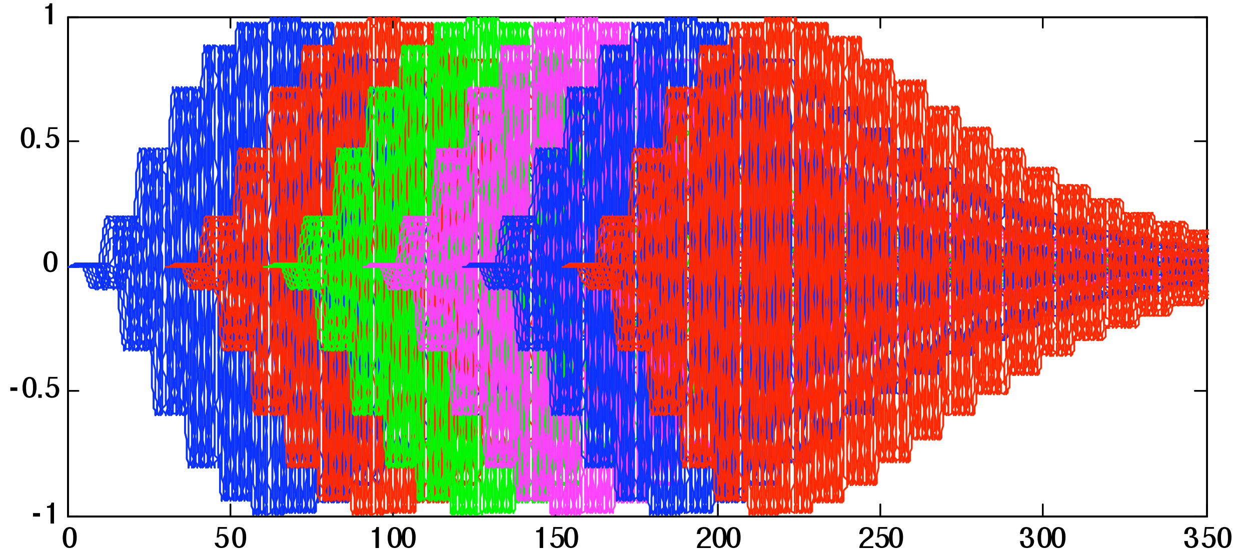
1. Separate codewords for each symbol
   - Correlation of symbol loss due to CRI and blanking
   - Not terribly interesting
2. Pairs of symbols vs "super symbol"
   - Pairs → codeword length of 12 groups
   - Super symbol would be 10 bits !!
   - Shannon Theory view

m-ary 9th Pulse, *m* > 32

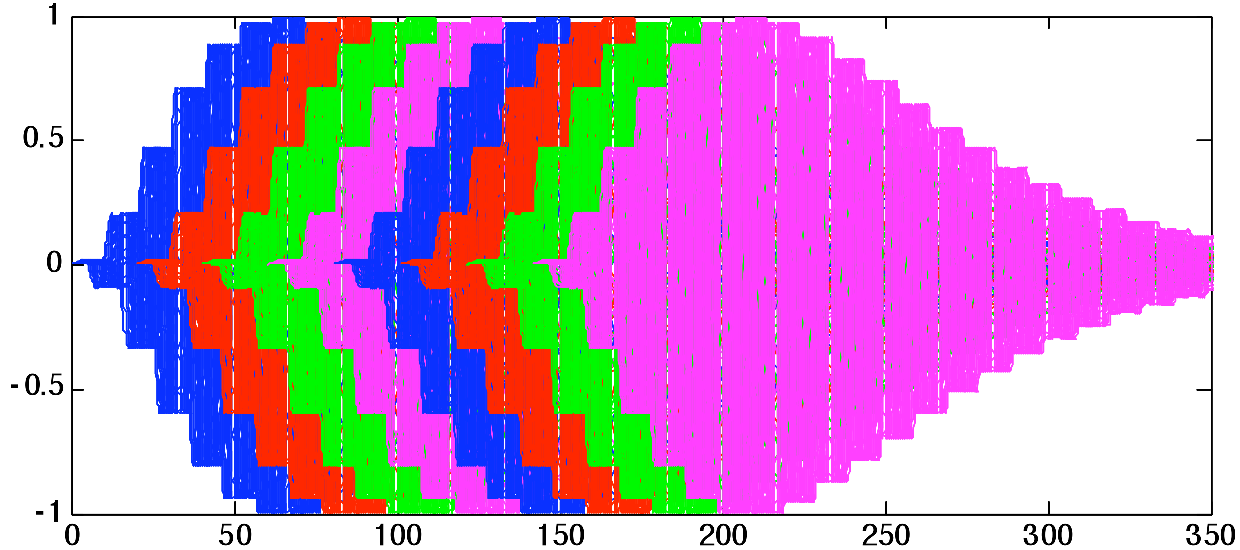
- Add more signals with same fine/coarse spacing
  - Elongated signal window
- Standard digital communications approach
  - Compromise in signal space
  - Modify both coarse and fine time spacing simultaneously

