Advanced Modulation Techniques for Telemetry

A Short Course at the
International Telemetering Conference
Las Vegas, NV • October 24, 2011

Terry Hill, Quasonix

Course Outline

- Historical Perspective
- Performance Metrics
- Modulation Universe
- Life on the Unit Circle
  - ARTM Tier 0
  - ARTM Tier I
  - ARTM Tier II
- Demodulation
- Diversity Combining
- Channel Impairments & Mitigation
  - Adjacent Channel Interference
  - Multipath Propagation
    - Adaptive Equalization
    - Space-Time Coding
  - Forward Error Correction (FEC)
- Performance Comparison & Summary

Evolution of Telemetry

- The Good Ol' Days
  - 1960's to mid-1990's
  - No spectrum shortage
  - Range Commander's Council (RCC) codifies PCM/FM in IRIG 106
- Wireless Everything Era
  - Late 1990's
  - Congress auctions telemetry spectrum to commercial interests
  - Test article complexity and telemetry data payloads balloon exponentially
  - More data, less bandwidth…
  - Now what?

ARTM Program

- Advanced Range Telemetry (ARTM) program, initiated in mid-1990's
- Funded through OSD, CTEIP (Central Test and Evaluation Investment Program)
- Fostered R&D in spectrally efficient modulation techniques
  - Tier I (2 x the spectral efficiency of PCM/FM)
  - Tier II (2.5 x)
- Both Tier I & II adopted by the RCC
  - Fully defined and characterized in IRIG 106-04
  - Latest version (IRIG 106-09): http://www.irig106.org/docs/106-09/

ARTM Deployment

- Receiving infrastructure in place today
  - Edwards AFB
  - Eglin AFB
  - Patuxent River NAS
  - China Lake
  - White Sands
  - Pt. Mugu
  - Vandenberg
  - Kwajalein
- Numerous commercial users
  - Boeing
  - Honeywell
  - Sandia
  - Lawrence Livermore
  - Lockheed Aircraft
  - Lockheed Missiles

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World View of Communications

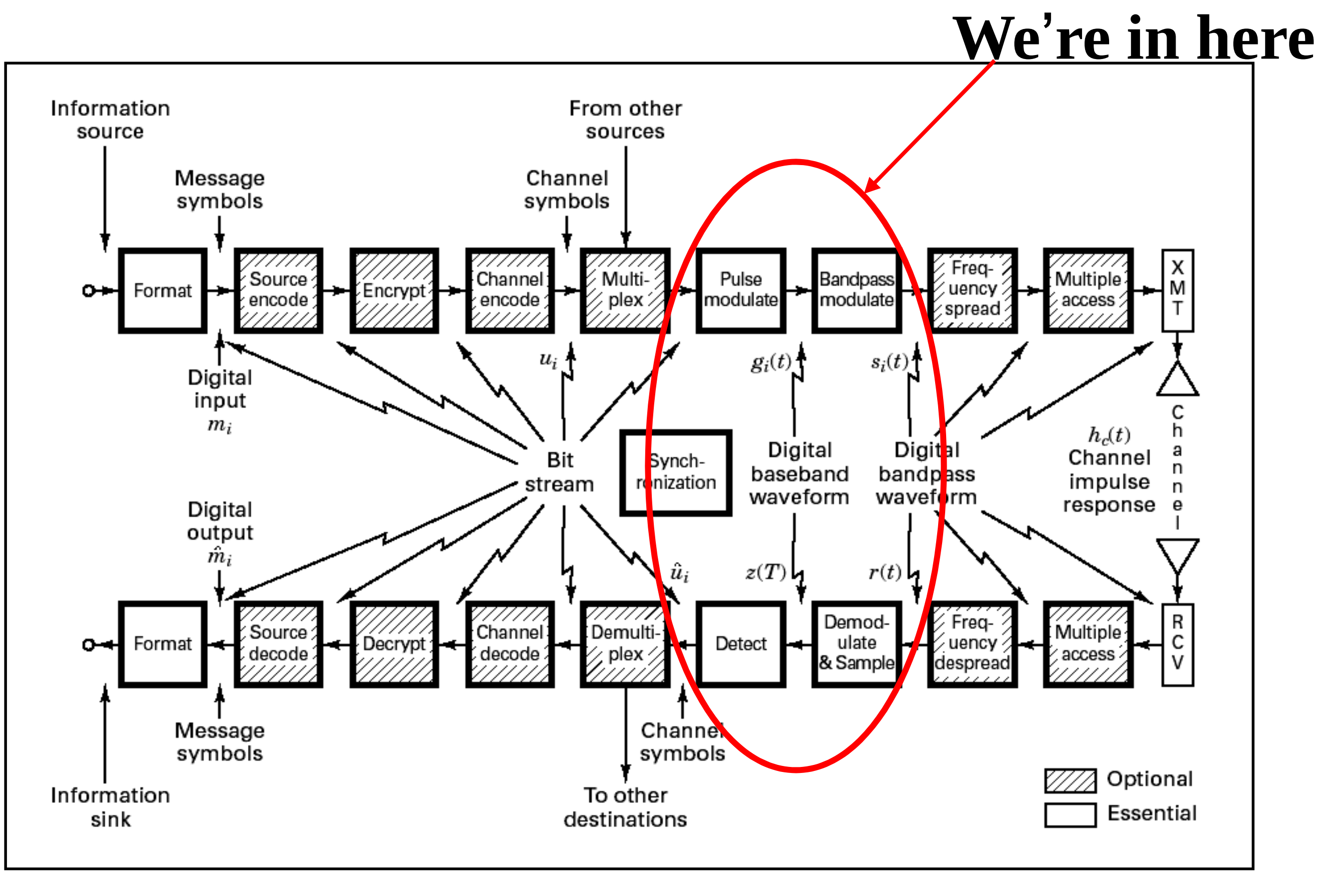


Figure from "Digital Communications: Fundamentals and Applications," by Bernard Sklar, 2nd Edition, Prentice-Hall, 2001. Reprinted by permission of the author.

Performance Metrics

- Information Fidelity
  - Additive White Gaussian Noise (AWGN) channels
    - Bit Error Probability (BEP) or Bit Error Rate (BER)
  - Bursty (dropout) channels
    - Cumulative error count
- Bandwidth Efficiency
  - Power spectral density
  - Fractional Out-of-band Power
  - Channel spacing with adjacent channel interference (ACI)
- Bandwidth-Power plane

Bit Error Rate - in AWGN

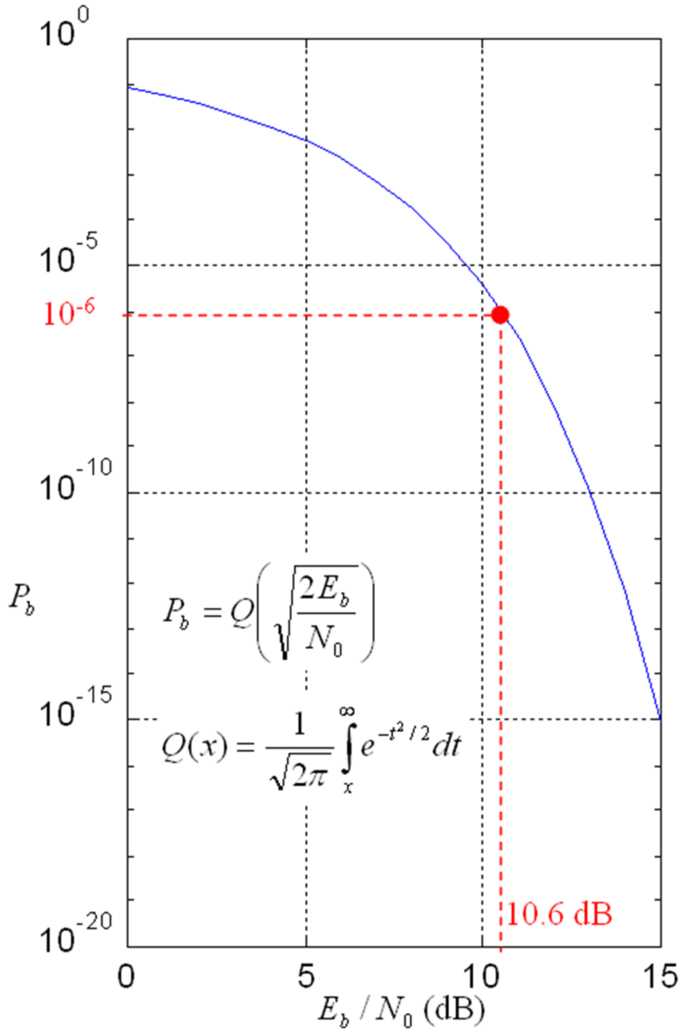
Key Ratio $= \dfrac{E_b}{N_0}$

E_b = signal energy per bit (in Joules/bit or Watt-seconds/bit)
= carrier power × bit time
= $C\,T_b$
= carrier power / bit rate
= C/R_b

N_0 = noise level (in Watts/Hz)
= Boltzmann's constant × Equivalent System Temperature
= $k \times T_{eq}$
= $k \times (F\text{-}1)T_0$ (where F = system noise figure)

In terms of Carrier-to-Noise Ratio C/N:

$$\frac{E_b}{N_0} = \frac{C}{N}\frac{BW}{R_b}$$



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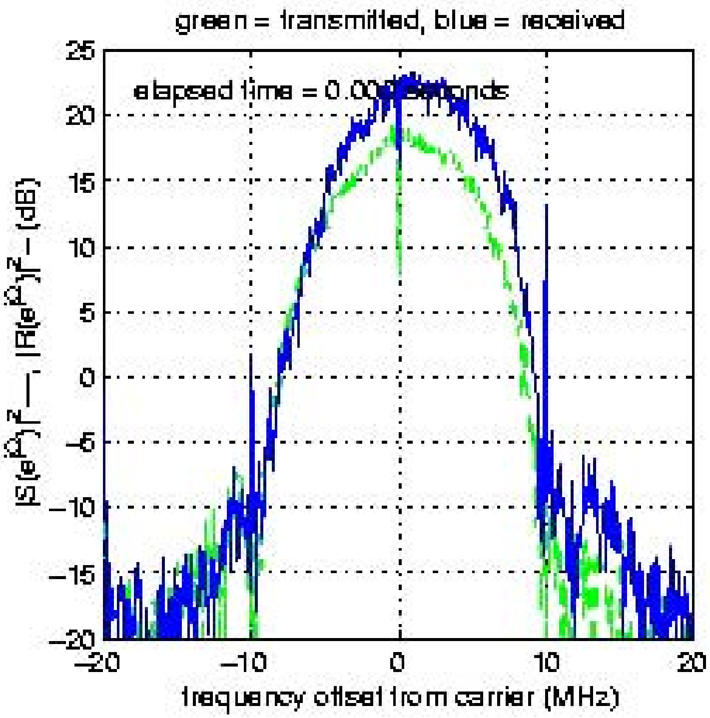
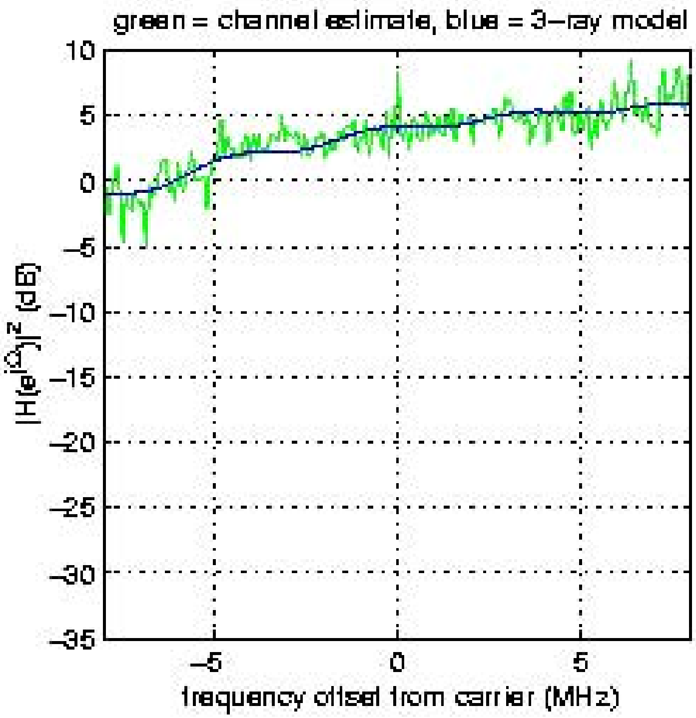
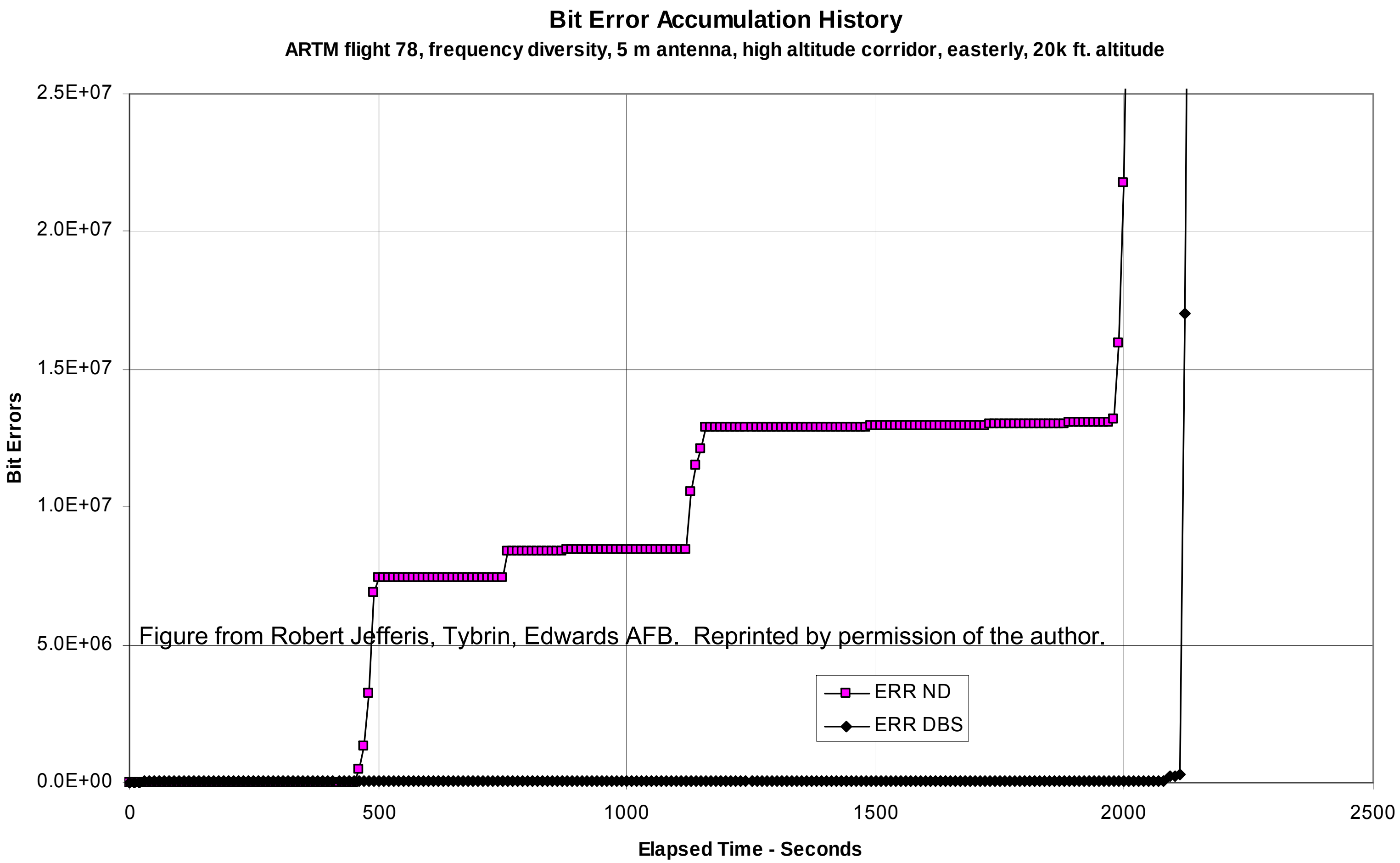
Aeronautical Channels





- From http://www.ee.byu.edu/telemetry/projects/widebandchannel/

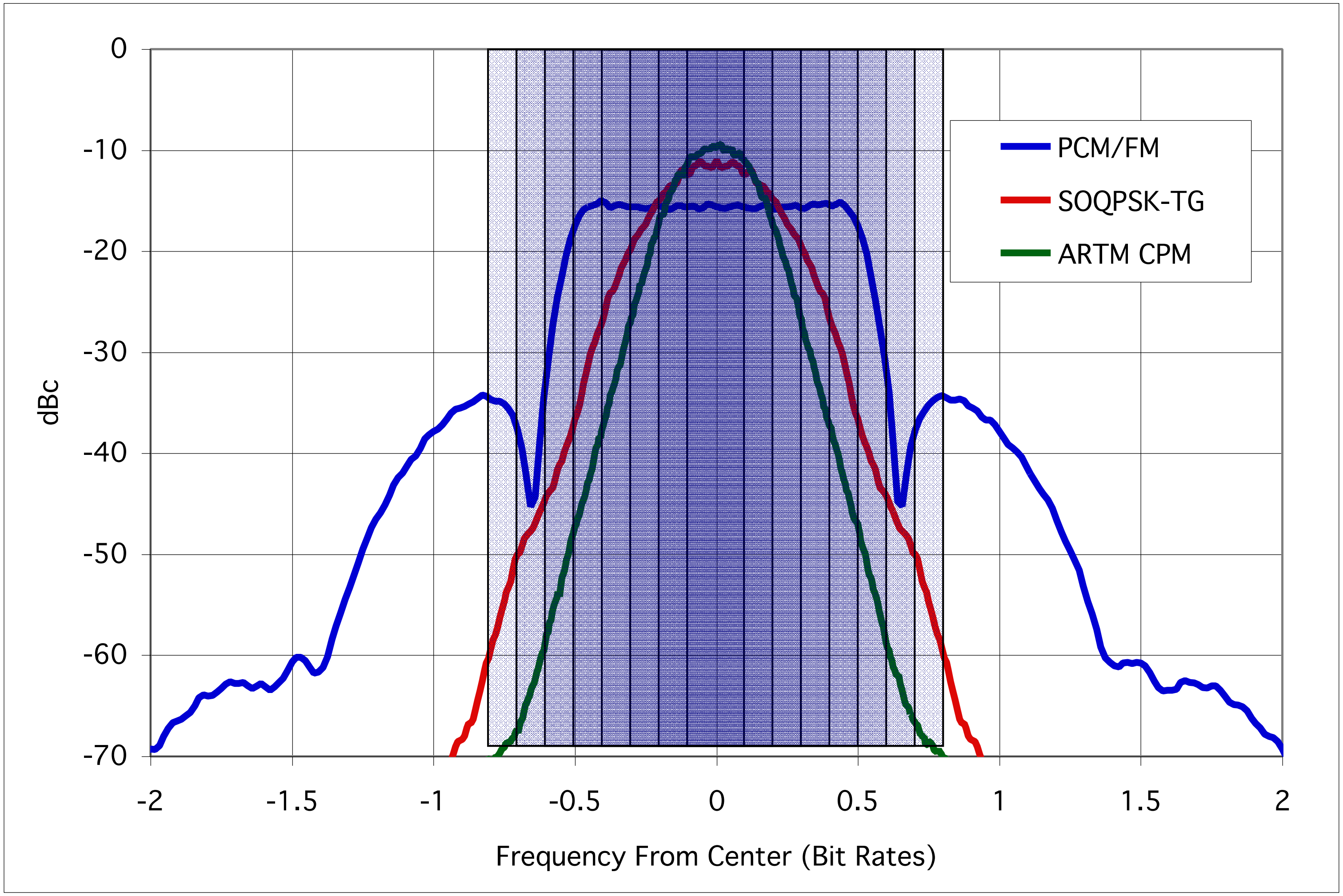
Cumulative Error Counts in Bursty Channels



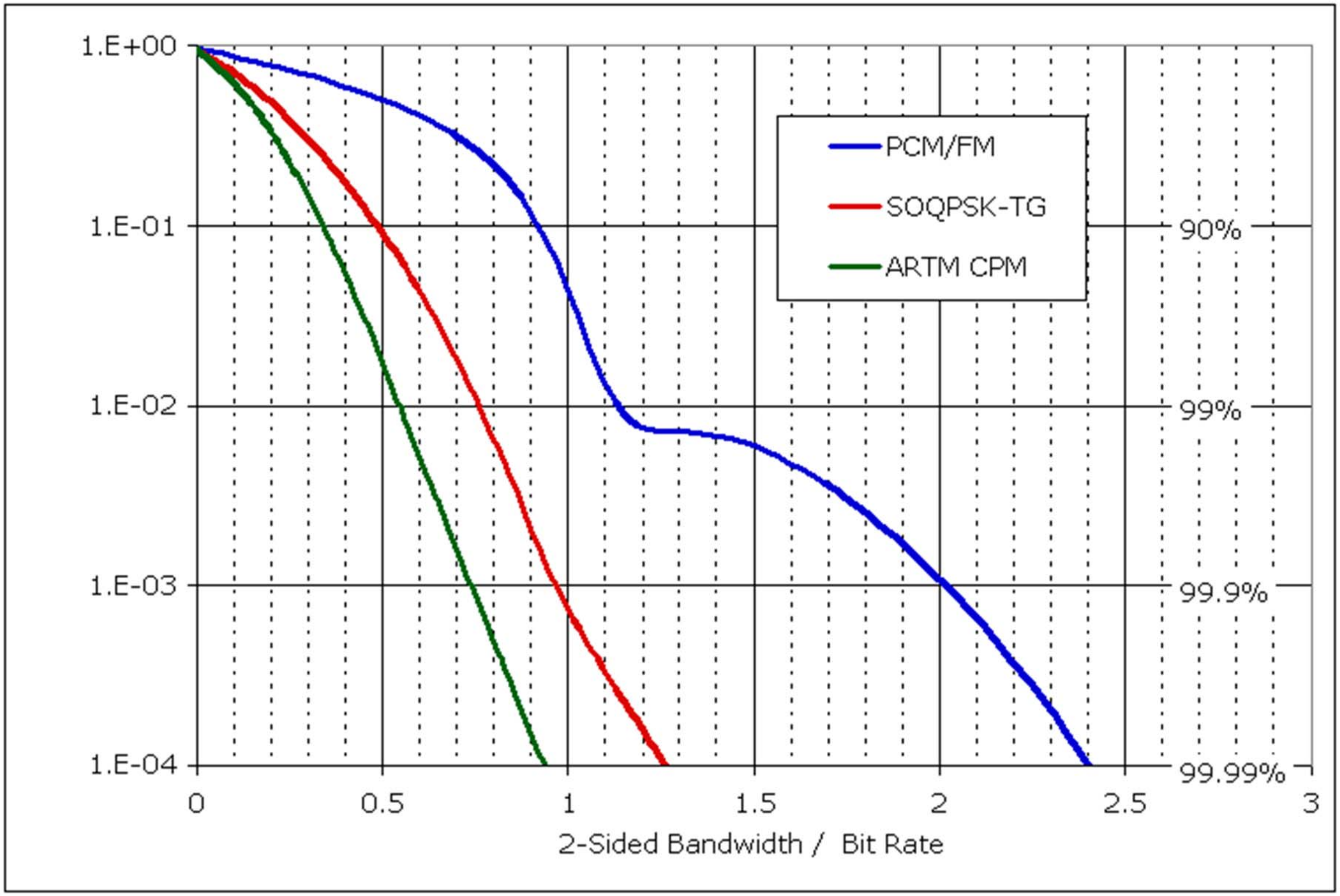
Which Bandwidth?

- Fixed level
  - -60 dBc is common
  - -25 dBm is “standard” in IRIG-106
- Fractional out-of-band power
  - 99%, 99.9%, 99.99% are all used
- Minimum frequency separation
  - Accounts for receive-side effects
    - Receiver IF filtering
    - Demodulator interference tolerance
    - Relative levels of interfering signals
    - Depends on application

Power Spectral Density (PSD)



Fractional Out-of-band Power



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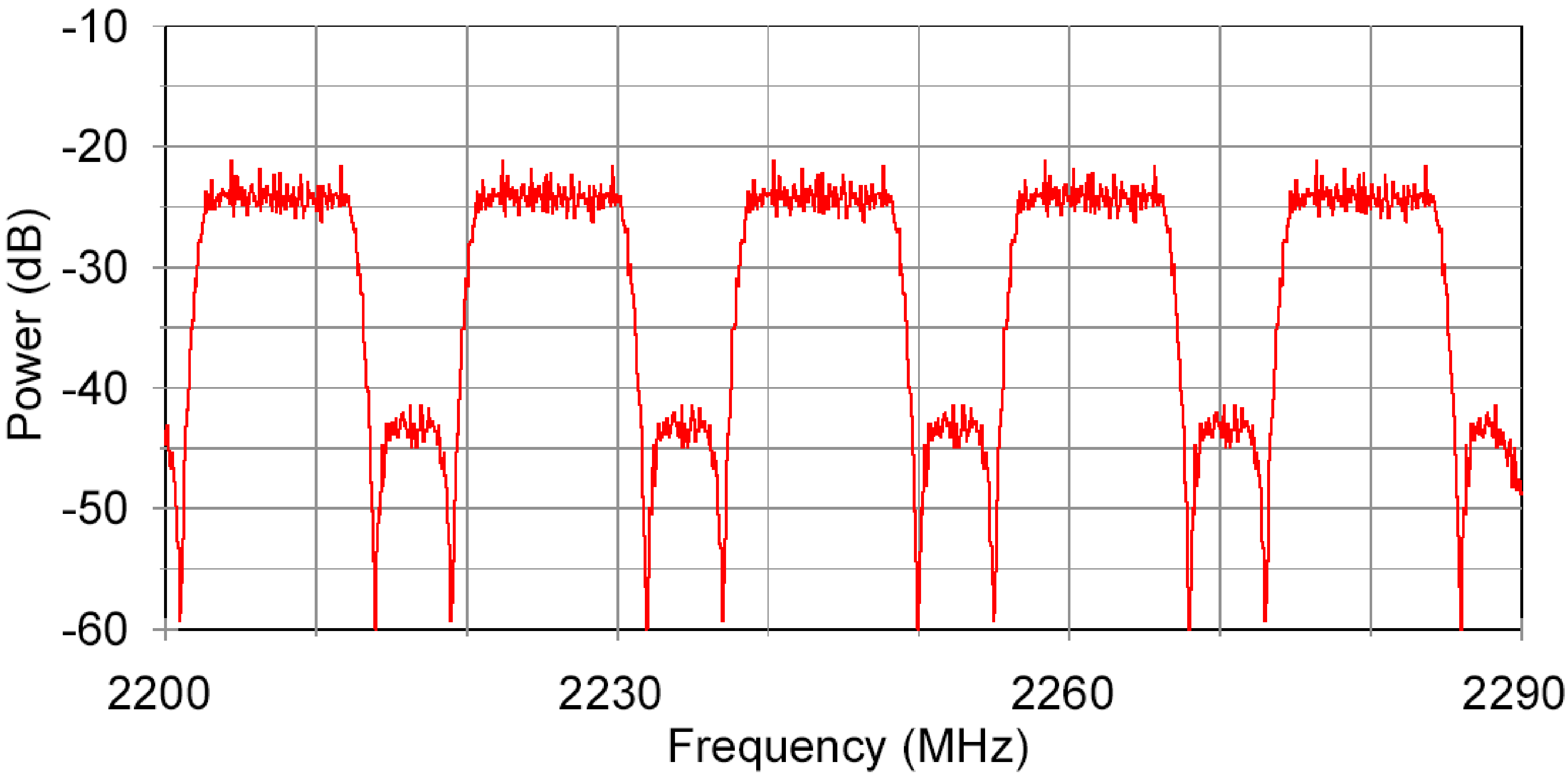
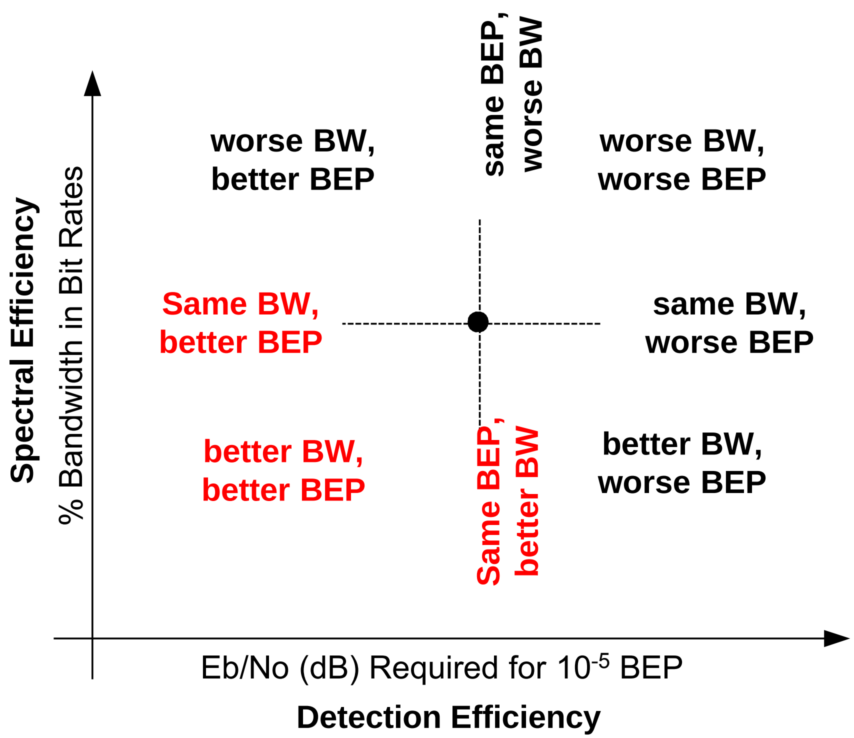
Channel Spacing



Bandwidth-Power Plane

- Simultaneous representation of
  - Bandwidth Efficiency (Bandwidth normalized to Bit Rate)
  - Power Efficiency (Eb/No required to achieve 10^{-5} BEP)



Bandwidth-Power Tradeoffs

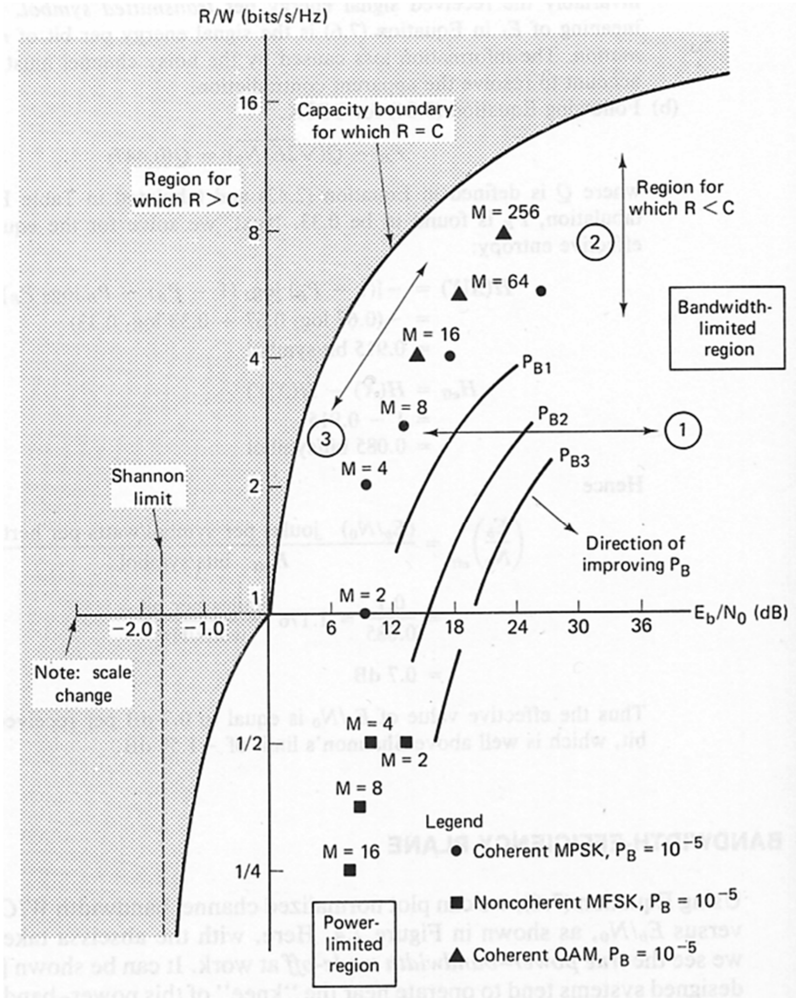


Figure 7.6 Bandwidth-efficiency plane.

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The Modulation Universe

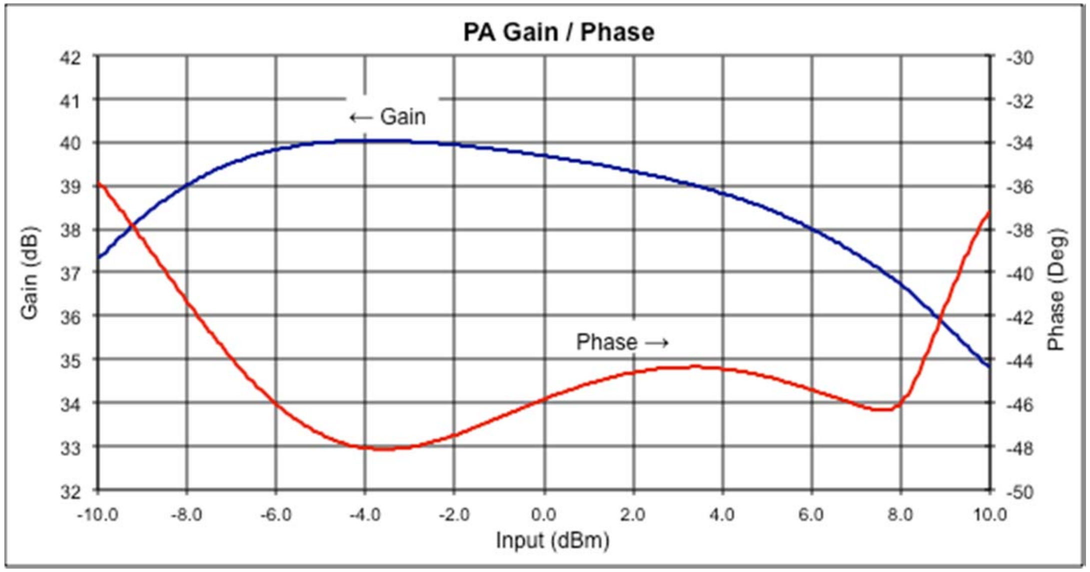
- Analog, Digital
- Amplitude modulation
- Quadrature amplitude modulation
- Angle modulations
  - Frequency modulation
  - Phase modulation

Angle Modulations

- Includes both frequency modulation and phase modulation
- Some have an amplitude modulation component
  - BPSK
  - QPSK
  - Offset QPSK
- Some are constant envelope
  - Binary FM
    - FSK, MSK, premod filtered MSK, GMSK
  - M-ary FSK
  - SOQPSK
  - Multi-h continuous phase modulation
  - No amplitude variation
- Saturated power amplifiers are ideal for <u>constant envelope waveforms</u>

Saturated Power Amplifiers

- DC-to-RF conversion efficiency is important
  - Minimizes cooling requirements
  - Maximizes battery life
- Maximizing efficiency demands nonlinear operation
- Non-linear operation creates AM-AM and AM-PM conversion:



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Constant Envelope Modulations

- Before ARTM (Tier 0)
  - PCM/FM
  - “Legacy” waveform for telemetry
- Advanced Range Telemetry (ARTM) Program
  - ARTM Tier 1
    - Proprietary Feher-patented FQPSK
      - FQPSK-B, Revision A1
      - FQPSK-JR
    - SOQPSK-TG
      - Equivalent in performance to FQPSK
      - Non-proprietary
  - ARTM Tier 2
    - Multi-h CPM (M=4, L=3RC, h1 = 4/16, h2 = 5/16)
- PCM/FM, SOQPSK and Multi-h CPM are all <u>continuous phase modulations</u>

CPM Notation and Parameters

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)d\tau \quad -\infty < t < +\infty$$

- Where α_i represents an M-ary symbol sequence
  - α_i derived from input bits d_i
- h is the modulation index
- g(t) is the frequency pulse shape in the interval 0 < t < LT
  - L = 1 is "full response" signaling
  - L > 1 yields "partial response"
- CPM is a modulation with memory due to the constraint of continuous phase. Further memory is introduced with L > 1.

Key Parameters

- M – Order of Modulation (2-ary, 4-ary, etc.)
- g(t) - Frequency Pulse (Rectangular, Raised Cosine, etc.)
- L – Length of Frequency Pulse
- h – Modulation Index
- Increase Spectral Efficiency by
  - Increasing M
  - Reducing h
  - Increasing L
  - Choosing Smoother Frequency Pulse Shape
- In general, increasing spectral efficiency decreases detection efficiency

CPM Tradeoffs

- To reduce bandwidth of a CPM signal, the phase transitions must be smoothed by:
  - Requiring phase to have more continuous derivatives
  - Spreading the phase change over more intervals (i.e., L > 1)
  - Reducing h
- The shape of g(t) determines the smoothness of the information-carrying phase
- An endless variety of CPM schemes can be obtained by choosing different g(t) pulse shapes and varying the parameters h and M.

Frequency Pulse Shapes

- LREC - Rectangular pulse, length L
  - L=1, h = 0.5 gives MSK
- LRC - Raised cosine, pulse length L
  - Time domain RC pulse
- LSRC - Spectral raised cosine, length L
  - Spectral domain RC filter response
- TFM - Tamed FM
- GMSK - Gaussian shaped MSK

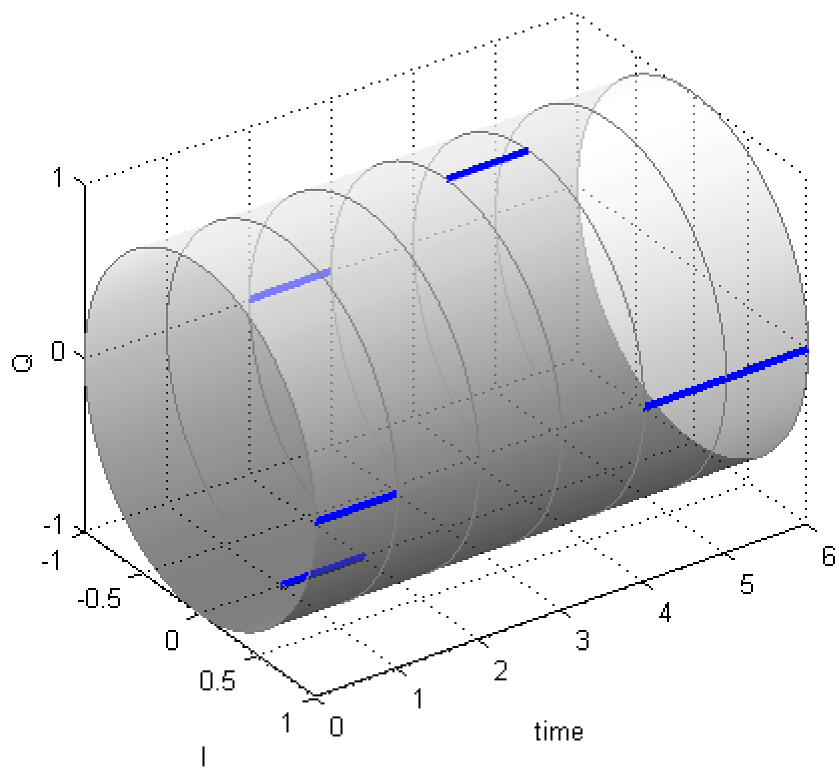
CPM Characteristics

- Continuous Phase
- Constant envelope
- Signals are described by their phase trajectories
  - Phase tree representation is complete
- PSD and BER can be “traded” by
  - Varying h, modulation index
  - Changing g(t), the frequency pulse shape
- Phase trellis decoder is optimum for any variant of CPM
- Footnote
  - FQPSK-B (Revision A1) is not a CPM waveform because of its AM component; i. e., requires I/Q implementation
  - FQPSK-JR is constant envelope, so it could be described in CPM terminology, but this raises patent issues

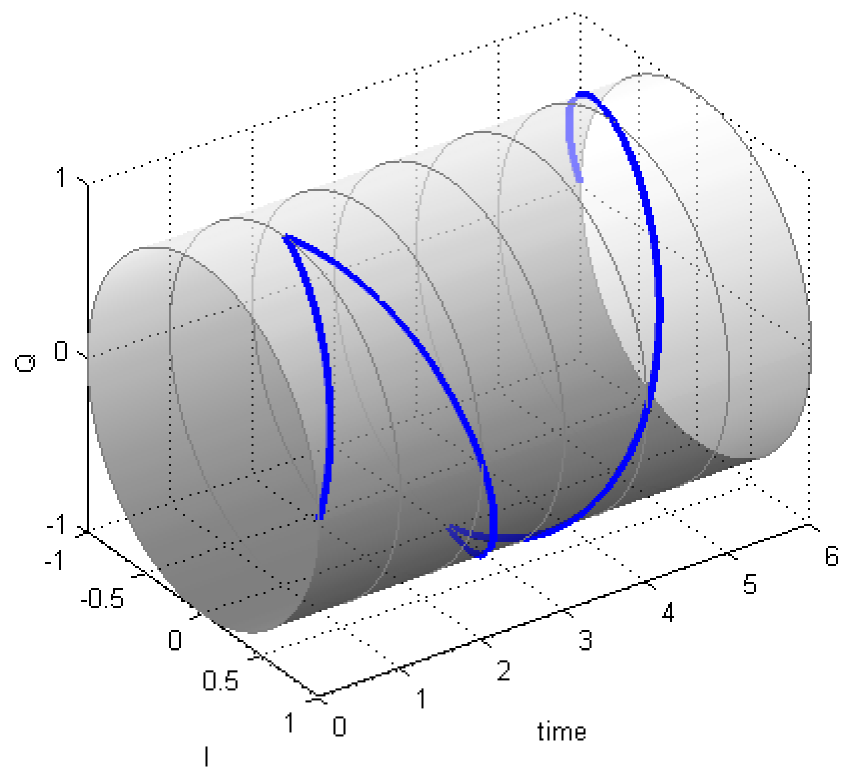
CPM Examples

- Minimum Shift Keying (MSK)
- Gaussian MSK (GMSK)
  - GSM Cell phones (Europe)
- SOQPSK
  - UHF SATCOM (MIL-STD-188-181A, -181B(draft), -182A, -183A)
  - -TG (IRIG 106-04)
- FQPSK (or very similar)
- “CPM”
  - Nearly unlimited variation

QPSK and CPM



QPSK



CPM

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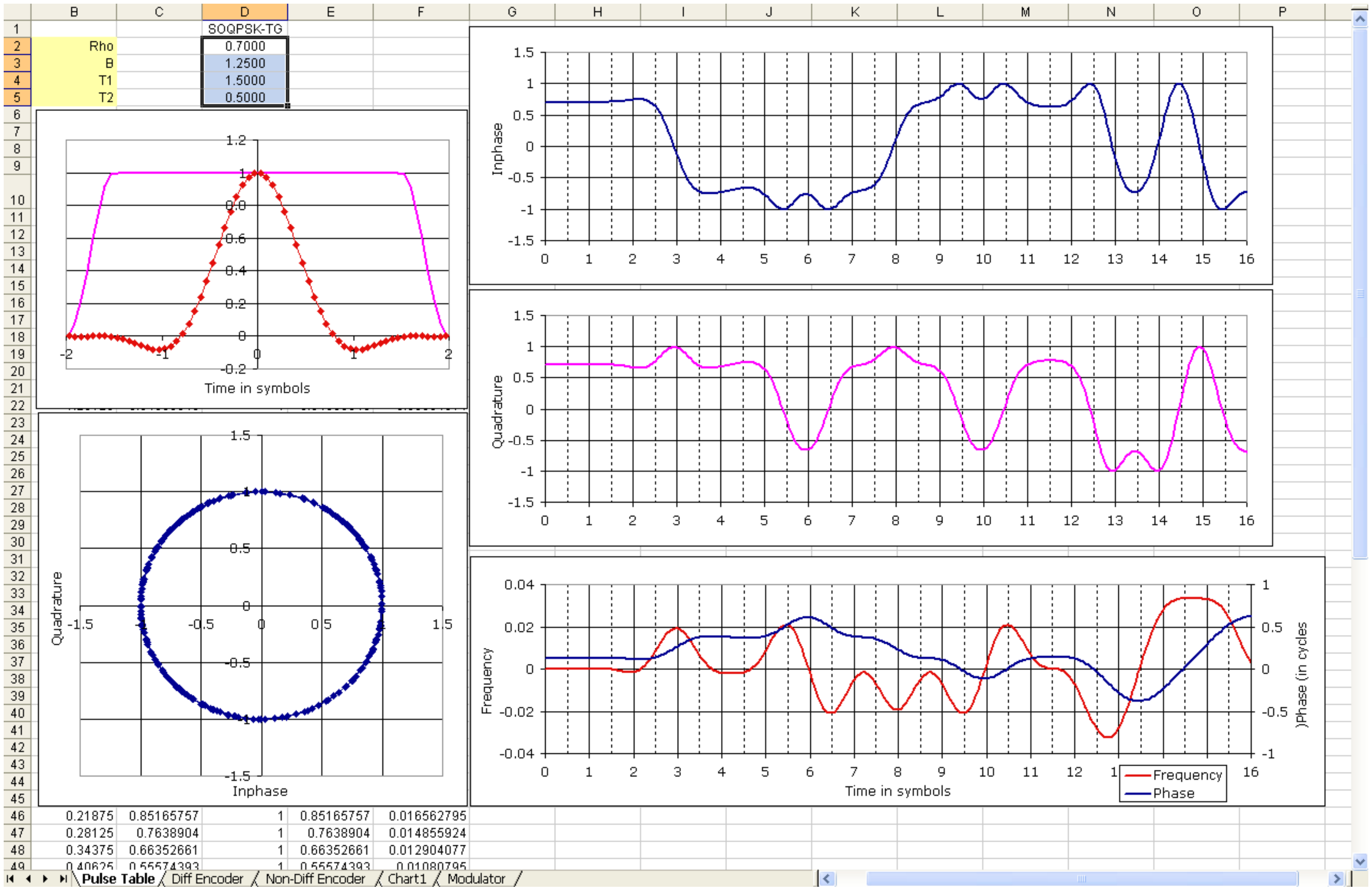
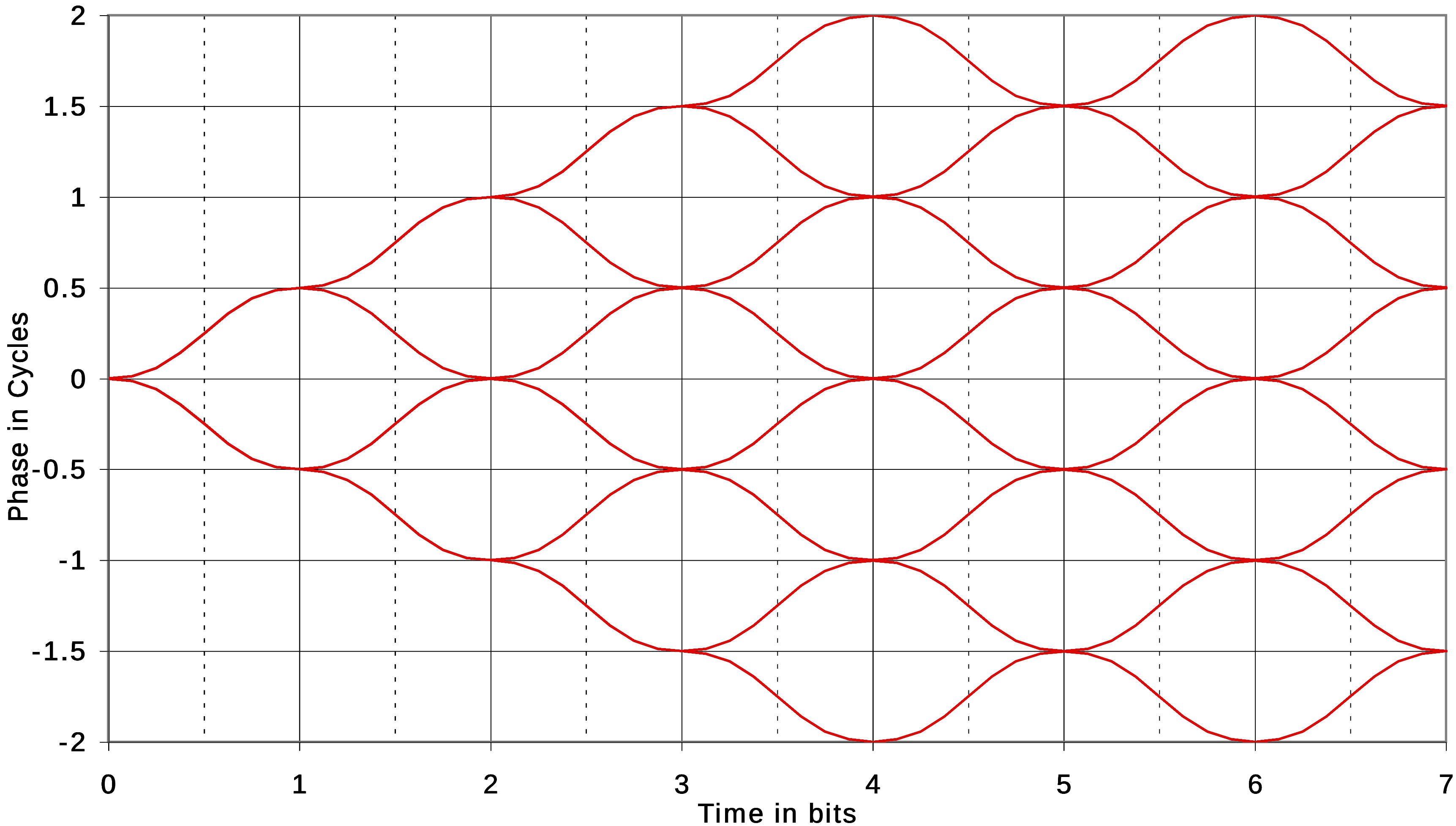
SOQPSK-TG as a CPM Example

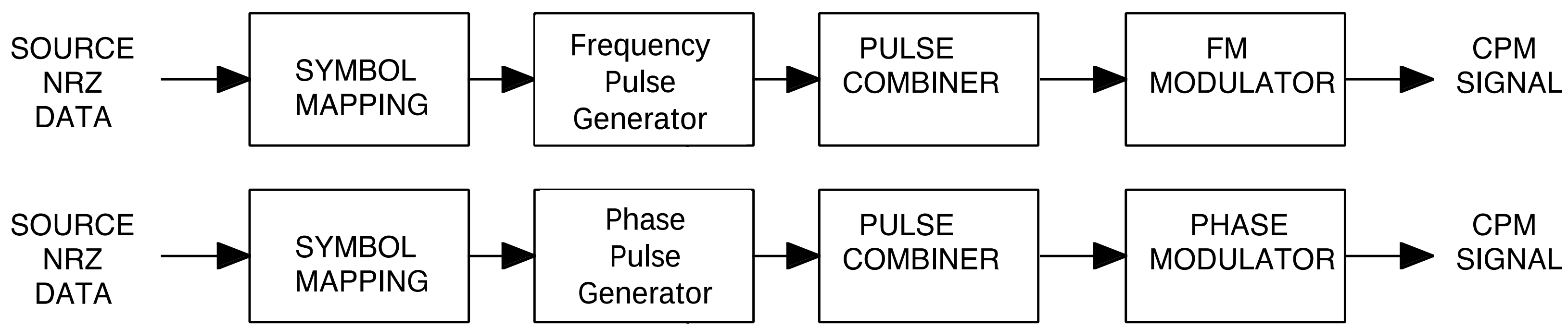


Phase Tree Representation



Modulator Designs

- Angle modulators
  - Combine frequency pulses and apply to frequency modulator.
  - Combine phase pulses and apply to phase modulator.