6 and 7 Bit Versions

- 6 x 11



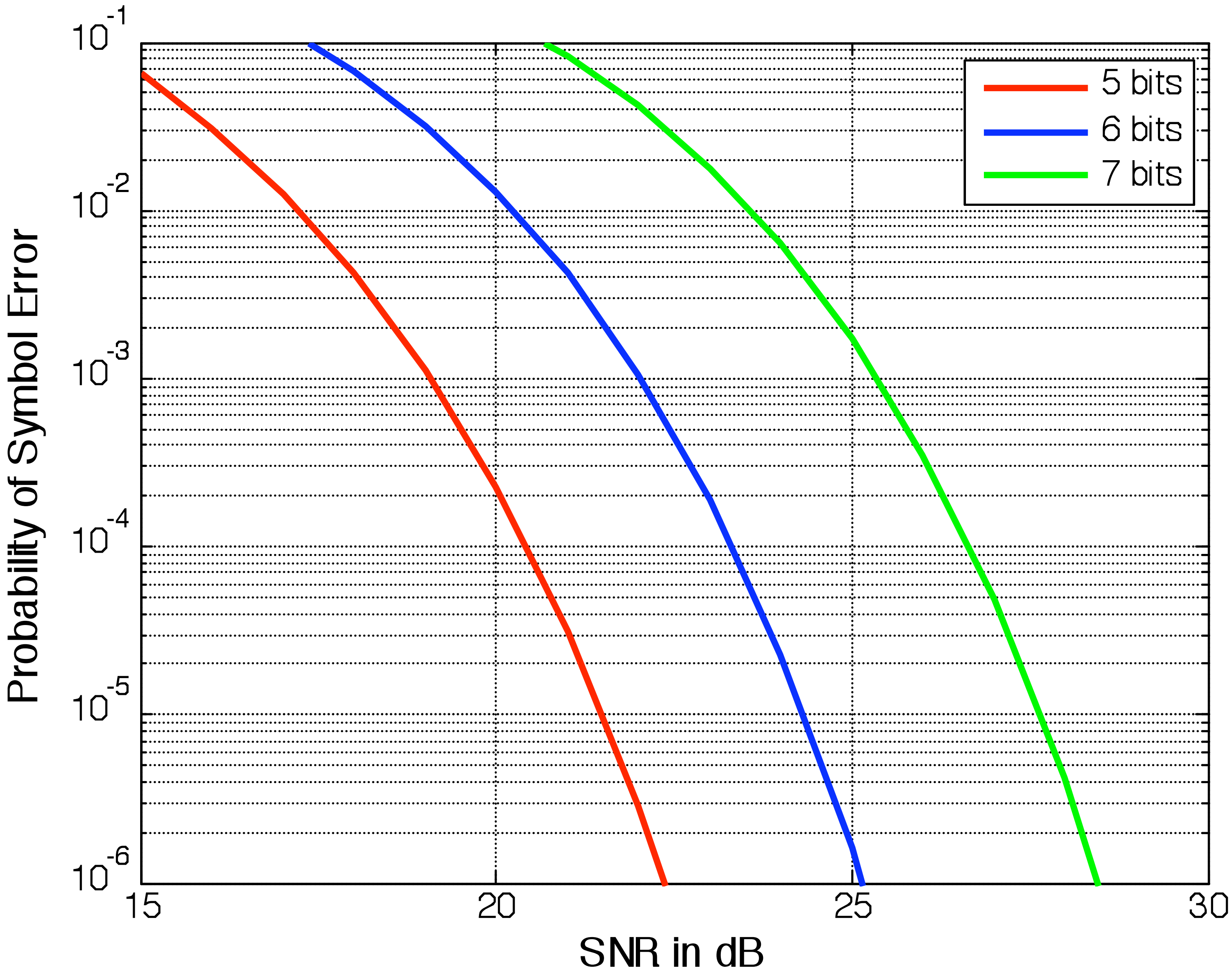
- 8 x 16



- Channel error analysis
  - White Gaussian noise assumption
  - Union bound (γ is the SNR)

$$P_e \leq \frac{1}{m} \sum_{k=1}^{m} \sum_{j \neq i} Q\left(d_{k.j} \sqrt{\frac{\gamma}{2}} \right)$$

  - Useful also for weak CRI analysis



Probability of Symbol Error
SNR in dB
5 bits
6 bits
7 bits
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
15
20
25
30

NAV08/ILA37

Phase Code Analysis

- Frequency domain analysis
  - Loran is periodic on a PCI
  - Fourier Series
    - Start with a single pulse at baseband
    - Add 16 such pulses with phase code and time delays
    - Modulate to 100 kHz
  - Spectral lines with spacing 1/PCI

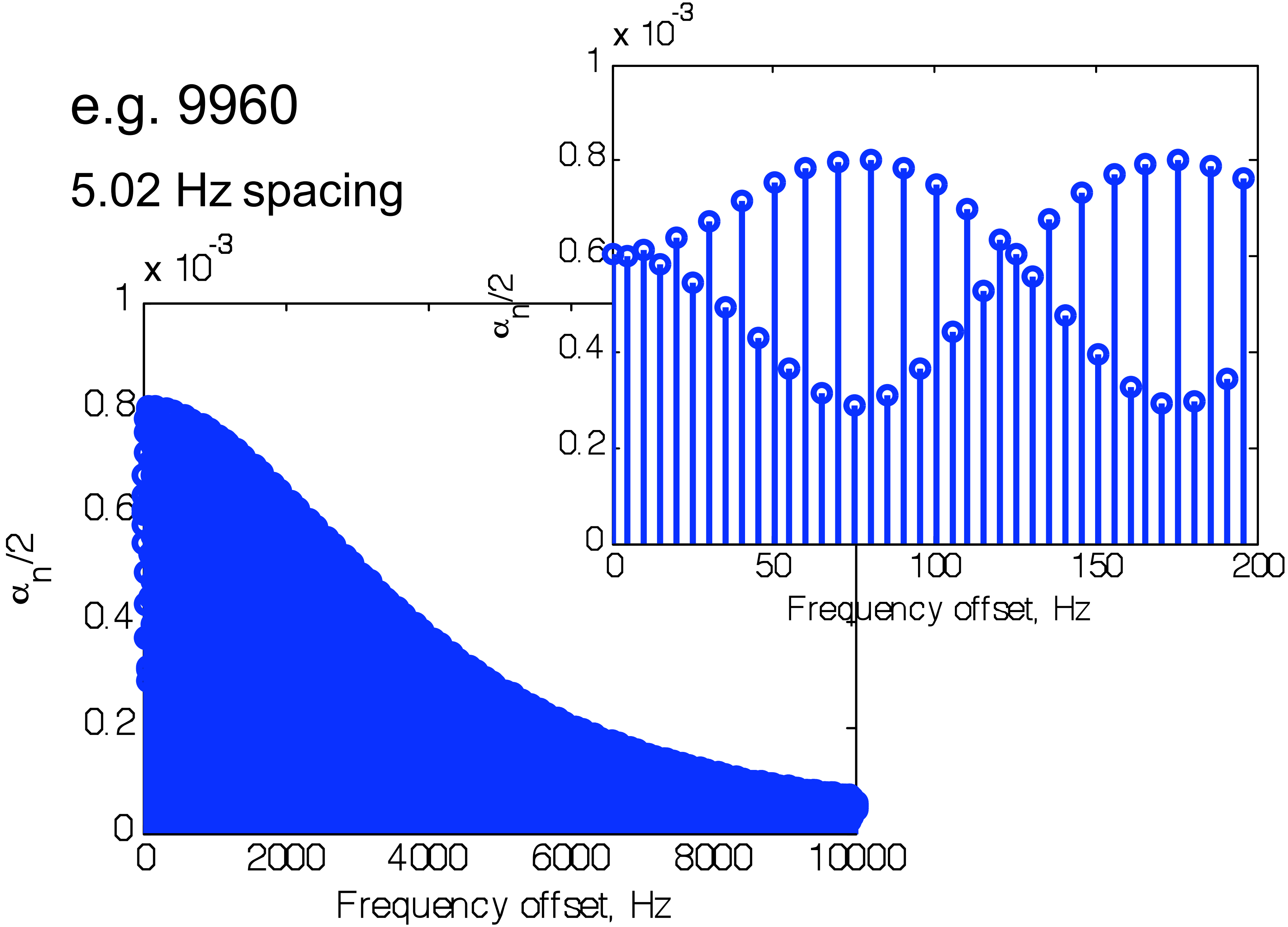
$$s(t) = \sum_n \alpha_n \sin\left(2\pi\left(0.1 + n / PCI\right)t + \beta_n\right)$$