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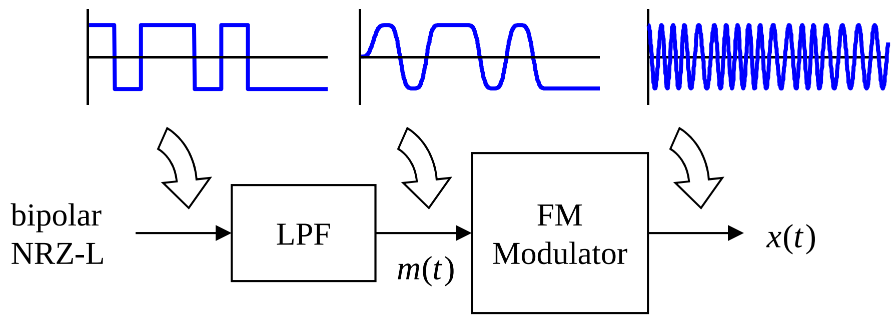
CPM as Frequency Modulation



$$x(t) = A\cos\left(2\pi f_0 t + \phi(t)\right)$$

time-varying phase

$$\phi(t) = 2\pi f_d \int_{-\infty}^{t} m(\lambda)\,d\lambda$$

frequency is the time-derivative of the phase
since the phase is proportional to the integral of $m(t)$, the frequency is proportional to $m(t)$.

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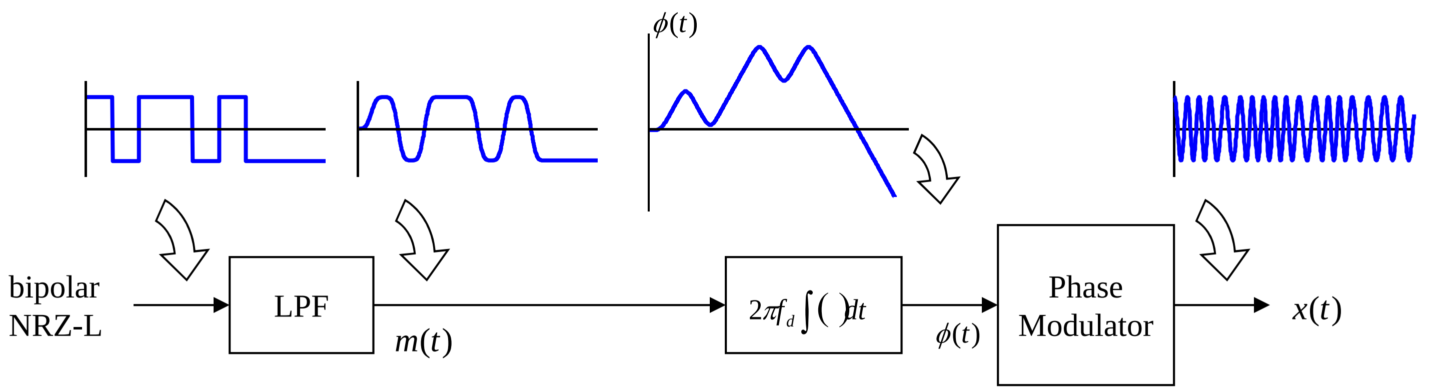
CPM as Phase Modulation



$$x(t) = A\cos\left(2\pi f_0 t + \phi(t)\right)$$

CPM as QAM

The Equations

Apply the trigonometric identity

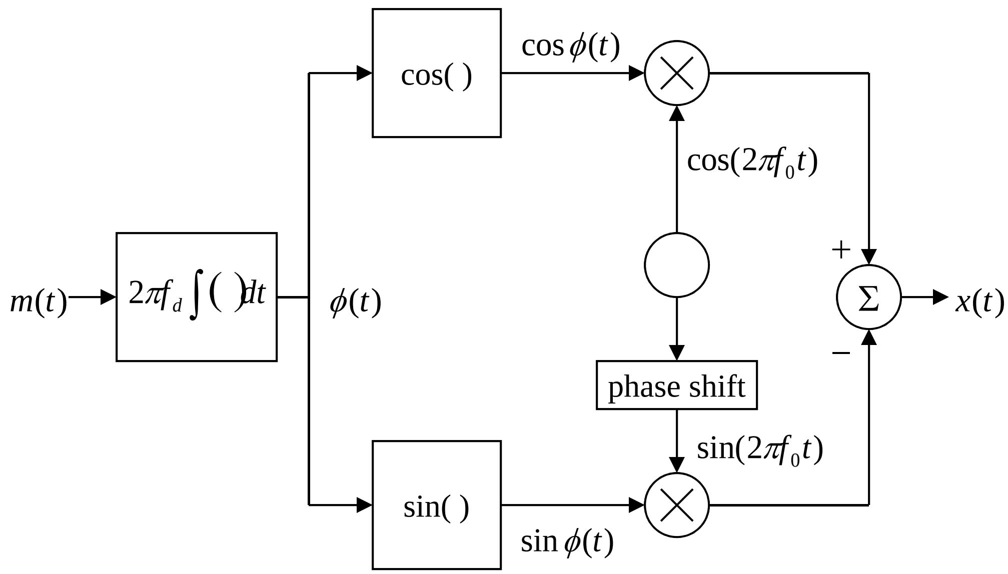
$$\cos(X+Y) = \cos X \cos Y - \sin X \sin Y$$

to our expression for the CPM modulated carrier:

$$\begin{aligned} x(t) &= A\cos(\underbrace{2\pi f_0 t}_{X} + \underbrace{\phi(t)}_{Y}) \\ &= A\cos(2\pi f_0 t)\cos(\phi(t)) - A\sin(2\pi f_0 t)\sin(\phi(t)) \\ &= A\cos(\phi(t))\underbrace{\cos(2\pi f_0 t)} - A\sin(\phi(t))\underbrace{\sin(2\pi f_0 t)} \end{aligned}$$

"quadrature carriers"

What the Equations Tell Us to Build



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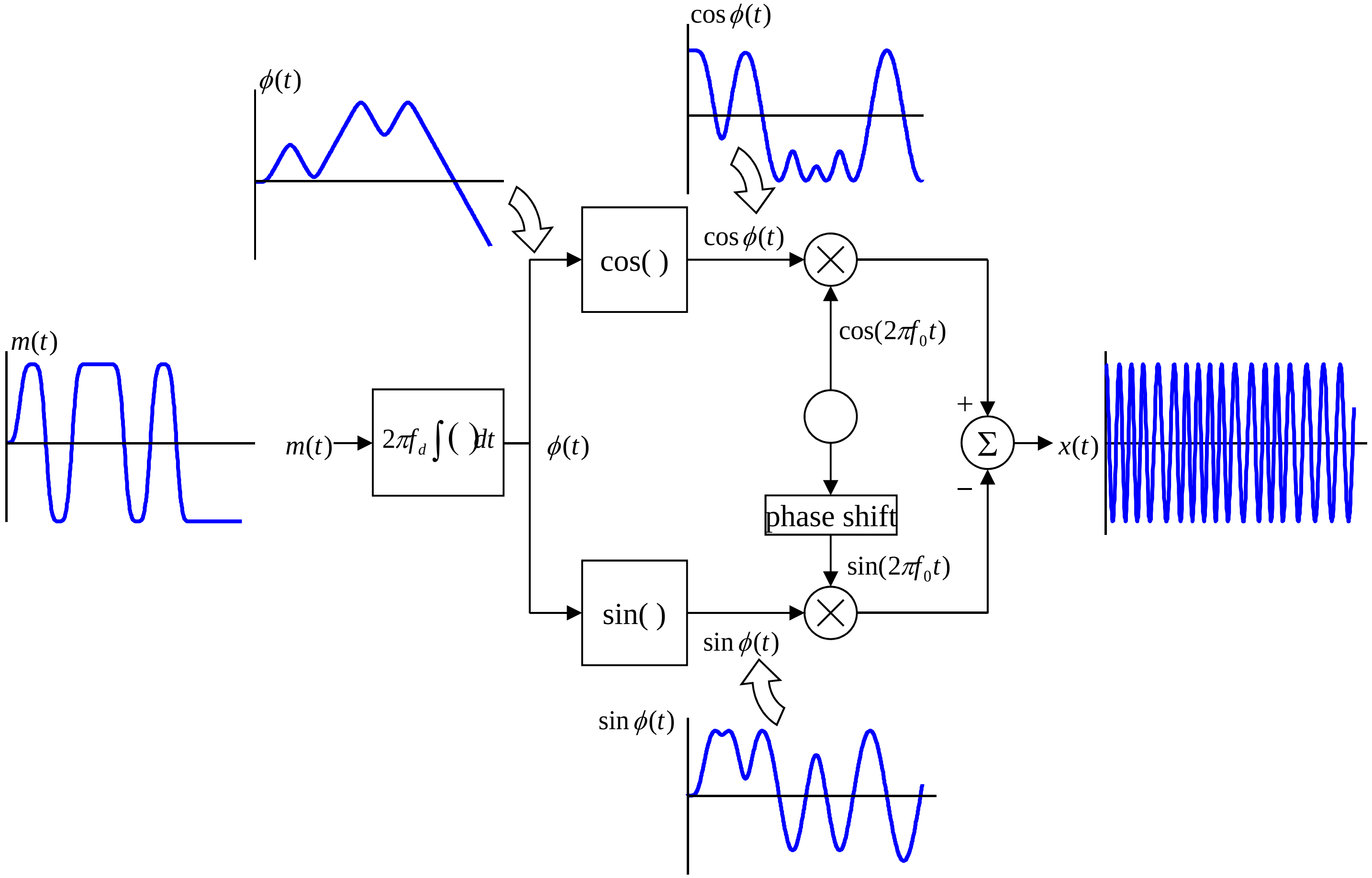
CPM Quadrature Signals



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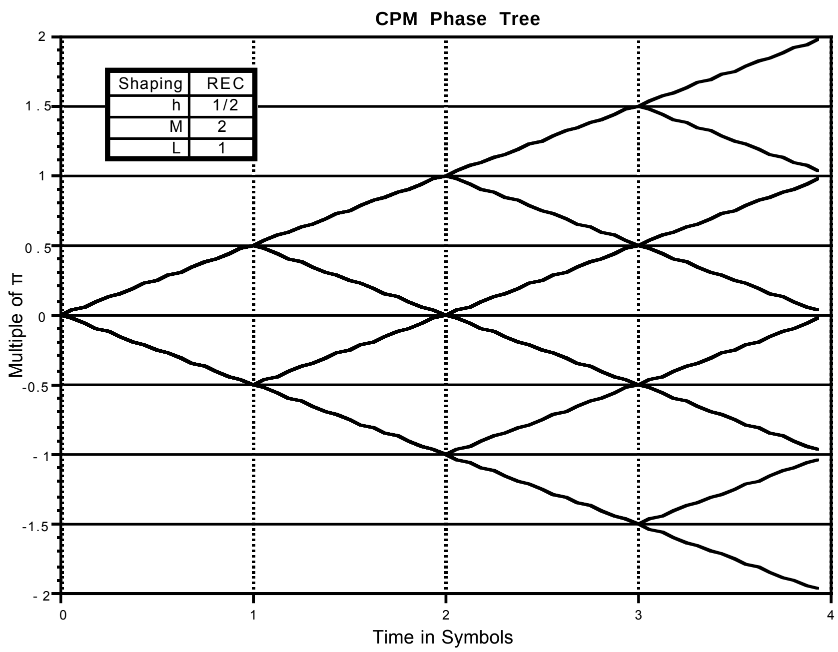
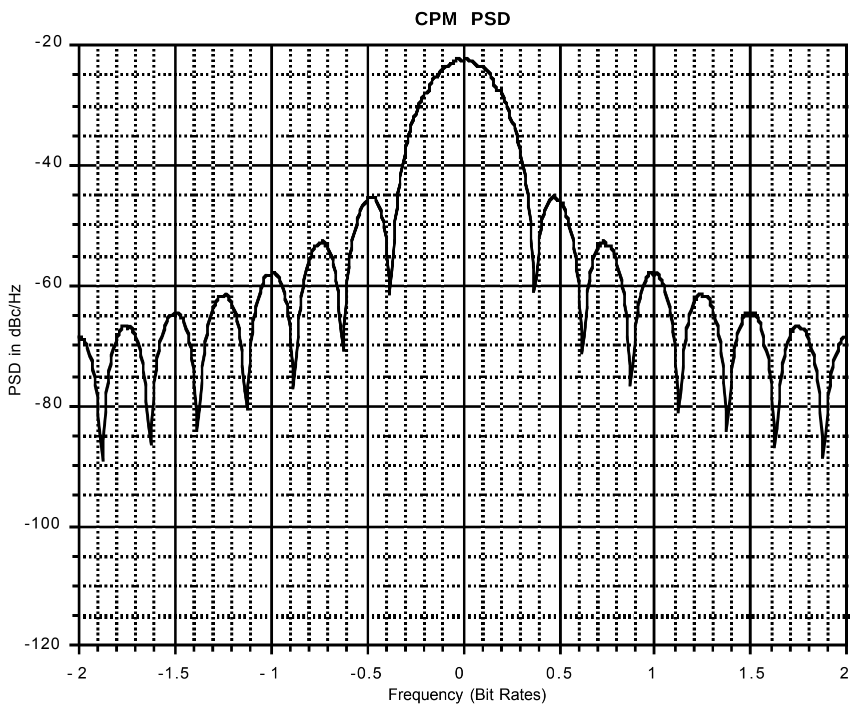
M=2, h=1/2, 1REC (MSK)

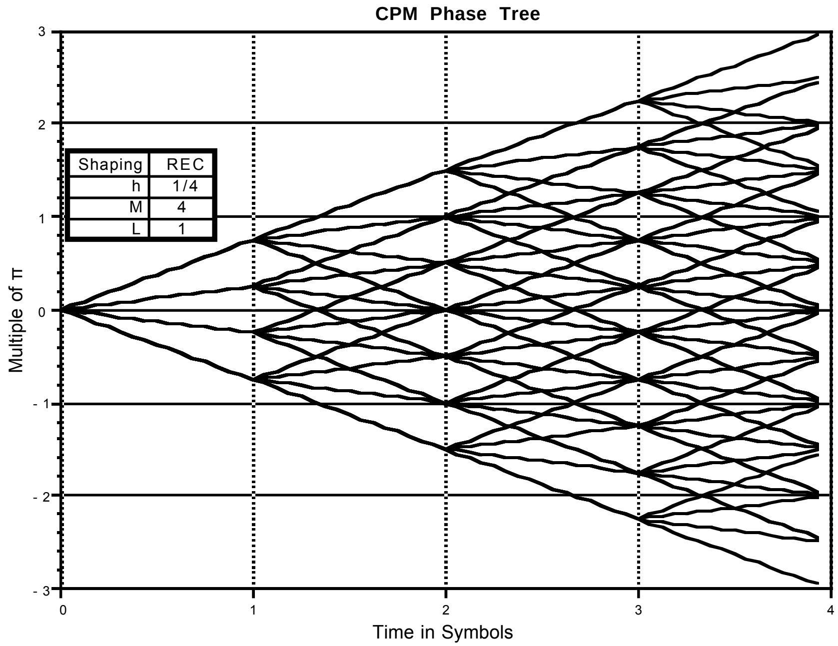
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

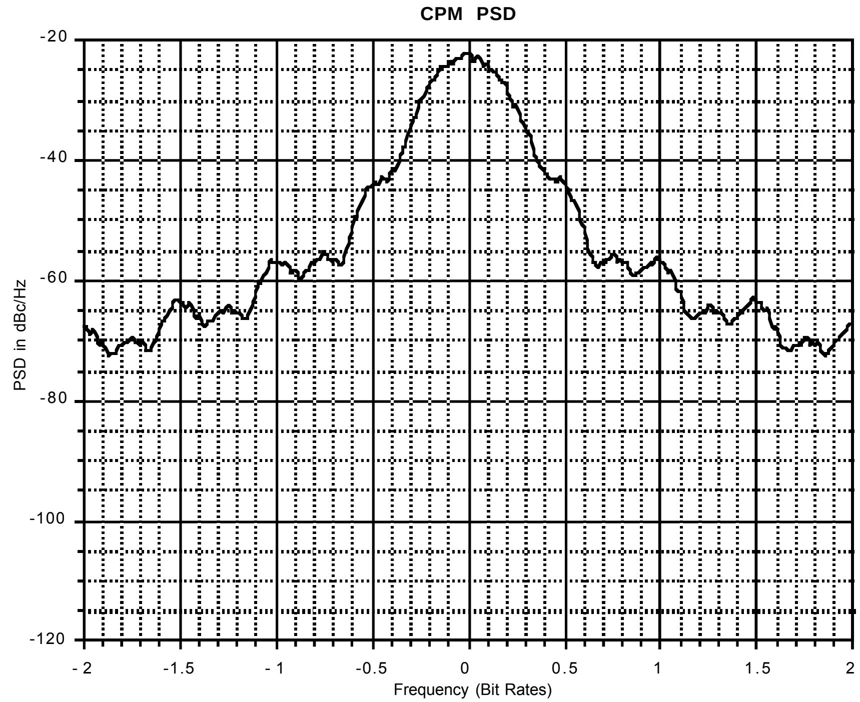




M=4, h=1/4, 1REC

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate





M=4, h=1/4, 1RC

PSD vertical axis is dBc per FFT bin
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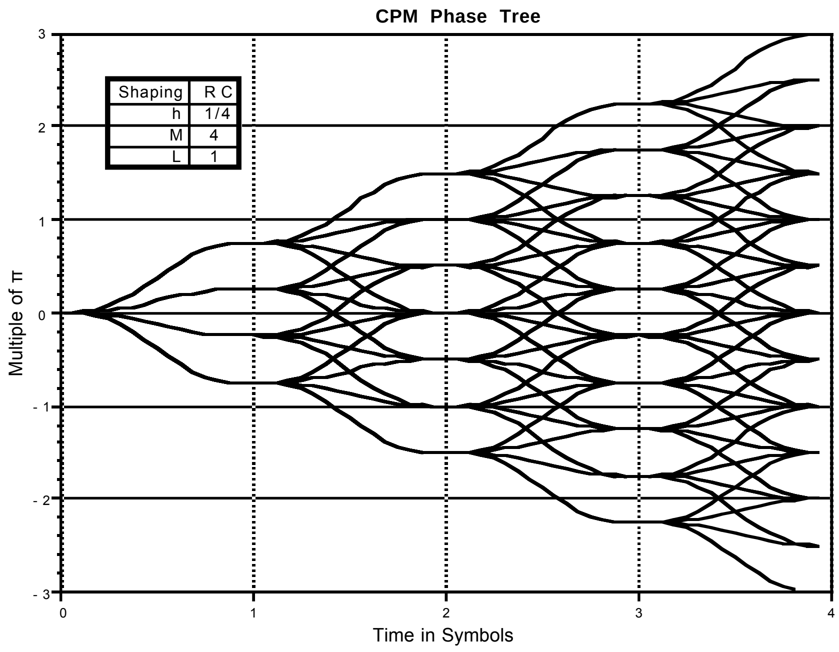
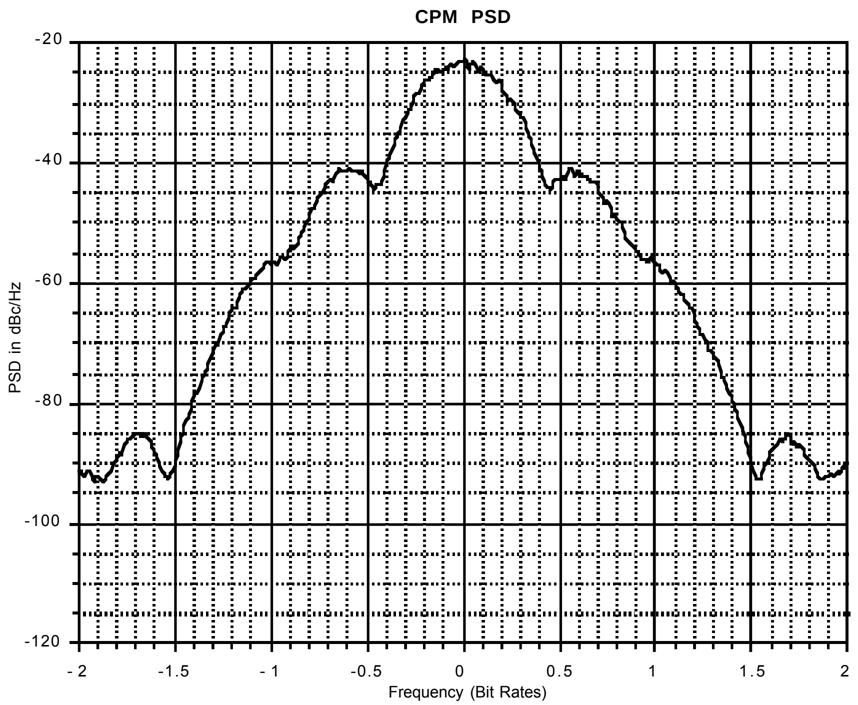
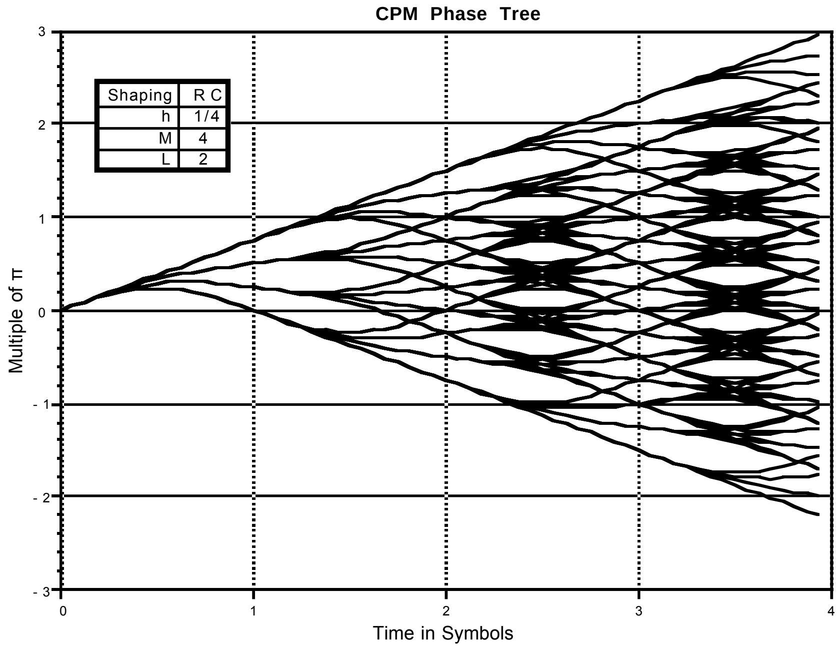
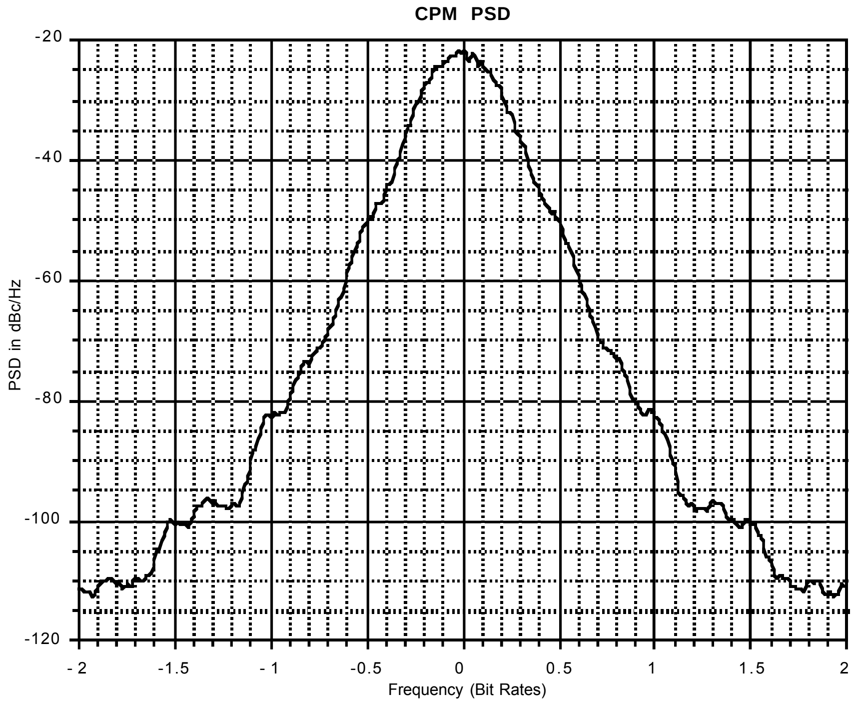




M=4, h=1/4, 2RC

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate





M=4, h=1/4, 3RC

PSD vertical axis is dBc per FFT bin
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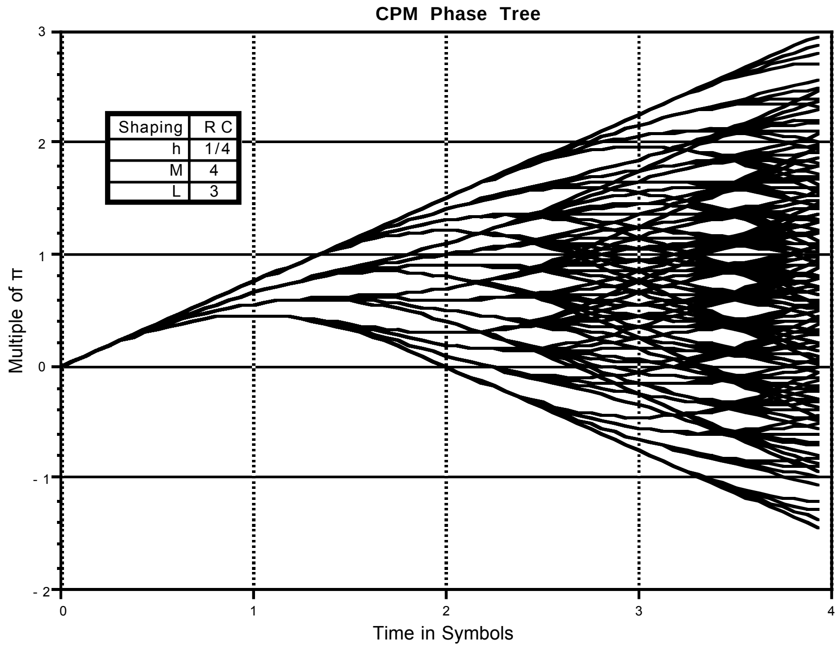

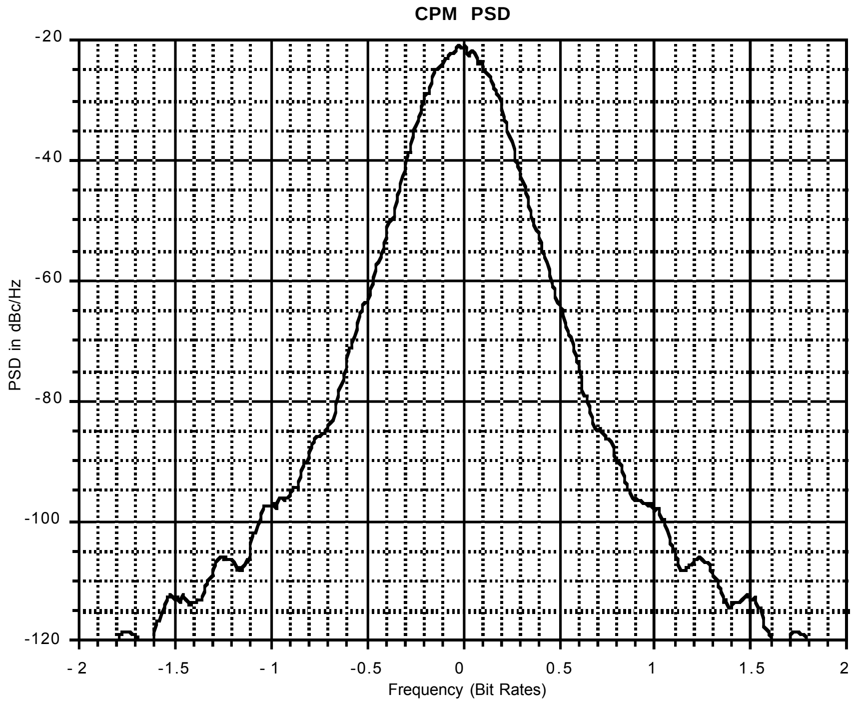

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Multi-h CPM

- Cyclically rotates through multiple “sets” of FSK tones
- Increases minimum distance in trellis
  - Improves BER performance
- Widely proposed for high-performance nonlinear channels
  - MIL-STD-188-181B

$M=2,\ h_1=1/4,\ h_2=1/2,\ 1REC$

PSD vertical axis is dBc per FFT bin
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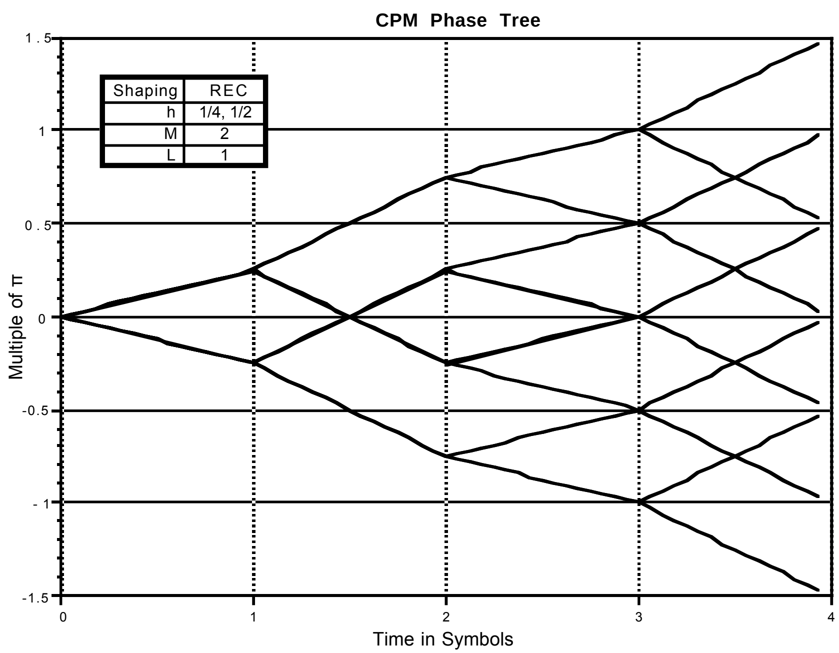

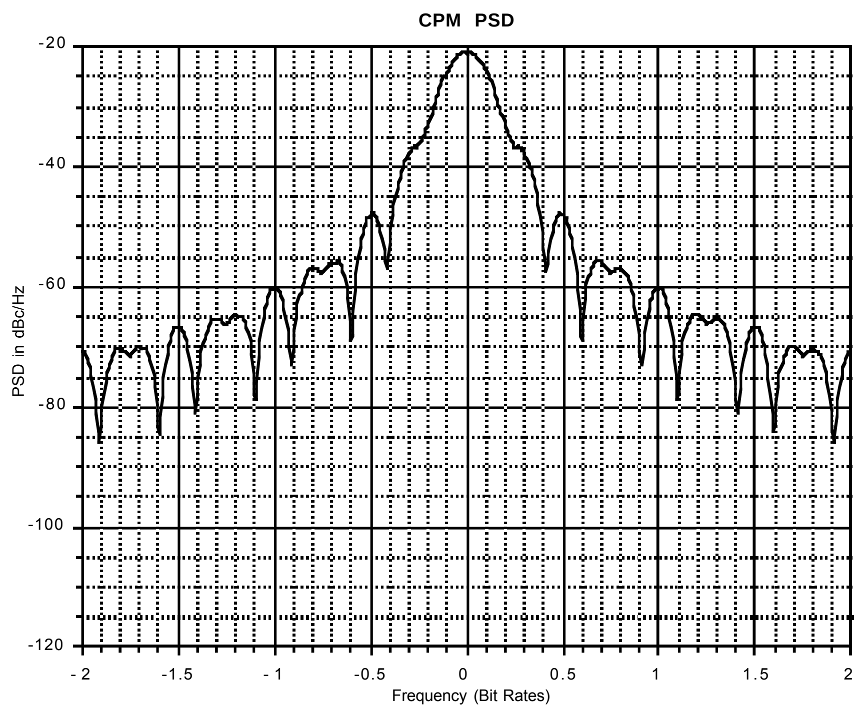

$M=4,\ h_1=4/16,\ h_2=5/16,$ 3RC

ARTM Tier II Waveform

PSD vertical axis is dBc per FFT bin
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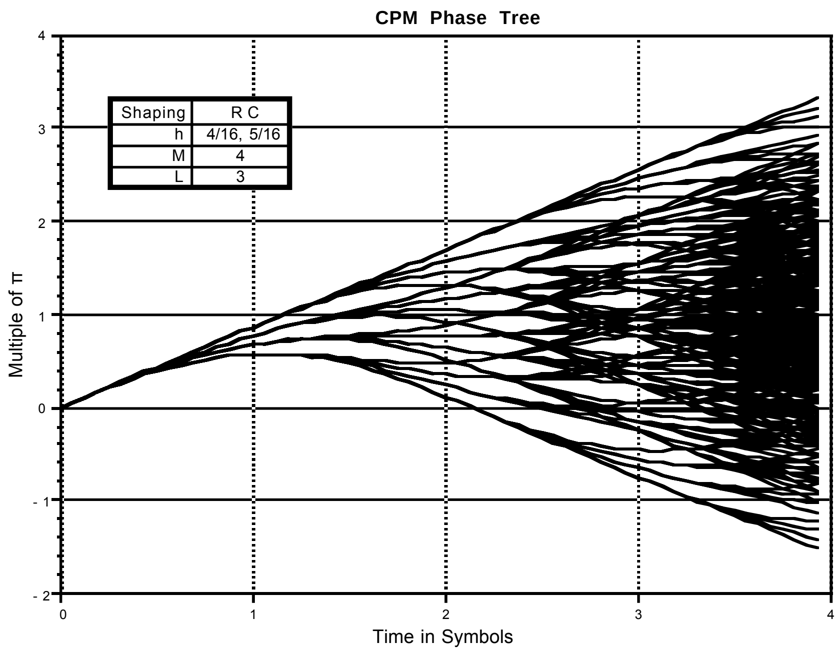

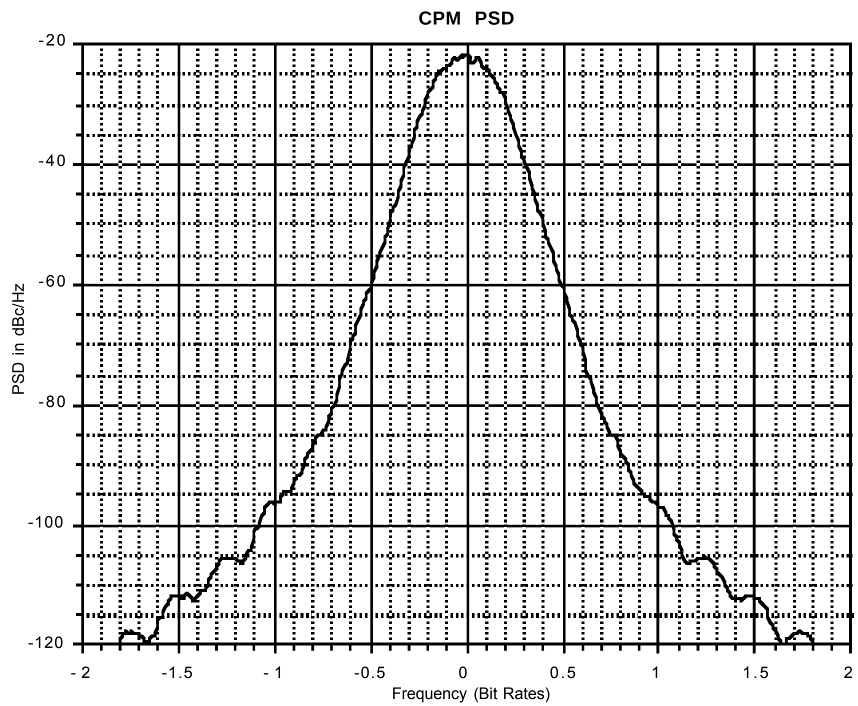

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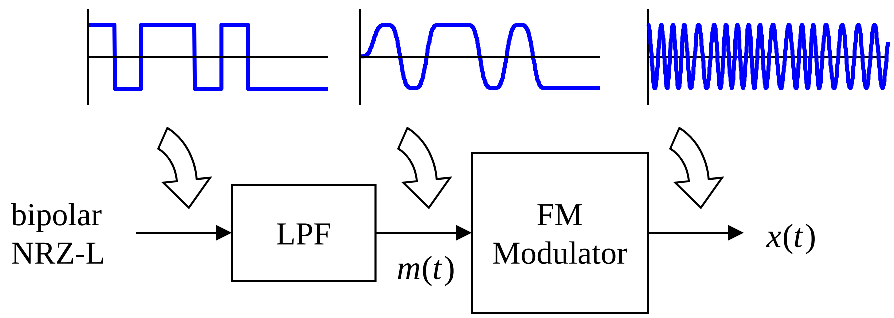
PCM/FM (Tier 0)



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Tier 0 in CPM Notation

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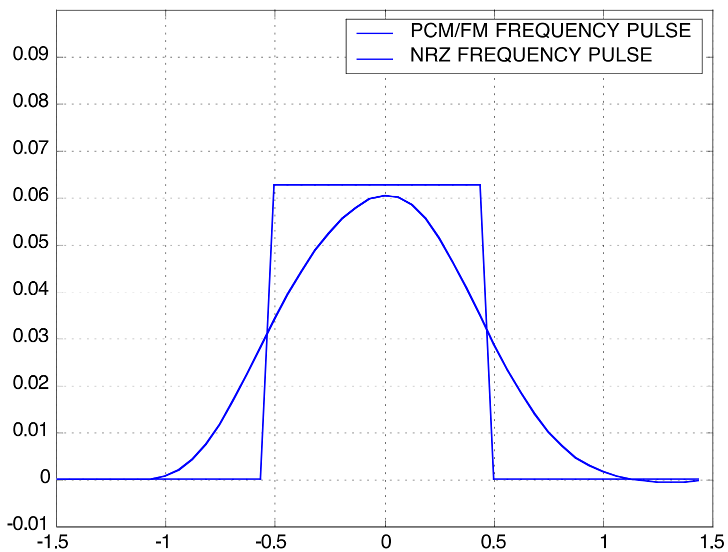
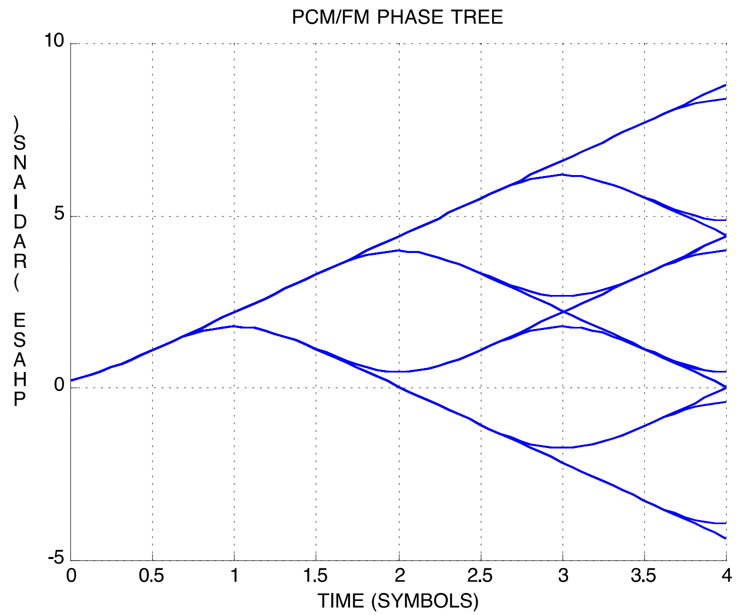
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\, d\tau \quad -\infty < t < +\infty$$

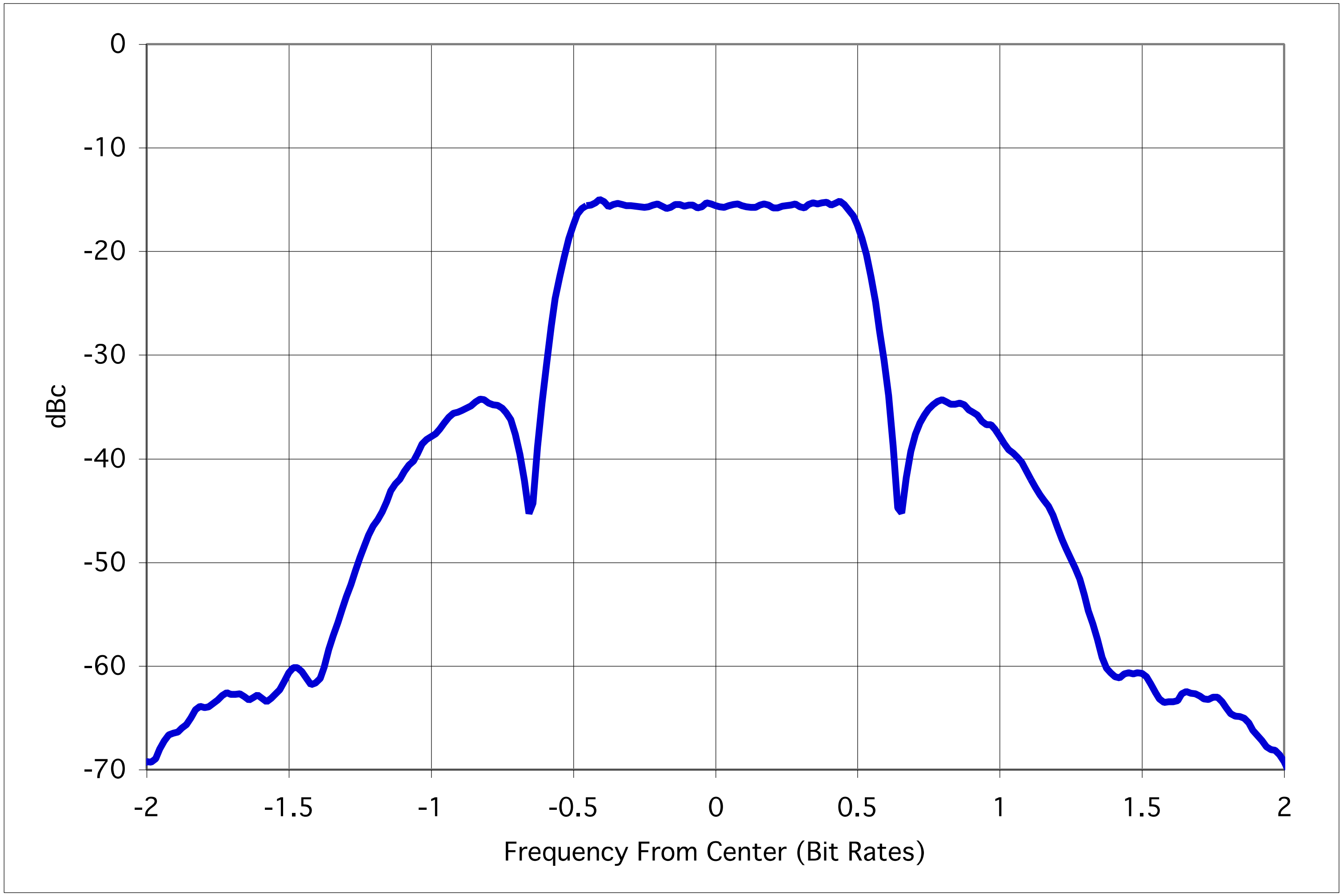
- M = 2 (binary)
- $\alpha_i = 2d_i - 1$
  - $d_i = \{0, 1\}$, $\alpha_i = \{-1, +1\}$
- h = 0.7
- g(t) is the normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
  - Normalized such that the integral over all time = 1/2

PCM/FM as a Phase Modulation

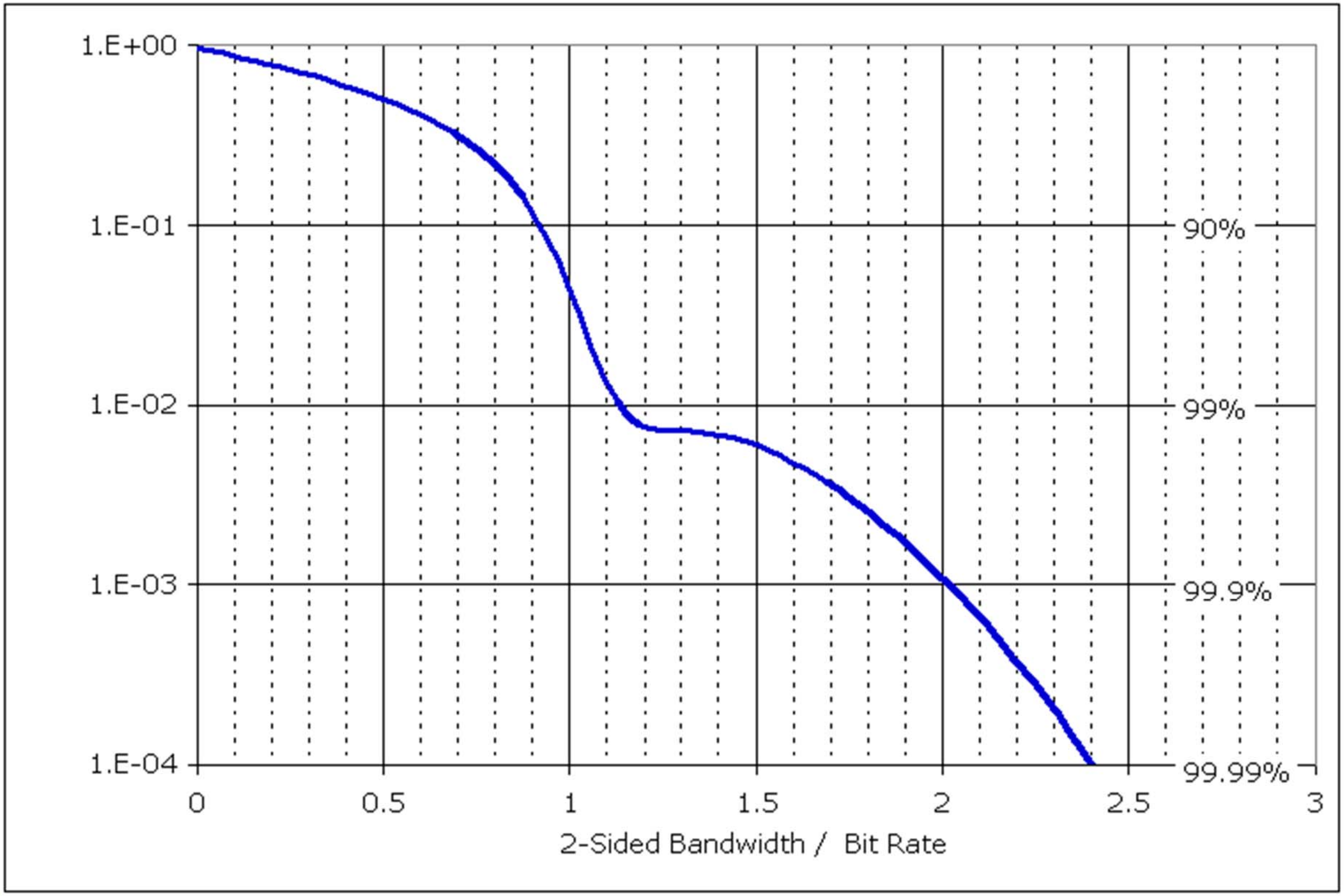




Power Spectral Density (PSD)



Fractional Out-of-band Power



PCM/FM Summary

- Legacy waveform
  - Equipment is ubiquitous
- Constant envelope
- Several practical implementations
- 99.9% bandwidth: 2.03 times bit rate

M	α_i	h	g(t)
2	{-1, +1}	0.7	Normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate

Course Outline

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  - Adjacent Channel Interference
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    - Adaptive Equalization
    - Space-Time Coding
  - Forward Error Correction (FEC)
- Performance Comparison & Summary

Tier I Overview

- Shaped OQPSK (SOQPSK)
  - Constant envelope modulation(s) introduced by Hill (ITC 2000)
  - Defined by 4 parameters (ρ, B, T_1, T_2)
  - Compatible with existing efficient non-linear class C power amplifier
  - Non-proprietary waveform
  - Comparable in performance and interoperable with FQPSK
- FQPSK
  - Patented by K. Feher
  - Defined by I and Q components
  - Non-constant envelope
  - Details are proprietary, contact Digcom

SOQPSK in CPM Notation

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\, d\tau \quad -\infty < t < +\infty$$

- M = 3 (ternary)
- $\alpha_i = (-1)^{i+1} \dfrac{a_{i-1}(a_i - a_{i-2})}{2}$, α_i = {-1, 0, +1}
  - $a_i = 2d_i - 1$
  - a_i = {-1, +1}, d_i = {0, 1}
- h = 0.5
- g(t) = windowed impulse response of spectral raised cosine
  - Normalized such that the integral over all time = 1/2

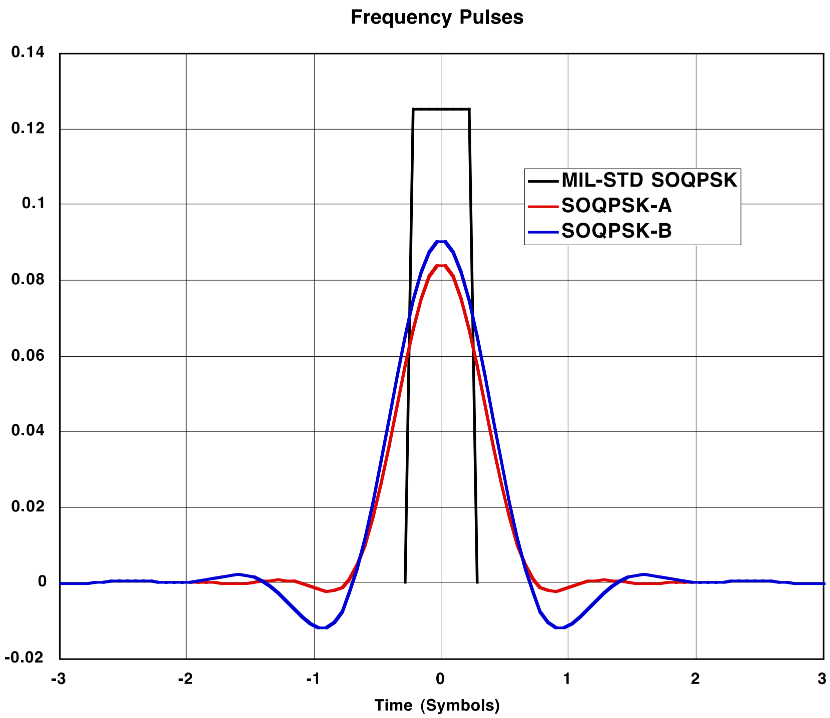
Definition of SOQPSK Pulse

g(t) = n(t) * w(t), where

$$n(t) = \frac{A\cos(\pi\rho Bt/T)}{1-4(\rho Bt/T)^2} * \frac{\sin(\pi Bt/T)}{(\pi Bt/T)}$$

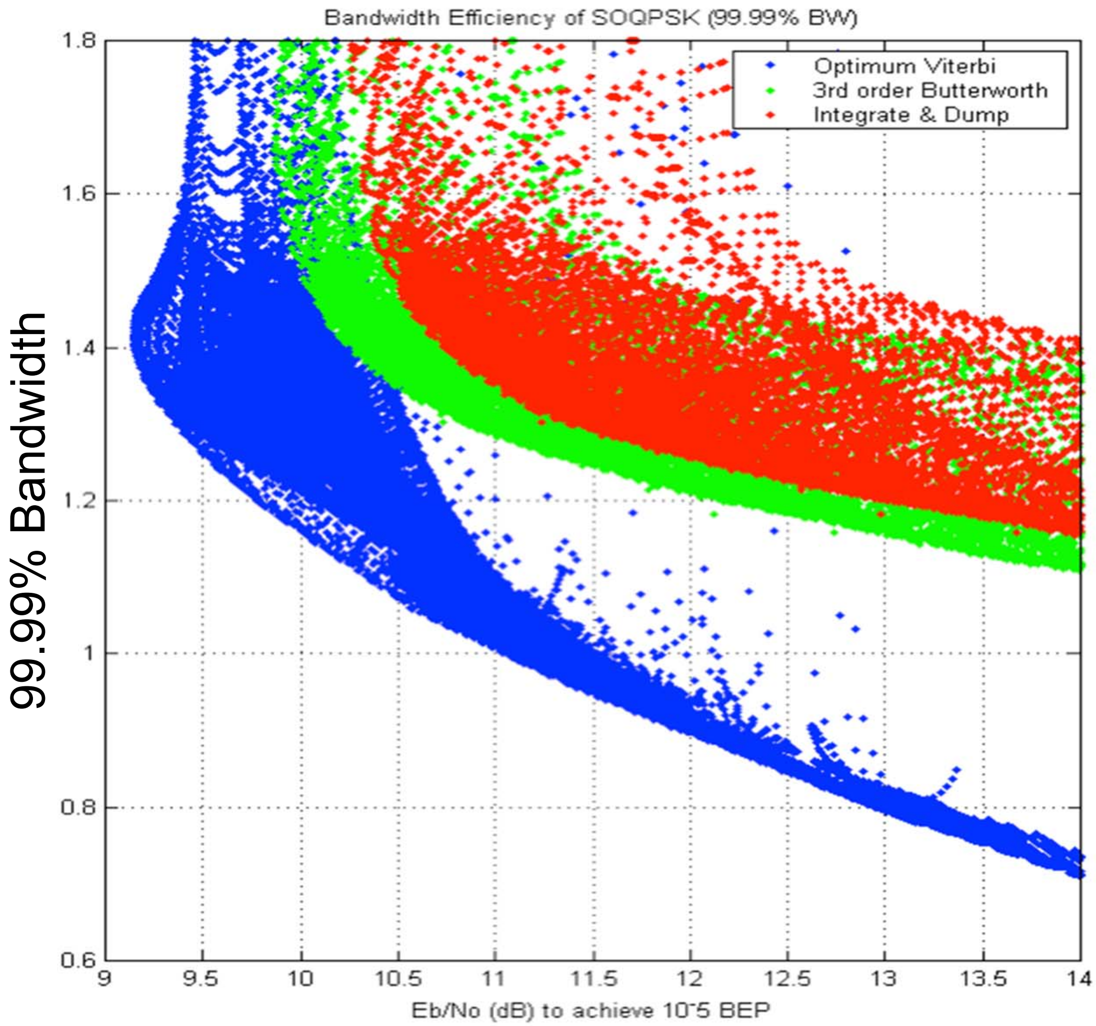
$$w(t) = \begin{cases} 1, & \text{for} \quad |t/T| < T_1 \\ \frac{1}{2} + \frac{1}{2}\cos\frac{\pi(|t/T| - T_1)}{T_2}, & \text{for} \quad T_1 < |t/T| < T_1 + T_2 \\ 0, & \text{for} \quad |t/T| > T_1 + T_2 \end{cases}$$