with $d_n = \alpha_n \exp(j\beta_n)$ and

$$d_n = \begin{cases} \dfrac{65e^2 PCI^2}{4\left(PCI + j65\pi n\right)^3}\left[\begin{array}{l} 1 + e^{-j2\pi n 2000/PCI} \\ + e^{-j2\pi n 4000/PCI} - e^{-j2\pi n 6000/PCI} \end{array}\right] & n \text{ even} \\ \dfrac{65e^2 PCI^2}{4\left(PCI + j65\pi n\right)^3}\left[\begin{array}{l} e^{-j2\pi n 1000/PCI} + e^{-j2\pi n 3000/PCI} \\ - e^{-j2\pi n 5000/PCI} + e^{-j2\pi n 7000/PCI} \end{array}\right] & n \text{ odd} \end{cases}$$

e.g. 9960

5.02 Hz spacing



- Result is common spectral lines between two rates
  - Locations depend on gcd of PCIs
- Minimally
  - US: 90, 95, 100, 105, 110 kHz
  - Europe: 100 kHz
- Impact: CRI energy <u>not</u> removed by PCI averaging
  - Need other processing at the receiver

- For a generic phase code $\{b_0 \ldots b_{15}\}$, lines at 5000 Hz spacing have

$$d_n = \frac{65e^2}{4(PCI + j65\pi n)^3}\left(\sum_{k=0}^{7} b_k \pm \sum_{k=8}^{15} b_k\right)$$

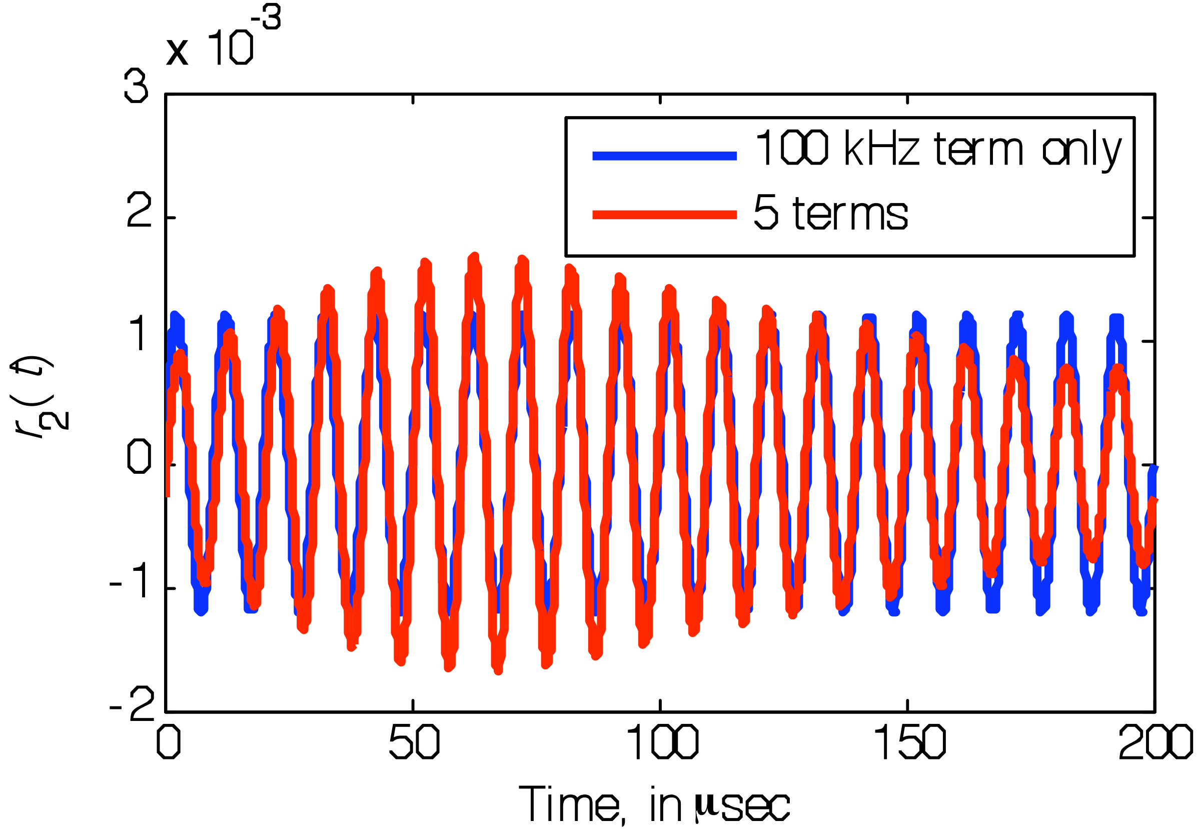
- Using "balanced" phase codes would cancel these lines

$$\sum_{k=0}^{7} b_k = 0, \sum_{k=8}^{15} b_k = 0 \quad \Rightarrow \quad d_n = 0$$

- So, what's left currently?

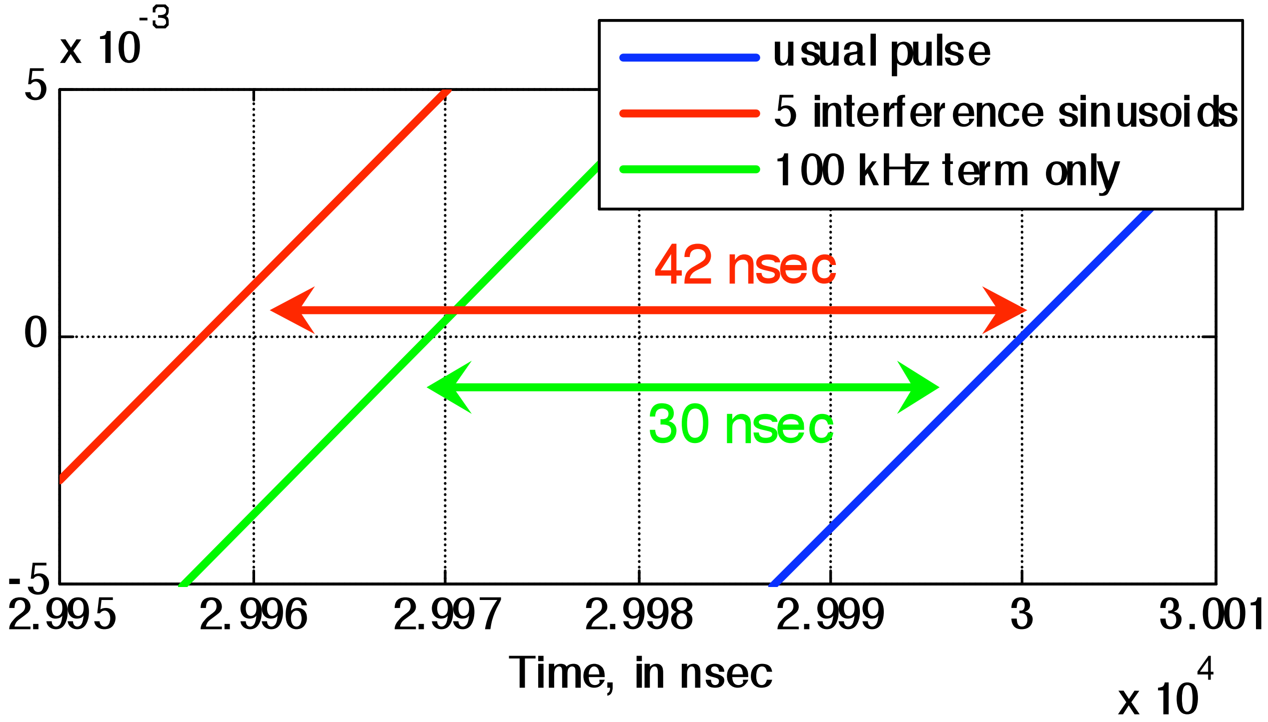
- Residual signal

$$r(t) \approx A \sum_{m=-2}^{2} \alpha_{(m)} \sin\left(2\pi\left(0.1 + 0.005m\right)\left(t + \tau\right) + \beta_{(m)}\right)$$



After PCI averaging, what is the effect at the 30 μsec point?