Frequency Pulse Shape, g(t)

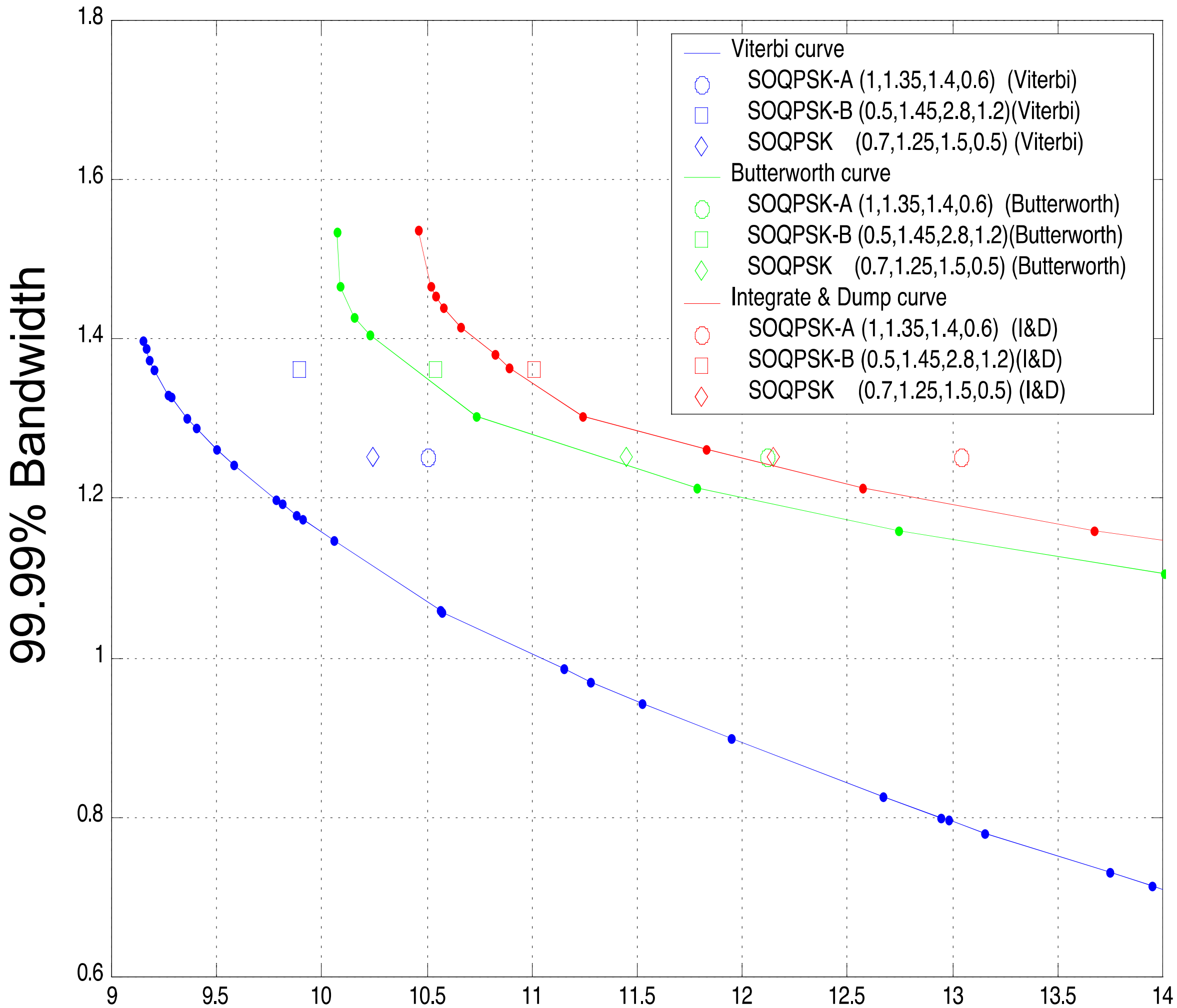


Parameter	SOQPSK-A	SOQPSK-B
ρ	1.0	0.5
B	1.35	1.45
T_1	1.4	2.8
T_2	0.6	1.2

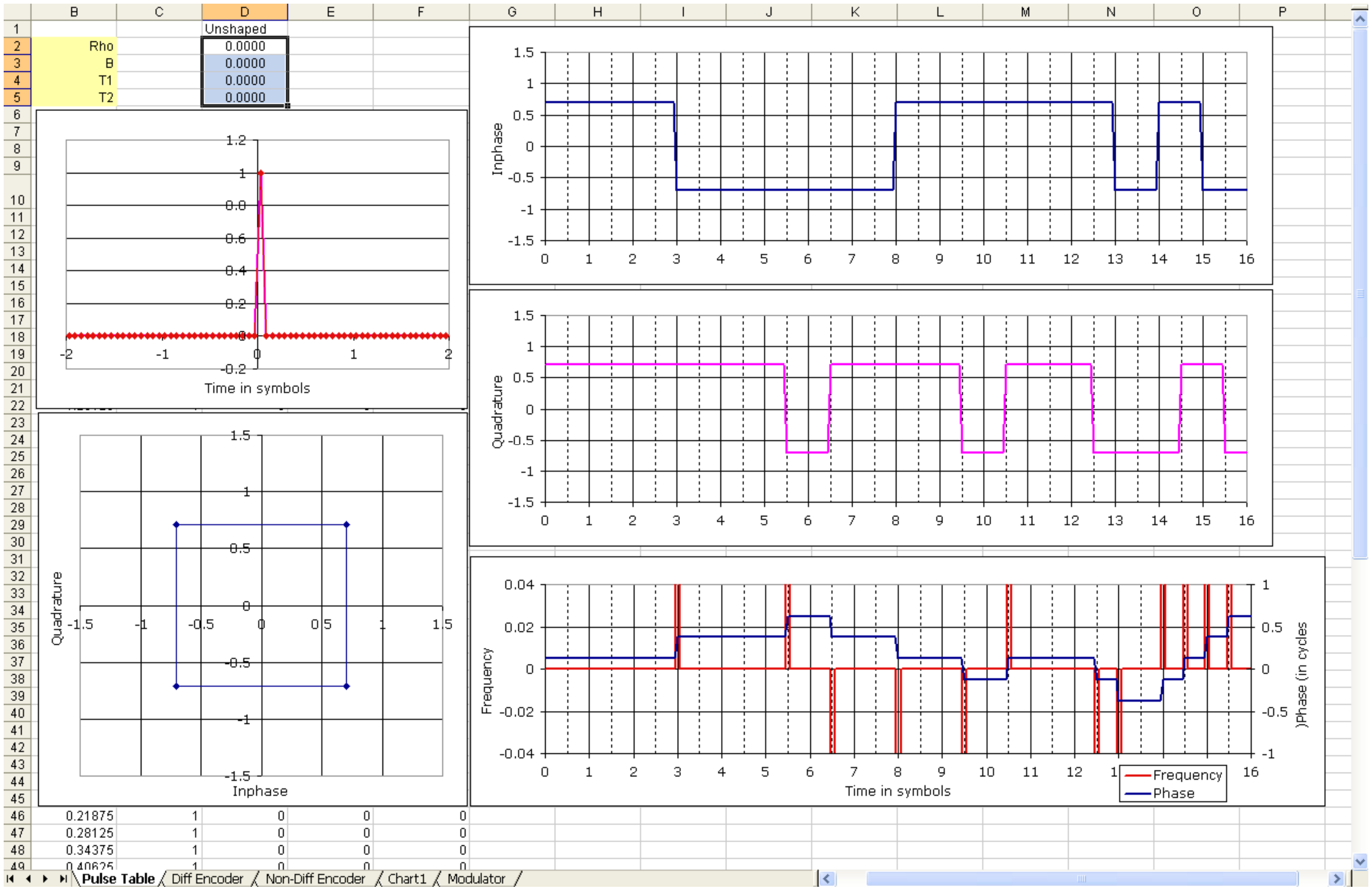
SOQPSK Variants



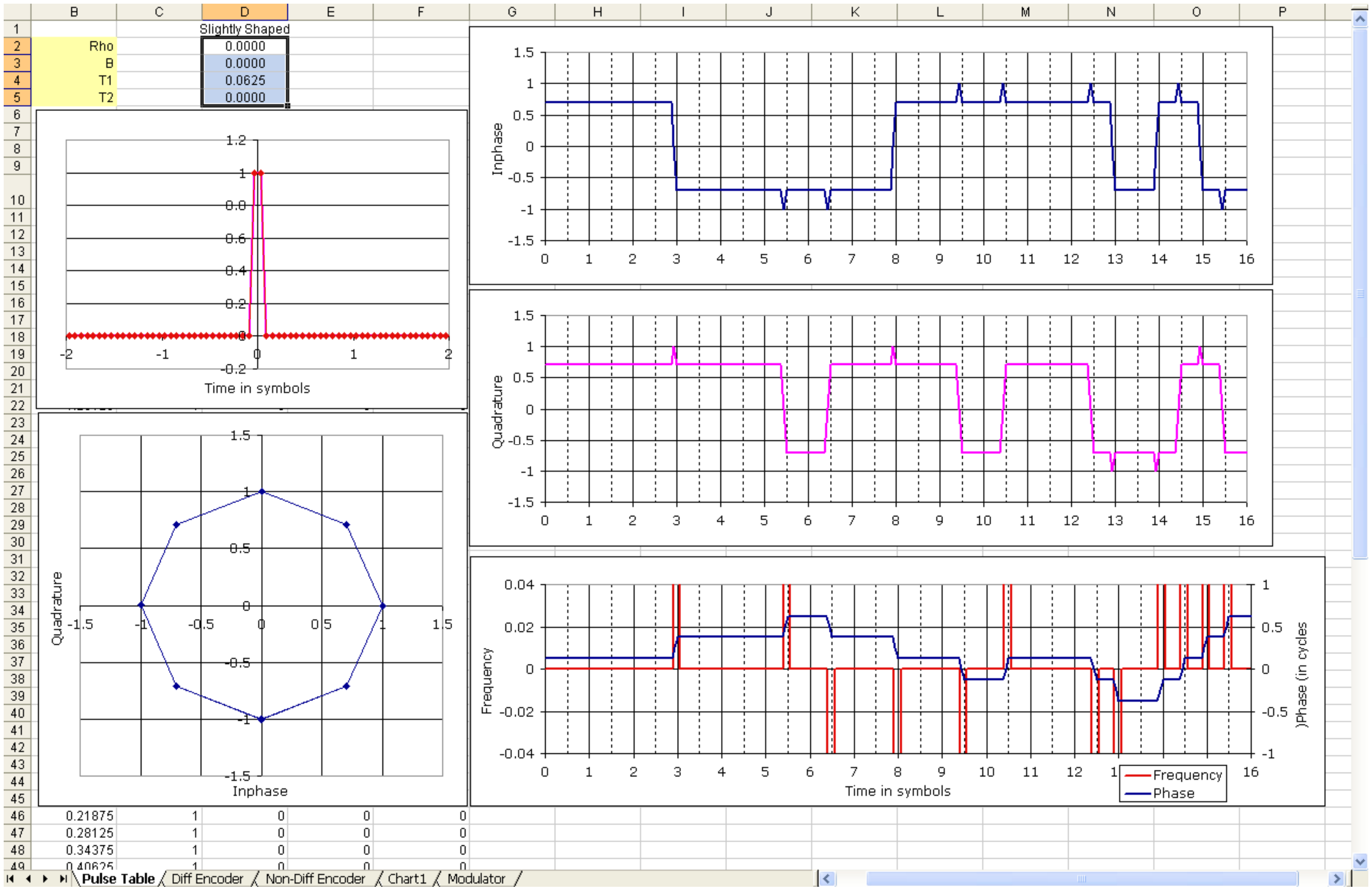
Optimal SOQPSK Variants



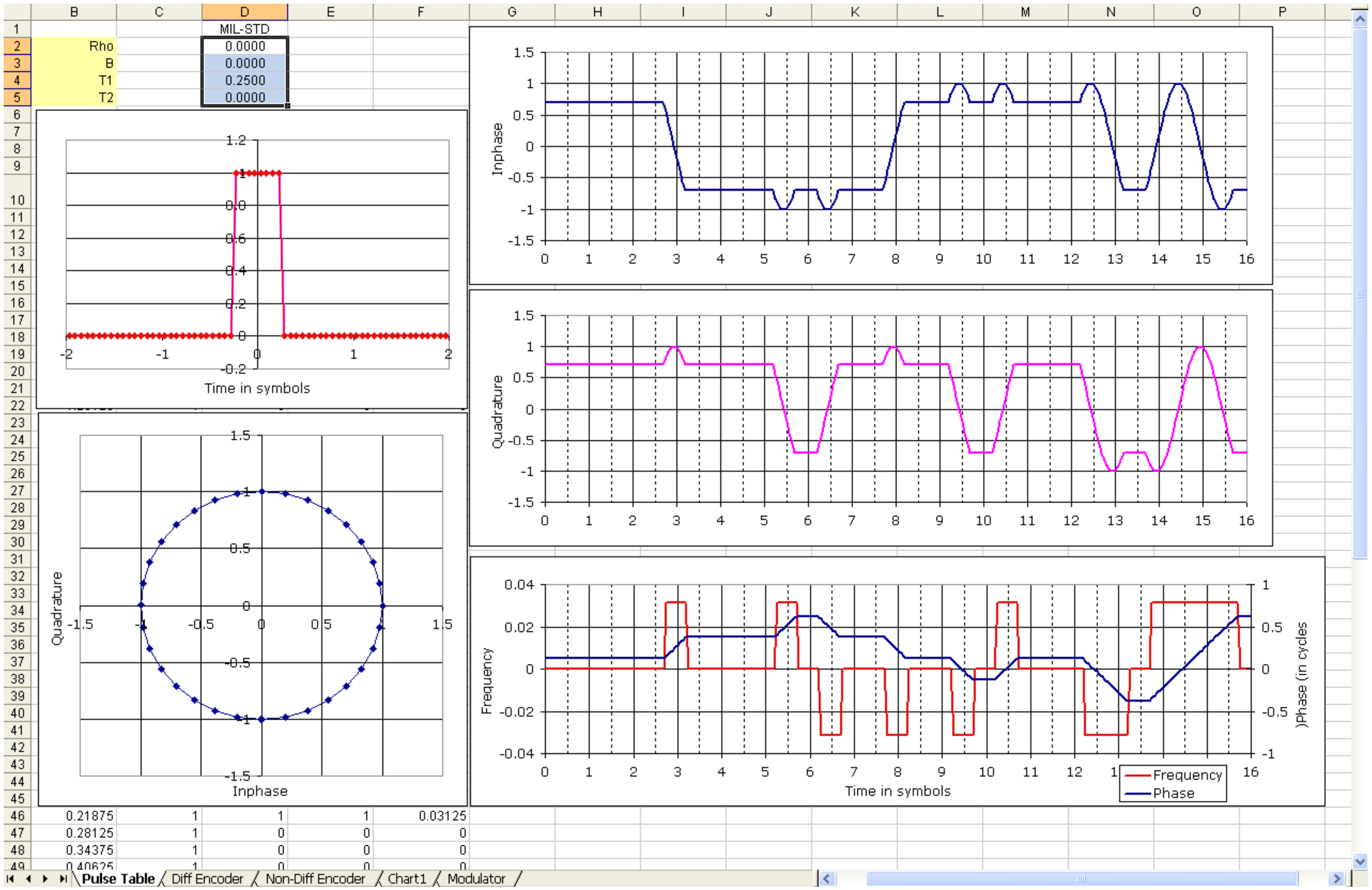
Unshaped Offset QPSK



Slightly Shaped OQPSK

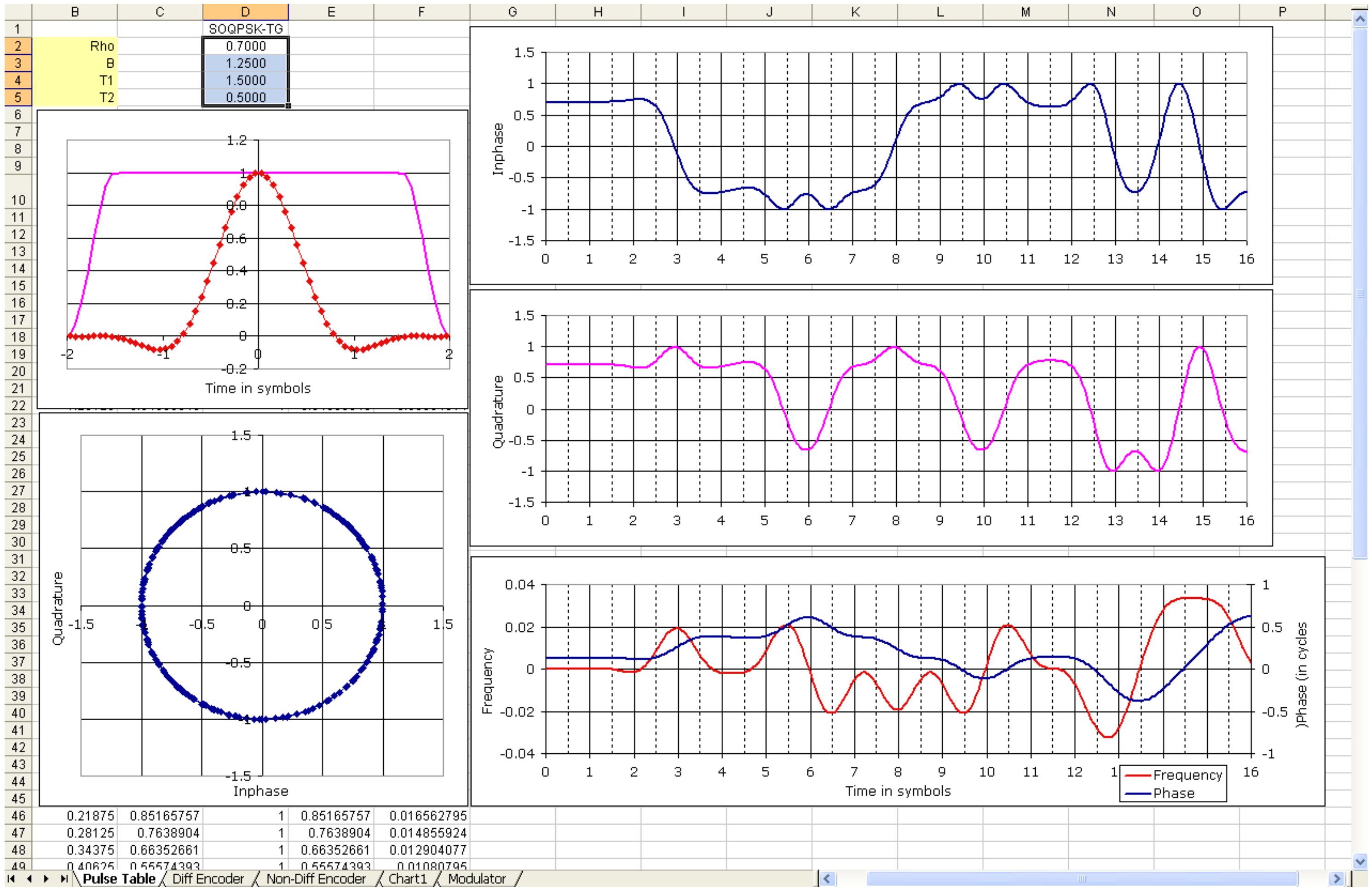


MIL-STD SOQSPK

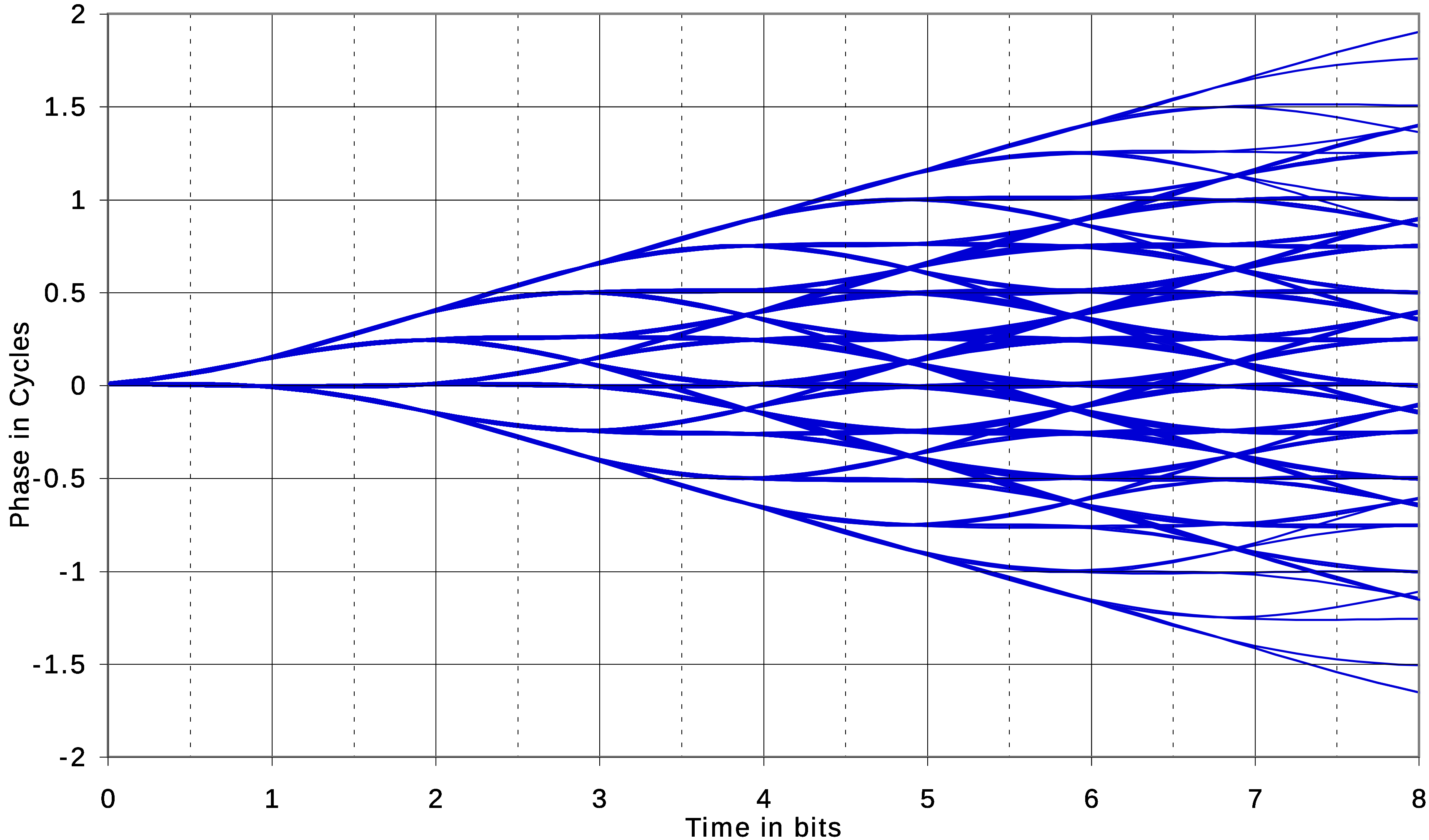


Quasonix

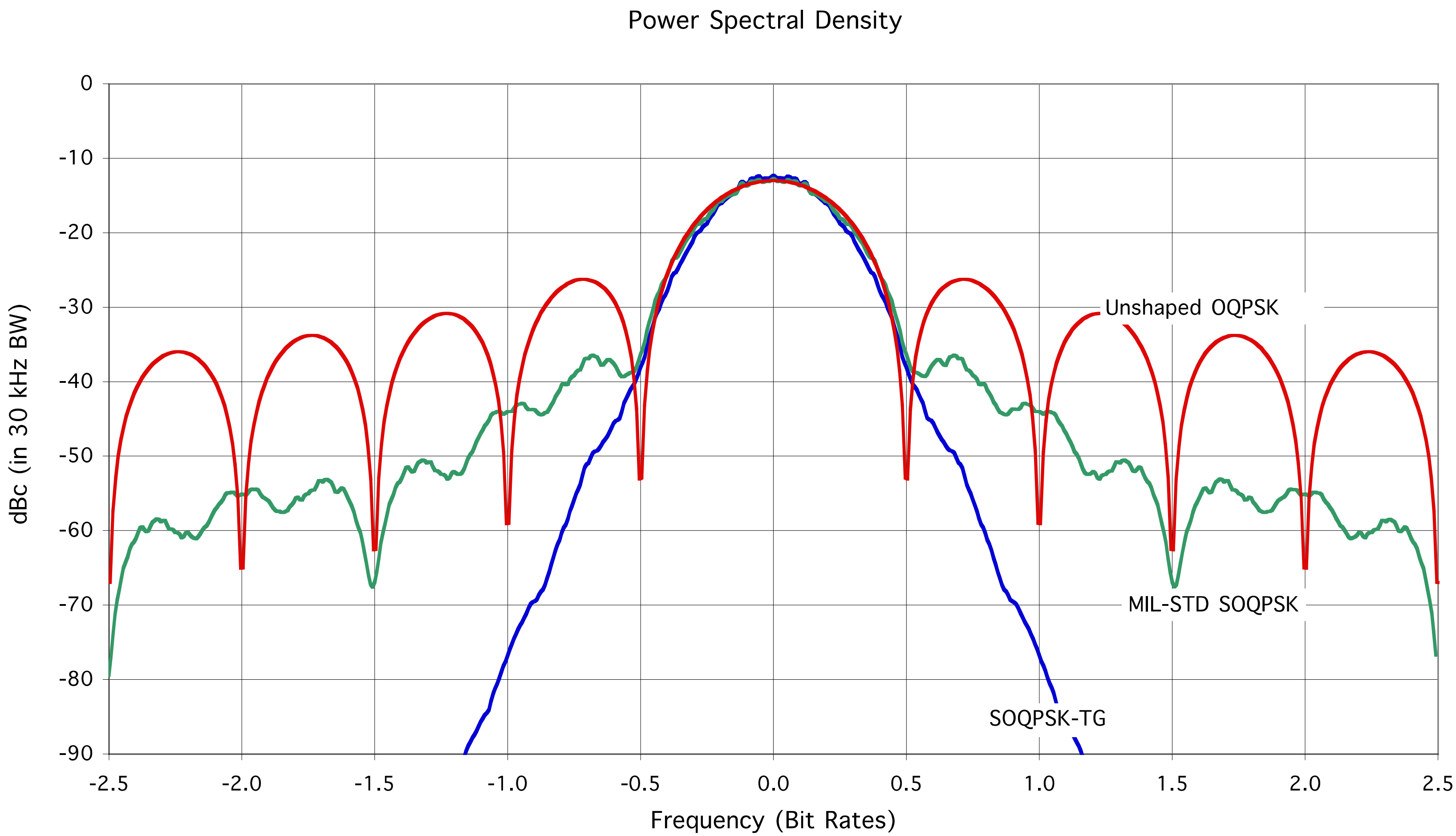
SOQPSK-TG


SOQPSK-TG
Rho 0.7000
B 1.2500
T1 1.5000
T2 0.5000
Time in symbols
Inphase
Quadrature
Frequency
Phase (in cycles)
Frequency
Phase
Time in symbols
Pulse Table
Diff Encoder
Non-Diff Encoder
Chart1
Modulator

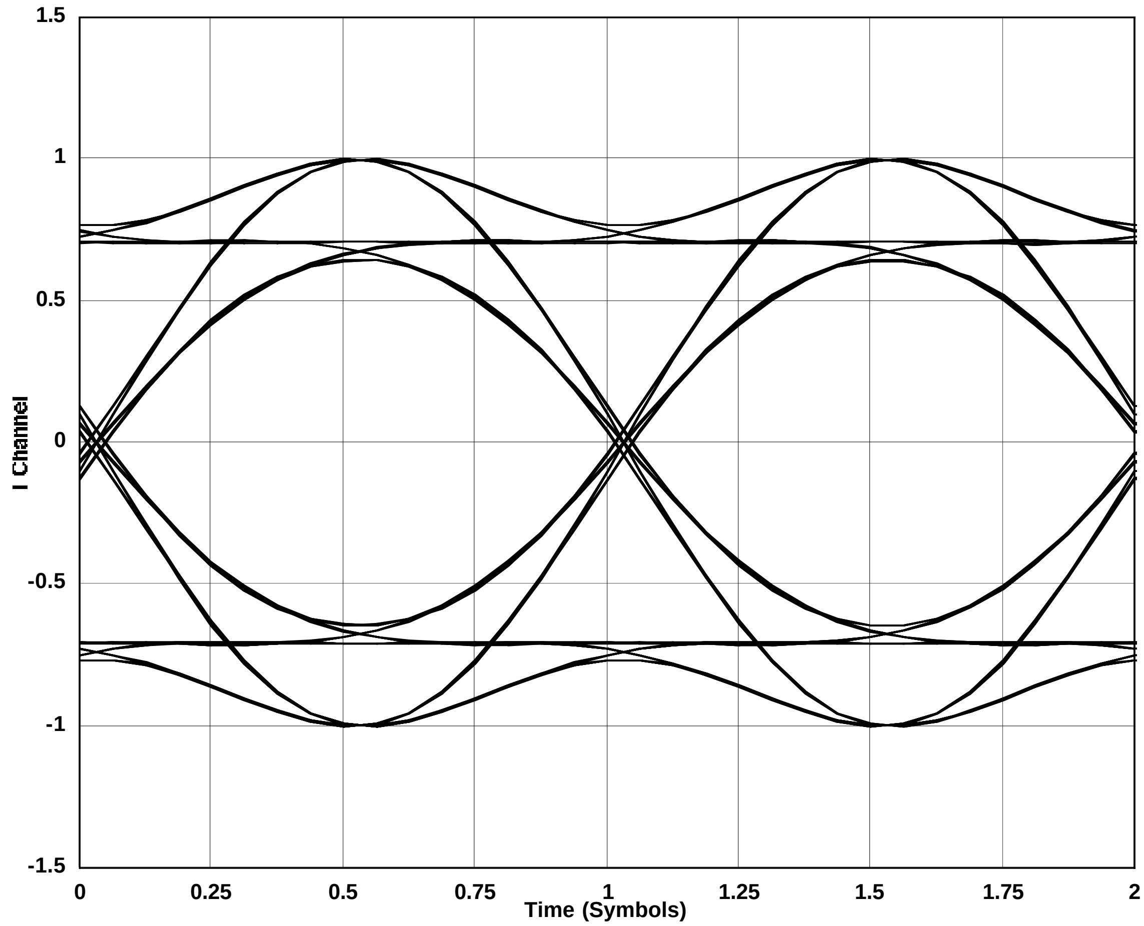
SOQPSK-TG Phase Tree



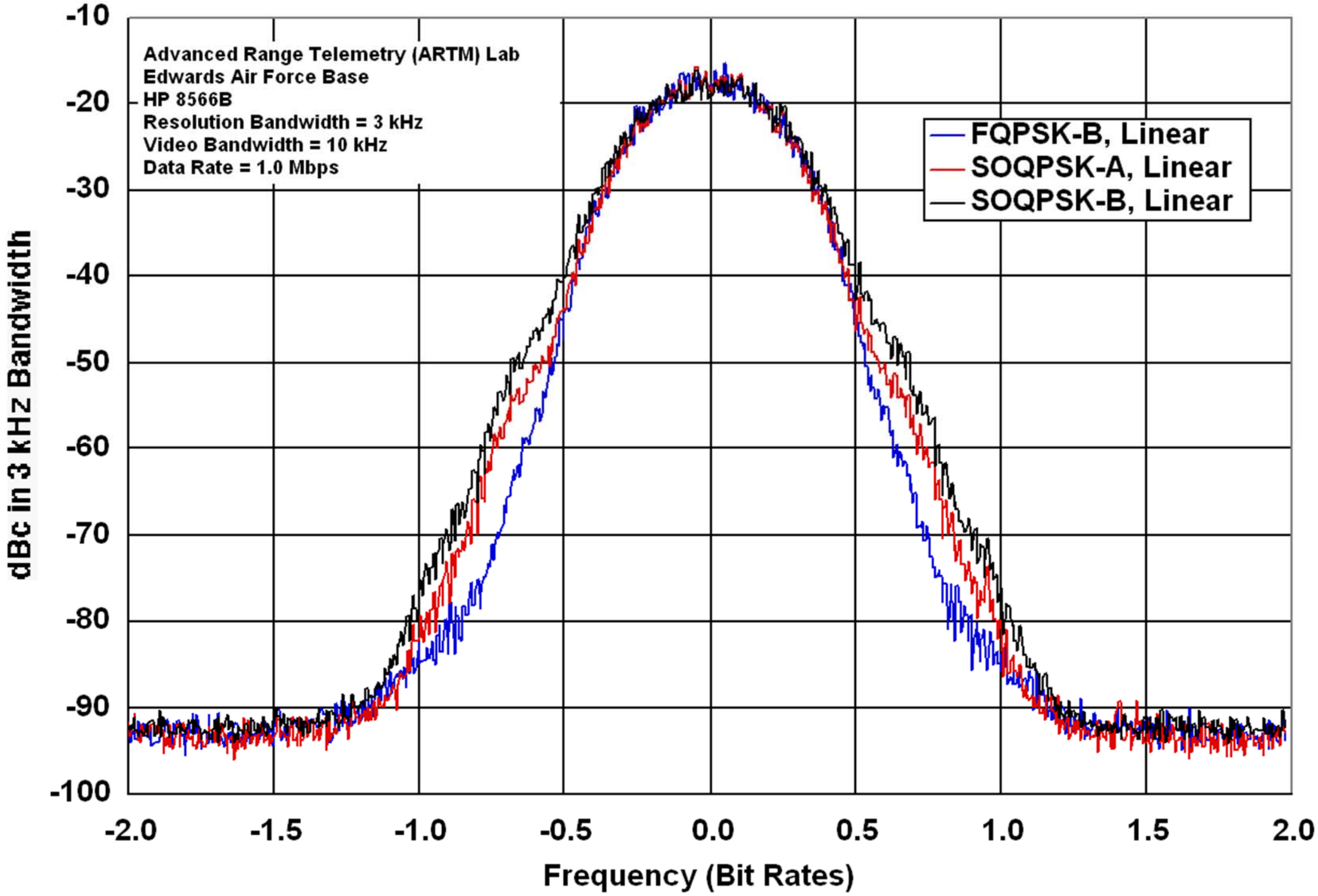
Power Spectral Density



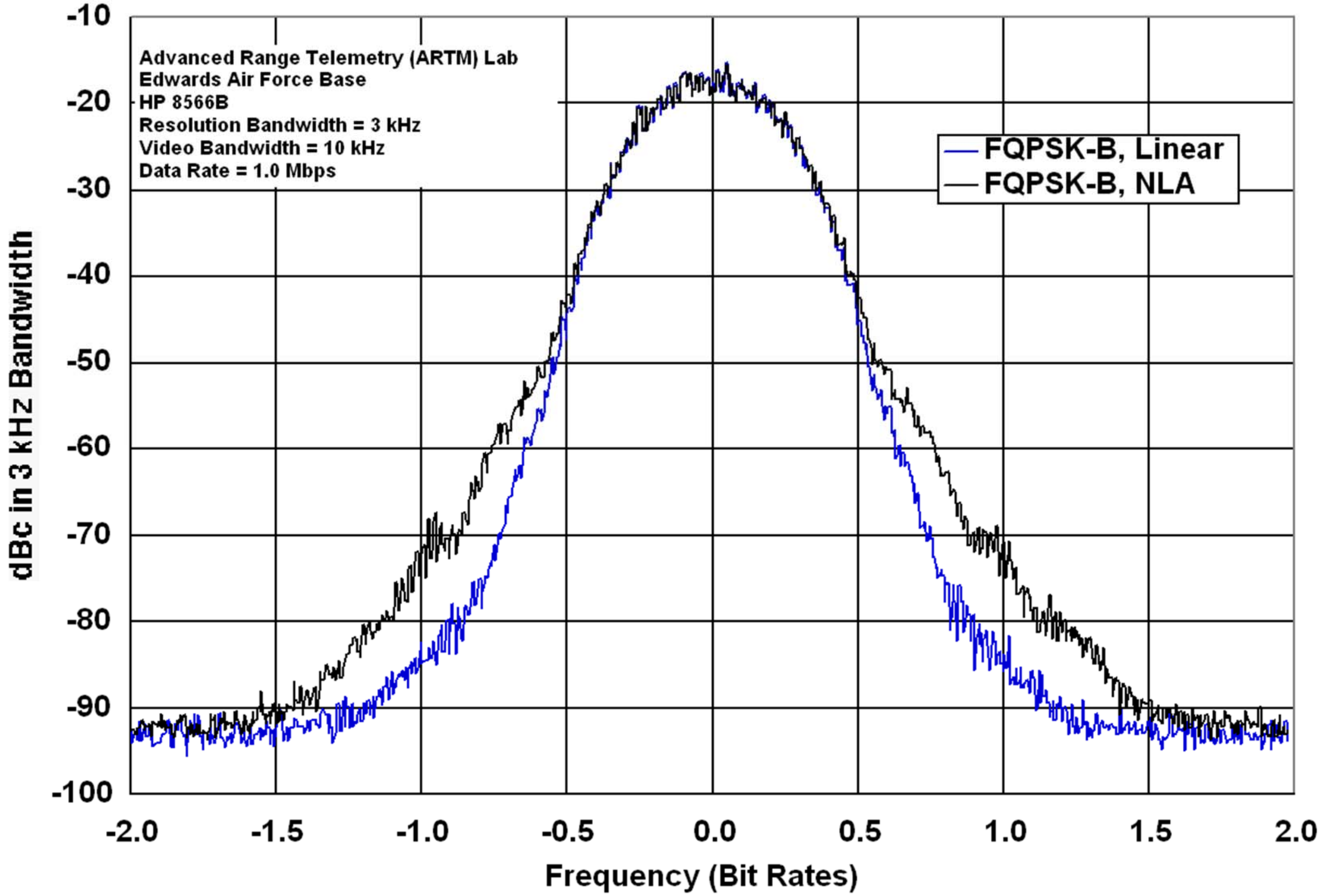
SOQPSK-A Eye Pattern



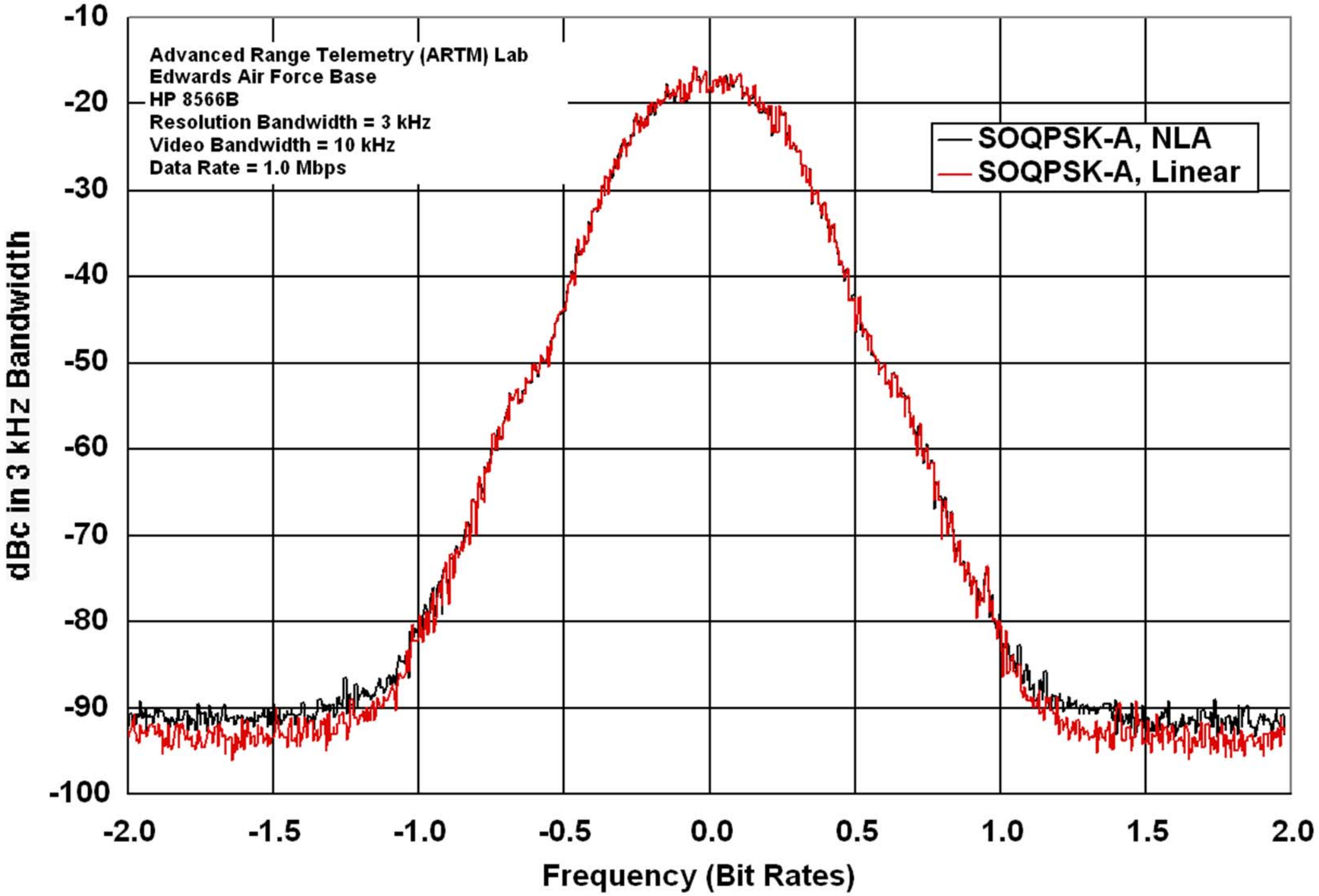
SOQPSK & FQPSK, Linear PA



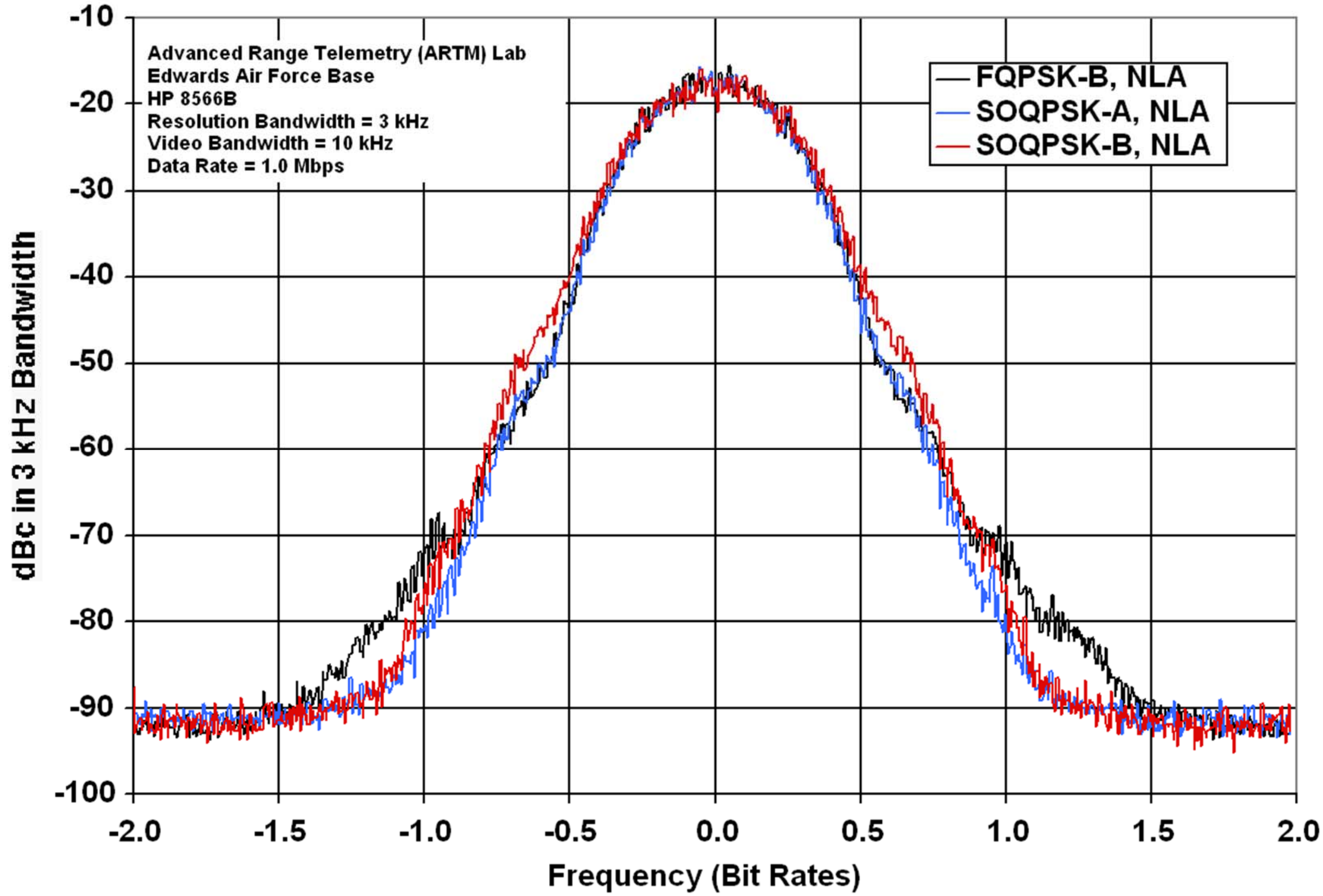
FQPSK, Non-Linear PA



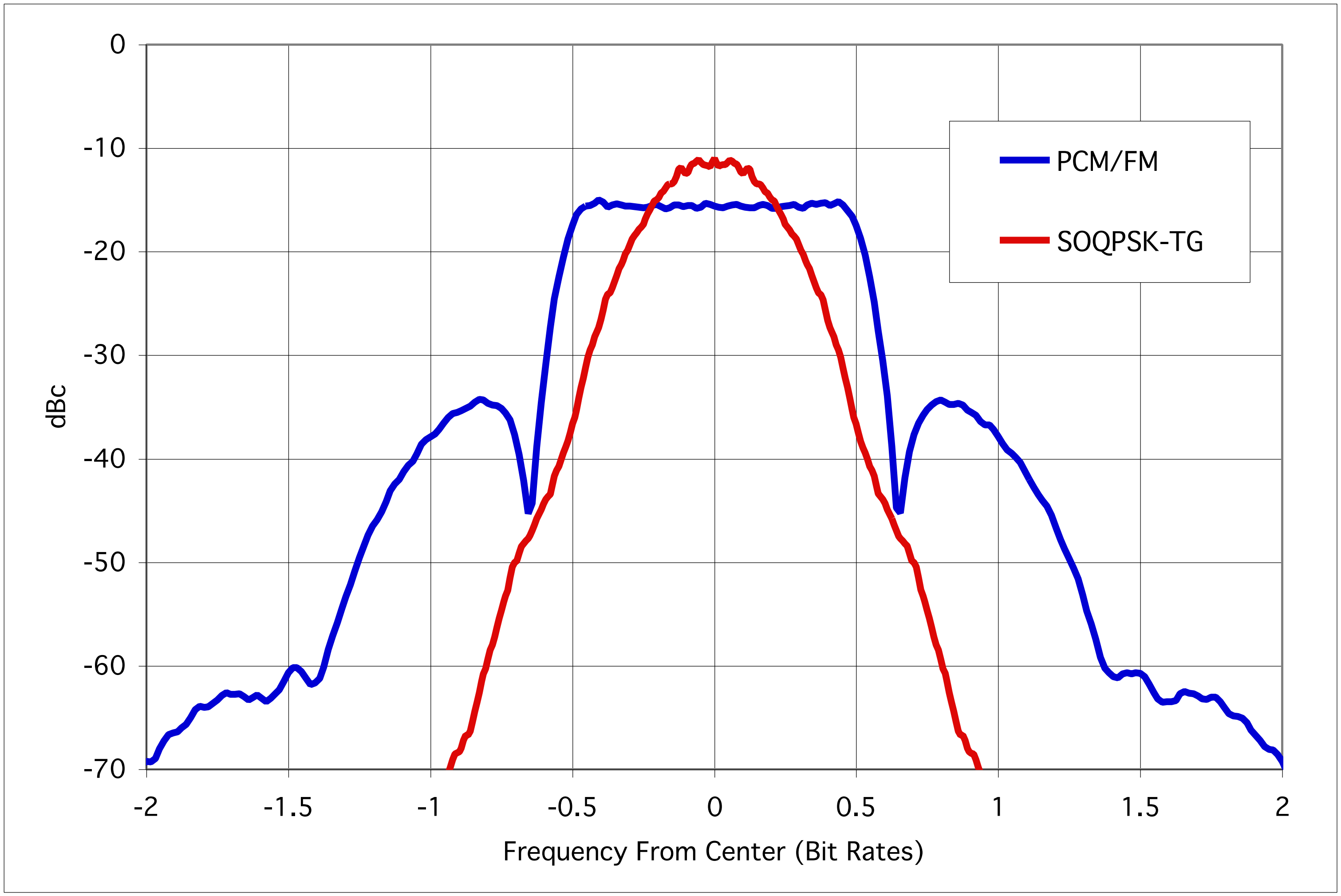
SOQPSK-A, Non-Linear PA



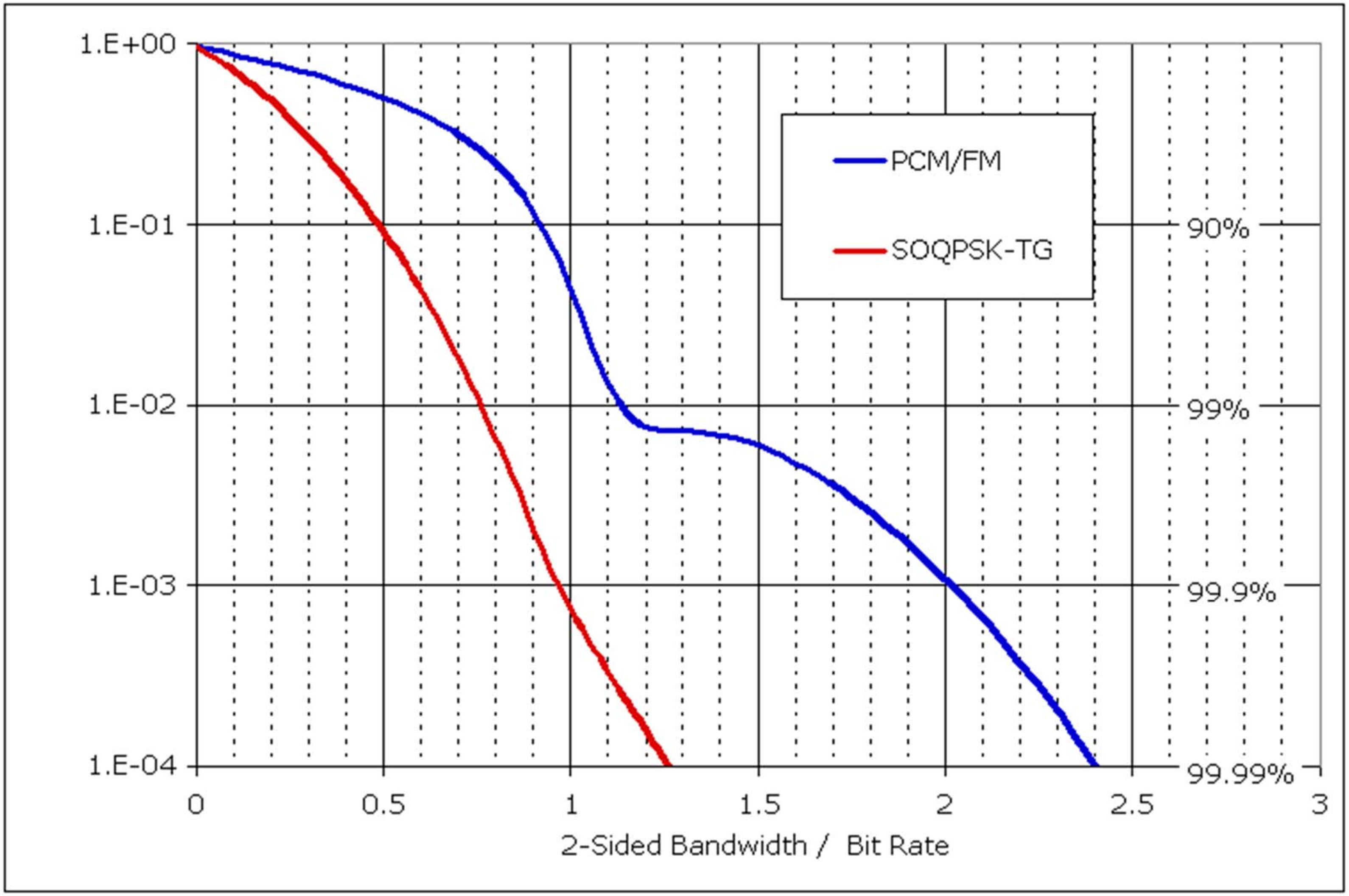
SOQPSK & FQPSK, Non-Linear



Measured PSD (Tier 0 & 1)



Fractional Out-of-band Power



Shaped Offset QPSK Summary

- Constant envelope, CPM waveform
- Adjustable shaping factor for BW and detection efficiency trade-off
- Improved spectral containment over OQPSK
- Compatible with standard OQPSK receivers and demodulators
- Adopted as an ARTM Tier I waveform
- 99.9% bandwidth: 0.98 times bit rate
- Interoperable with FQPSK

M	α_i	h	g(t)
3	{-1, 0, +1}	0.50	Normalized windowed impulse response of a spectral raised cosine

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Tier II Overview

- Multi-h CPM characteristics
  - Easy to trade off bandwidth and detection efficiency.
  - Constant envelope is ideal for high efficiency non-linear power amplifiers.
  - Detection efficiency is enhanced by periodically varying the modulation index (h).
    - Extends the point at which competing paths remerge thereby increasing the minimum distance and decreasing the probability of symbol error.
  - Nearly 2.5x improvement over PCM/FM in spectral efficiency with similar detection efficiency.

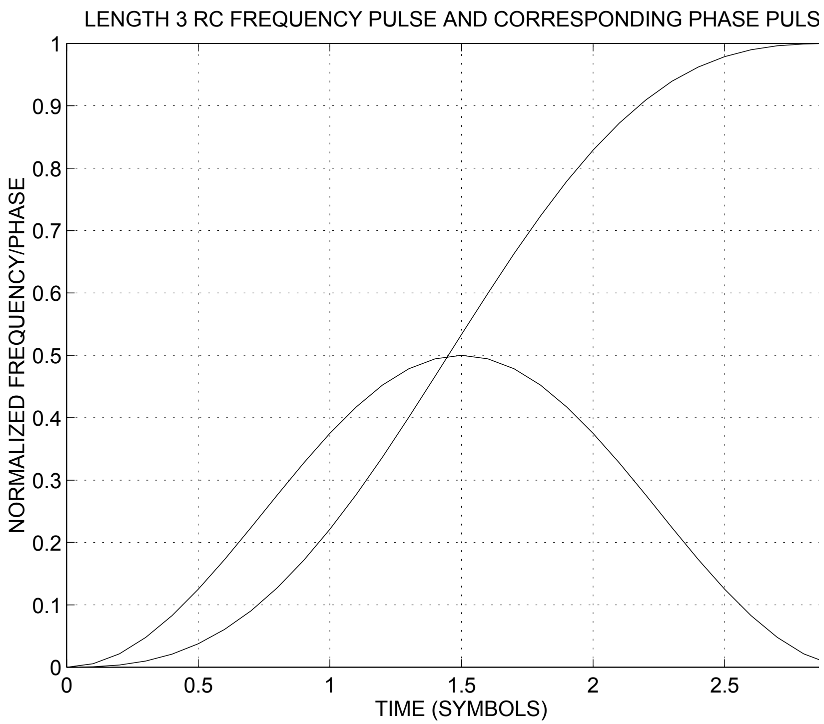
ARTM Tier II in CPM Notation

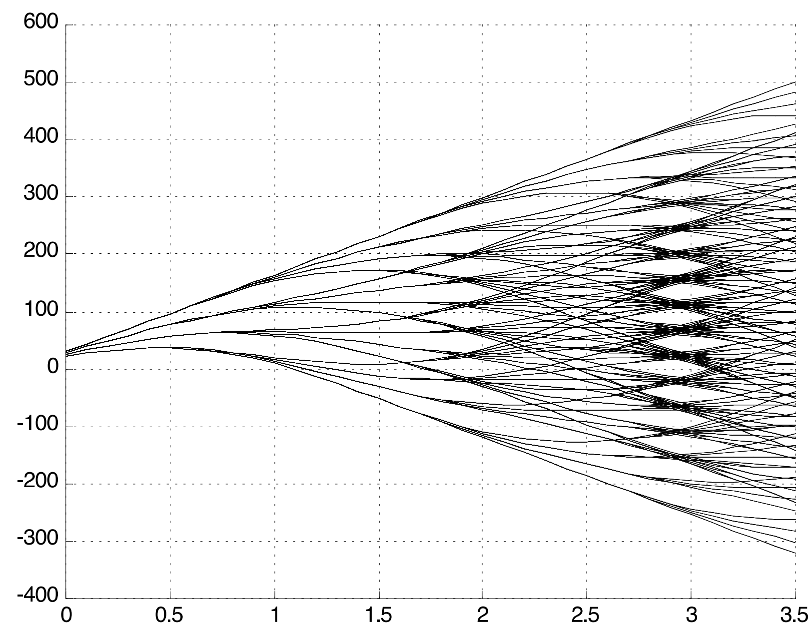
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau \quad -\infty < t < +\infty$$

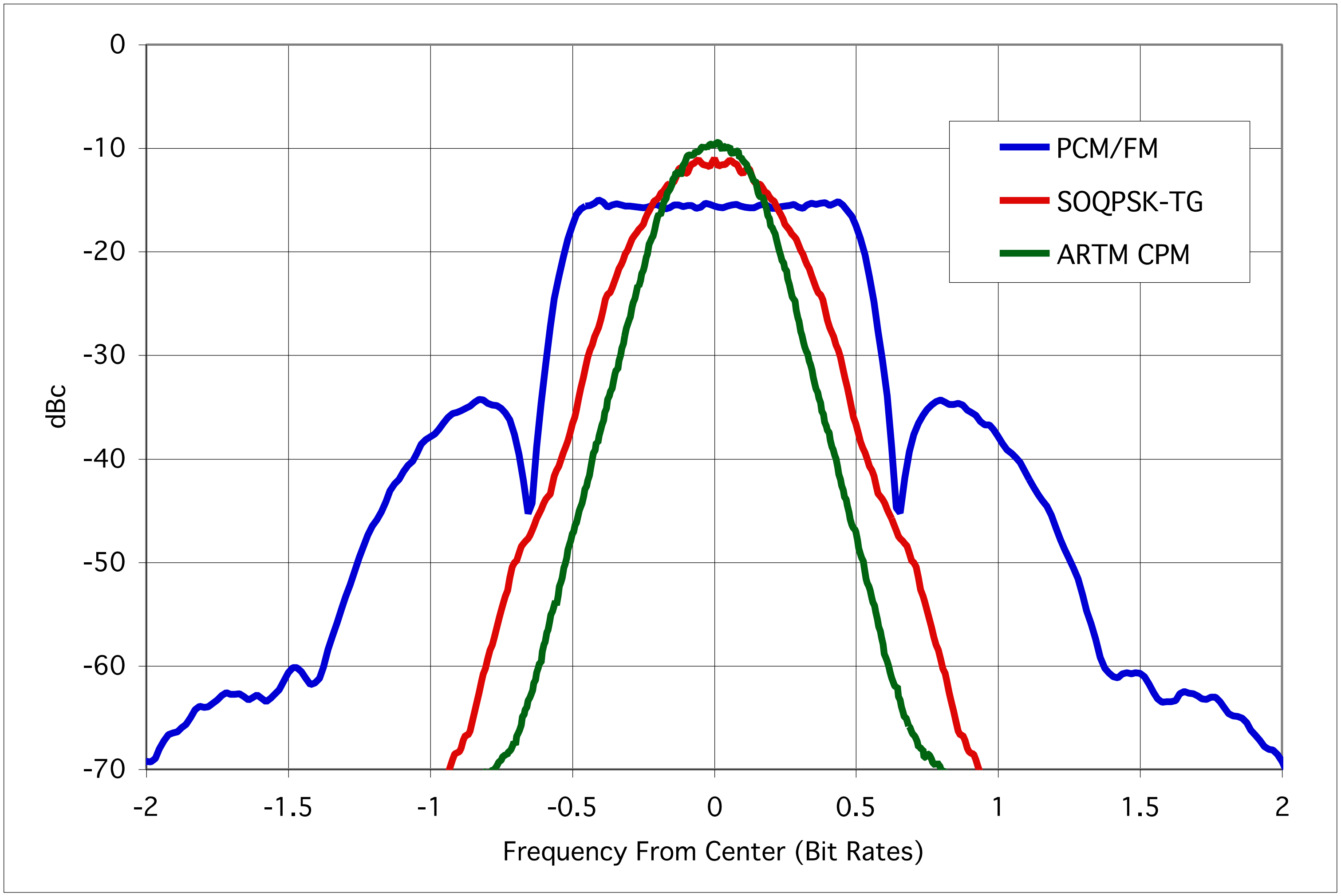
- M = 4 (quaternary)
- $\alpha_i = 2\,[2d_{1i} + d_{0i}] - 3$
  - $\alpha_i = \{-3, -1, +1, +3\}$
  - $d_i = \{0, 1\}$
- h = {4/16, 5/16}, alternating
- g(t) = raised cosine, 3 symbols (6 bits) in duration
  - Normalized such that the integral over all time = 1/2

Frequency Pulse & Phase Tree

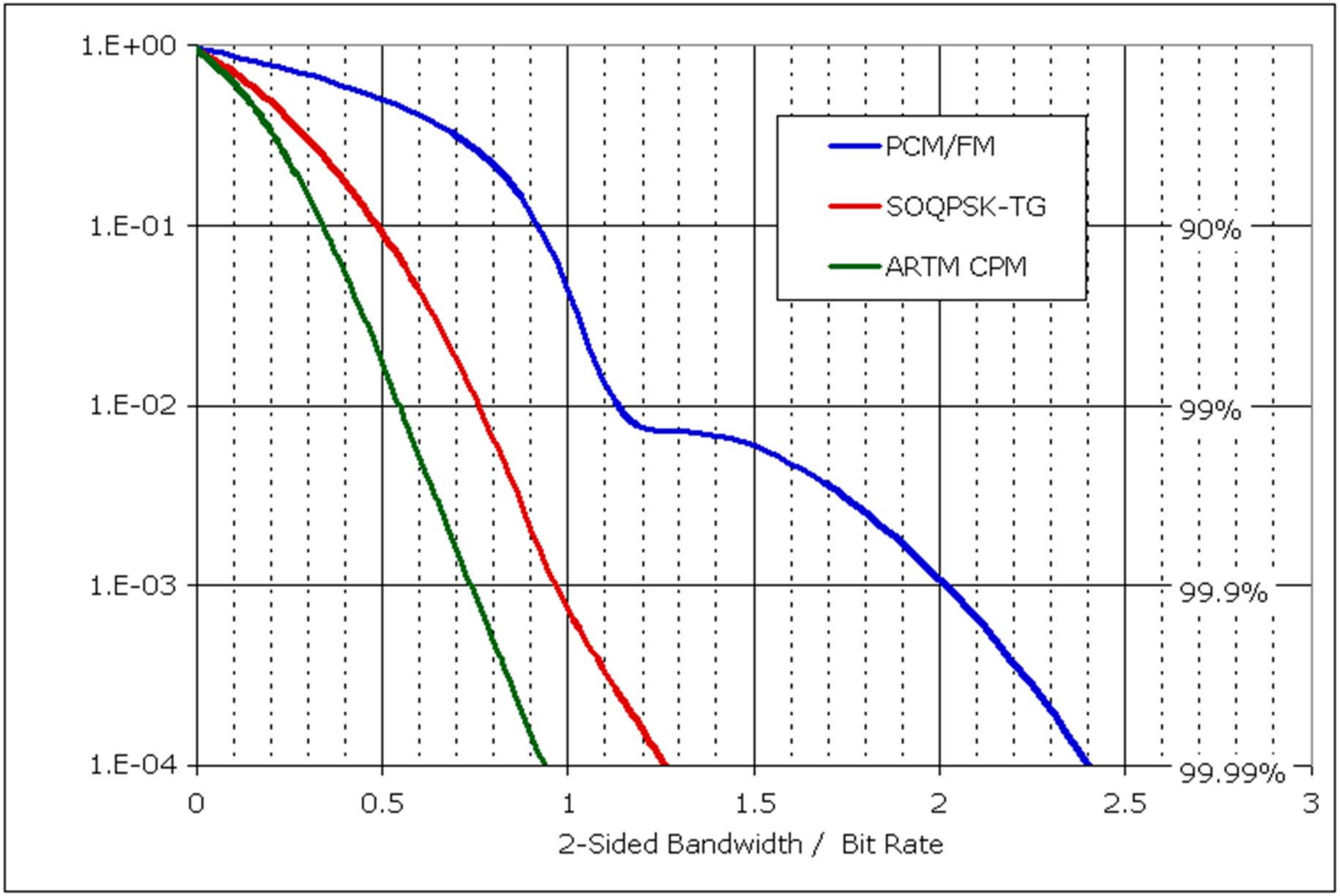




PSD (Tier 0, I, & II)



Fractional Out-of-band Power



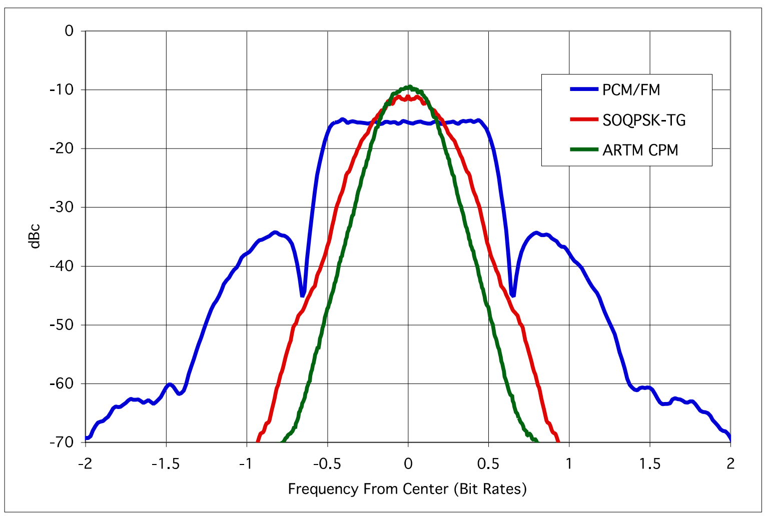
Tier II Multi-h CPM Summary

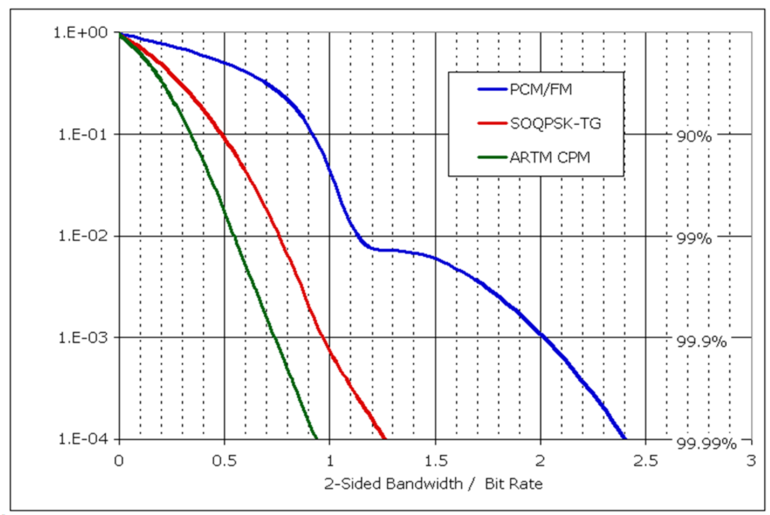
- Similar detection efficiency to PCM/FM.
- Constant envelope waveform is ideal for efficient non-linear PA's.
- Enhanced performance gained by increasing demodulator complexity.
- 99.9% bandwidth: 0.75 times bit rate

M	α_i	h	g(t)
4	{-3, -1, +1, +3}	{4/16, 5/16}	Normalized raised cosine, 3 symbols (6 bits) long

Side by Side Summary

Tier	M	α_i	h	g(t)
0	2	{-1, +1}	0.7	Normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
I	3	{-1, 0, +1}	0.5	Normalized windowed impulse response of a spectral raised cosine, 8 bits long
II	4	{-3, -1, +1, +3}	{4/16, 5/16}	Normalized raised cosine, 3 symbols (6 bits) long





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Demodulation

- As the shop manual says, “Installation is reverse of removal.”
- Demodulation is intrinsically more difficult
  - Unknown carrier frequency
  - Unknown carrier phase
  - Unknown clock frequency and phase
  - Signal corruption
    - Noise
    - Interference
    - Multipath
    - Doppler shift

Demodulation Overview

	Tier 0	Tier I	Tier II
Single-Symbol	Countless vendors BER = 1e-5 @ 12.1 to 13.0 dB Eb/N0	Numerous vendors BER = 1e-5 @ 11.7 to 12.5 dB Eb/N0	Not practical
Multi-Symbol (Trellis)	Two vendors BER = 1e-5 @ 8.6 to 9.4 dB Eb/N0	One vendor BER = 1e-5 @ 11.2 dB Eb/N0	Two vendors BER = 1e-5 @ 11.4 to 12.1 dB Eb/N0

Legacy (nearly exclusive prior to 2001)

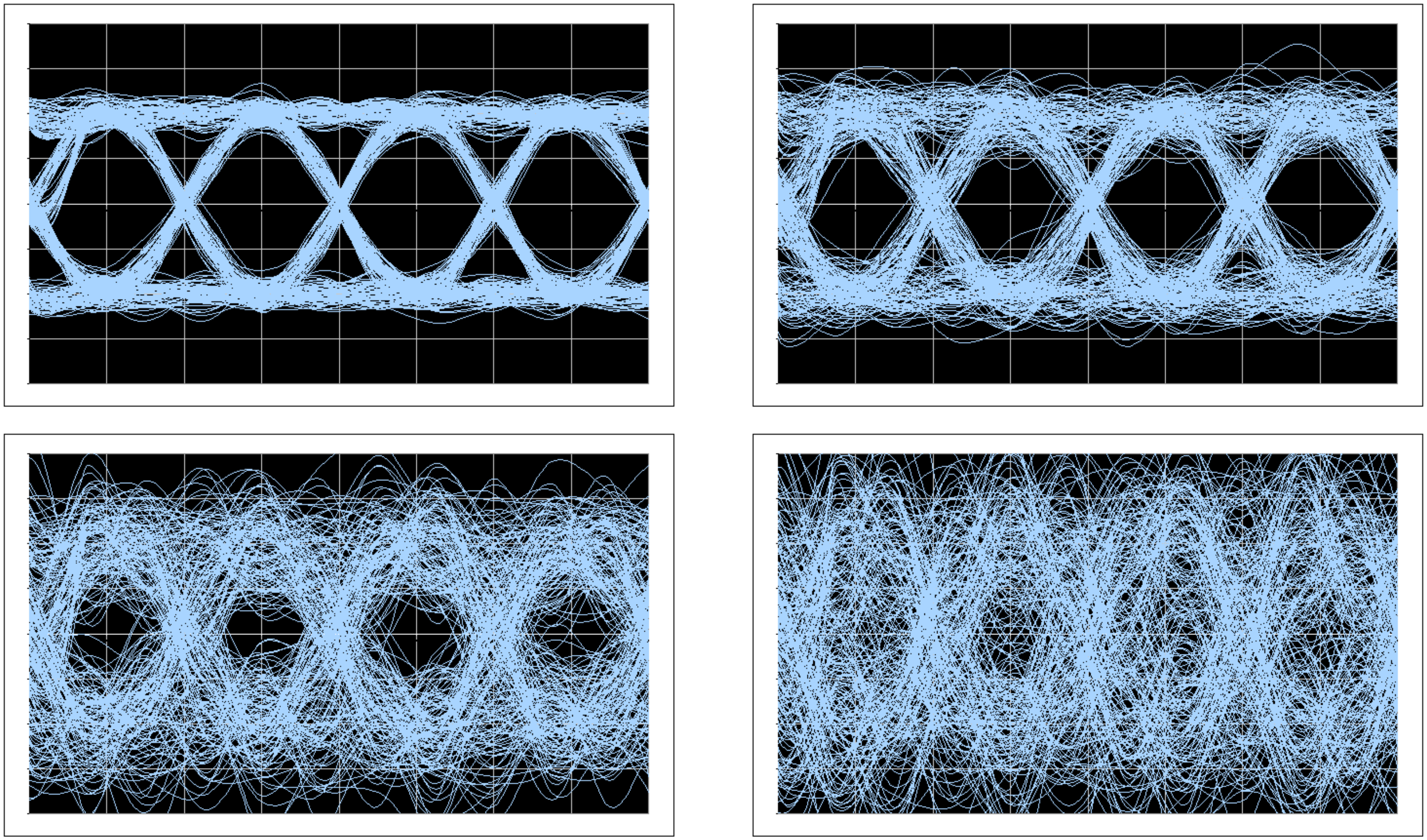
Tier 0 Single-Symbol Detection

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

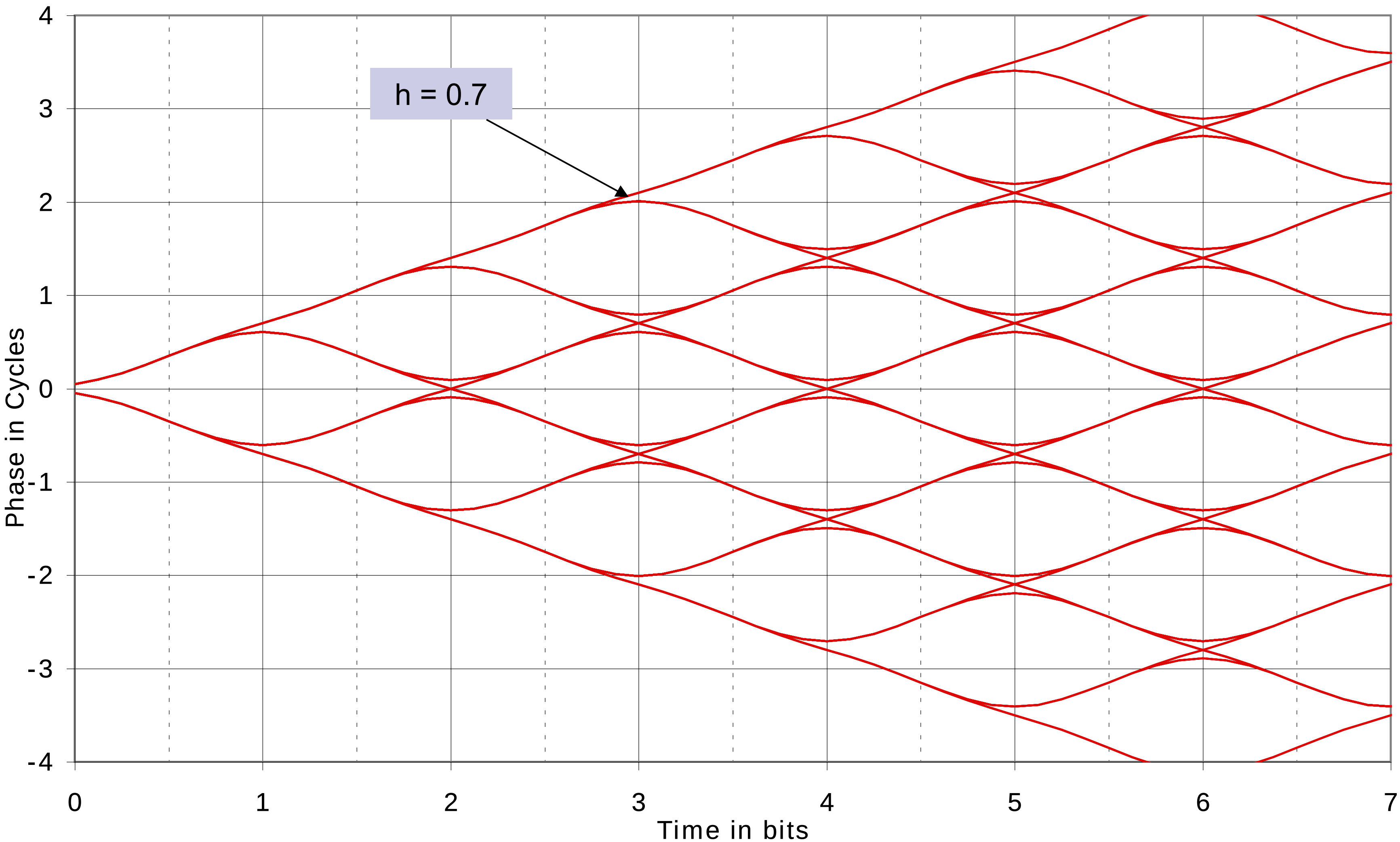
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)d\tau$$

- Differentiate the phase to get frequency
  - Limiter-discriminator
  - Phase locked loop
  - Digital processing
- If the frequency in this symbol > 0, data = 1
- If the frequency in this symbol < 0, data = 0

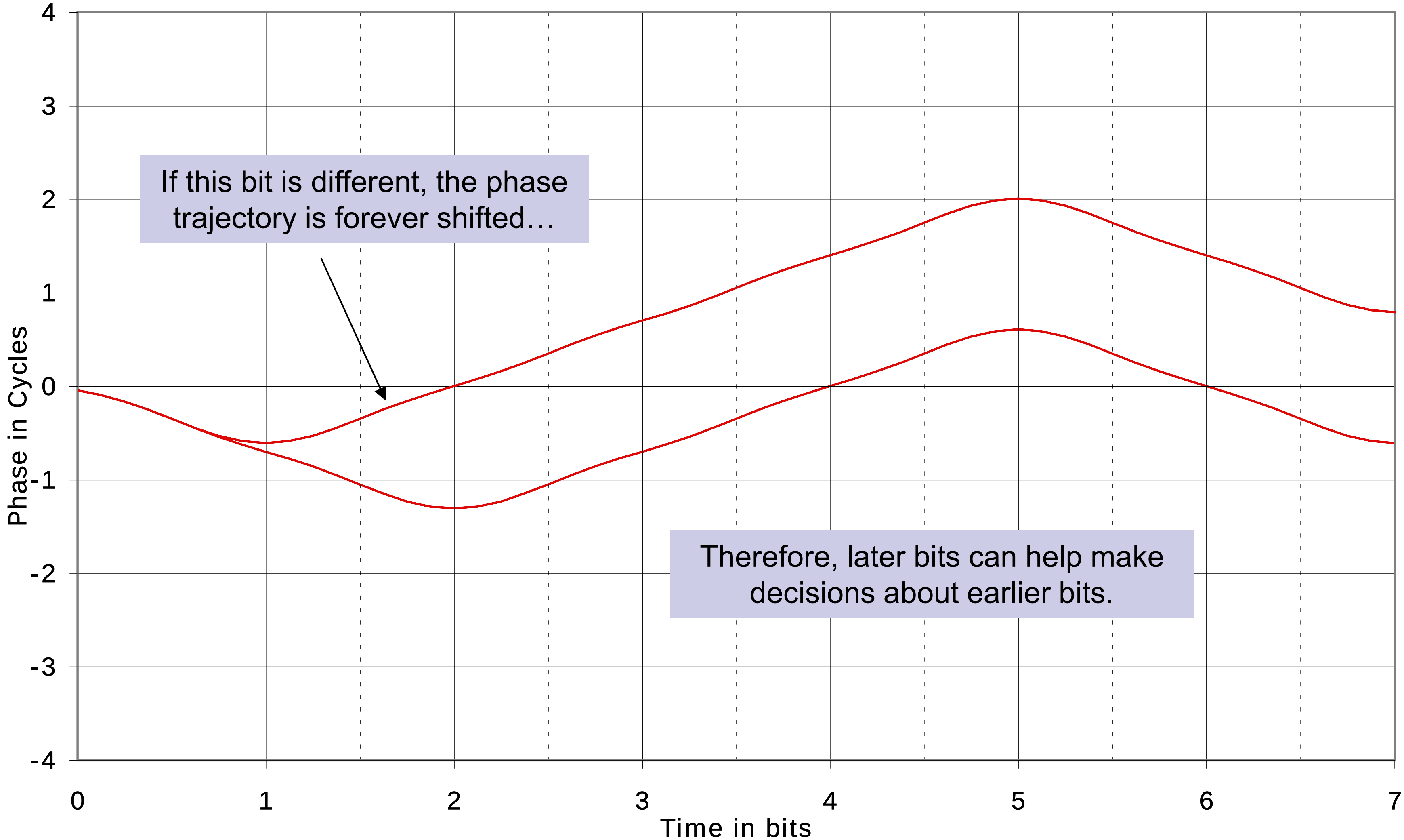
Tier 0 Frequency Detection



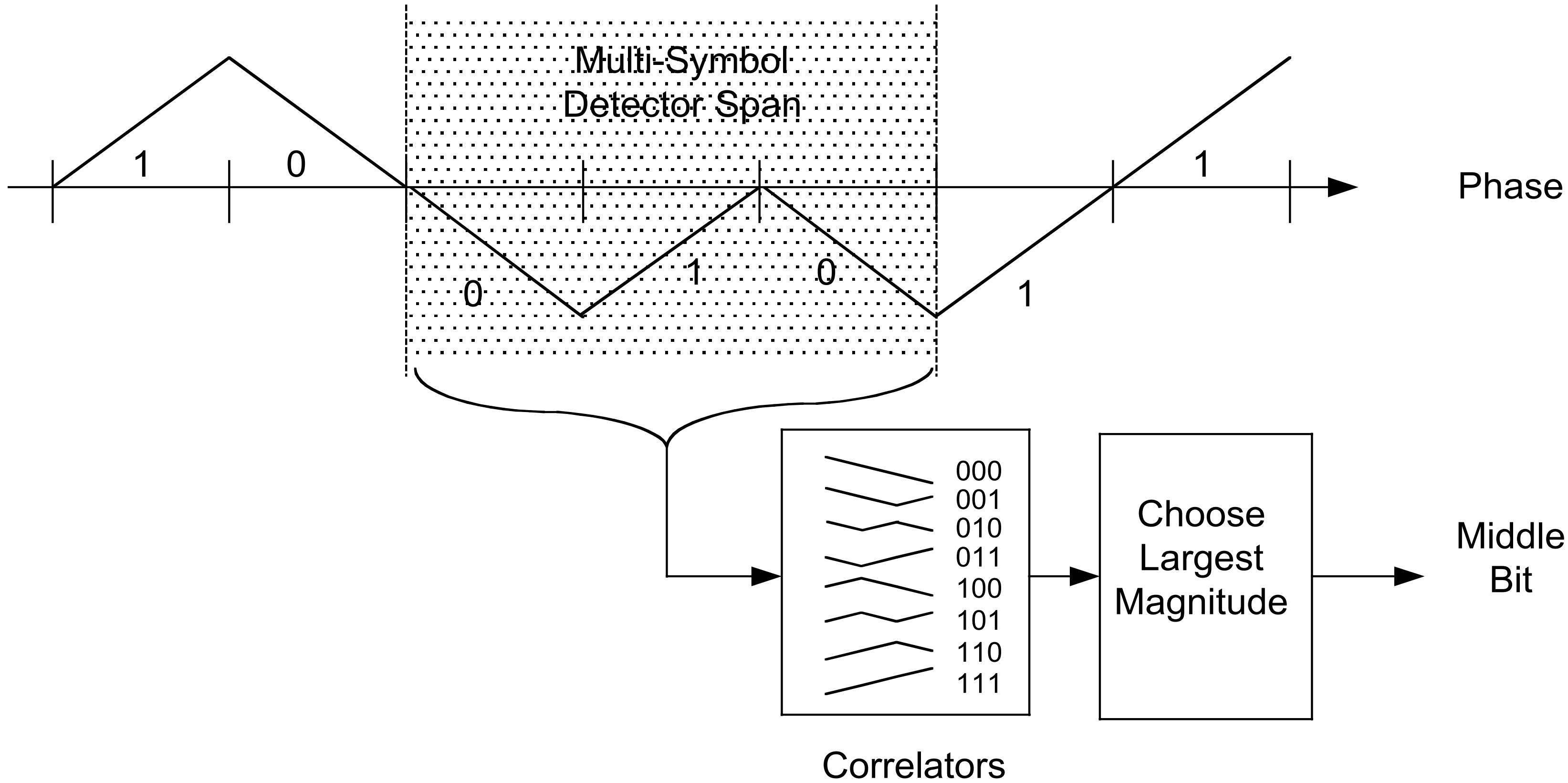
Tier 0 Phase Tree



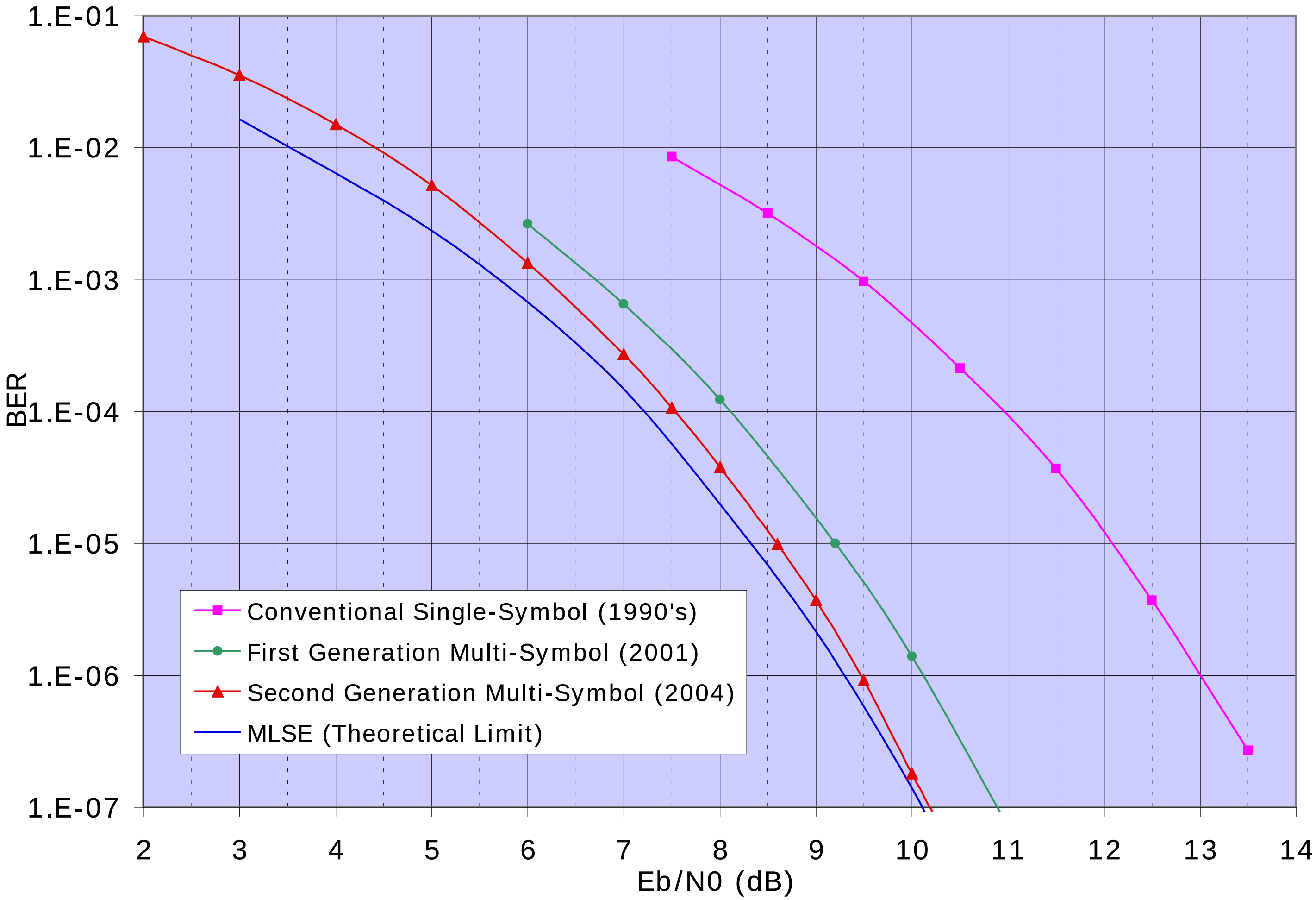
Phase Trajectory Never Forgets



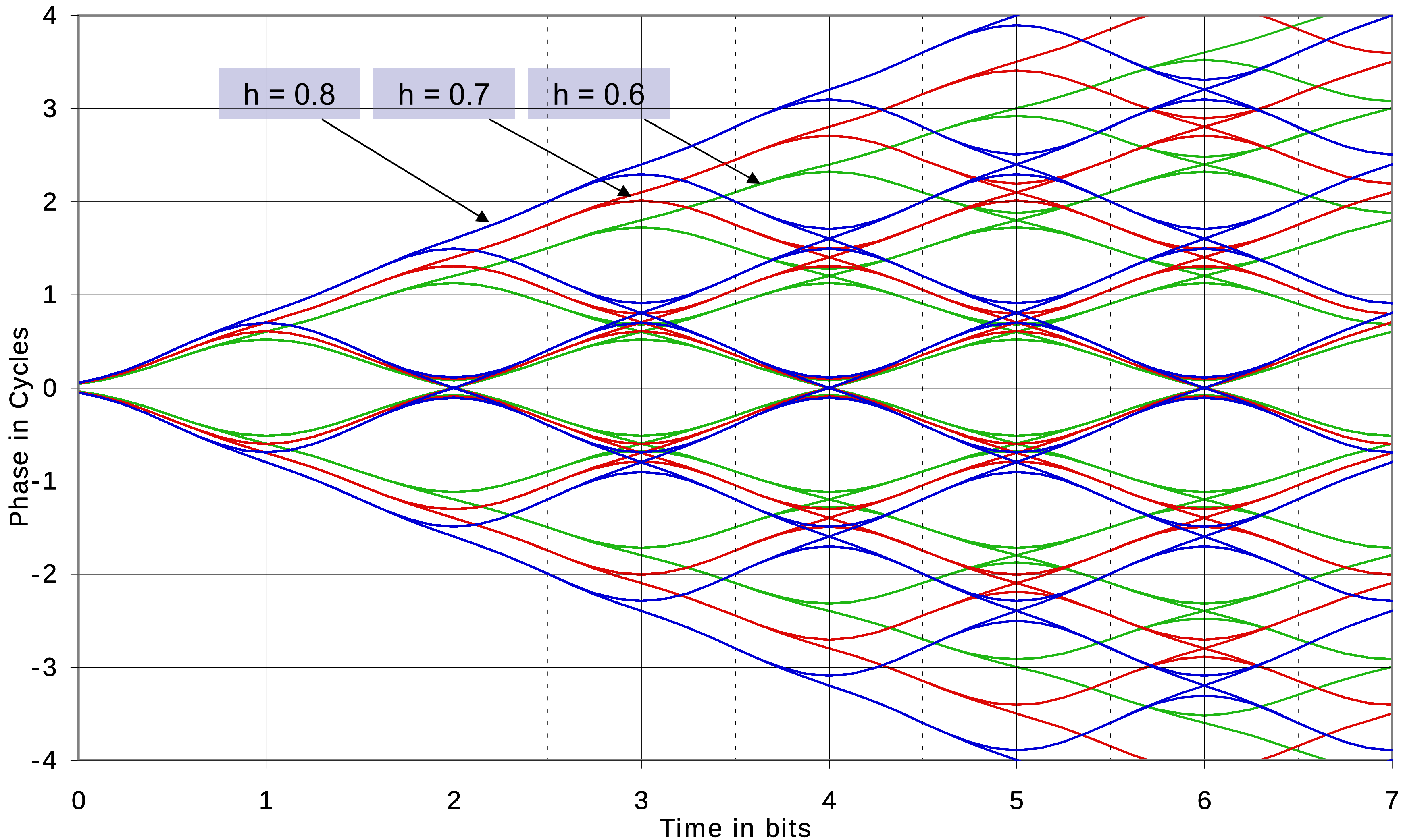
Multi-Symbol Detector Example



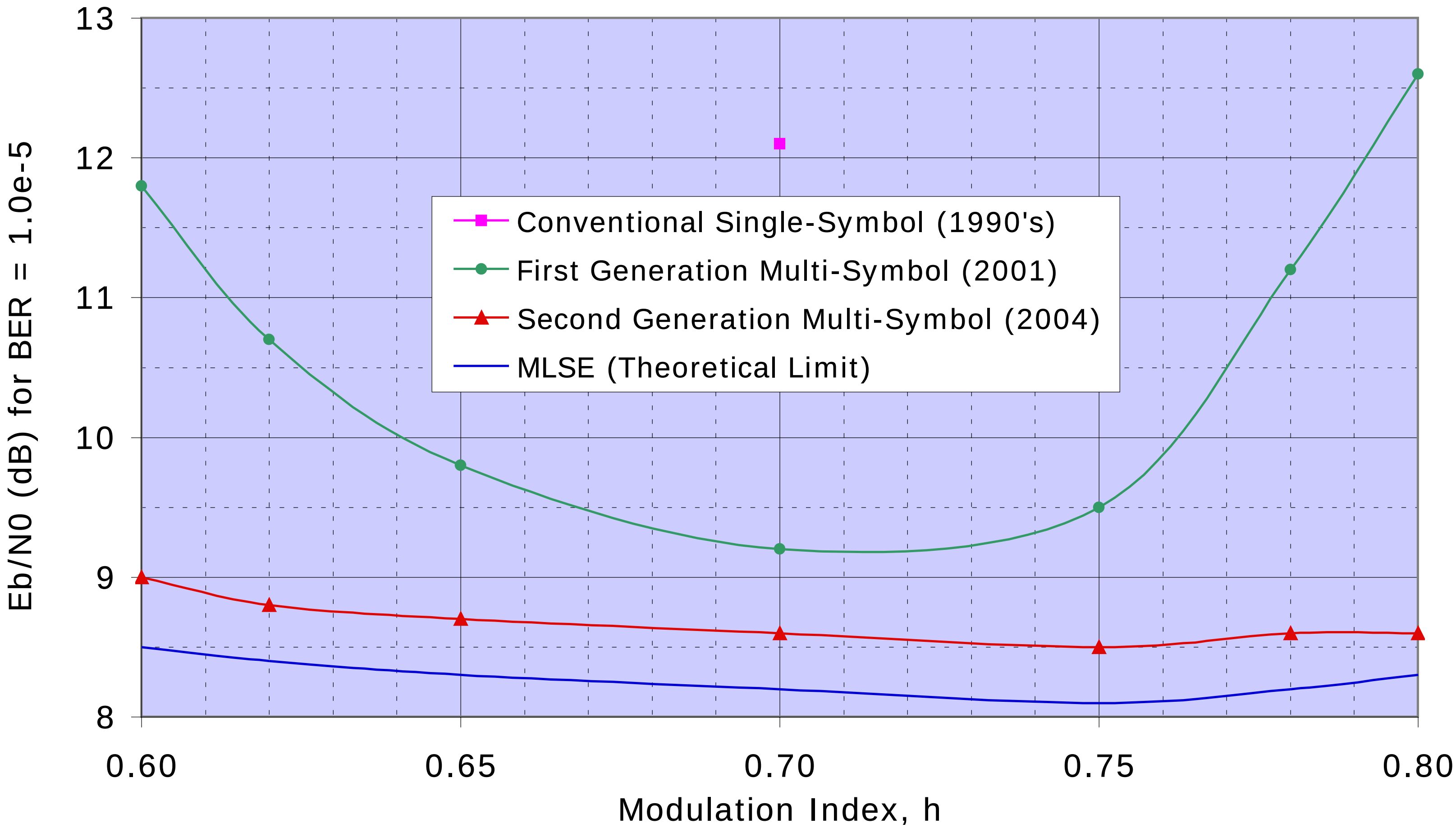
Tier 0 BER Performance



Legacy PCM/FM Transmitters



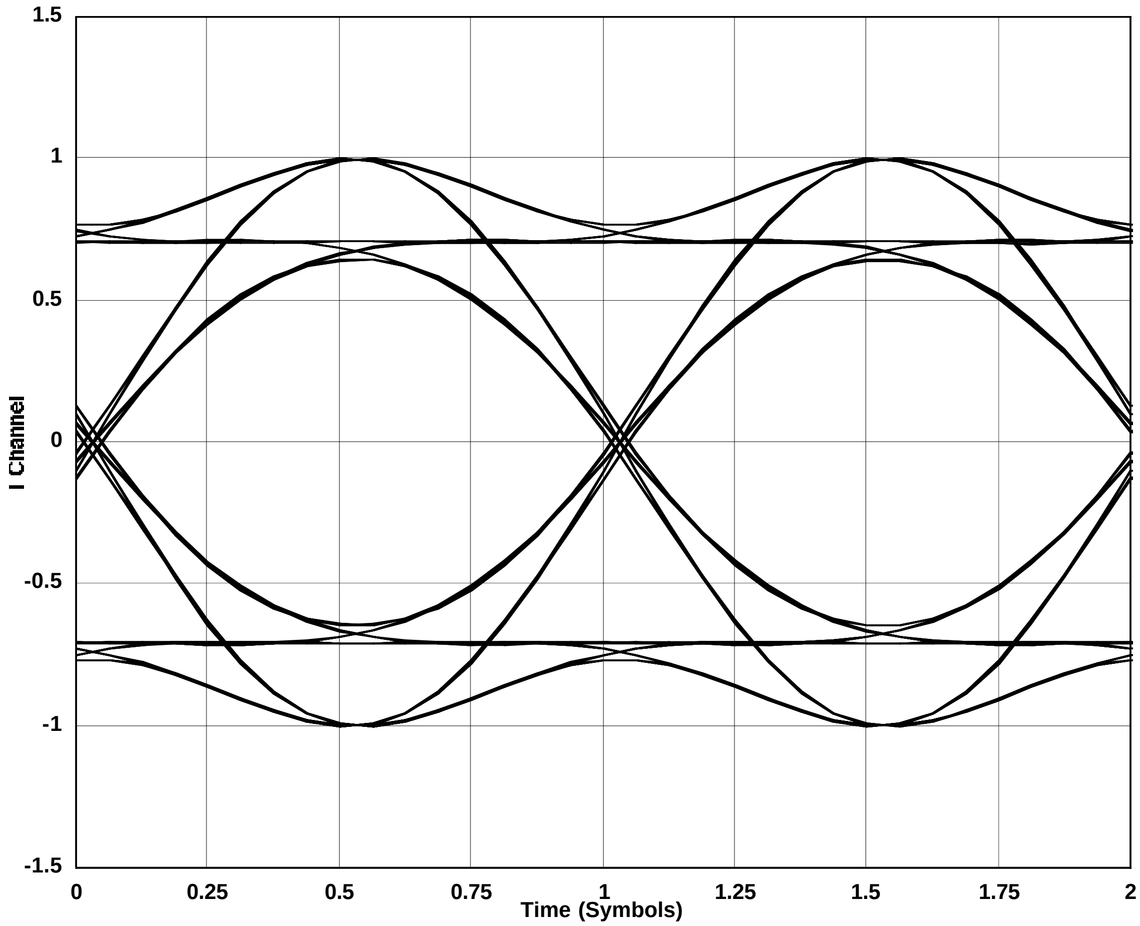
Effect of TX Deviation Error



SOQPSK Detection

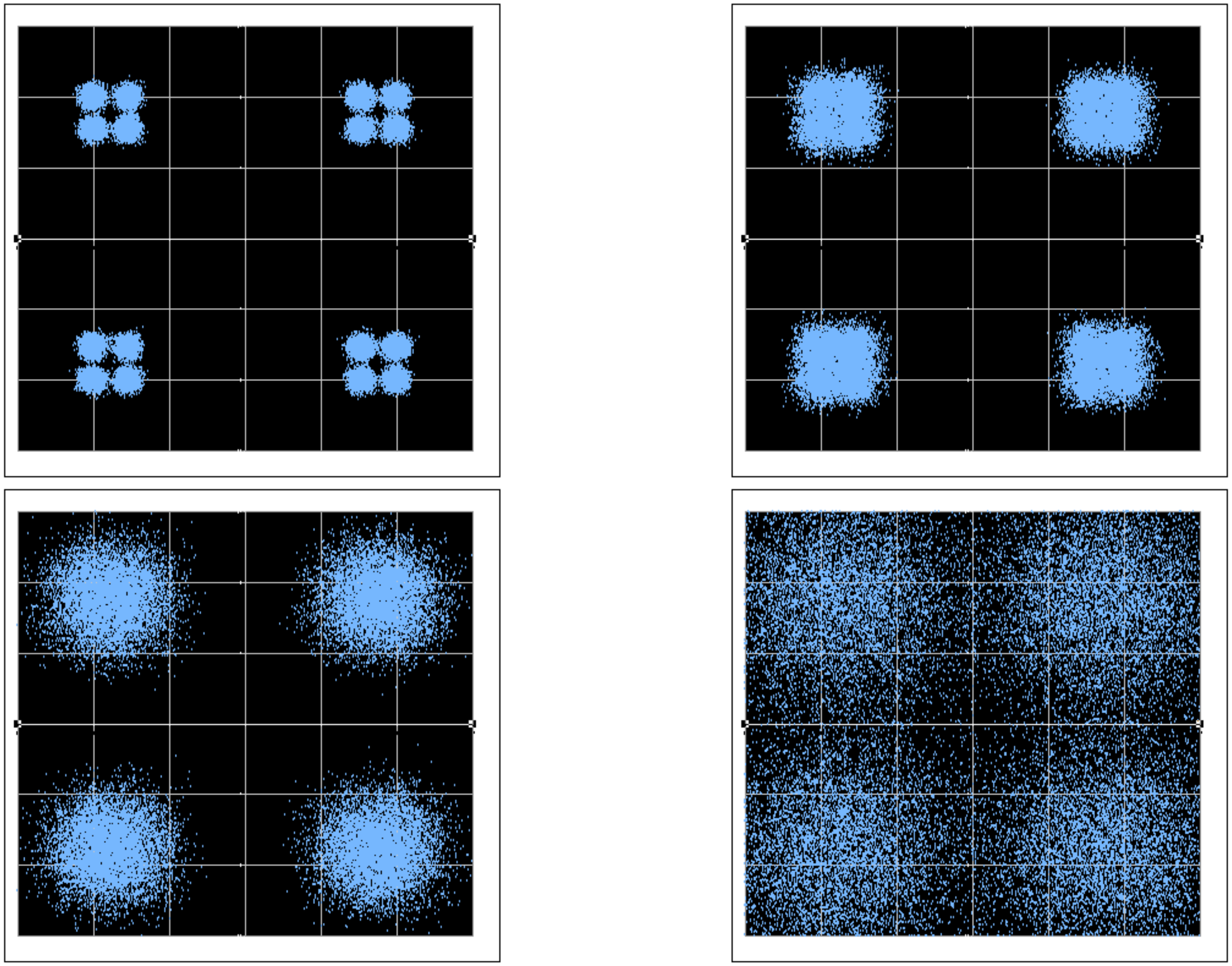
- Can be detected by conventional (non-shaped) offset QPSK demod
- Non-matched filtering loss of about 2 dB
- Butterworth lowpass filter is reasonable approximation to matched filter
- Trellis detection is optimum, but more complex