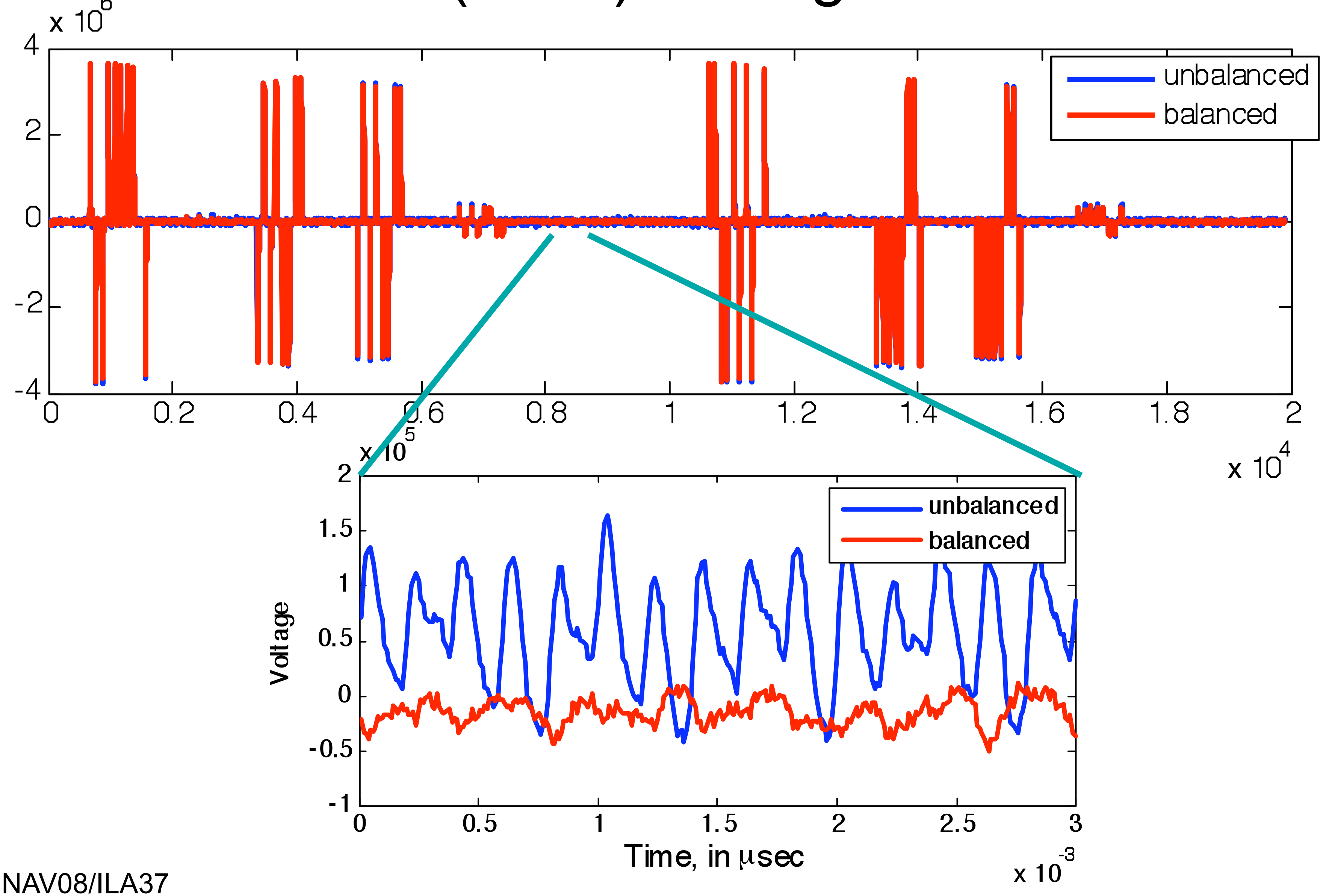
– Example: 20 dB stronger 9960 interferer, worst time offset between rates



On-Air Tests

- Implemented various 9th pulse extensions:
  - 10 pulse
  - 6 bit 9th pulse
  - 7 bit 9th pulse
- Achieved “signal in space”
  - Too little data for accurate error assessment
- Phase code:
  - Implemented current and “balanced” phase codes using test GRI of 5030
  - Collected data for PCI averaging

- 5-minute PCI (9960) average of ACY data



Conclusions/Recommendations

- Want to add bits to LDC?
  - 10th pulse with super symbols
- What about phase codes?
  - Change to a “balanced” version