SOQPSK-A Eye Pattern

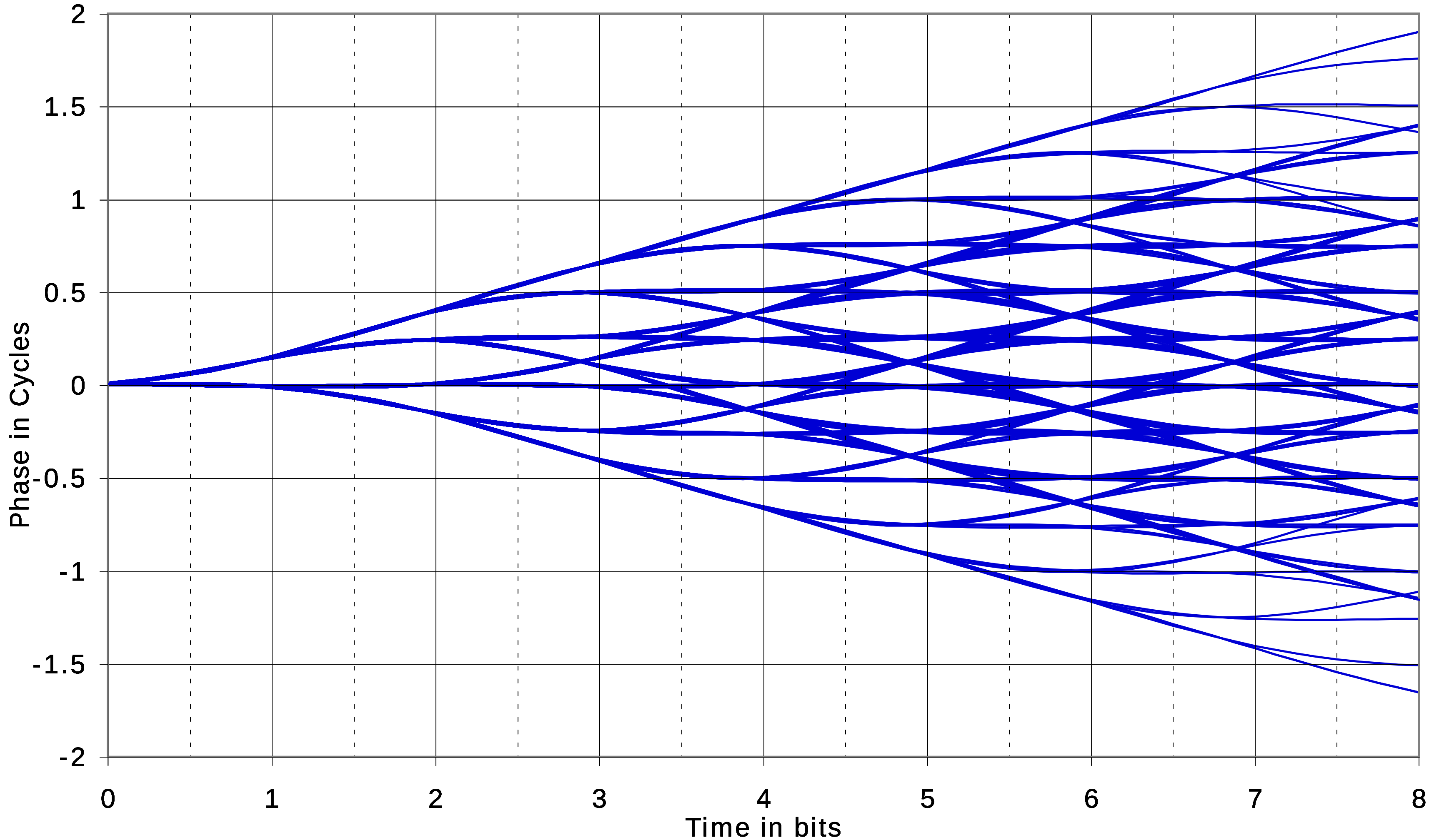


- Single-symbol detection ignores memory inherent in waveform
- Can be detected by conventional (non-shaped) offset QPSK demod
- I&D detector endures additional loss due to waveform mismatch

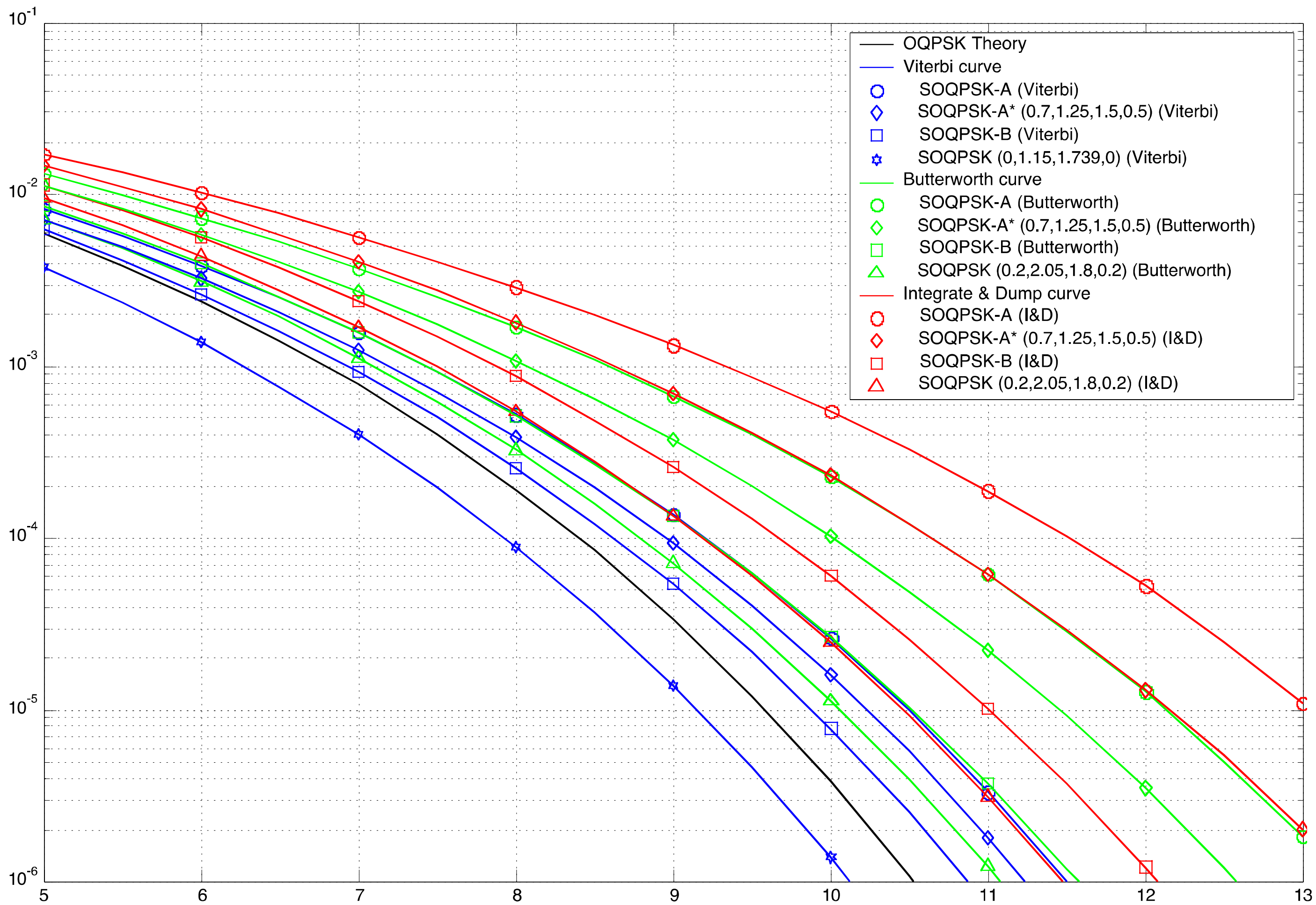
SOQPSK Constellations



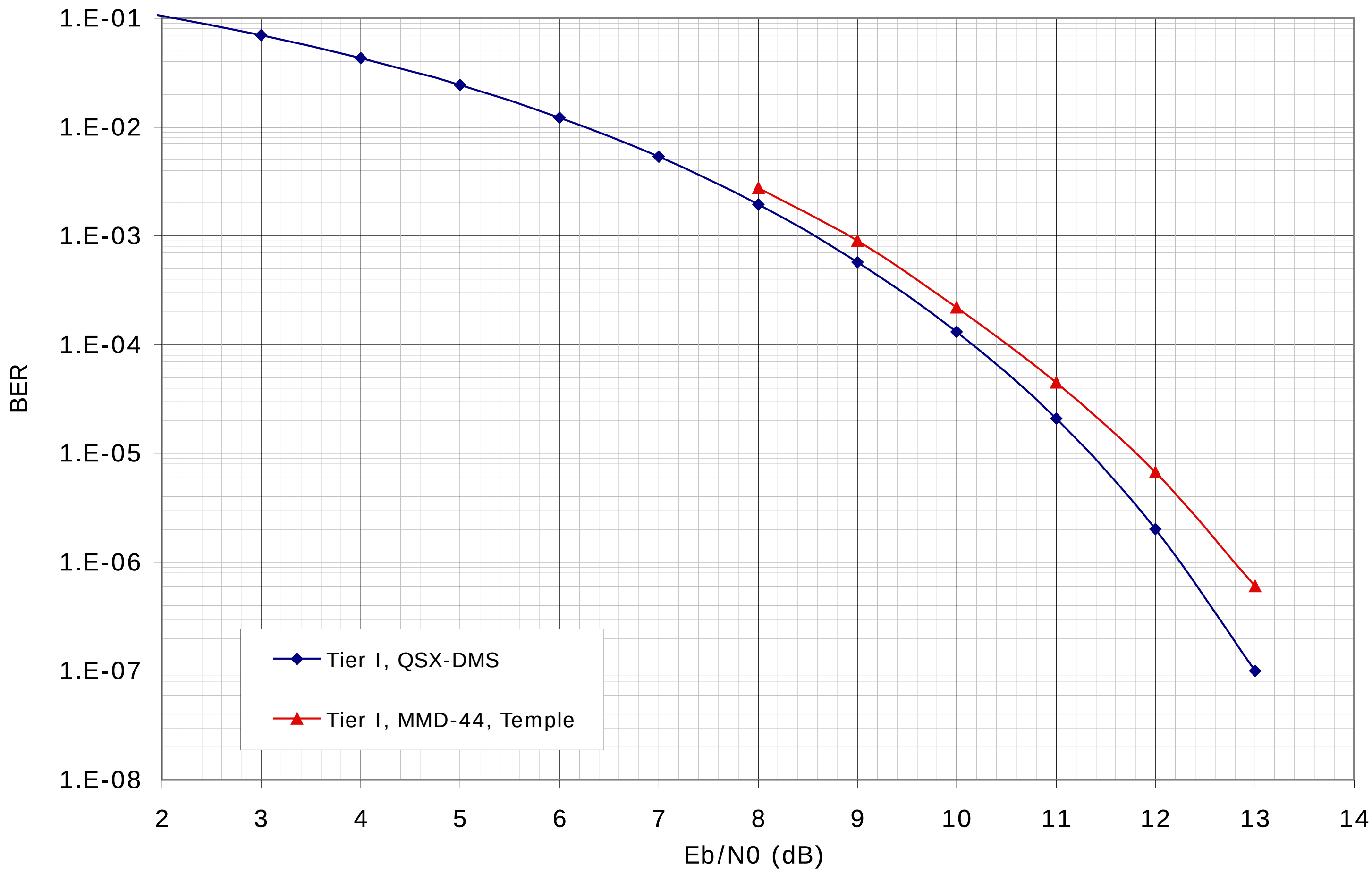
SOQPSK-TG Phase Tree



SOQPSK Detection Efficiency

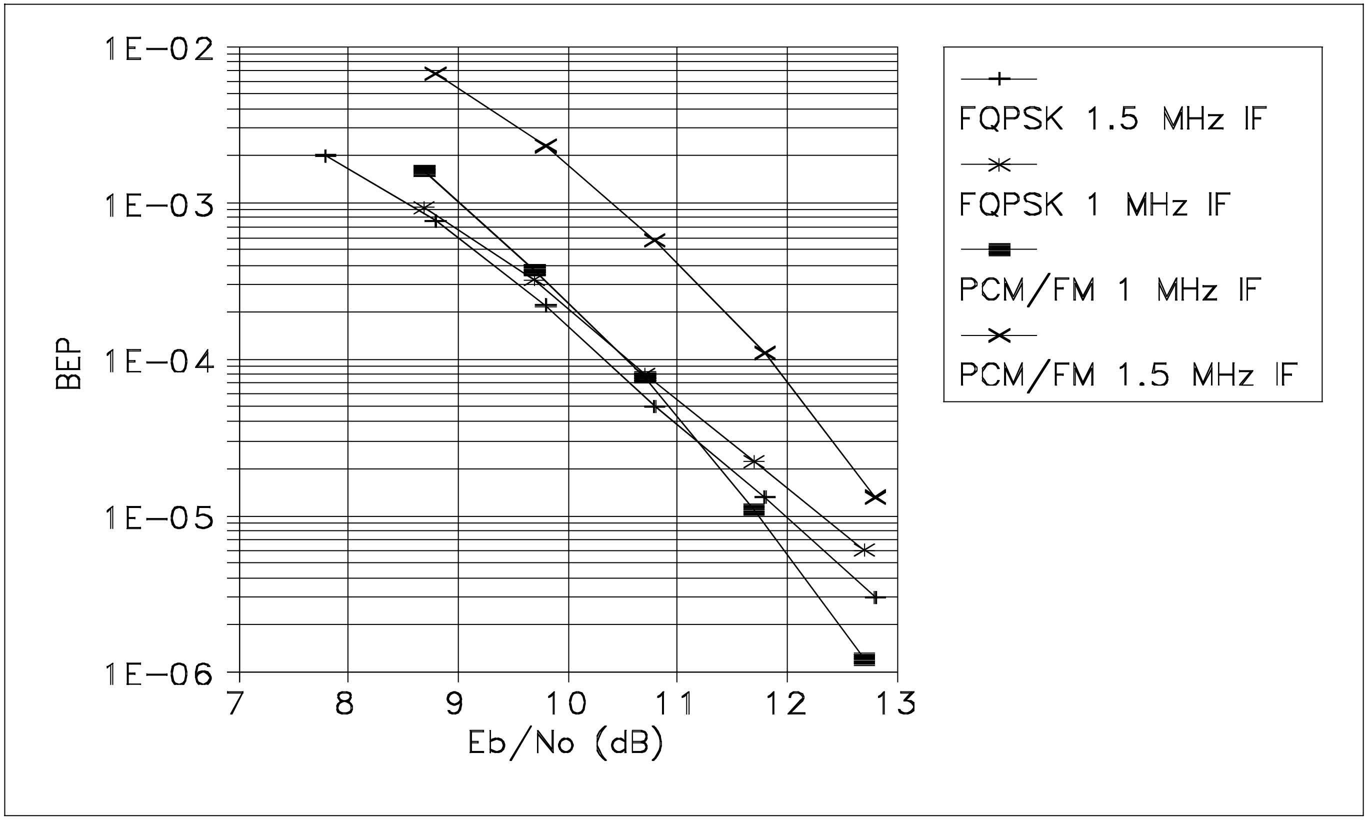


SOQPSK-TG



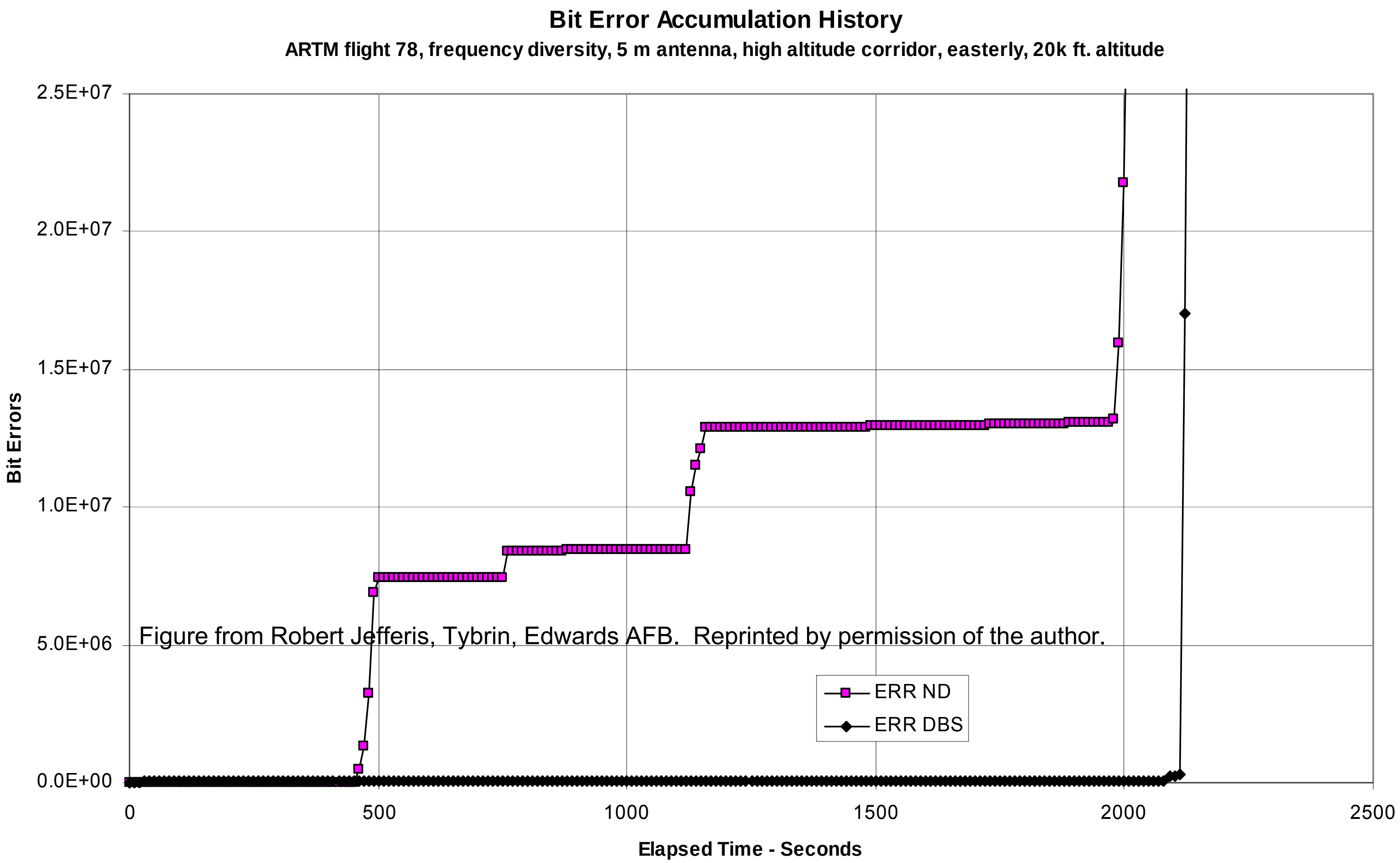
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
BER
2
3
4
5
6
7
8
9
10
11
12
13
14
Eb/N0 (dB)
Tier I, QSX-DMS
Tier I, MMD-44, Temple

BER Performance of FQPSK



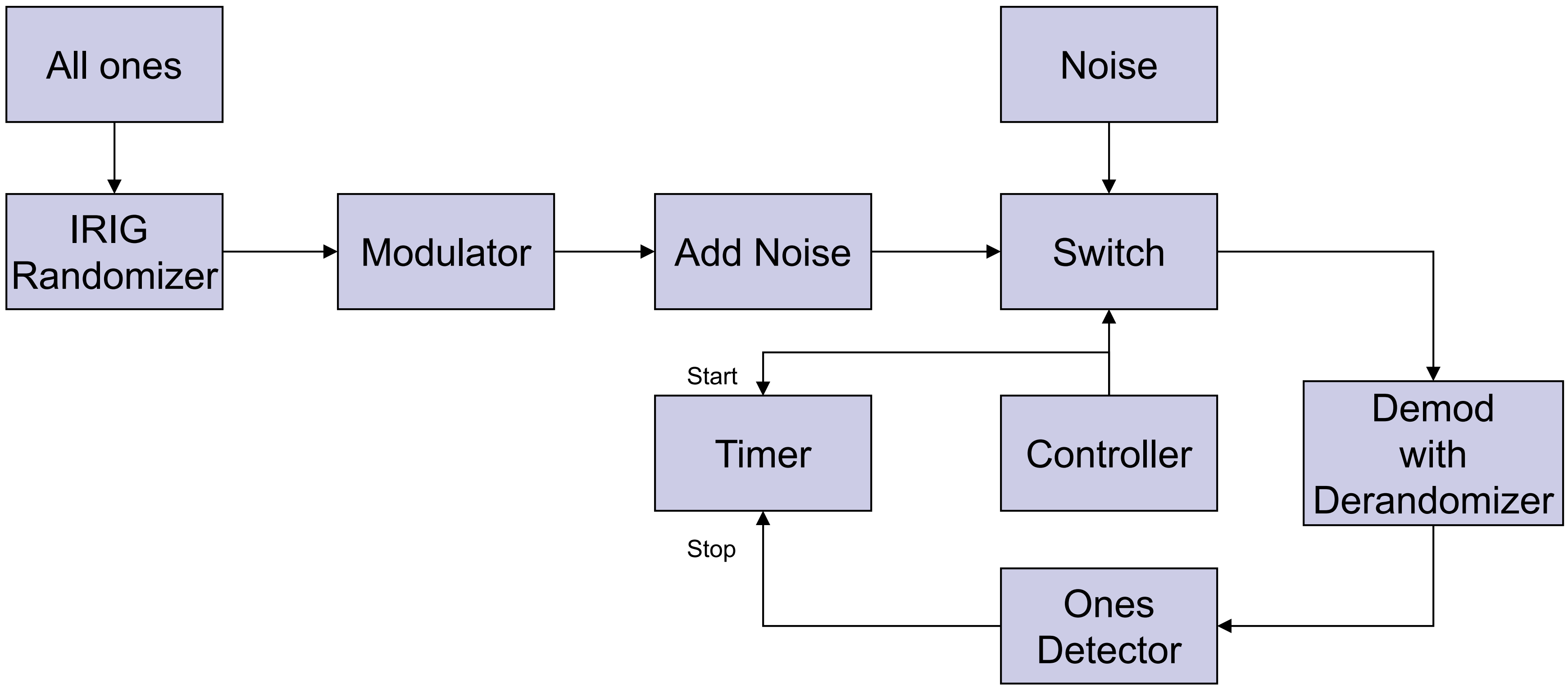
From Gene Law's Oct 98 paper

Cumulative Error Counts in Bursty Channels



Synchronization Test

- Transmit randomized ones pattern
- Measure time at which demod output becomes "all ones" (or mostly)



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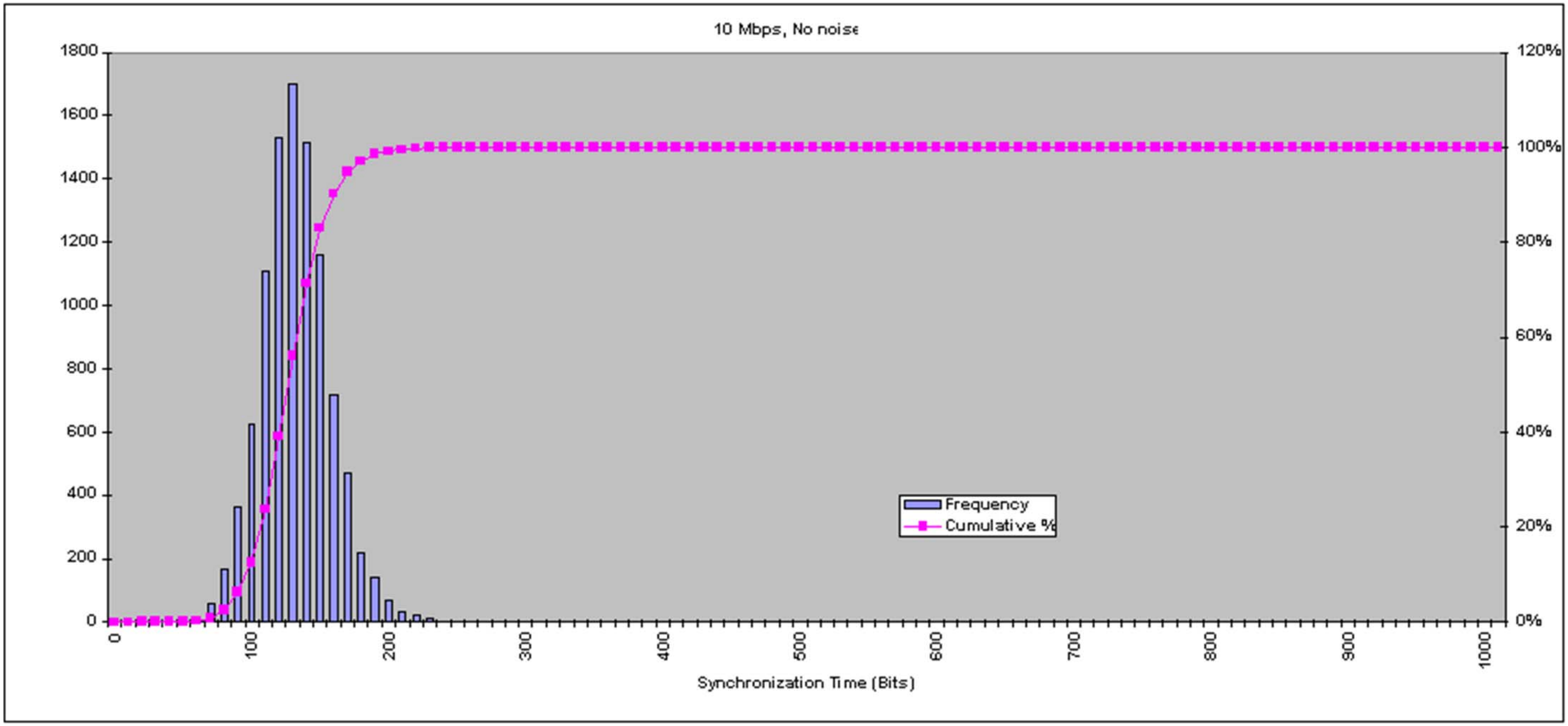
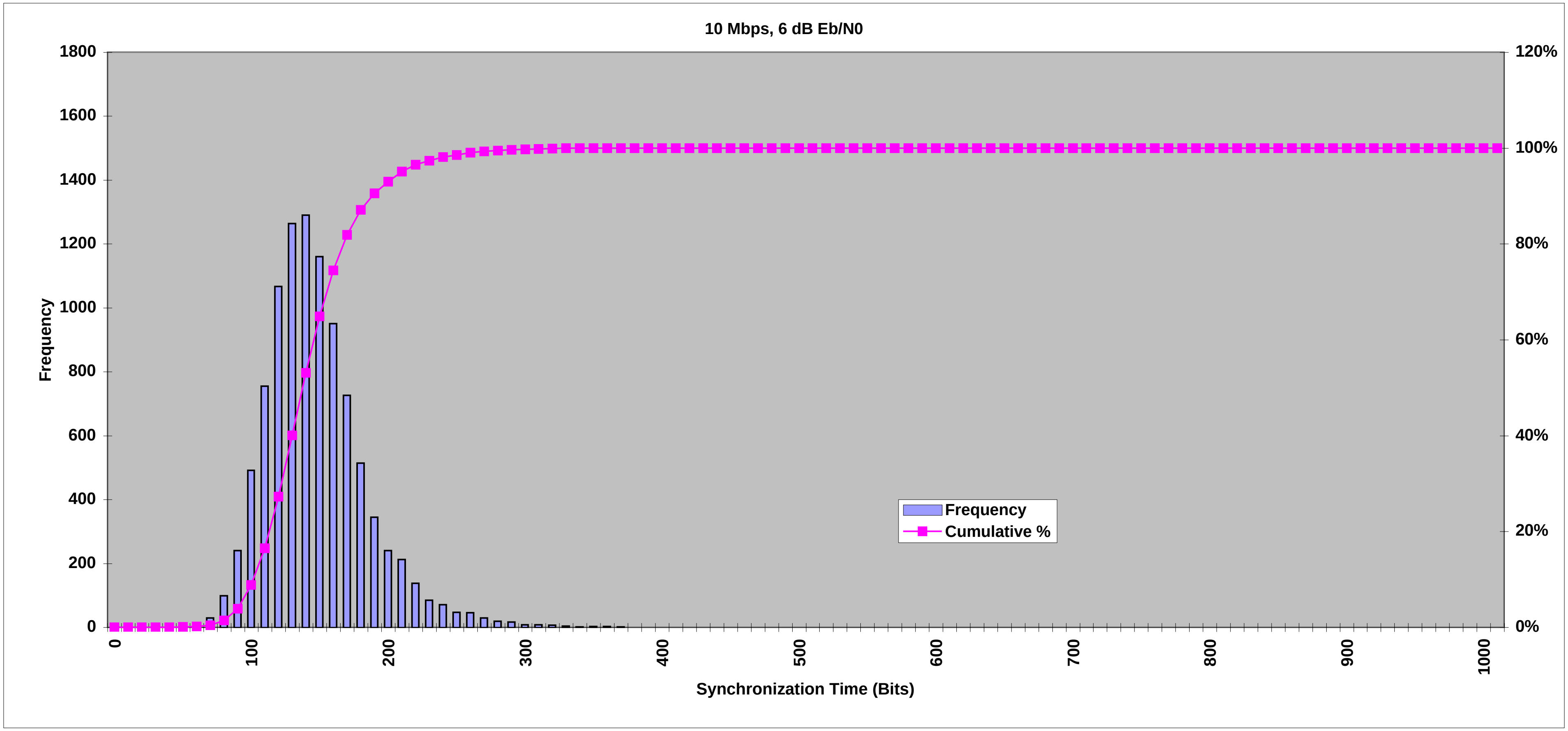
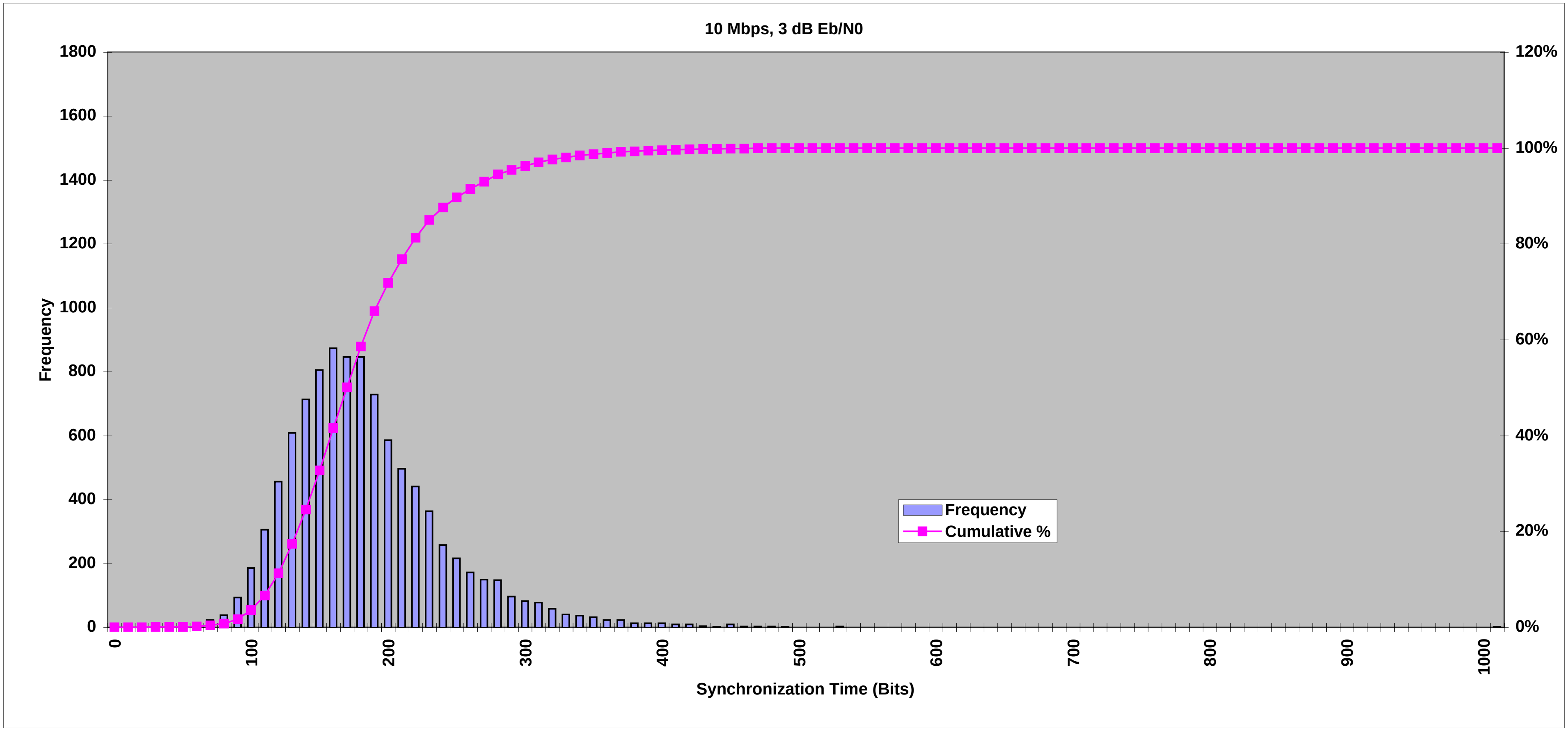
SOQPSK Synchronization, No Noise



SOQPSK Synchronization, 6 dB



SOQPSK Synchronization, 3 dB



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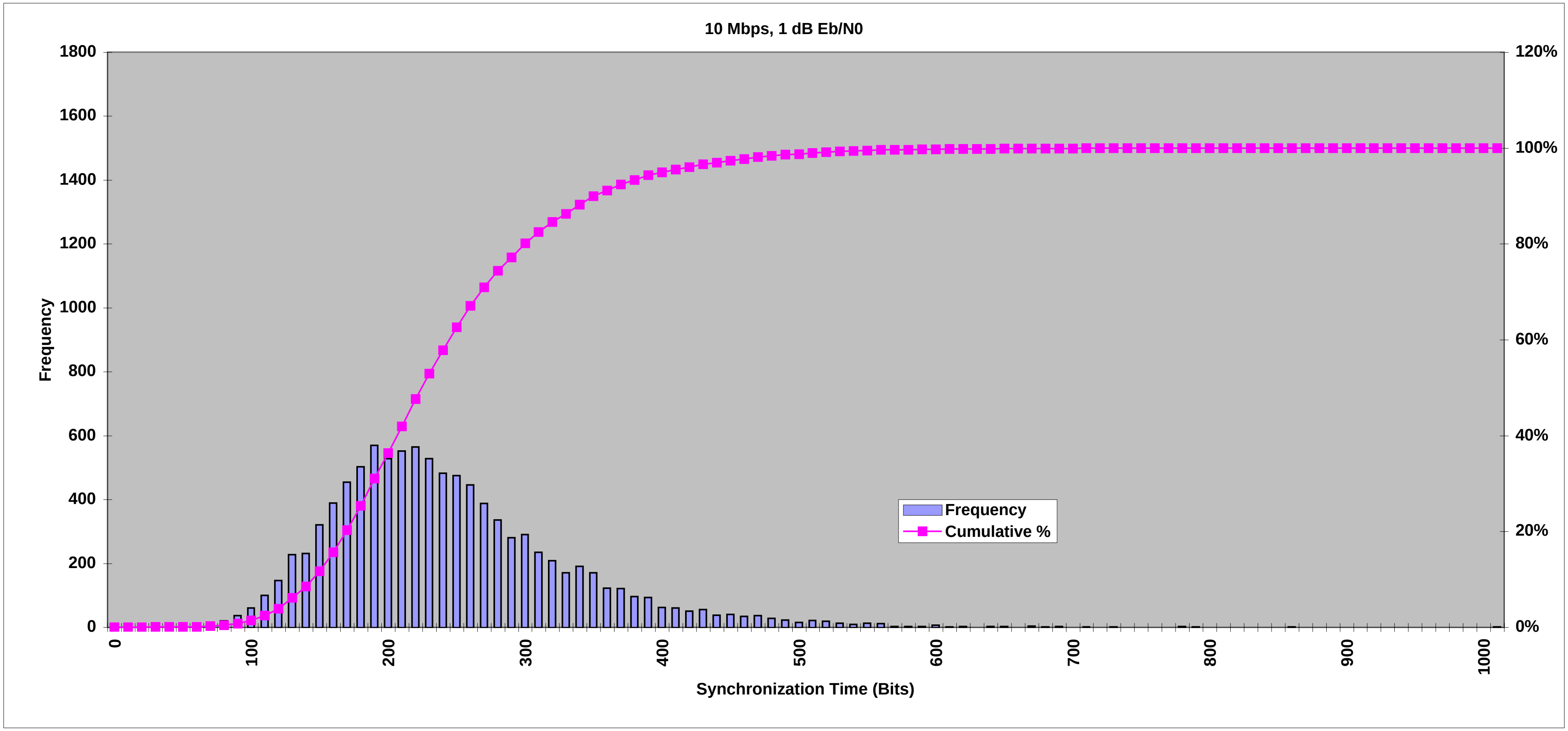
SOQPSK Synchronization, 1 dB



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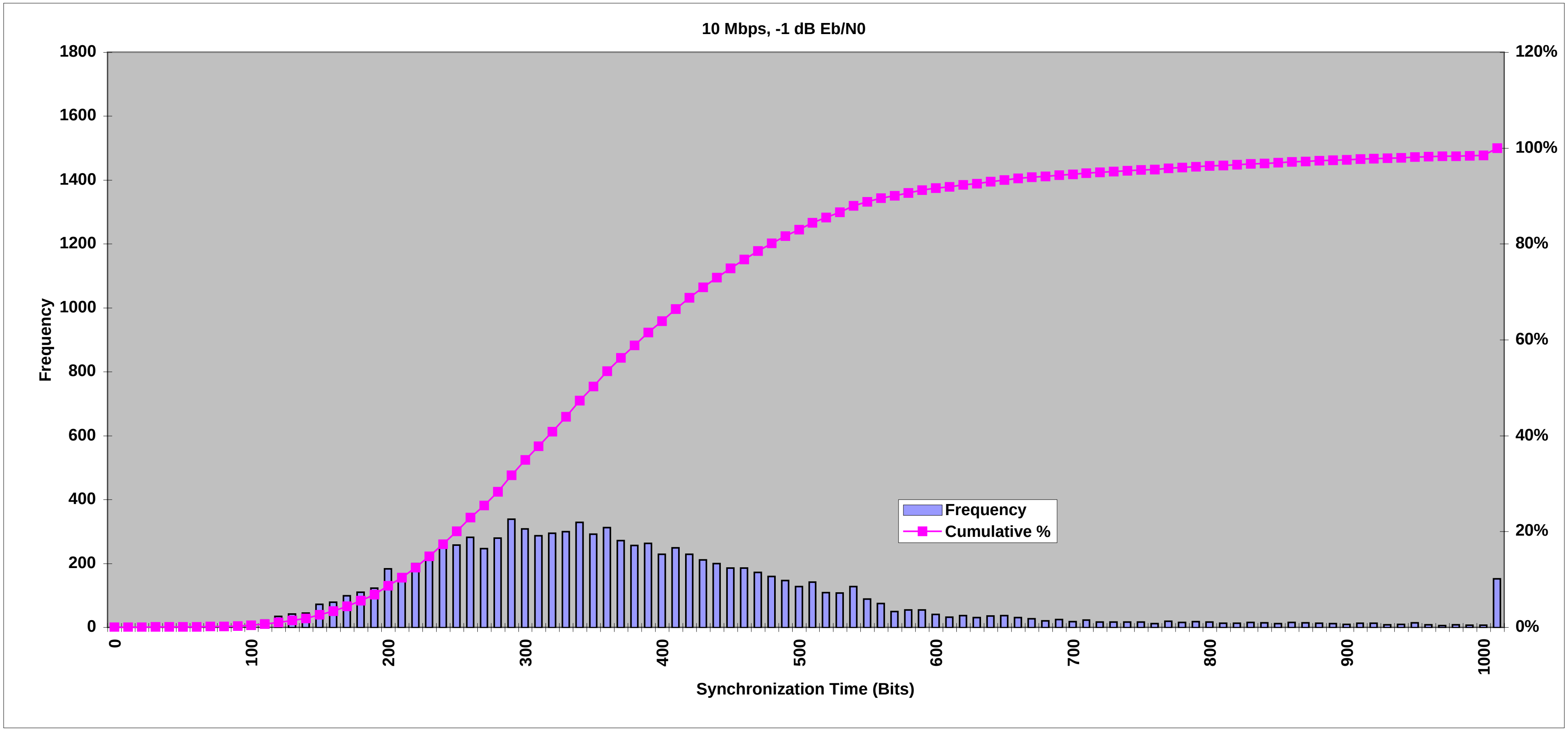
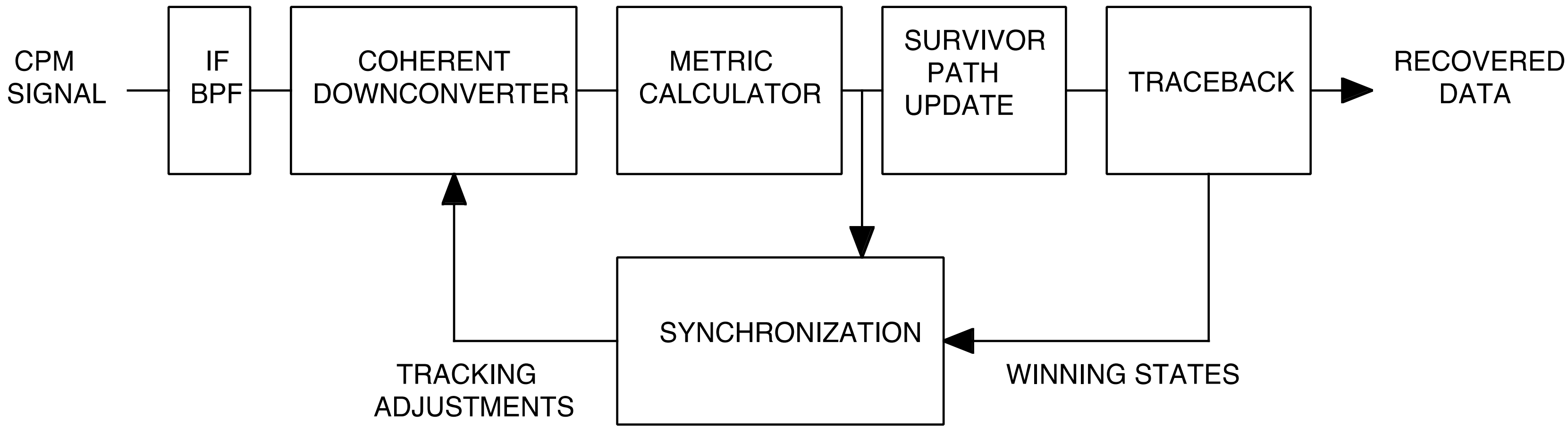
SOQPSK Synchronization, -1 dB



Multi-h CPM Detection

- Modulator intentionally creates severe inter-symbol interference
  - 3-symbol RC premod filter
- Symbol-by-symbol detection is essentially useless
- Trellis detection is required
- Enormously complex machine
  - 12.5 million gates

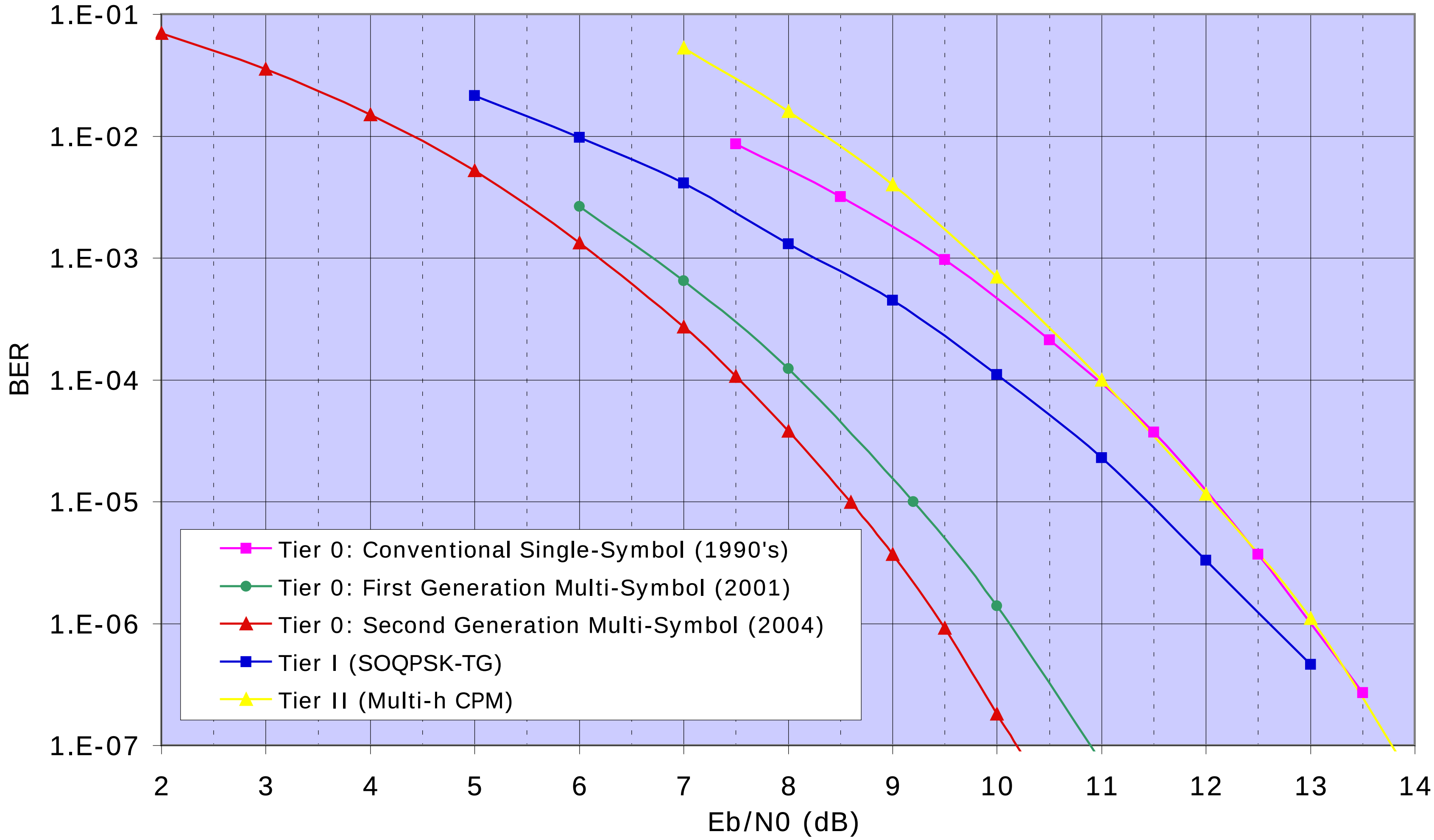
Demodulator Architecture



Demodulator Complexity

- If signal can be represented in a finite state trellis, the Viterbi Algorithm can be used for demodulation.
- Modulation indices = h = 2k/p
  - $M=4$, $L=3$, $h_1 = 4/16$, $h_2 = 5/16$
- Receiver implementation complexity
  - Number of Correlations $M^L = 64$
  - Number of Phase States $p = 32$
  - Number of Branch Metrics $pM^L = 2048$
  - Number of Trellis States $pM^{L-1} = 512$

BER Performance Comparison



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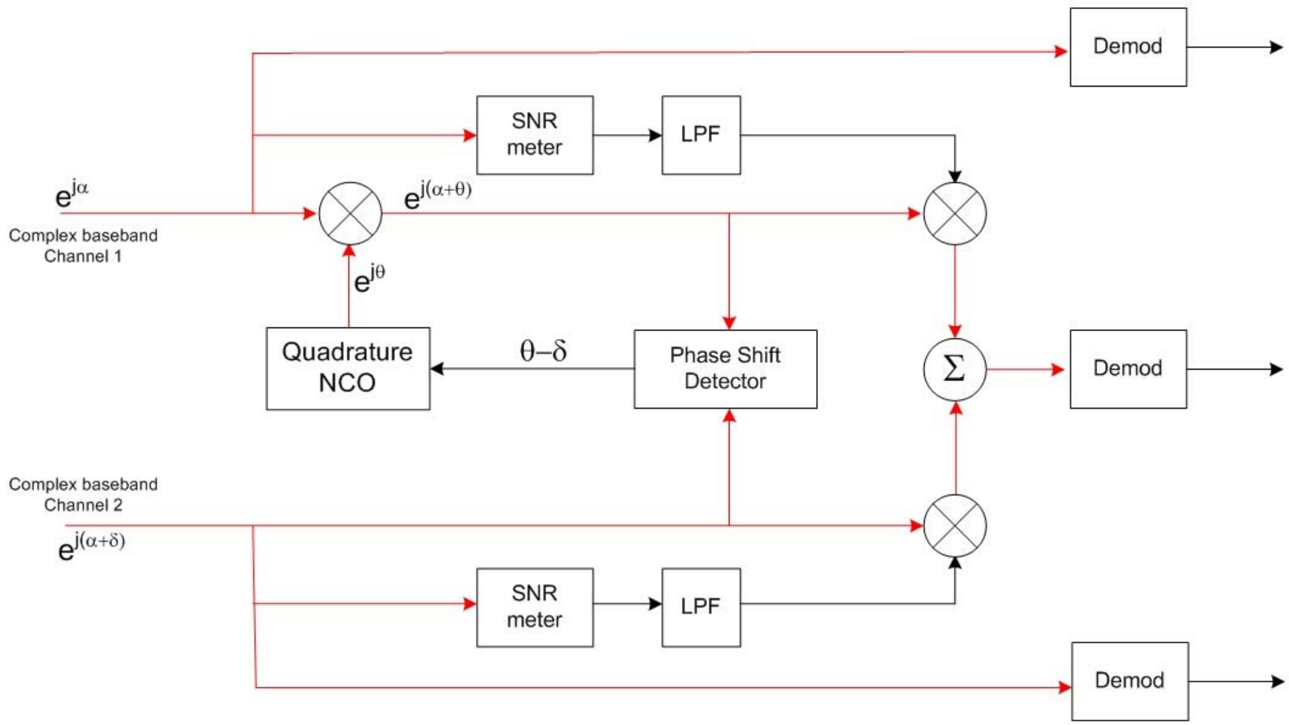
If One is Good…

- Two must be better
- Many telemetry systems utilize multiple antenna feeds
  - Spatial separation
  - Frequency separation
  - Orthogonal polarizations
- Combining two (or more) copies of the same signal
  - Diversity combining
  - Creates a third signal to be demodulated
  - BER performance of third signal is better than either of the individual signals

Maximal Ratio Combining



- Weight each signal in proportion to its SNR and add
- Yields optimum SNR on combined channel **<u>in AWGN</u>**
- $SNR_{combined} = SNR_a + SNR_b$

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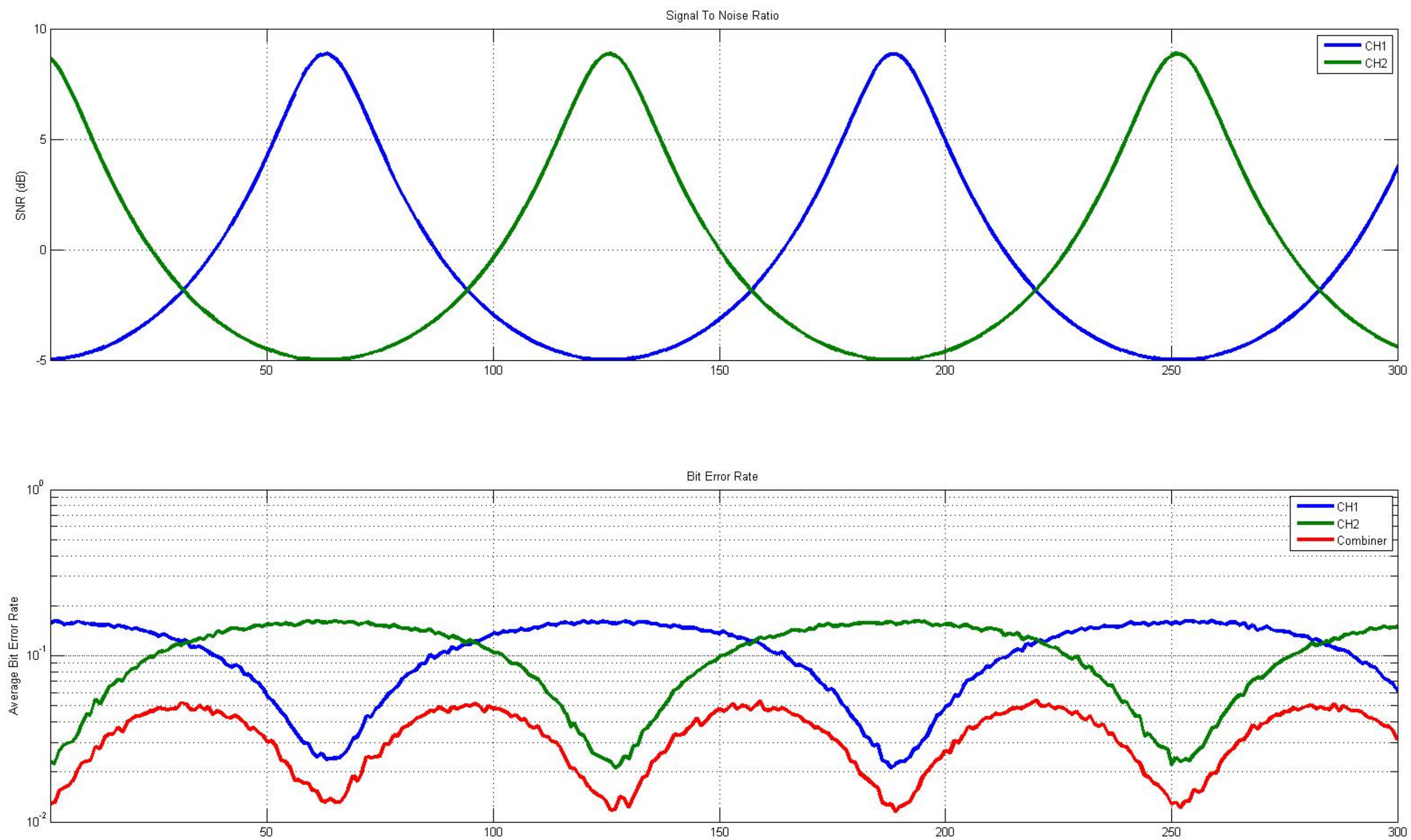
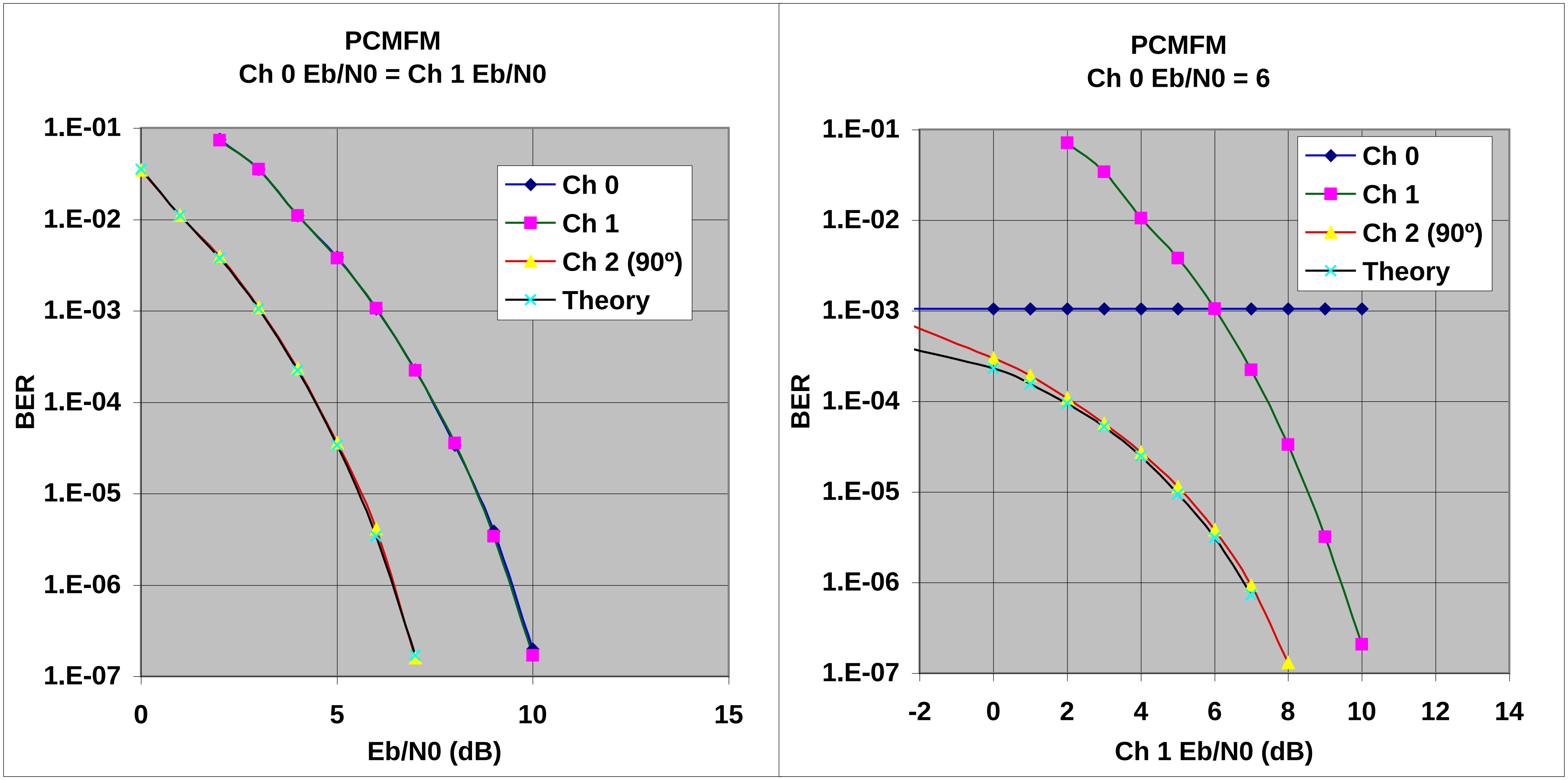
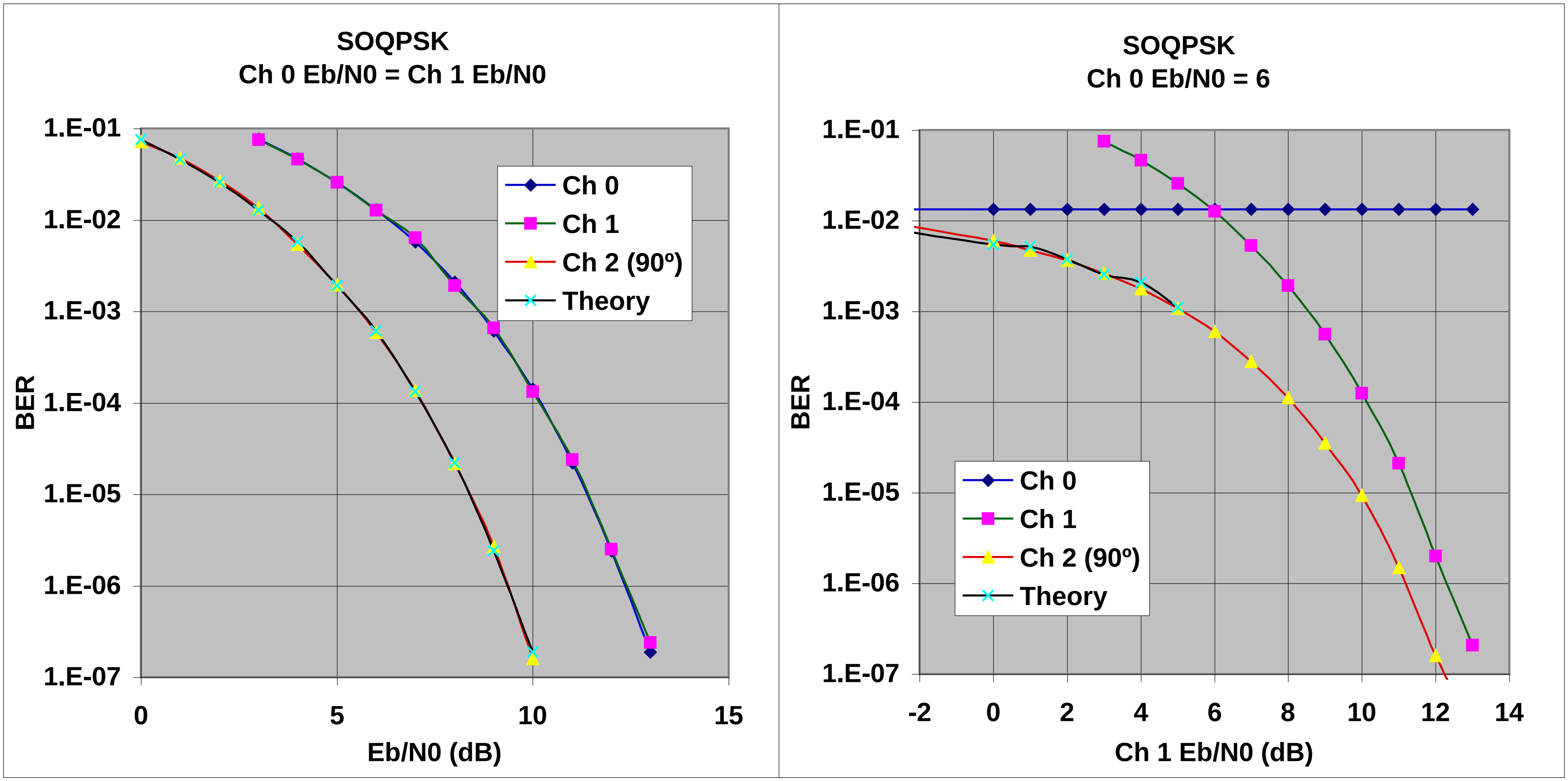
BER Results - Fading Signals



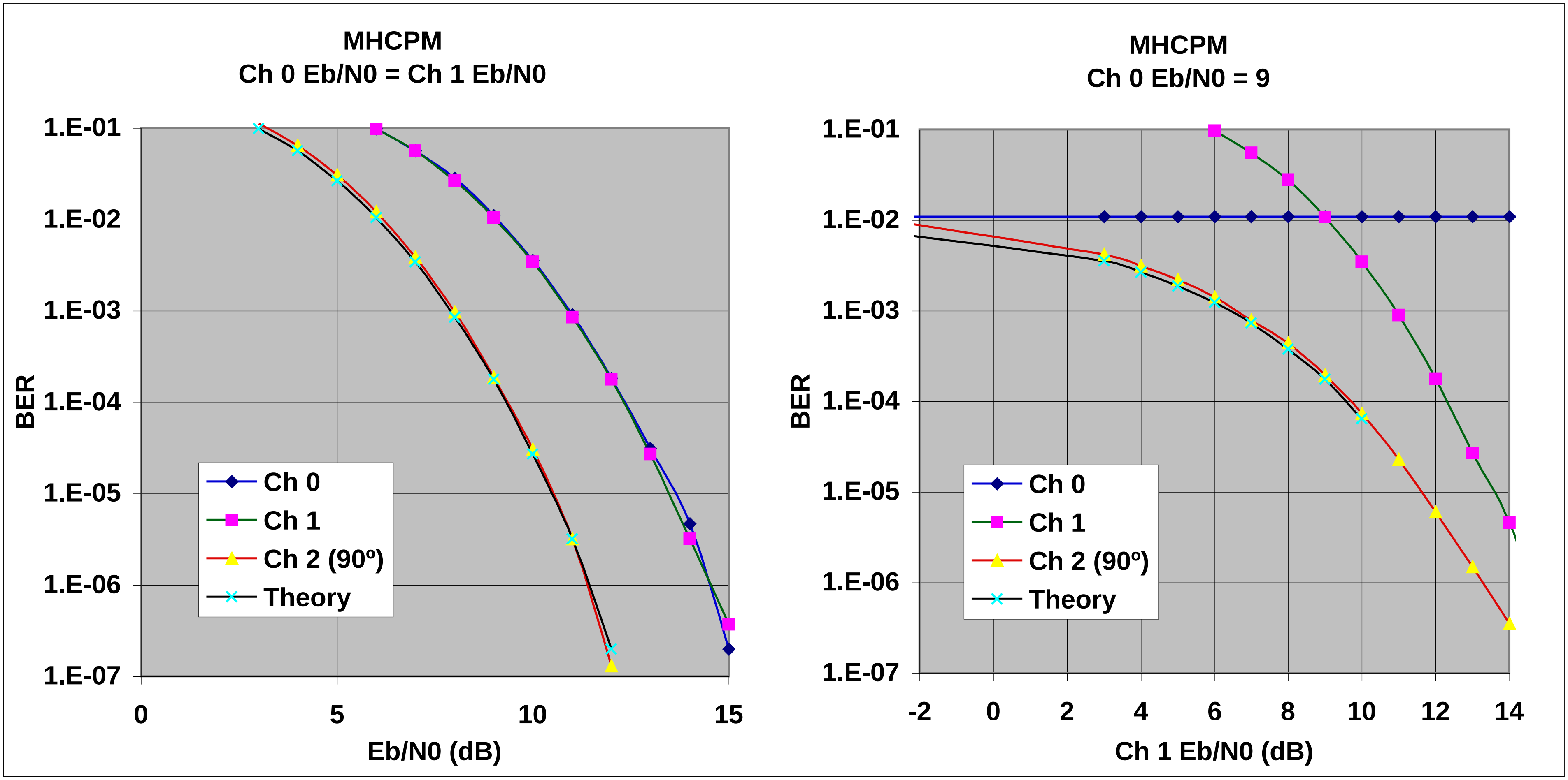
Measured Combiner BER - Tier 0



Measured Combiner BER - Tier I



Measured Combiner BER - Tier II



Quasonix

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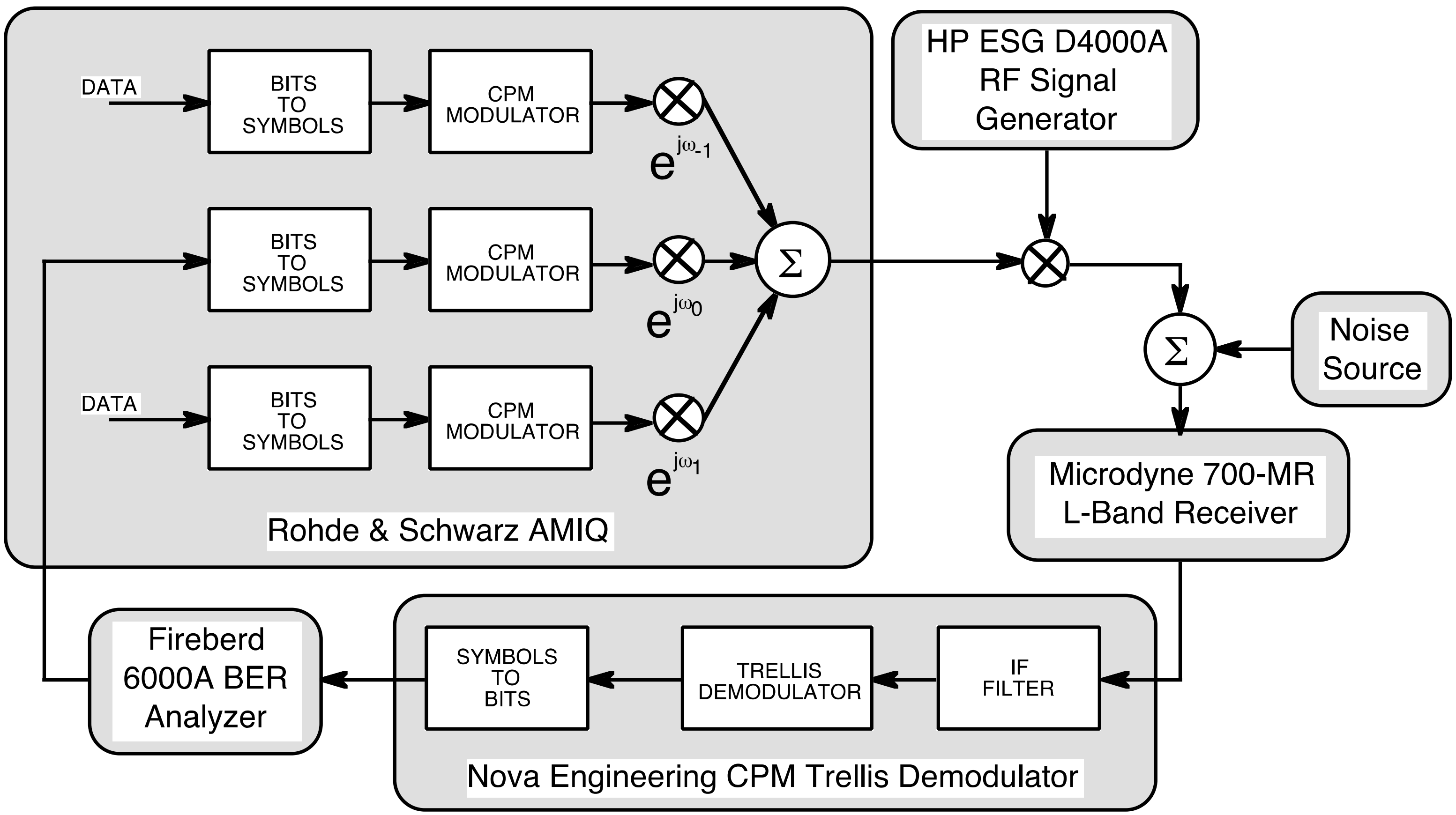
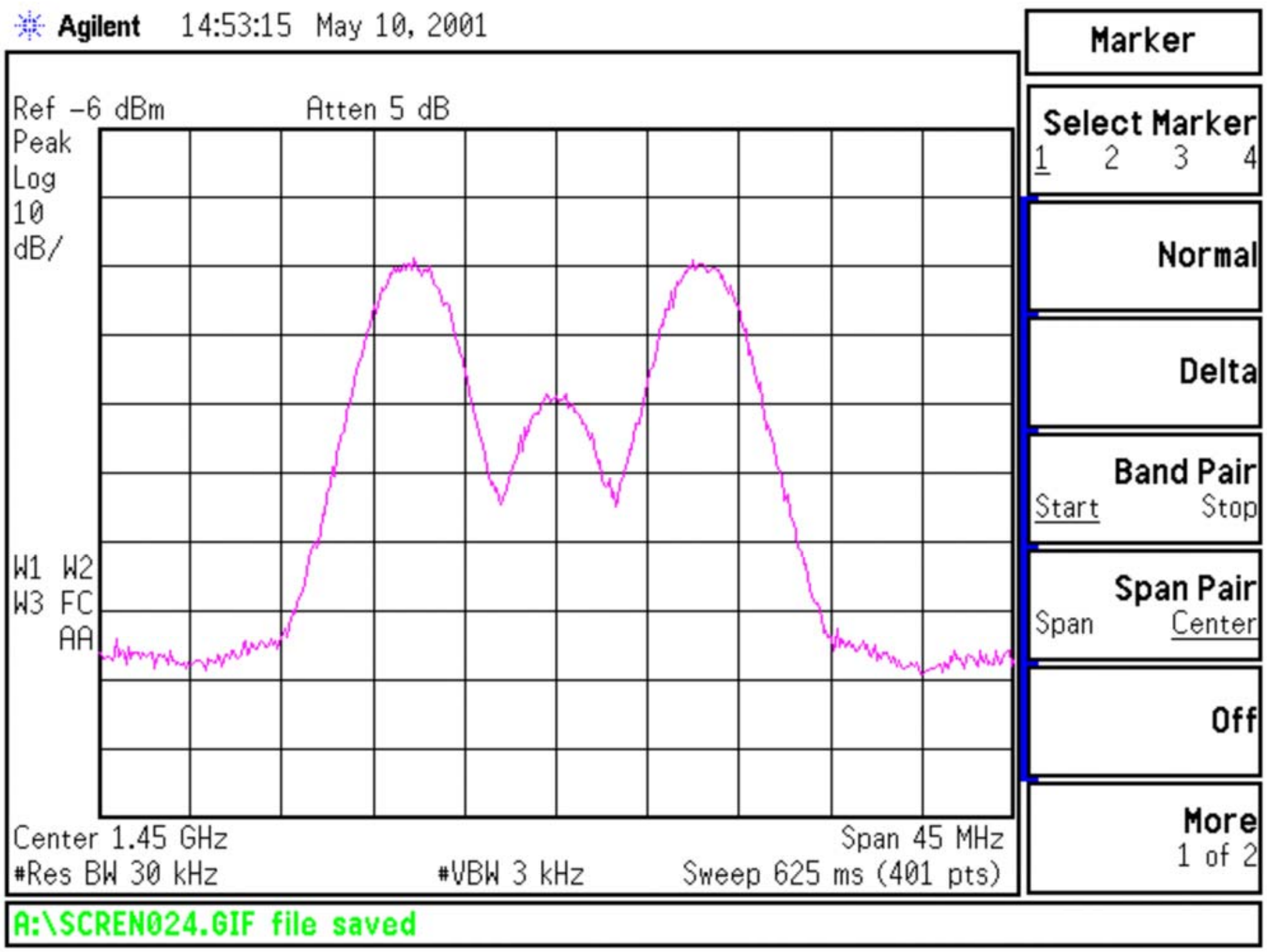
PSD is Half the Story

- Overall spectral efficiency is determined by spacing between channels
- Receiver selectivity affects channel spacing
- A valid comparison must account for both transmitted spectrum and “tolerable” receiver filtering
- Not all modulations are equally “tolerant” of IF filtering and interference
- **Multi-channel testing accounts for these factors**

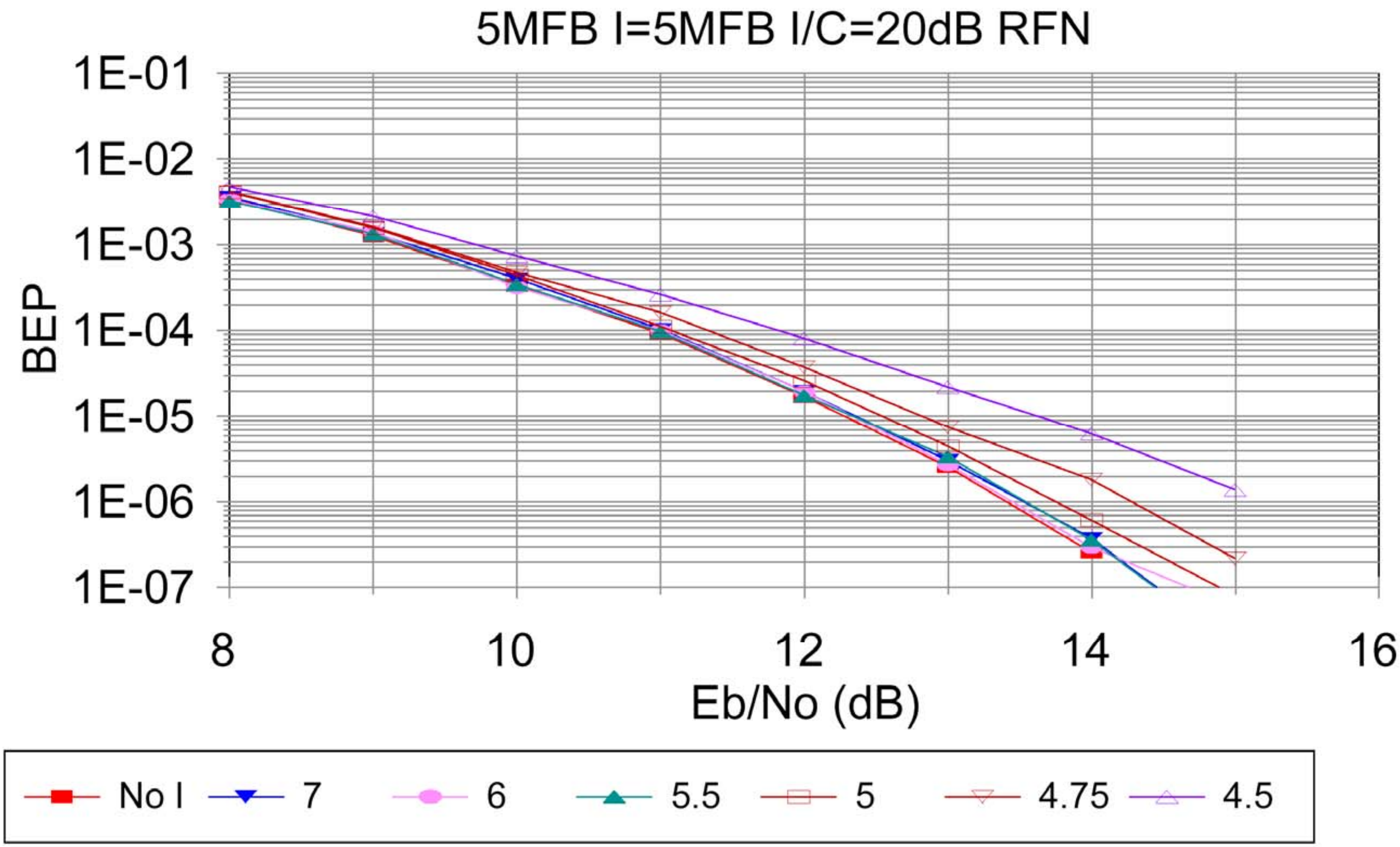
Multi-channel ACI Test Set



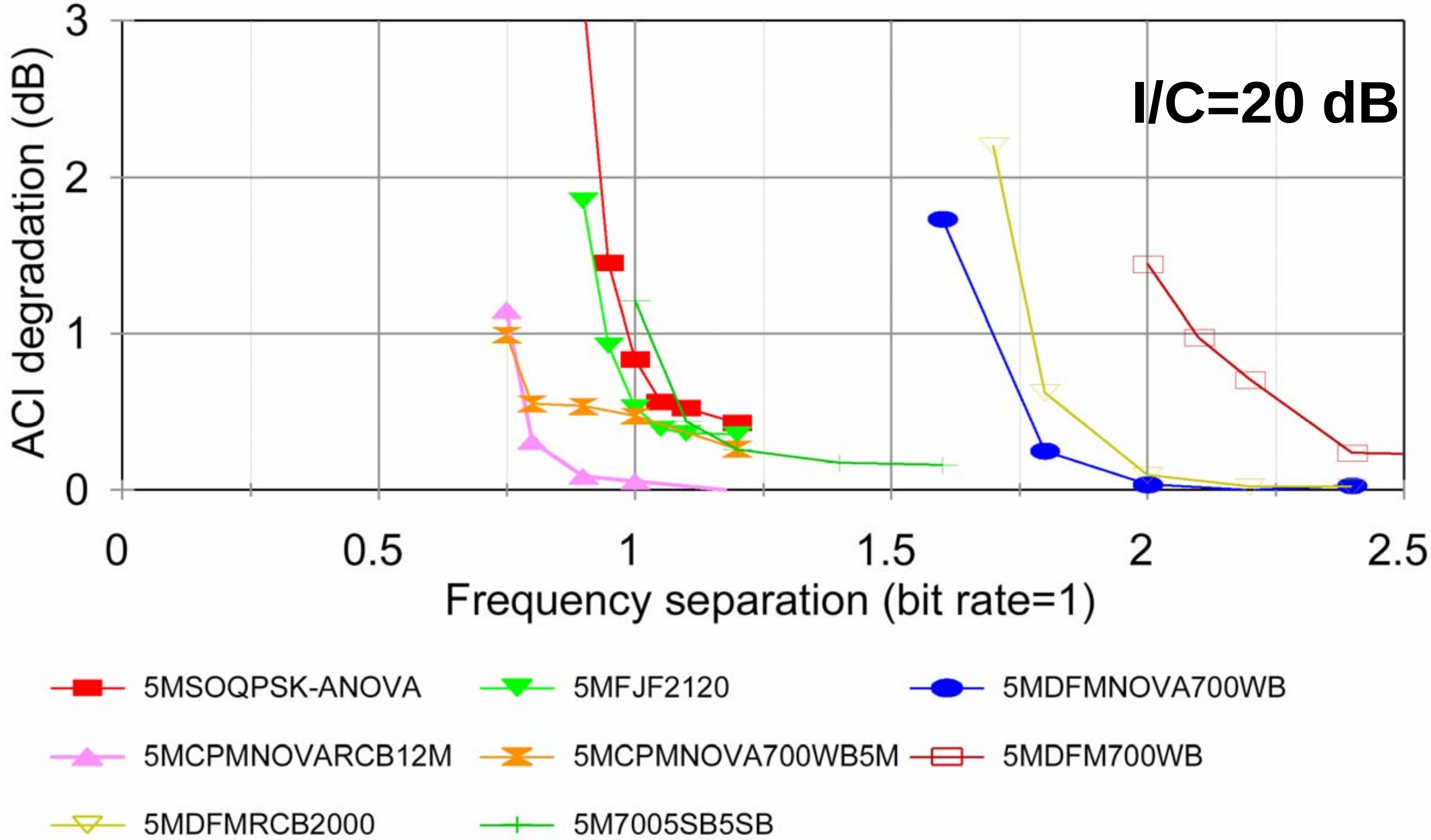
9 Mbps Multi-h CPM, Multichannel



BER as a Function of ΔF_0



ACI Summary



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Frequency Separation Rule

$$\Delta F_0 = a_s{*}R_s + a_i{*}R_i$$

where:

- ΔF_0 = the minimum center frequency separation in MHz
- R_s = bit rate of desired signal in Mb/s
- R_i = bit rate of interfering signal in Mb/s

Modulation Type	a_s		a_i	Rs = Ri
NRZ PCM/FM	1	for receivers with RLC final Intermediate Frequency (IF) filters	1.2	2.2
	0.7	for receivers with Surface Acoustic Wave (SAW) or digital IF filters	1.2	1.9
	0.5	with multi-symbol detectors (or equivalent devices)	1.2	1.7
FQPSK-B, FQPSK-JR, SOQPSK-TG	0.45		0.65	1.1
ARTM CPM	0.35		0.5	0.85

- The NRZ PCM/FM signals are assumed to be premodulation filtered with a multi-pole filter with 3 dB point of 0.7 times the bit rate and the peak deviation is assumed to be approximately 0.35 times the bit rate.
- The receiver IF filter is assumed to be no wider than 1.5 times the bit rate and provides at least 6 dB of attenuation of the interfering signal.
- The interfering signal is assumed to be no more than 20 dB stronger than the desired signal.
- The receiver is assumed to be operating in linear mode; no significant intermodulation products or spurious responses are present.

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Multipath Propagation

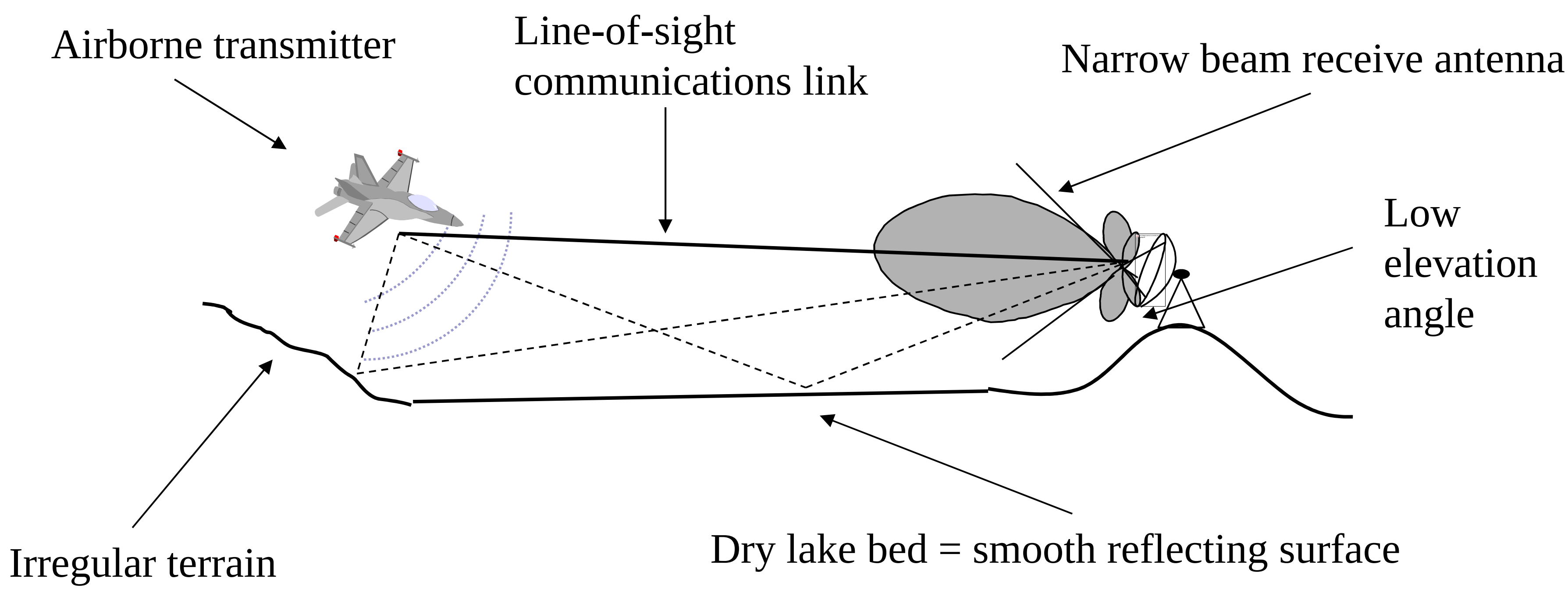


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Assumptions

- Channel can be modeled as LTI system over "short enough" time interval

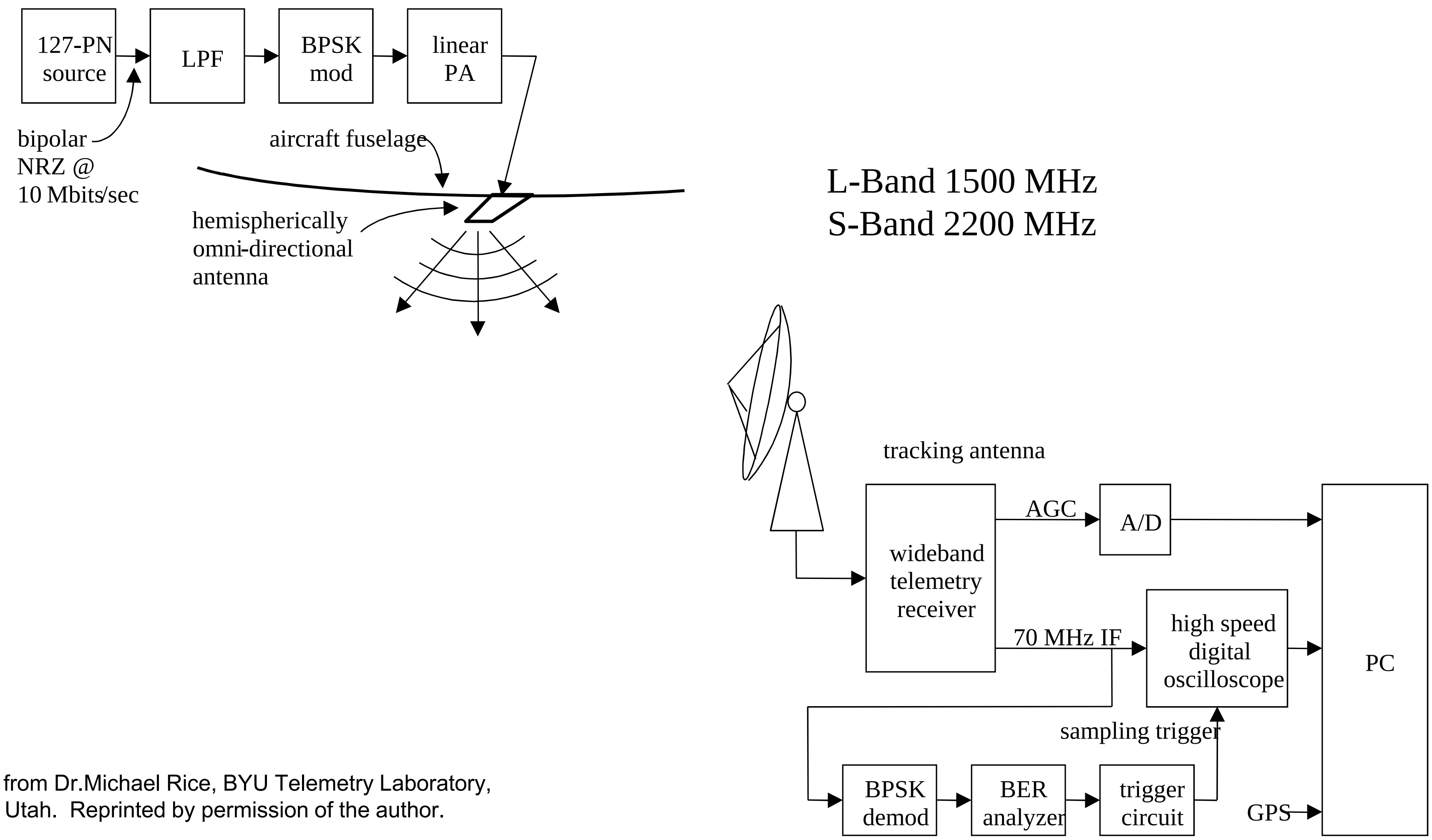
$$h(t;x) = \sum_{k=0}^{L-1} \Gamma_k(x) e^{-j\omega_c \tau_k(x)} \delta(t - \tau_k(x))$$

$$= \delta(t) + \underbrace{\sum_{k=1}^{L-1} \Gamma_k(x) e^{-j\omega_c \tau_k(x)} \delta(t - \tau_k(x))}_{L\text{-1 multipath propagation paths}}$$

Line-of-sight
propagation path

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

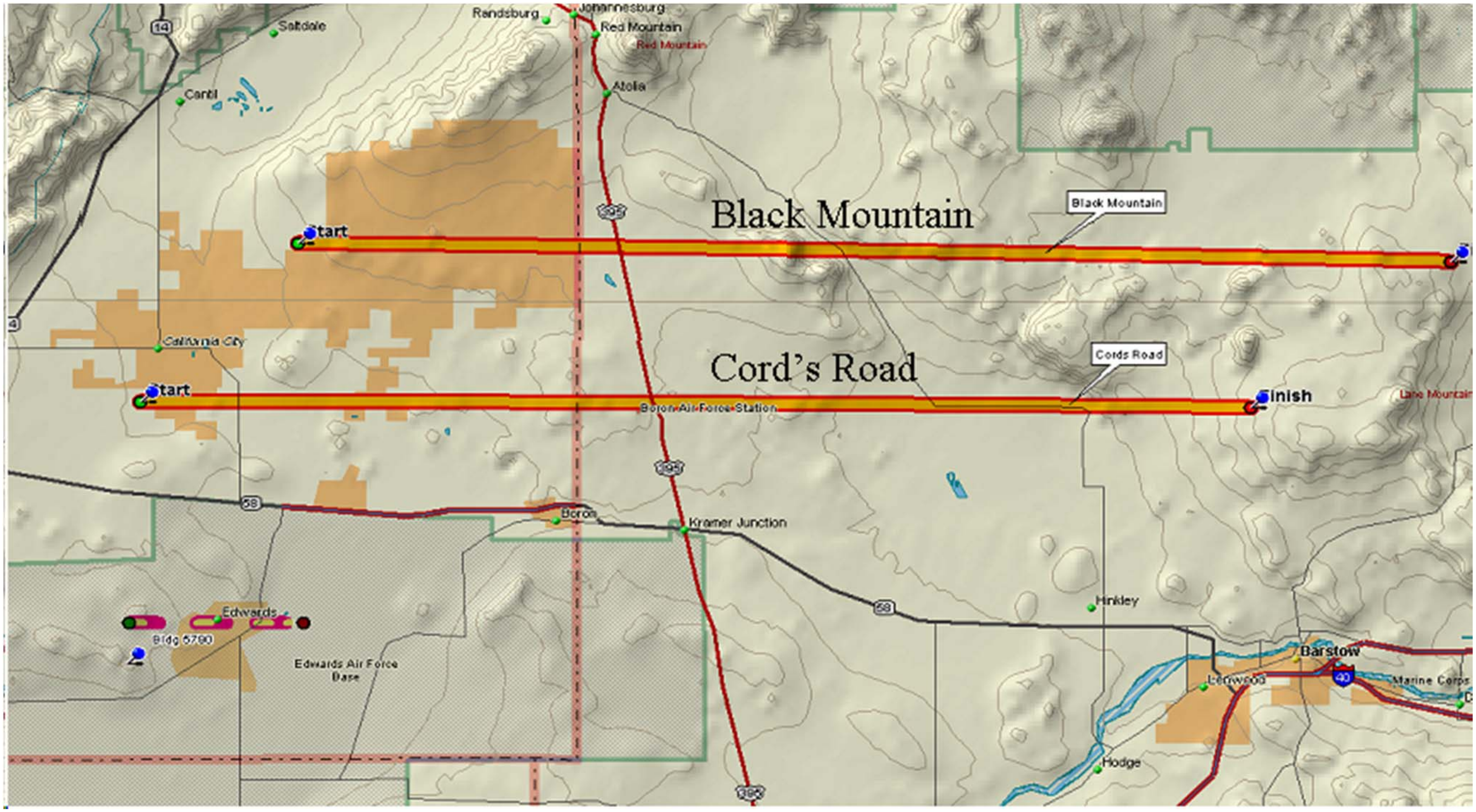
ARTM Experiments



L-Band 1500 MHz
S-Band 2200 MHz

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Edwards AFB Flight Paths



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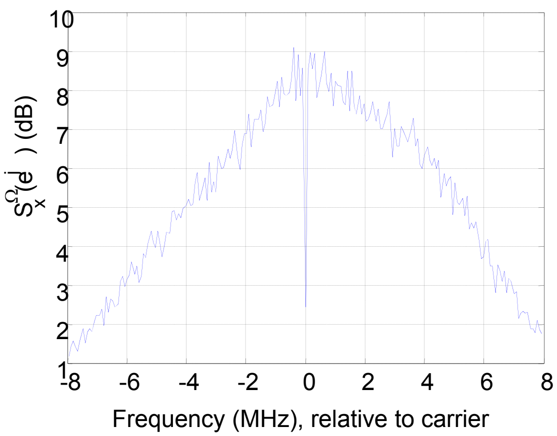
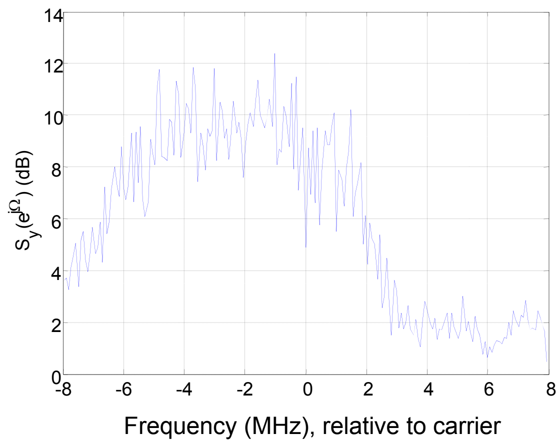
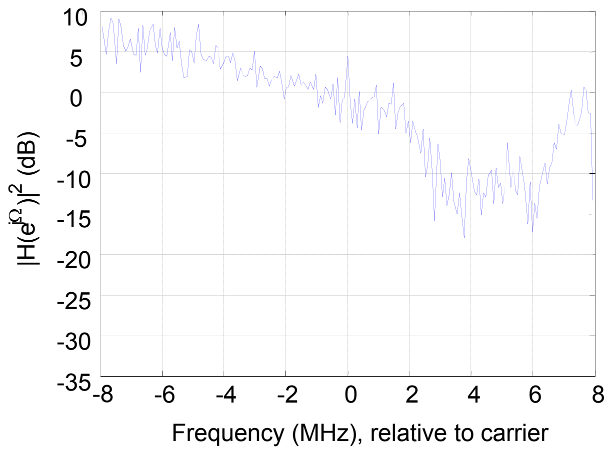
Signal Processing



Power spectral density of transmitted signal



Power spectral density of received signal



Estimate of channel transfer function

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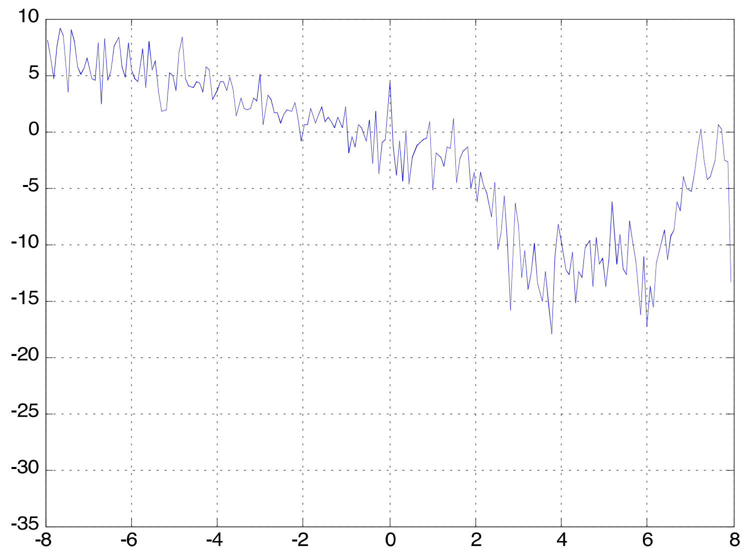
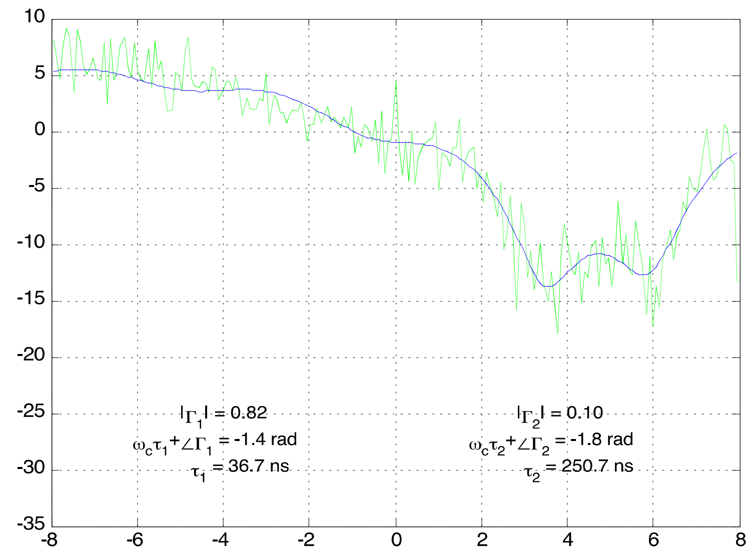
Modeling Procedure





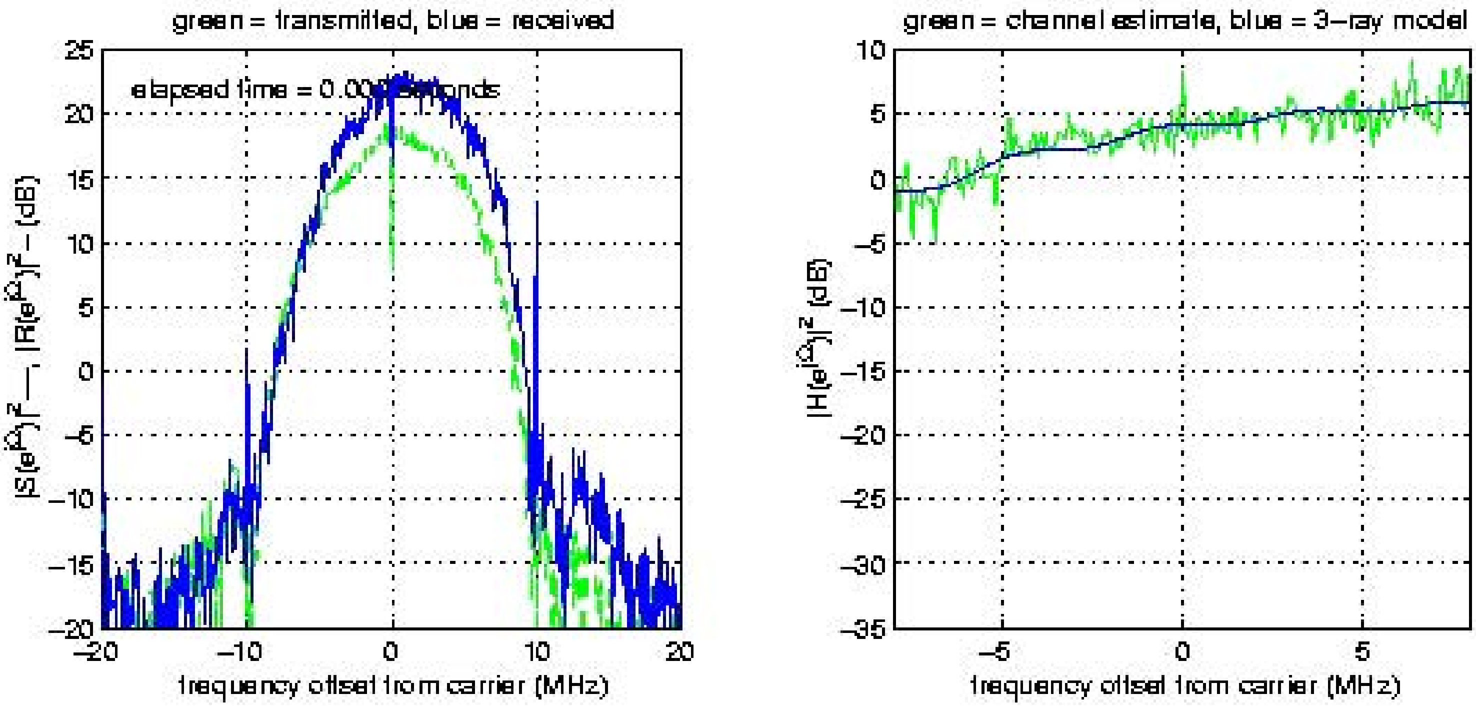
$$\widehat{H}(\omega) = \frac{R(\omega)}{S(\omega)}$$

$R(\omega)$: power spectral density of received signal

$S(\omega)$: power spectral density of transmitted signal

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Measurement and Modeling



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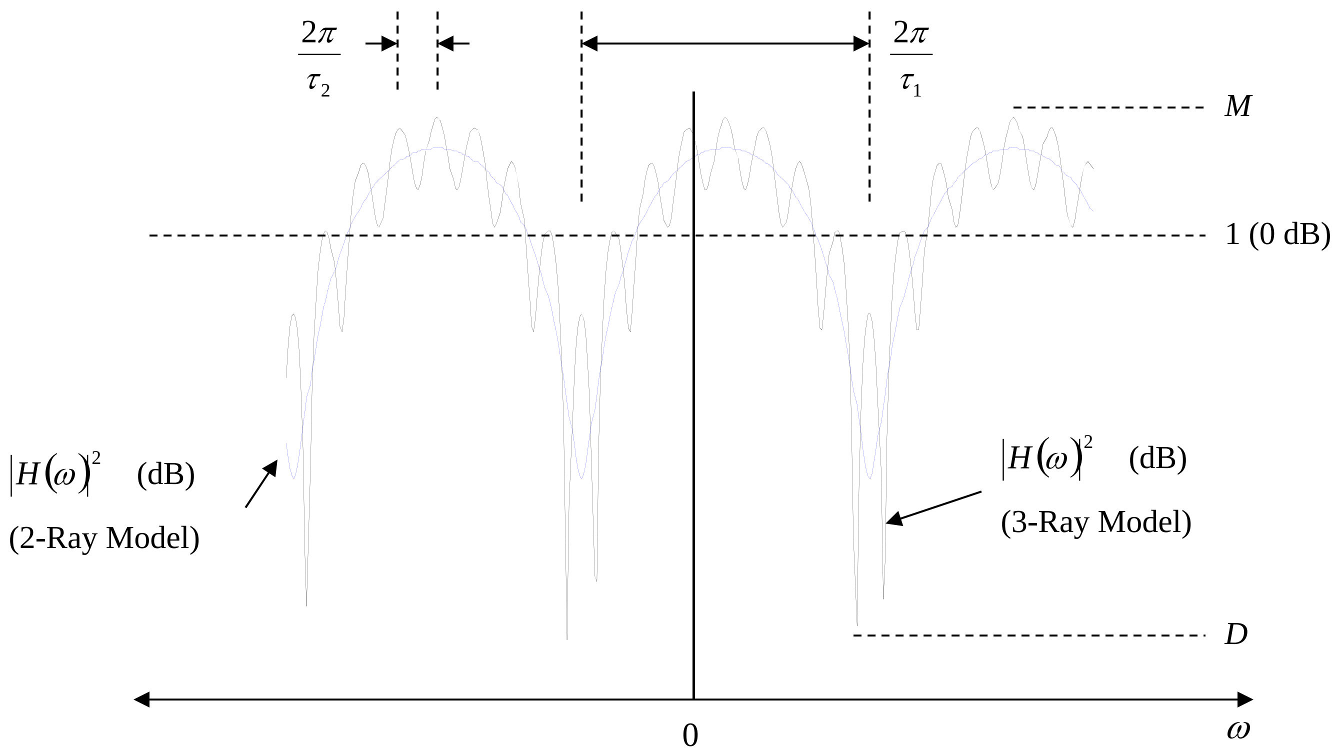
Channel Transfer Function

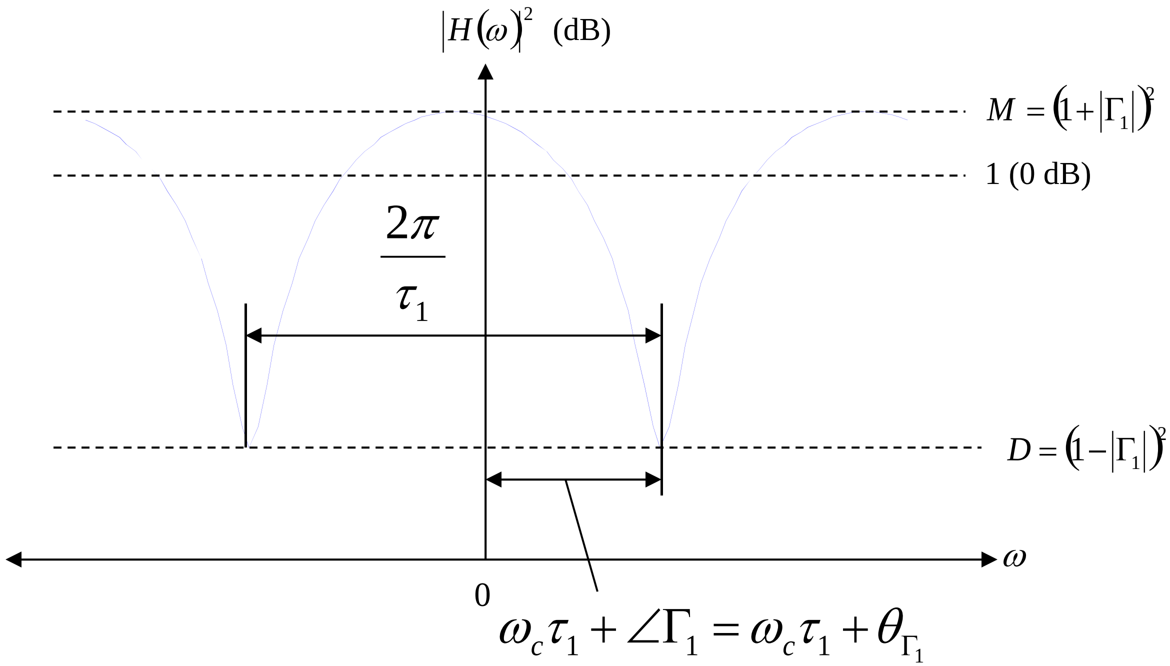


$$\text{Assumes } \tau_1 < \tau_2 \text{ and } |\Gamma_1| > |\Gamma_2|$$

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Frequency-Dependent Parameters

- magnitude of first multipath reflection: Γ_1
- "sweep rate" of multipath null



null "sweep rate" ~ $\omega_c\dot{\tau}_1 + \dot{\theta}_{\Gamma_1}$

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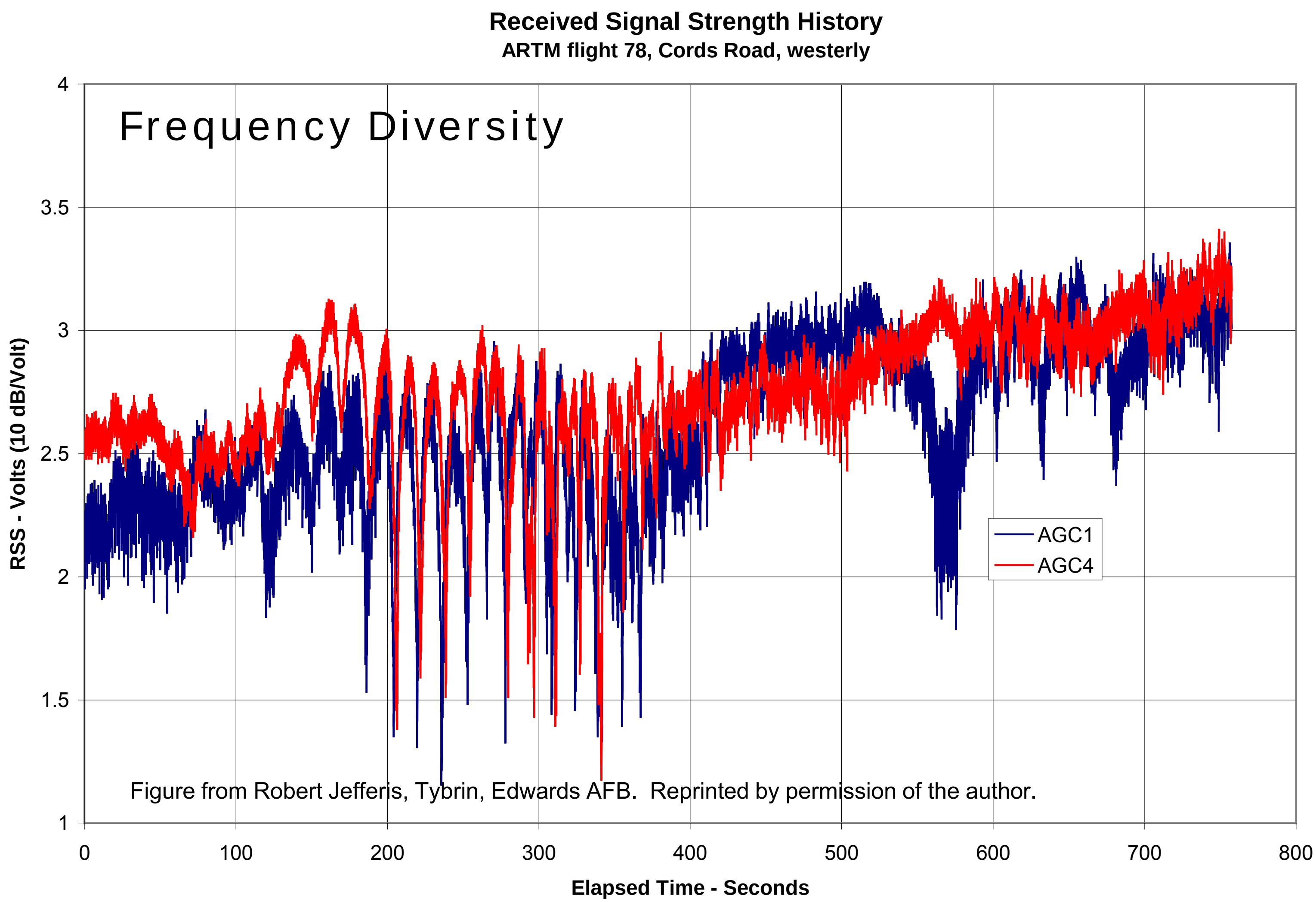
Measured Data



Classic Two-Ray Multipath

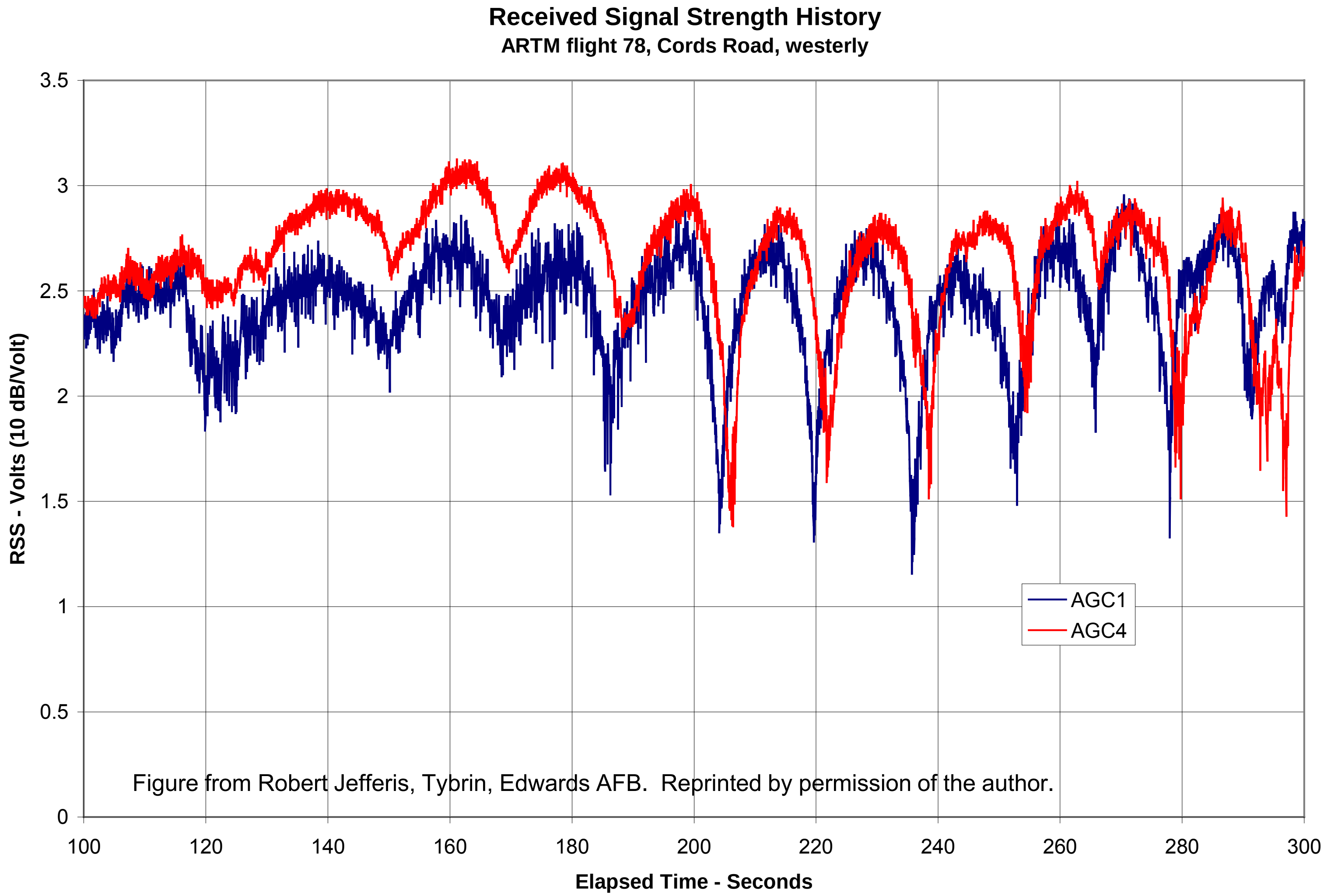
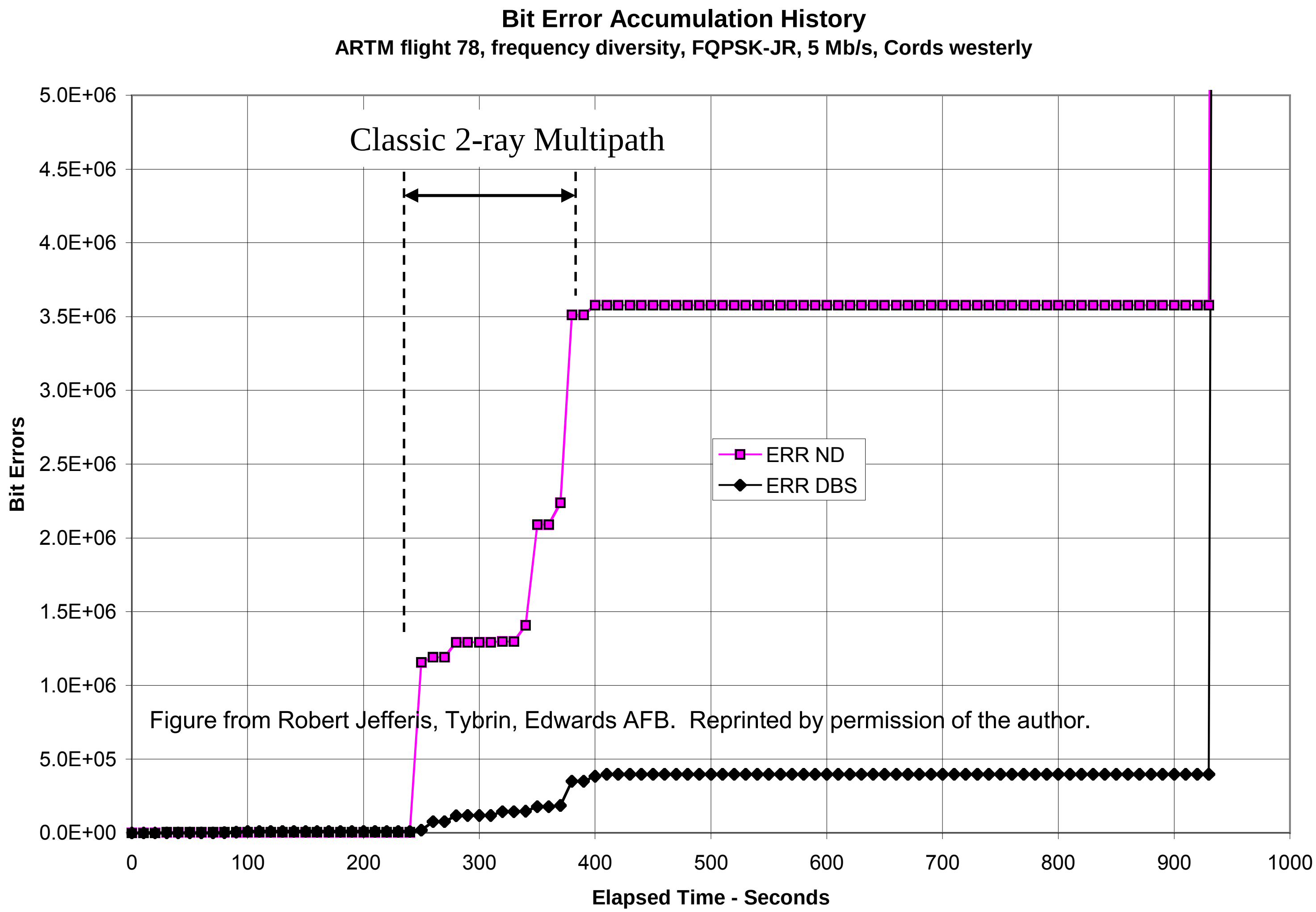
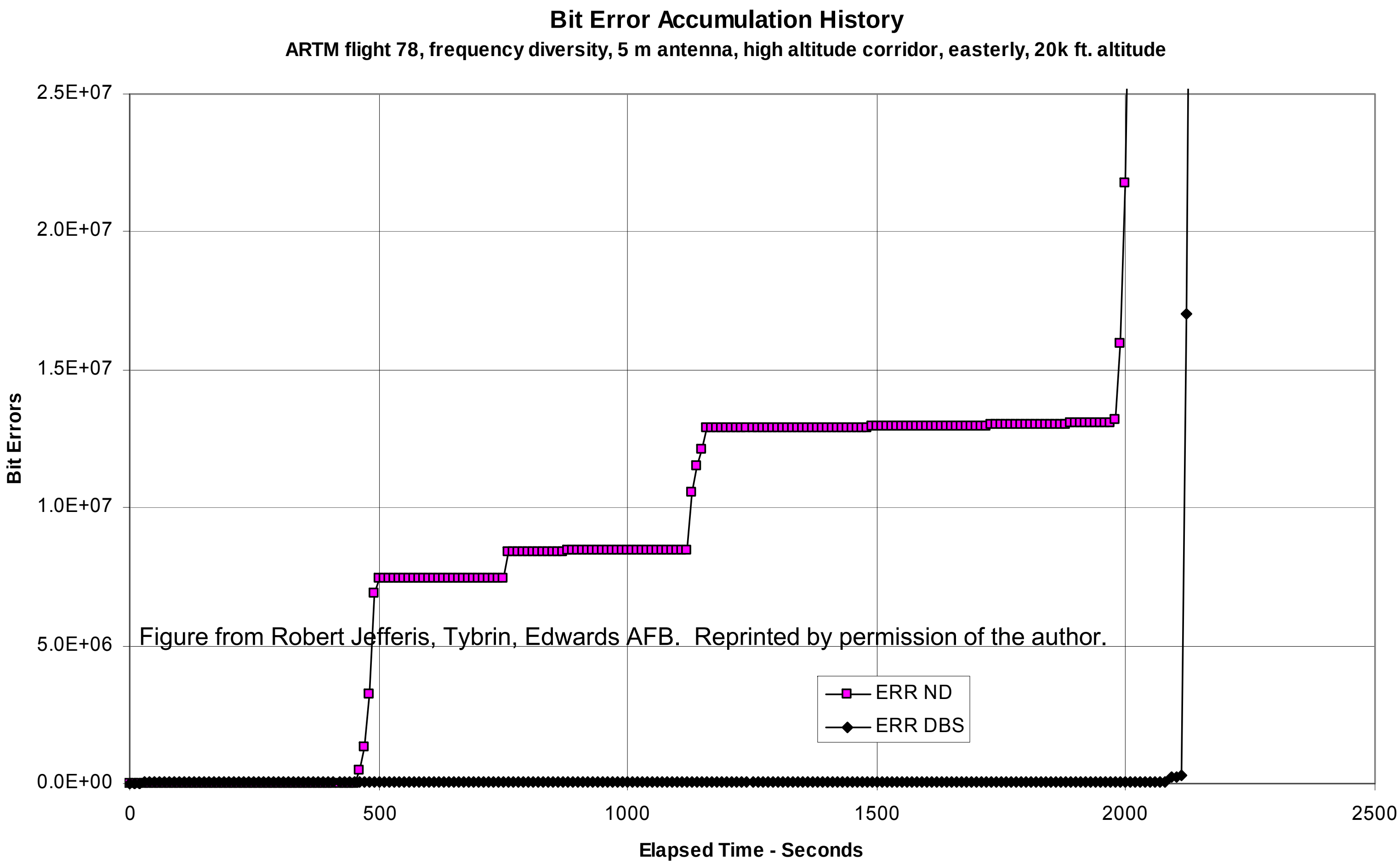


Figure from Robert Jefferis, Tybrin, Edwards AFB. Reprinted by permission of the author.

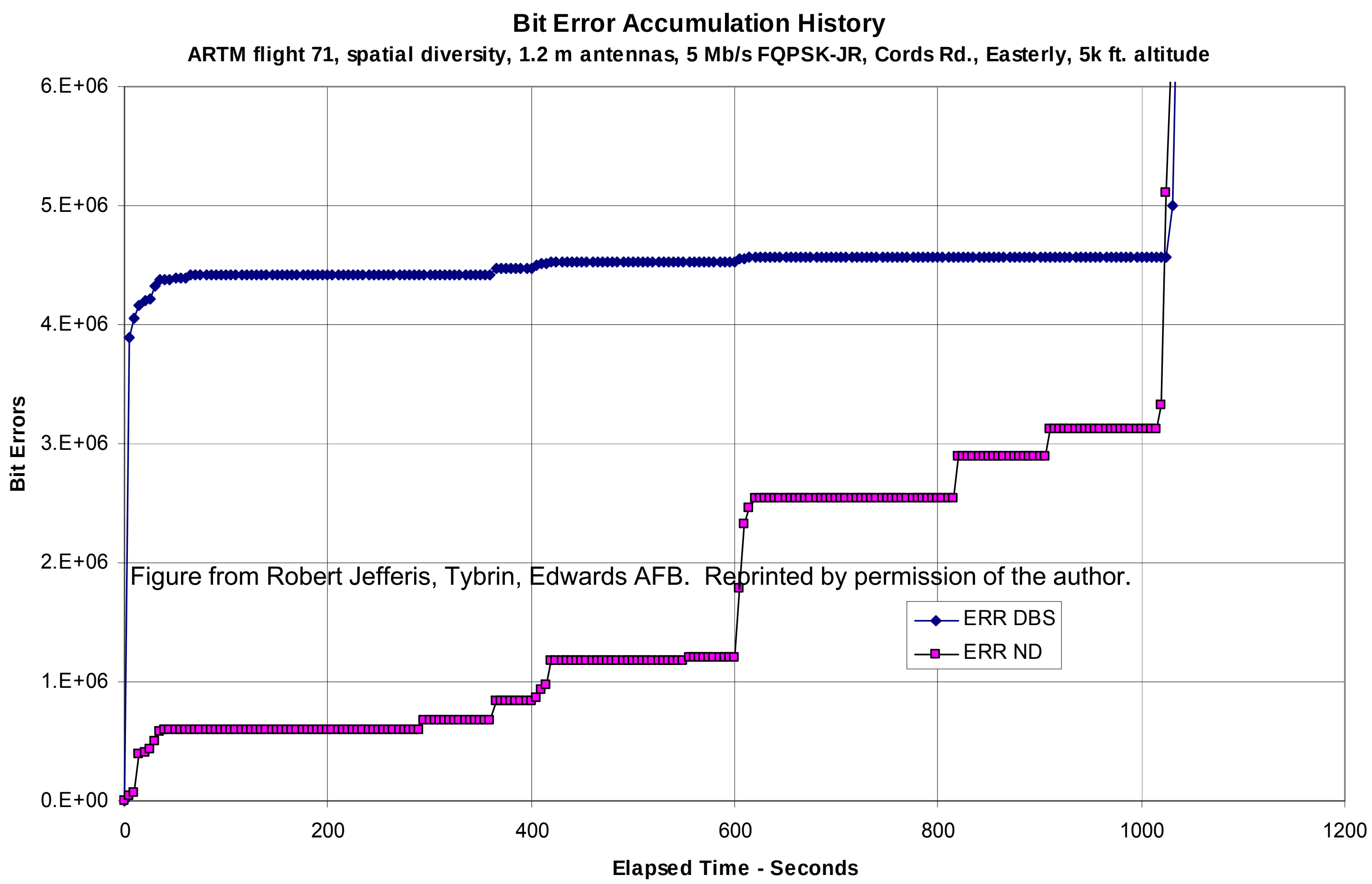
Frequency Diversity Example 1



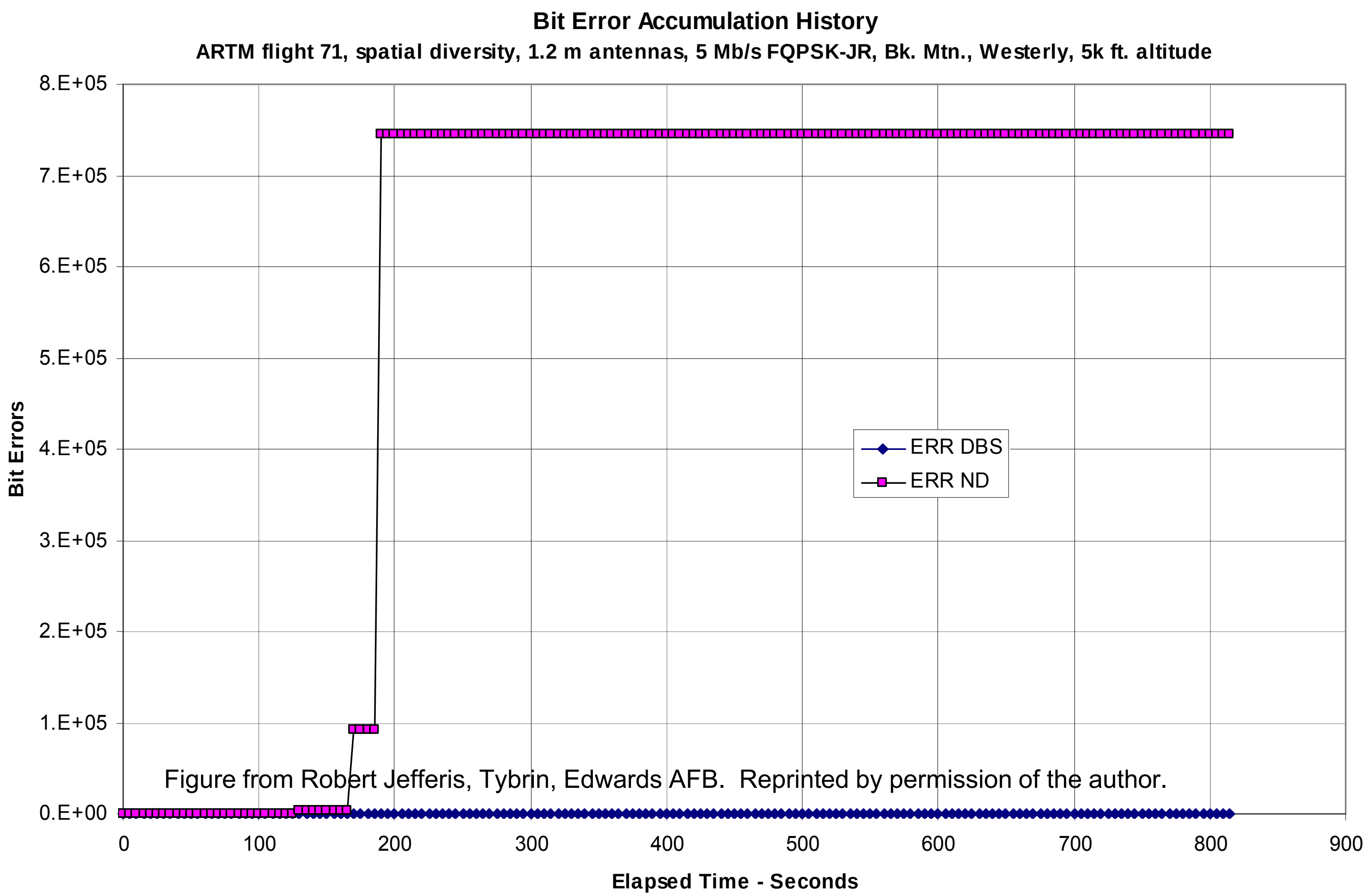
Frequency Diversity Example 2



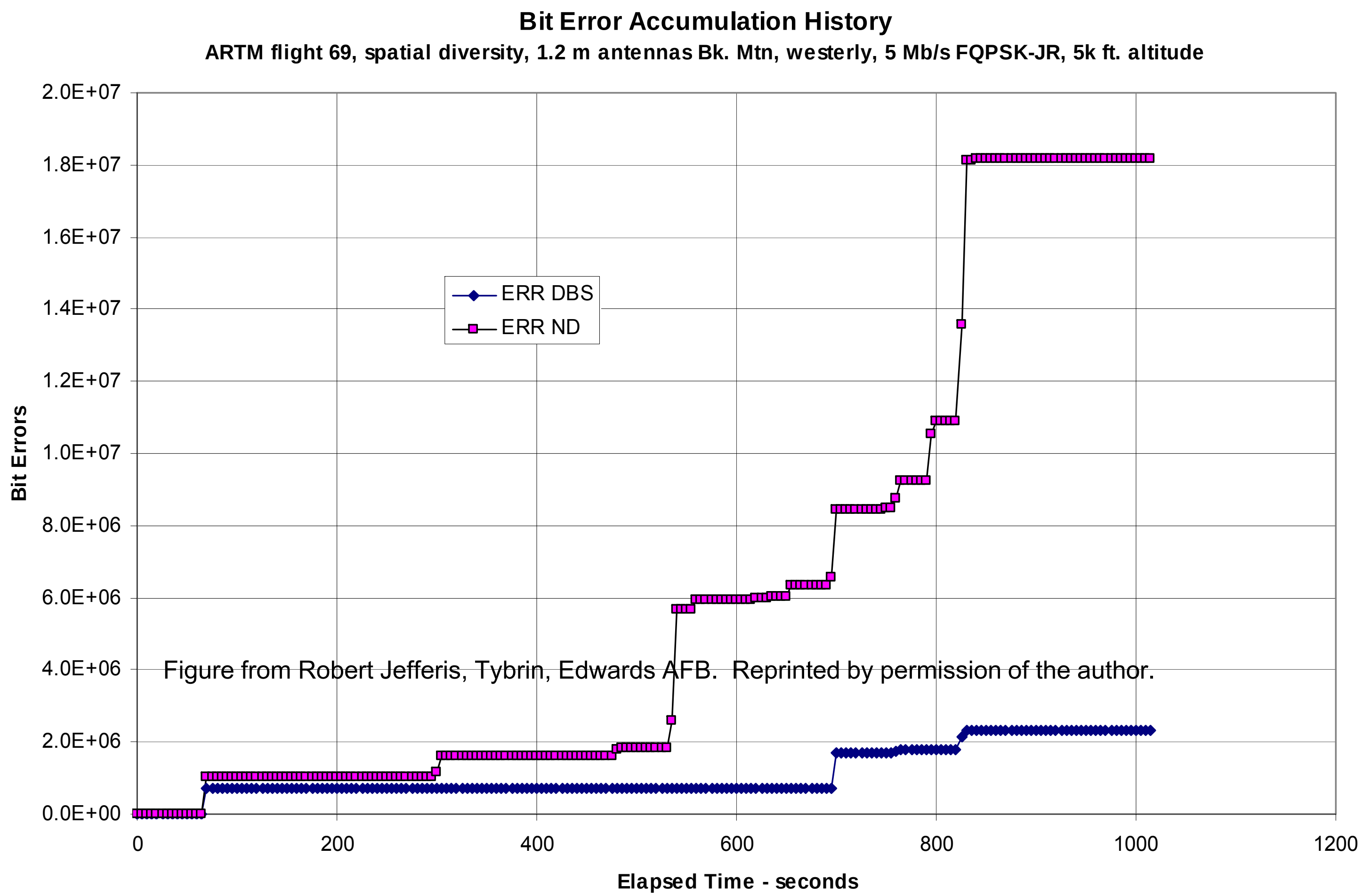
Spatial Diversity Example 1



Spatial Diversity Example 2



Spatial Diversity Example 3



Multipath Summary

- Your channel may - or may not - exhibit multipath propagation effects
- If so, there will be intervals during which no useful data is recovered
- Loss of bit count integrity is likely
  - Encrypted links will lose crypto sync
- What to do?
- Rewind to slide 130
- Use diversity!

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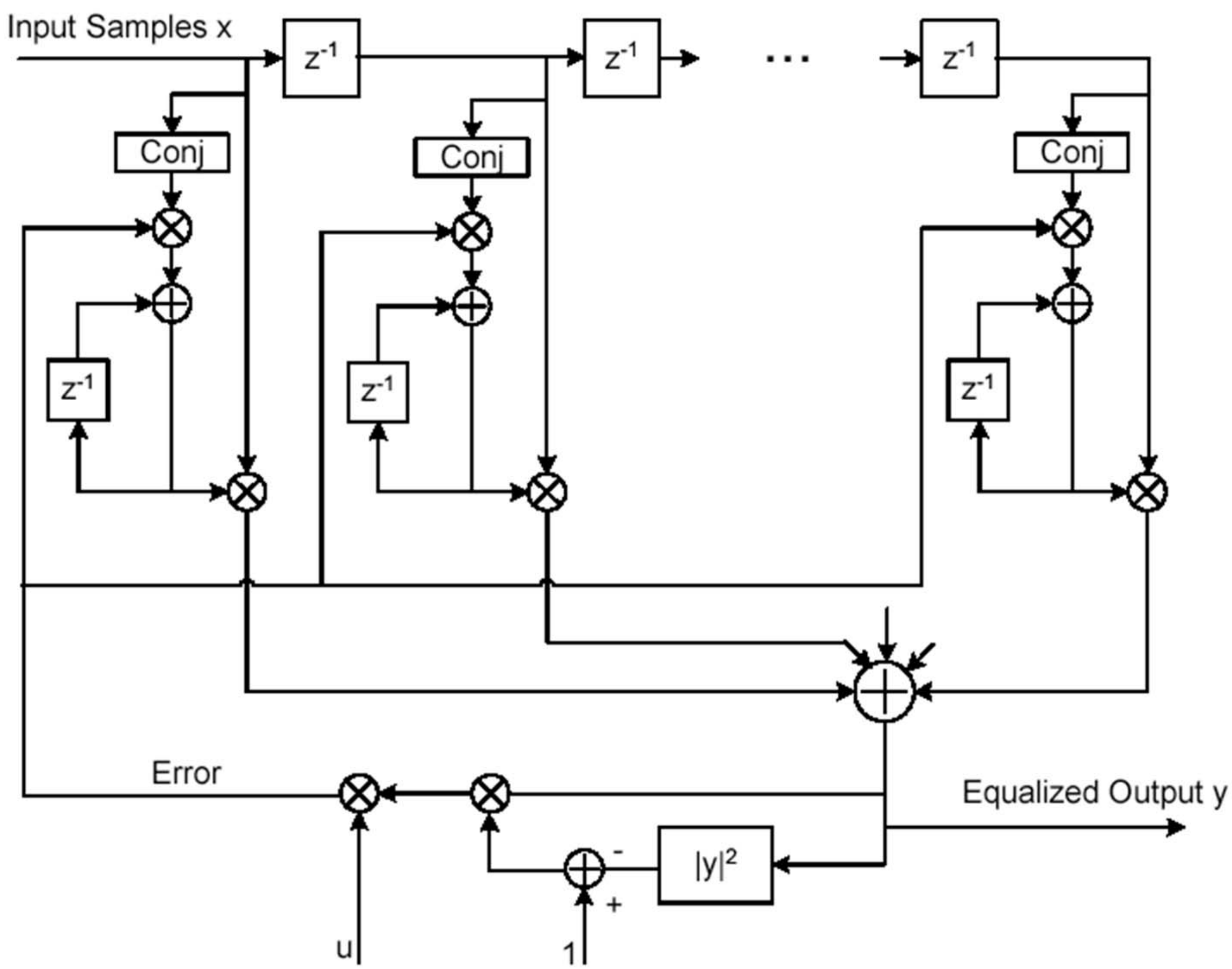
Adaptive Equalization

- Consider the multipath channel to be a filter
  - Varies over time
- Consider building a filter which “undoes” the filtering imposed by the channel
  - Let it keep track of the the channel and continuously adapt itself to the channel
- Presto! You have an adaptive equalizer
  - Can repair damage done by multipath
  - Works with a single receiver
  - Requires no bandwidth expansion

Adaptive Equalizer



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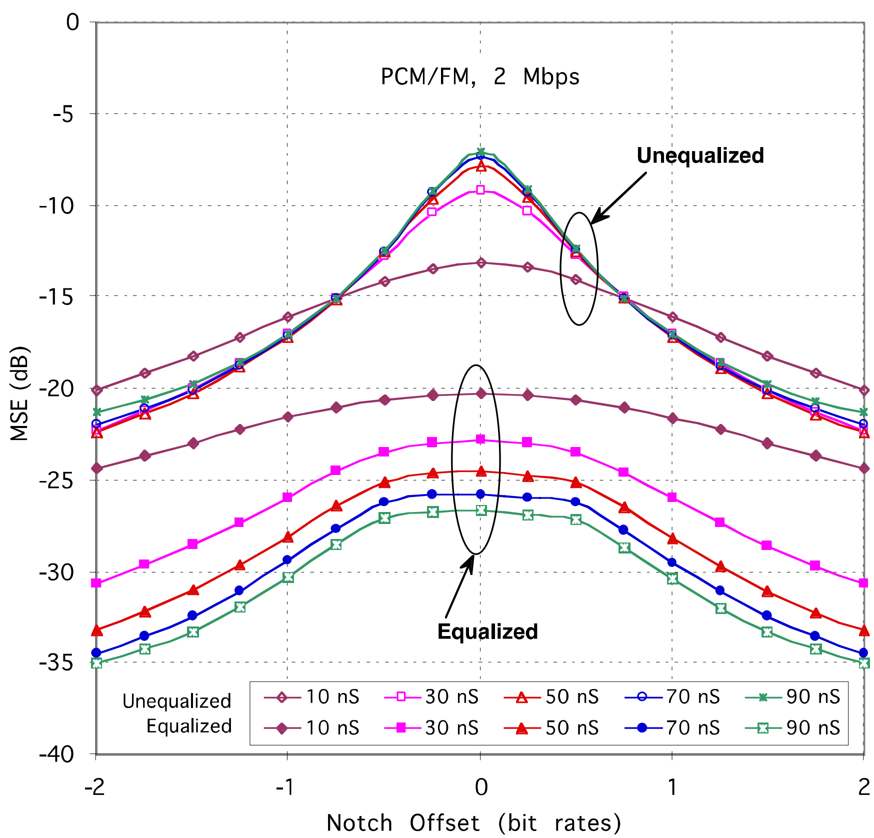
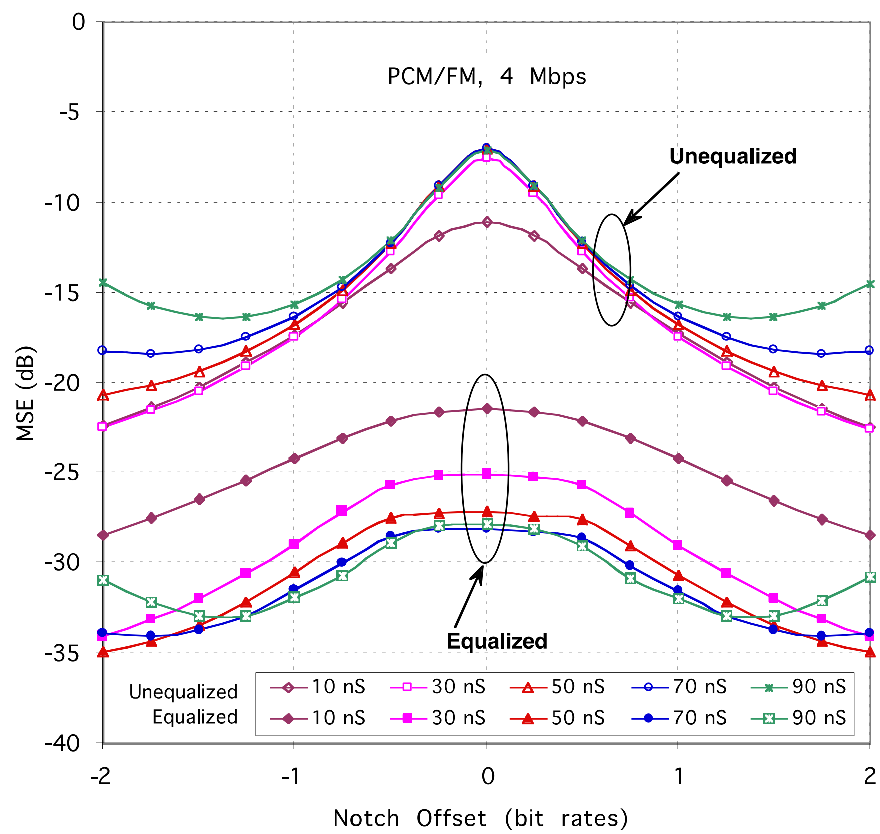
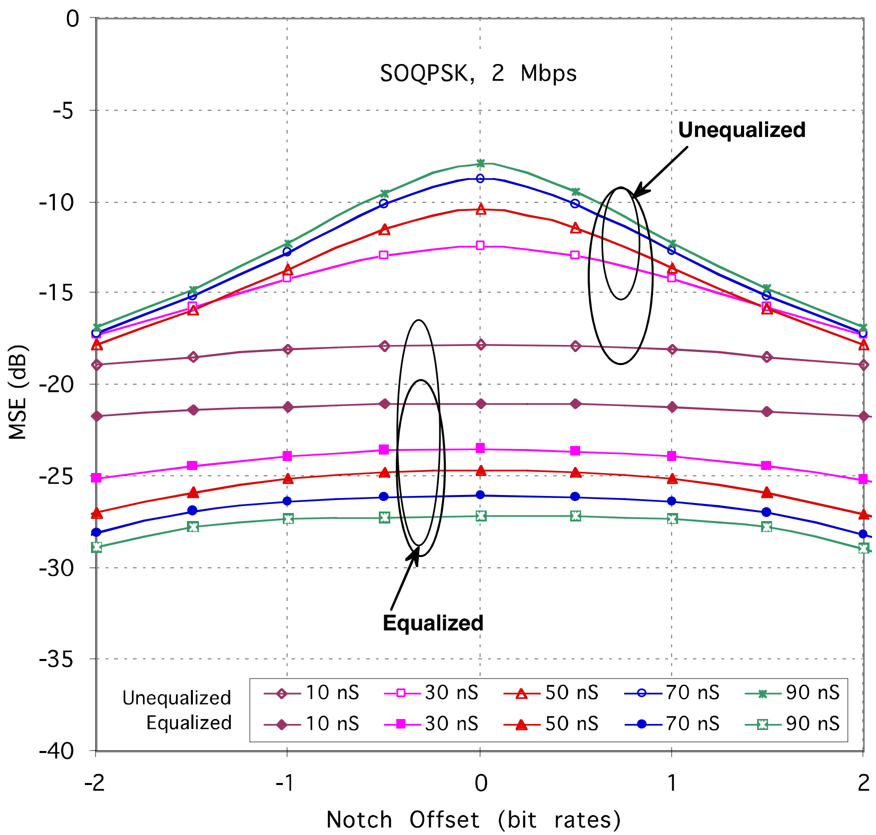
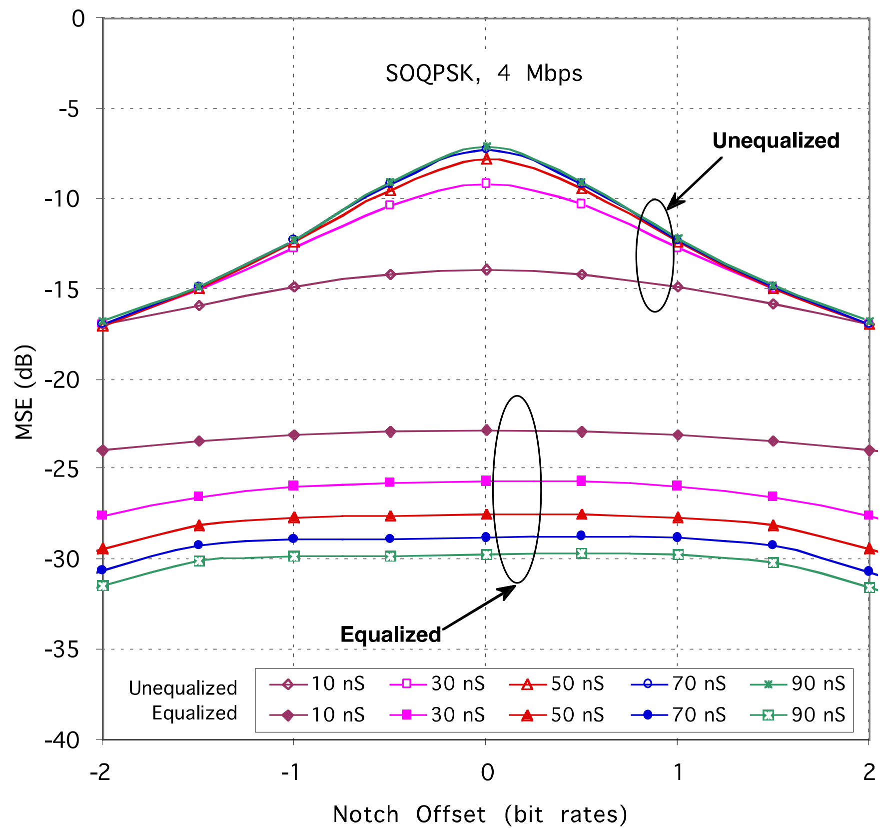
PCM/FM in Multipath



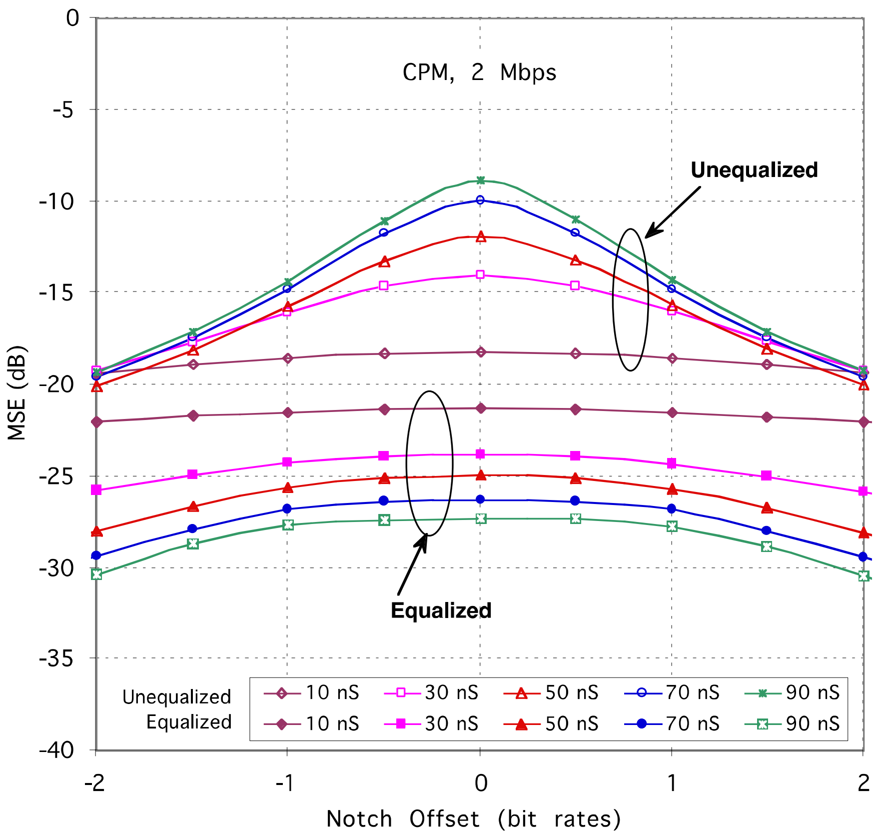


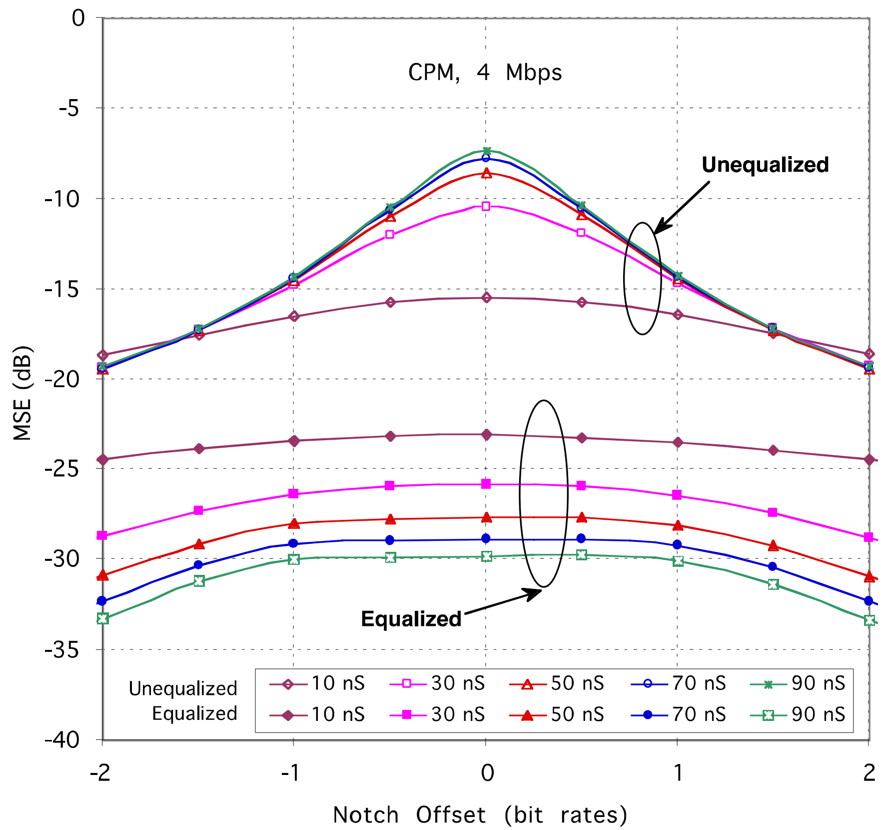
SOQPSK in Multipath





CPM in Multipath





Is Equalization Helpful?

- Adaptive equalizer can “undo” multipath distortion
- However, it must adapt
- Adaptation has limitations
  - Equalizer length (number of taps, and total span)
  - Adaptation rate
    - Trade off accuracy for speed
    - Fast adaptation necessarily degrades BER performance (relative to no equalizer)
- Within these limits, equalization helps
- When the equalizer gets lost, re-synchronization time is increased by the time required to re-adapt
- In severe multipath, equalization can do more harm than good
- Rapid synchronization and low acquisition threshold are always beneficial

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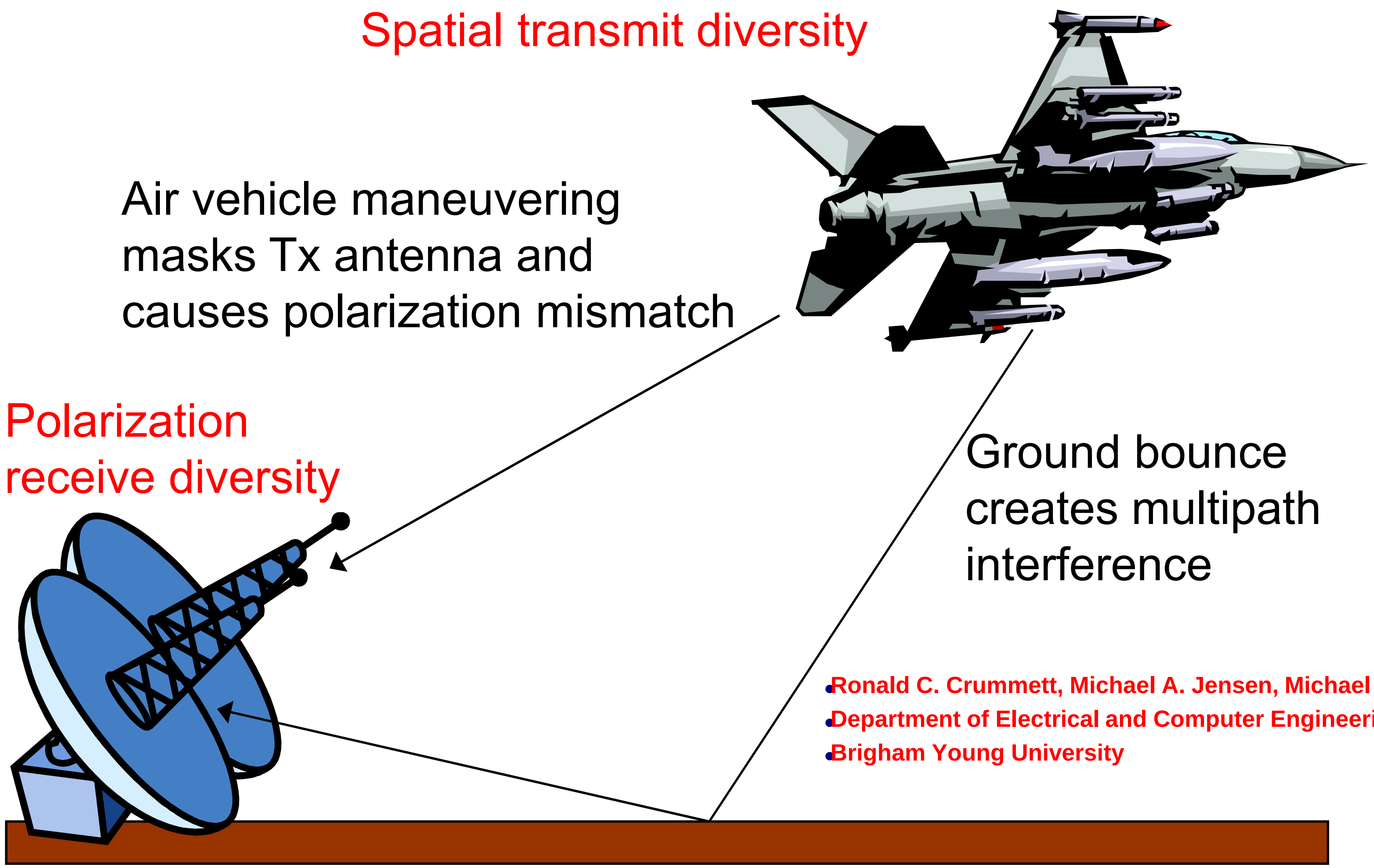
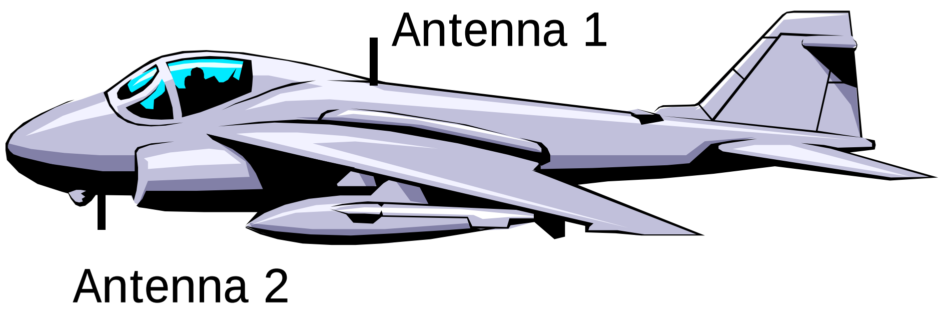
Space-Time Coding

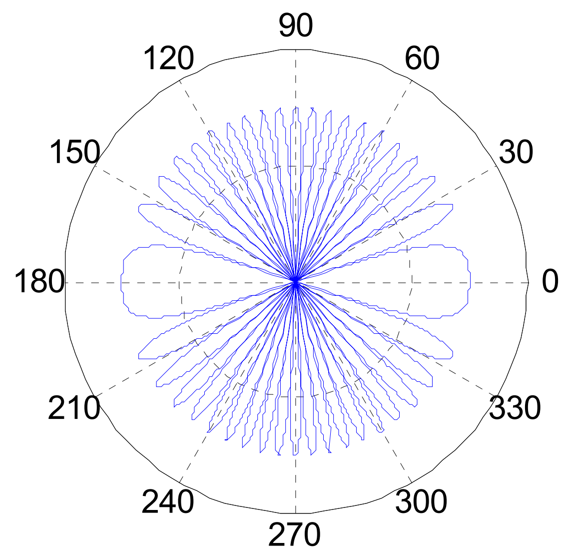


- Ronald C. Crummett, Michael A. Jensen, Michael D. Rice
- Department of Electrical and Computer Engineering
- Brigham Young University

Difficulties with TX Diversity

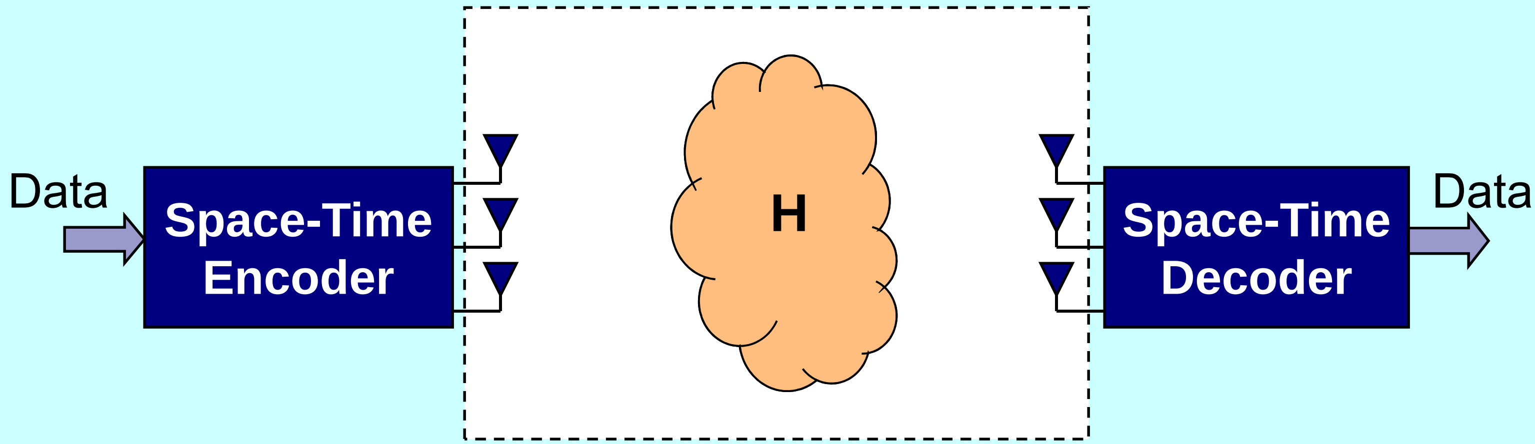
Spatially Separated Antennas Create Interference Pattern





MIMO Communications

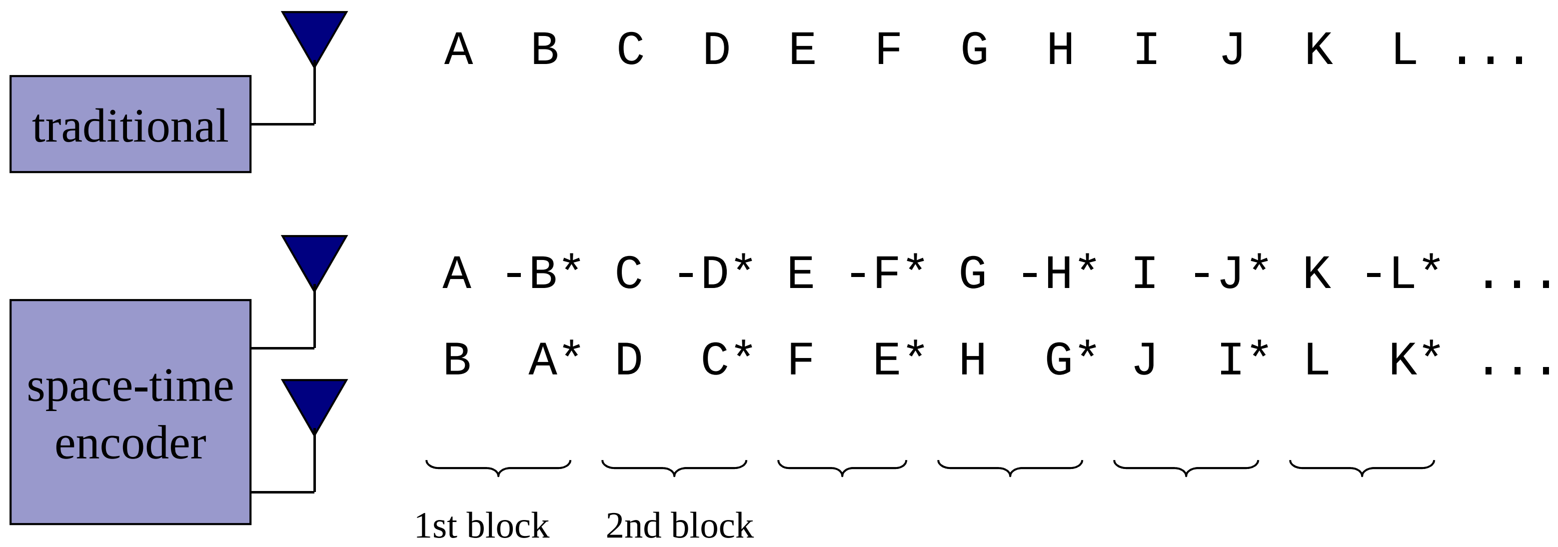
MIMO: Multiple-Input Multiple-Output
Exploit multiple communication ***modes***



Potential Benefits:

- Diversity (robust communications)
- Increased data throughput

Alamouti Space-Time Coding



- 2 transmit antennas + 1 receive antenna version
- 2 transmit antennas + 2 receive antennas version
- Calderbank showed that the Alamouti schemes are special cases of more general “orthogonal designs”

Traditional Transmission

Each symbol is simultaneously sent from both antennas

$$r = \frac{1}{\sqrt{2}}(h_1 + h_2)s + \eta$$

Power equally divided between antennas

Received signal energy

$$E_T = \mathrm{E}\left\{\frac{1}{2}[(h_1 + h_2)s]^*(h_1 + h_2)s\right\} = \frac{1}{2}|h_1 + h_2|^2 \mathrm{E}\{|s^2|\} = \frac{1}{2}|h_1 + h_2|^2 E_s$$

With the noise energy as N_o, the received SNR is

$$SNR_T = \frac{1}{2}|h_1 + h_2|^2 \frac{E_s}{N_o}$$

Alamouti Space-Time Coding

Signal energy over one symbol time:

$$E_{A,1} = \mathrm{E}\left\{ \left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2 \right) \right]^2 s_1^* s_1 \right\} = \left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2 \right) \right]^2 E_s$$

Received noise energy:

$$N_{A,1} = \mathrm{E}\left\{ \frac{1}{2}\left(h_1^* \eta_1 + h_2 \eta_2^* \right)^* \left(h_1^* \eta_1 + h_2 \eta_2^* \right) \right\} = \frac{1}{2}|h_1|^2 \mathrm{E}\left\{ |\eta_1|^2 \right\} + \frac{1}{2}|h_2|^2 \mathrm{E}\left\{ |\eta_2|^2 \right\} = \frac{1}{2}\left(|h_1|^2 + |h_2|^2 \right) N_o$$

Signal-to-Noise Ratio:

$$SNR_A = \frac{1}{2}\left(|h_1|^2 + |h_2|^2 \right) \frac{E_s}{N_o}$$

Symbol Error Rate - QPSK

SER for QPSK in AWGN

$$P(E) = 2Q\left(\sqrt{\frac{E_s}{N_o}}\right)$$

Using two transmit antennas (traditional signaling)

$$P(E \mid \theta,\phi) = 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)+h_2(\theta,\phi)\right|^2}{2}}\right)$$

If the aircraft is rotated 360° in the horizontal plane

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)+h_2(\theta,\phi)\right|^2}{2}}\right)d\phi$$

Symbol Error Rate - QPSK

Traditional signaling

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)+h_2(\theta,\phi)\right|^2}{2}}\right)d\phi$$

Addition of transfer functions leads to reduction in effective SNR

For Alamouti signaling

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)\right|^2+\left|h_2(\theta,\phi)\right|^2}{2}}\right)d\phi$$

Only magnitudes of transfer functions used in sum

Alamouti Scheme

Consider BPSK Signaling and Assume $s_1 = s_2 = 1$

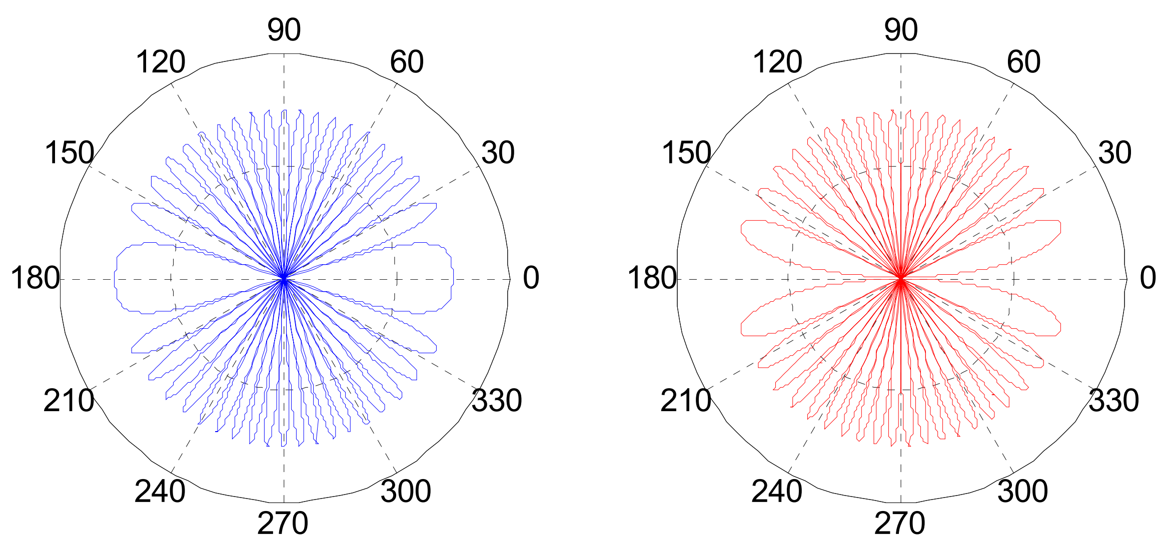
Time Slot 1:

Gain Pattern: $$G_{t1}(\phi) = 2\cos^2\left[\frac{kd}{2}\cos\phi\right]$$

Time Slot 2:

Gain Pattern: $$G_{t2}(\phi) = 2\sin^2\left[\frac{kd}{2}\cos\phi\right]$$

Antenna Pattern Interpretation



Symbol Error Rate

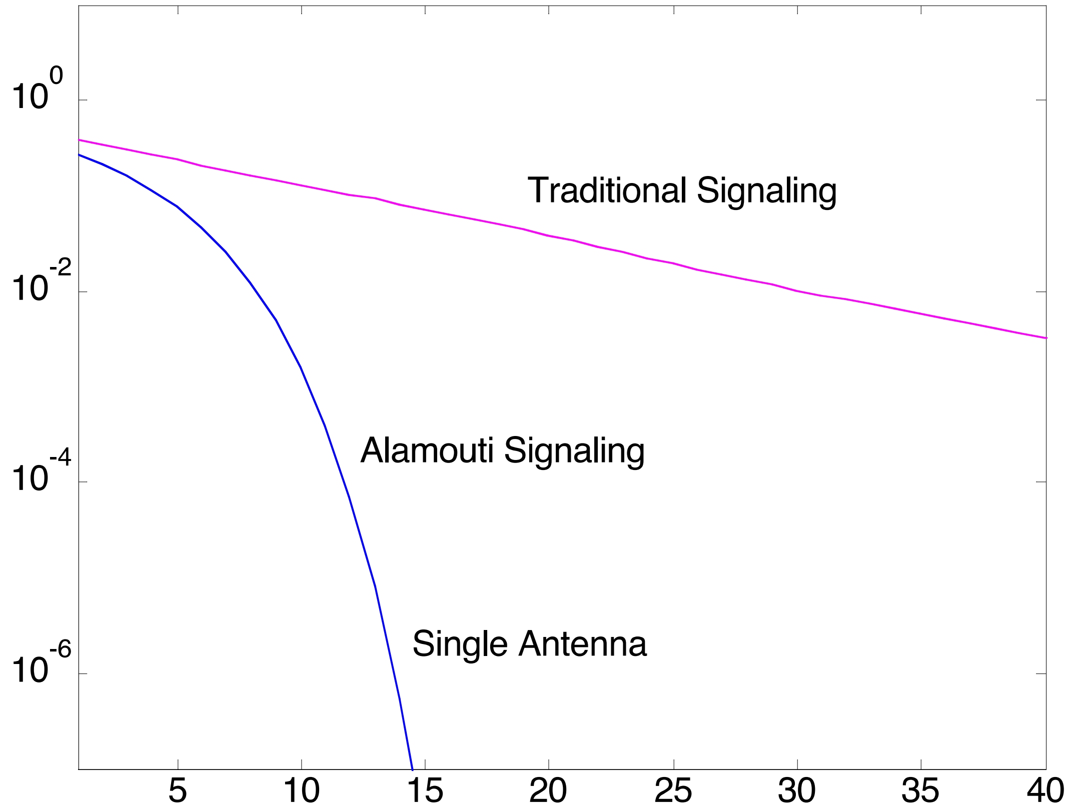
Similar expressions have been derived for:

- Polarization diversity at receiver (Maximal Ratio combining)
- One multipath (ground) bounce
- BPSK and 16-QAM signal constellations

for both Traditional Signaling and Alamouti Signaling

SER Simulations

Antenna Separation: 20' Horizontal, 8' Vertical
Antenna Patterns: Isotropic



Simple AWGN Channel

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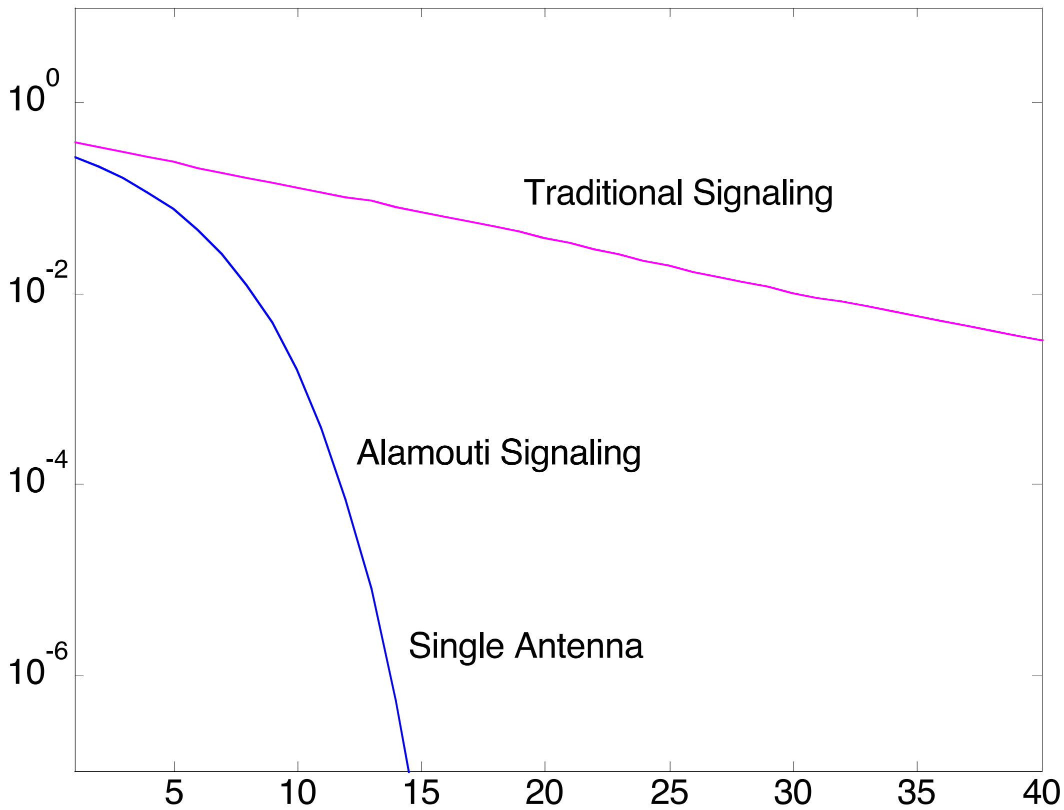
SER Simulations



Circular Polarization Diversity Reception

Results Identical to Single Receive Antenna System

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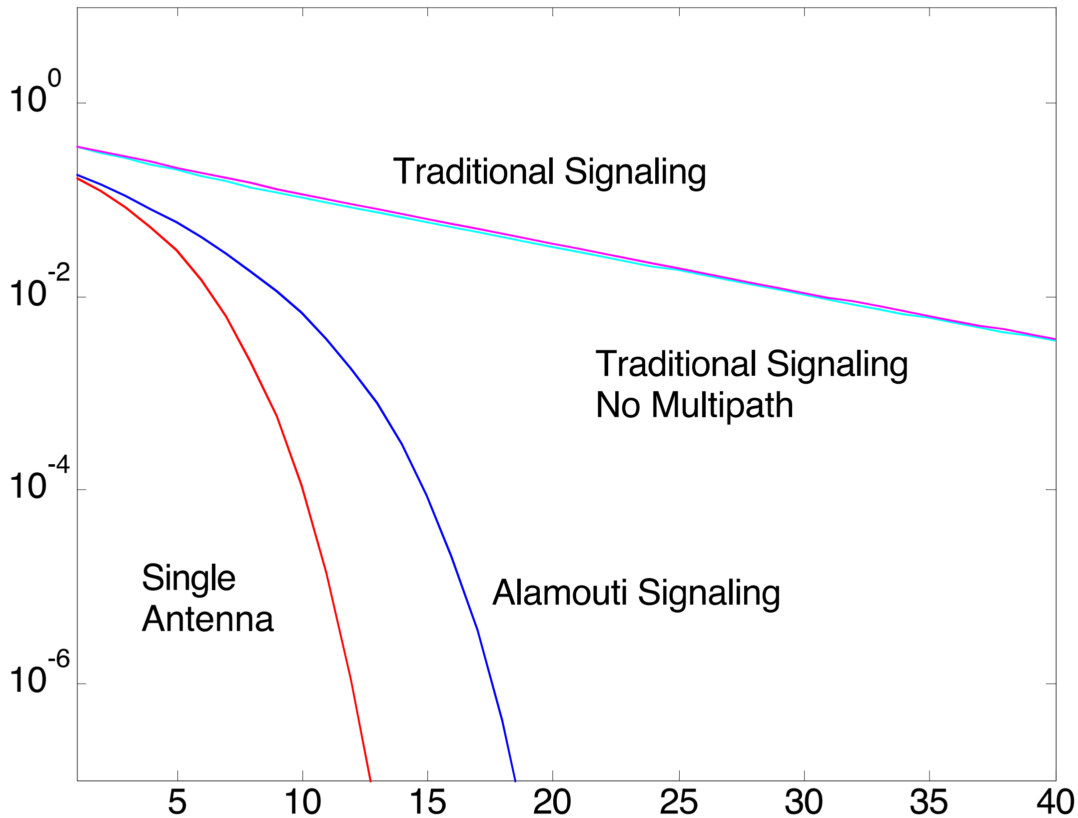
SER Simulations

Antenna Separation: 20’ Horizontal, 8’ Vertical
Antenna Patterns: Isotropic



One Ground Bounce (Multipath)

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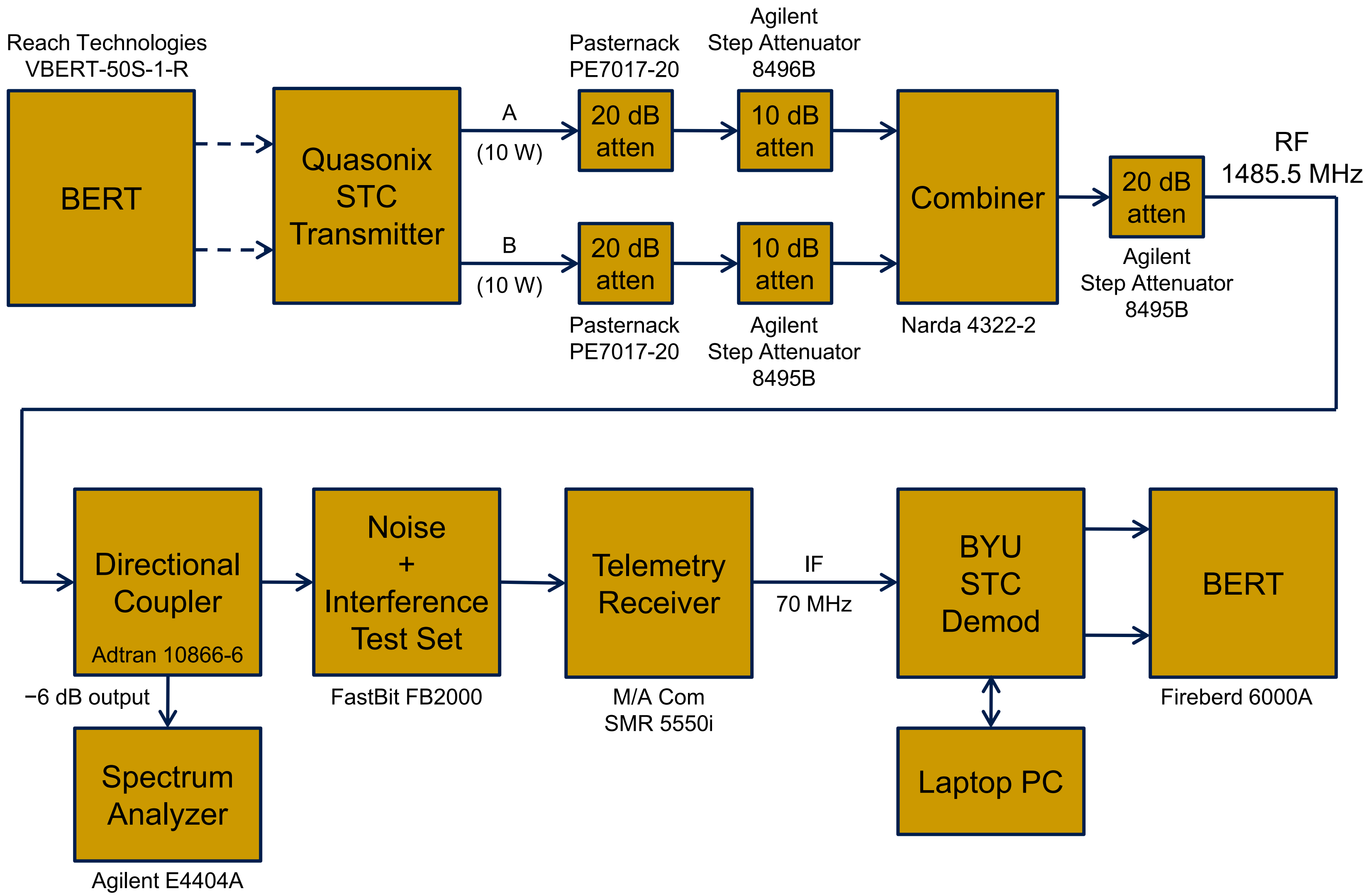
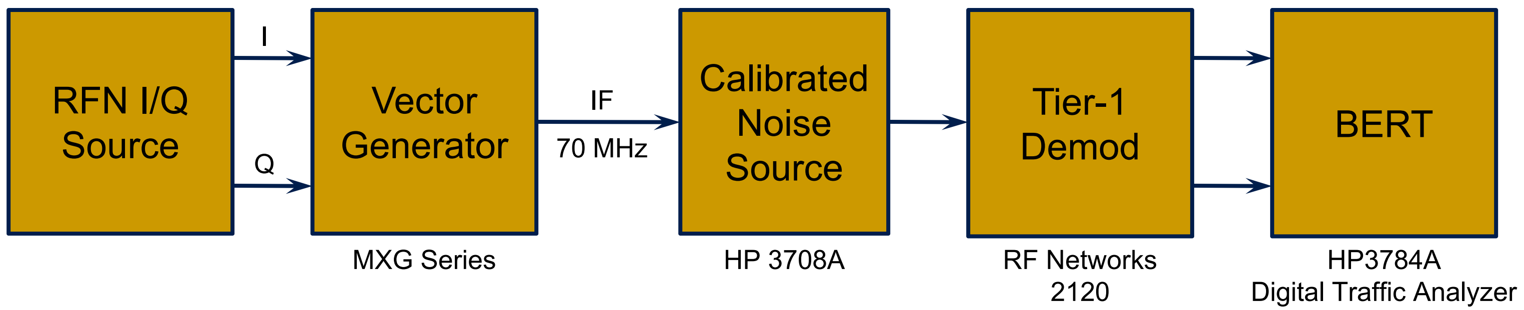
Prototype Testing

BYU

EAFB Telemetry Lab Configuration

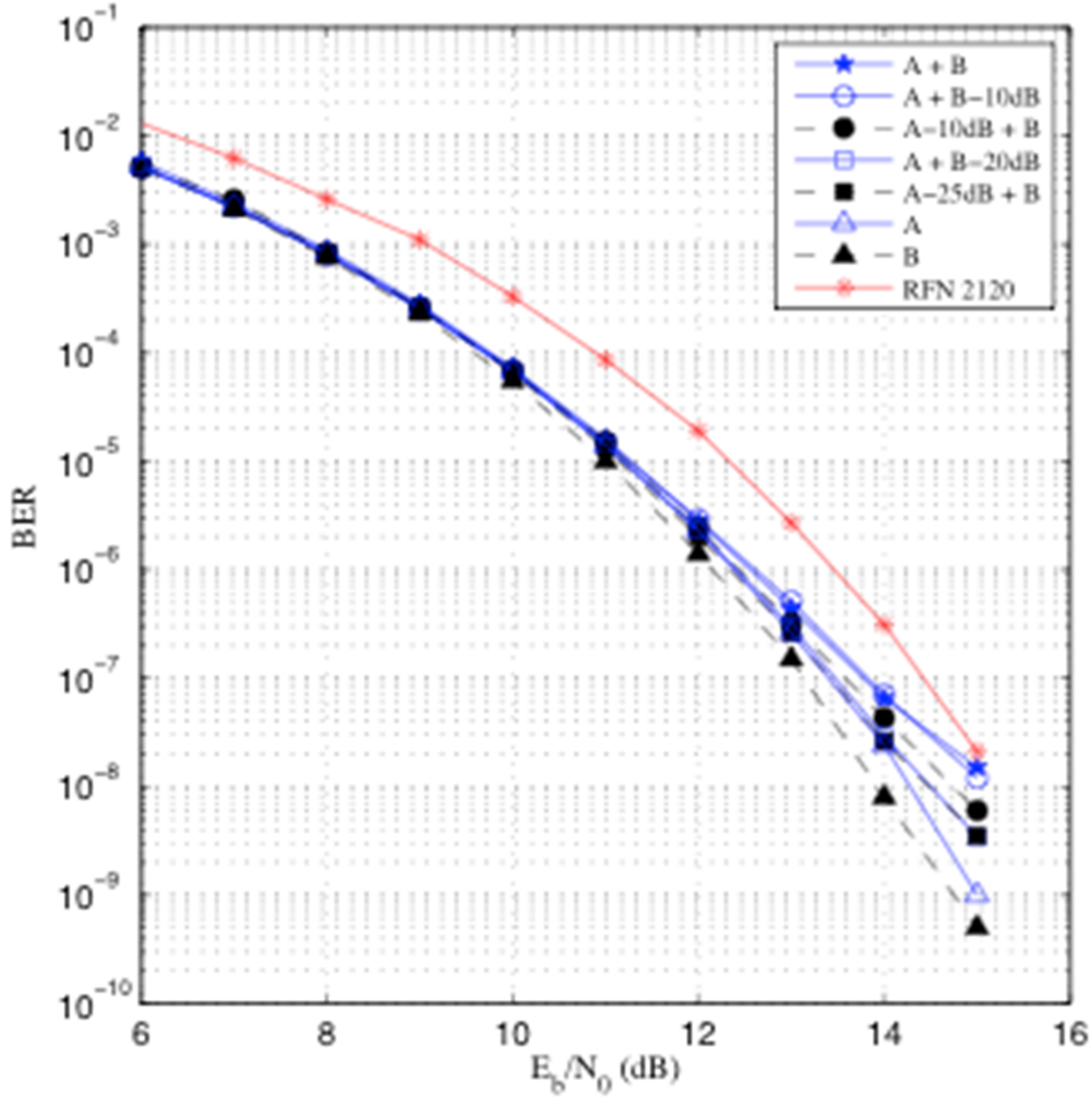


Reference Link BER Calibration



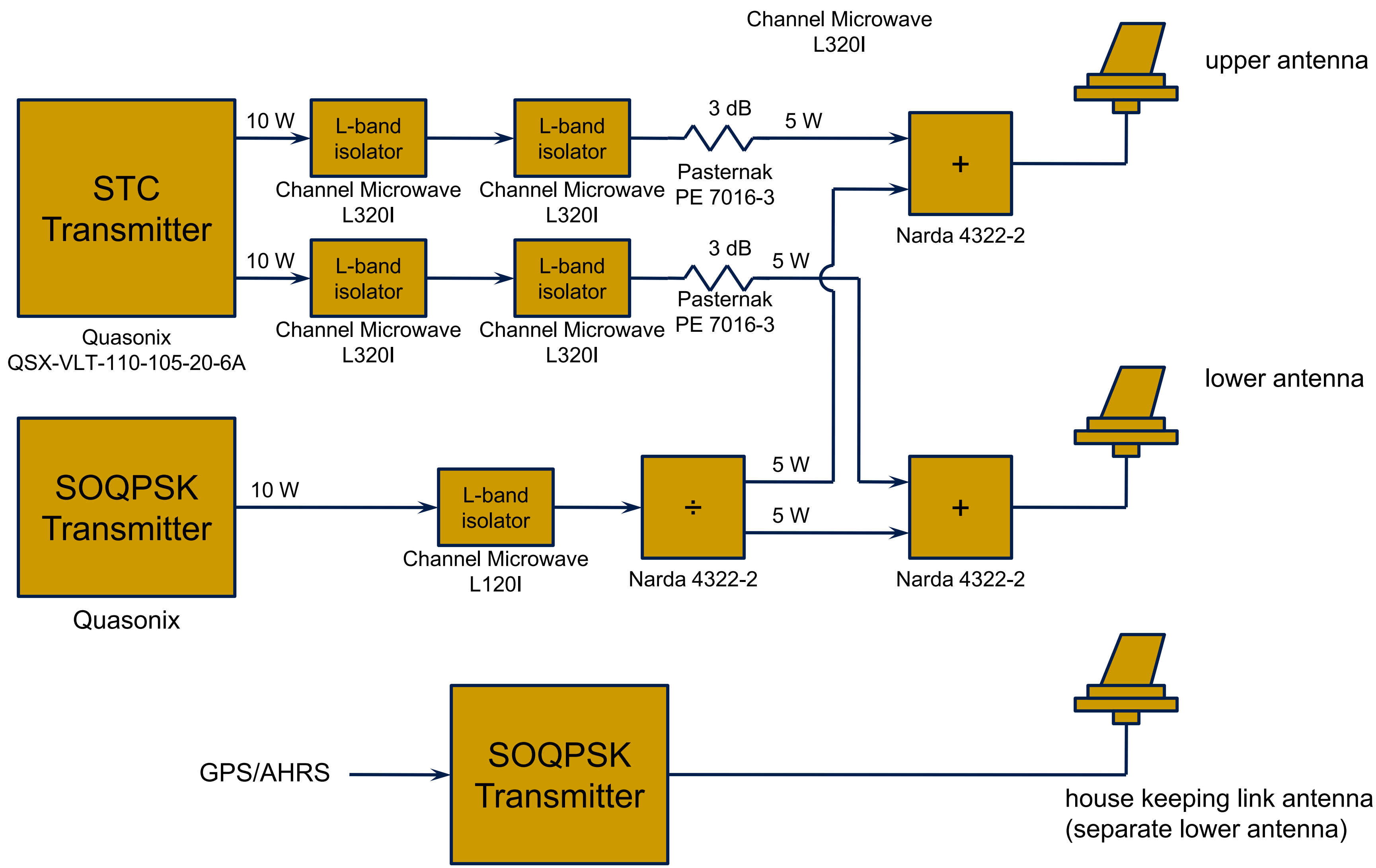
Reference Link BER Calibration

BYU



Flight Tests: Airborne Configuration

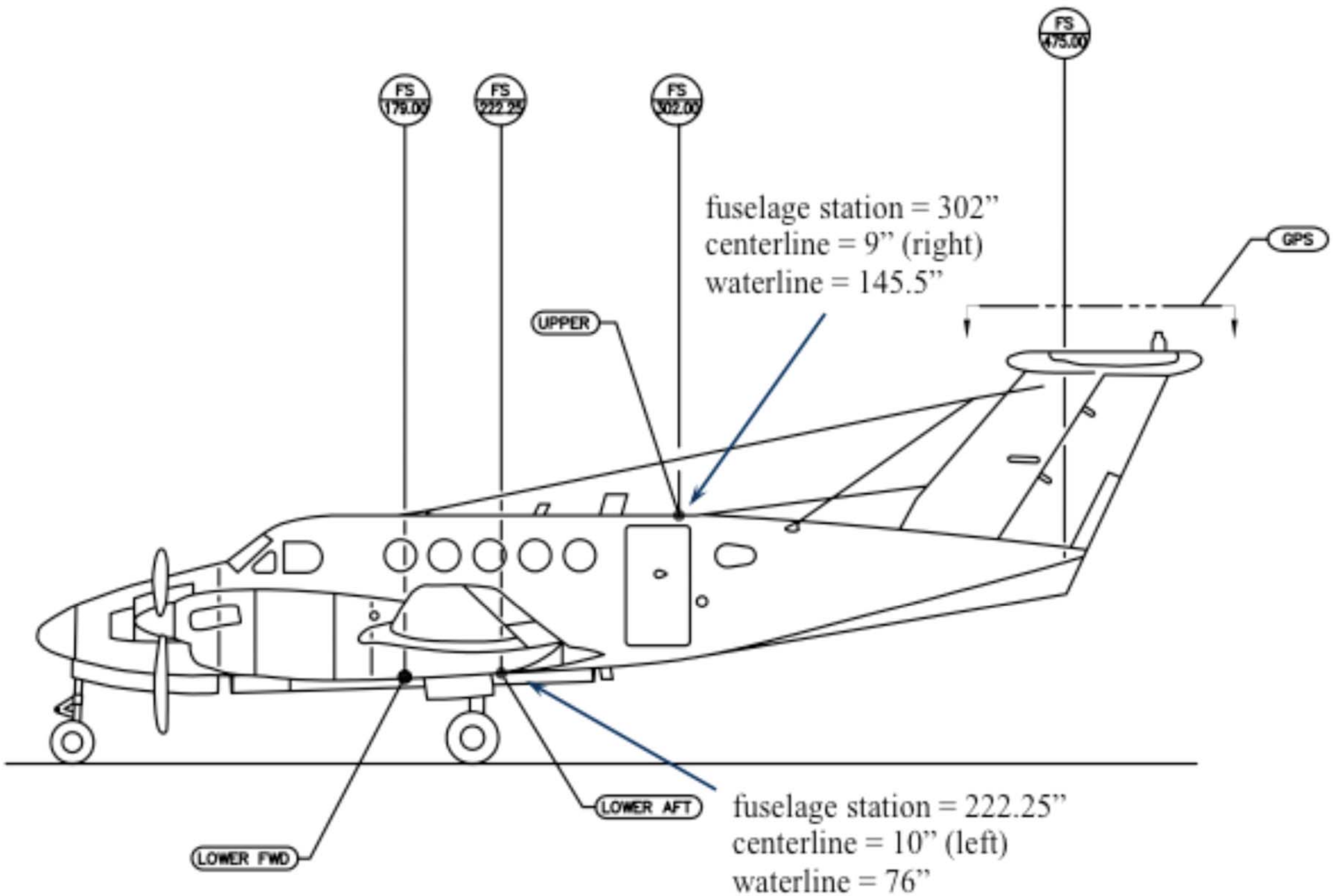
BYU



C-12 Beechcraft: Airborne Platform

BYU

Antenna Locations



Flight Tests: Transmit Antennas

BYU

Lower Telemetry Antenna
(behind the antenna looking forward)

fuselage station = 222.25”
centerline = 10” (left)
waterline = 76”

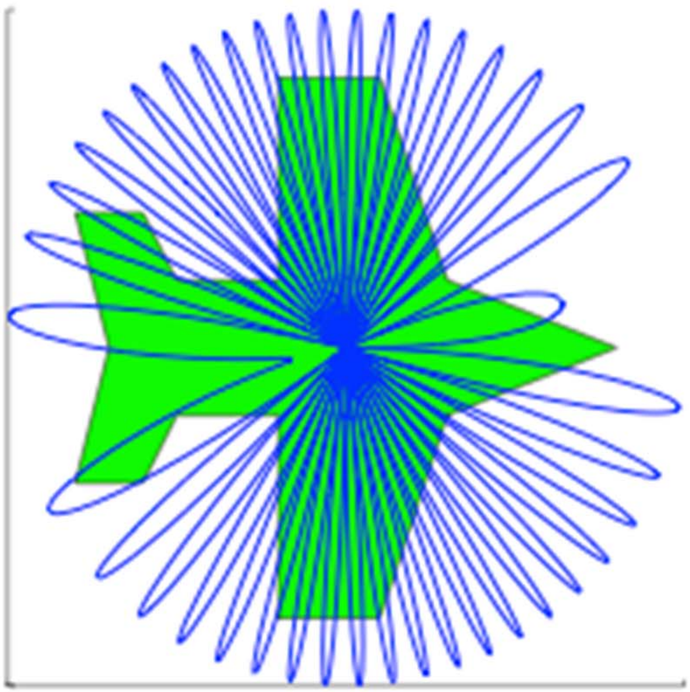
Upper Telemetry Antenna
(looking across the fuselage)

fuselage station = 302””
centerline = 9” (right)
waterline = 145.5”

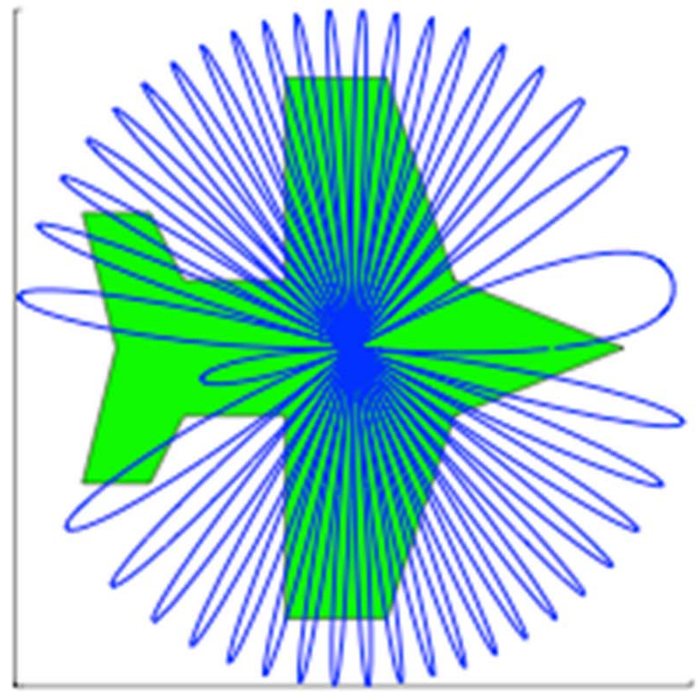
Flight Tests: Idealized Gain Patterns

BYU

STC Frequency

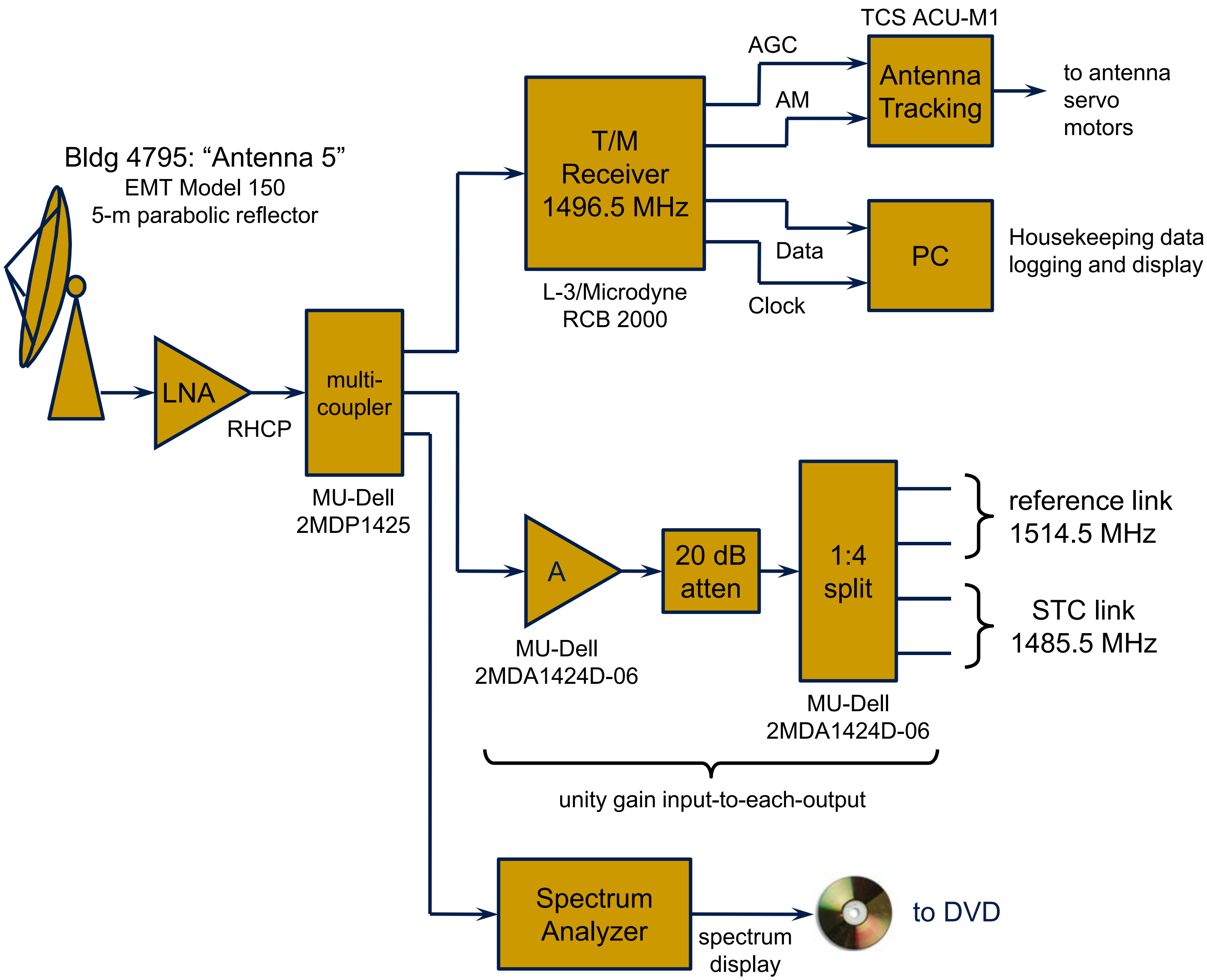


Reference Link Frequency



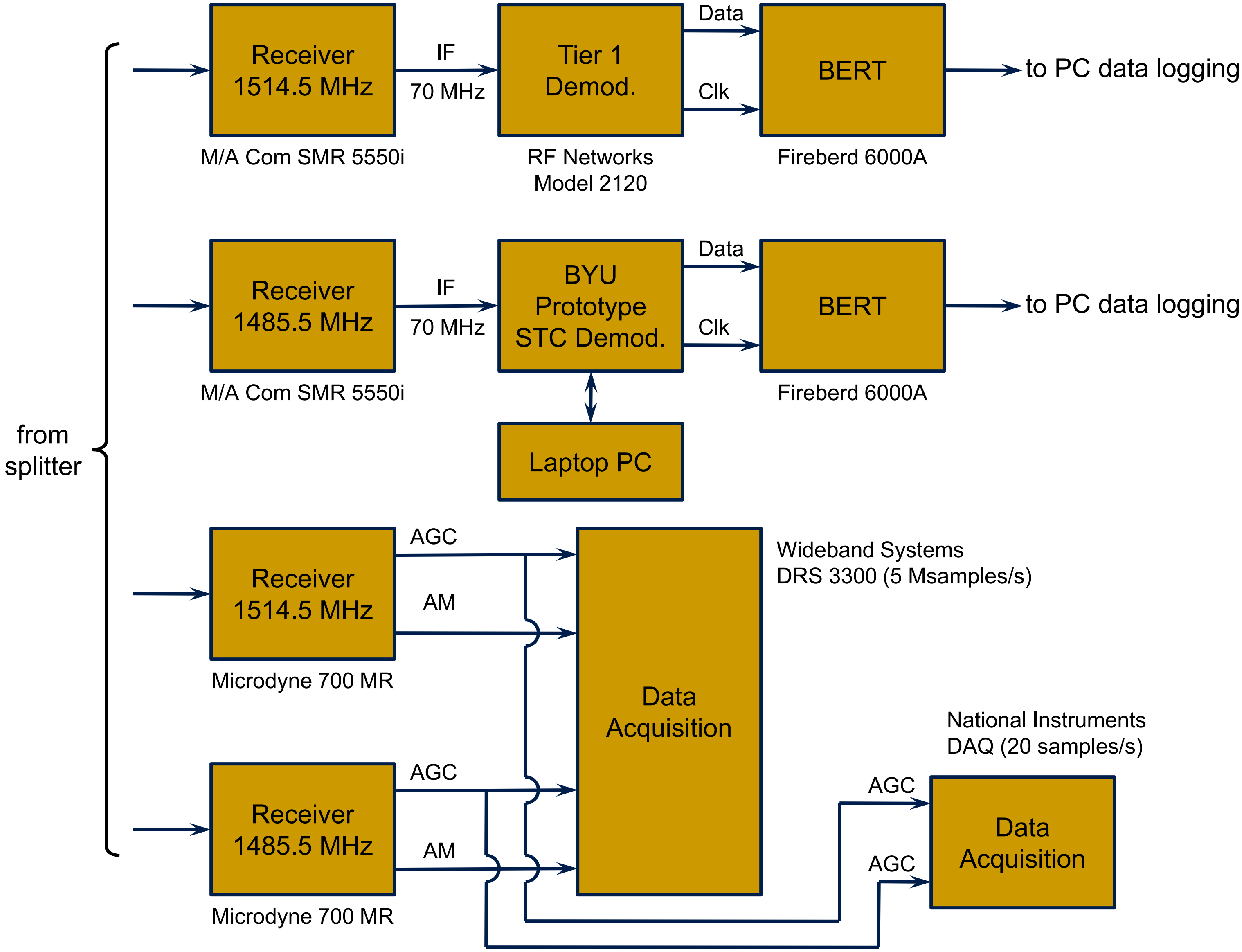
Flight Tests: Ground Station Configuration

BYU



Test Flights: Ground Station Configuration

BYU

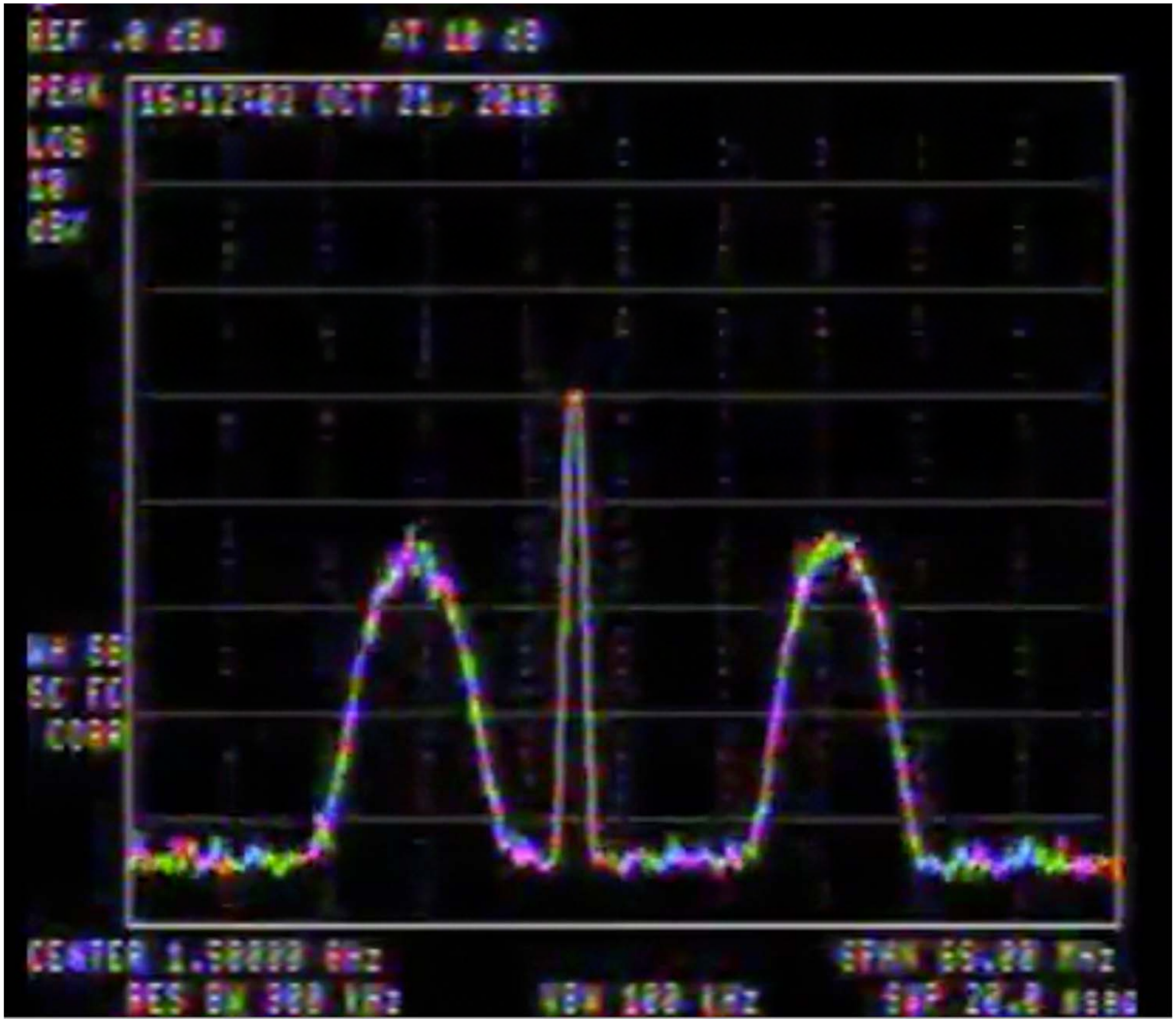


Test Flights: Ground Station Configuration

BYU

Test Flights: Ground Station Configuration

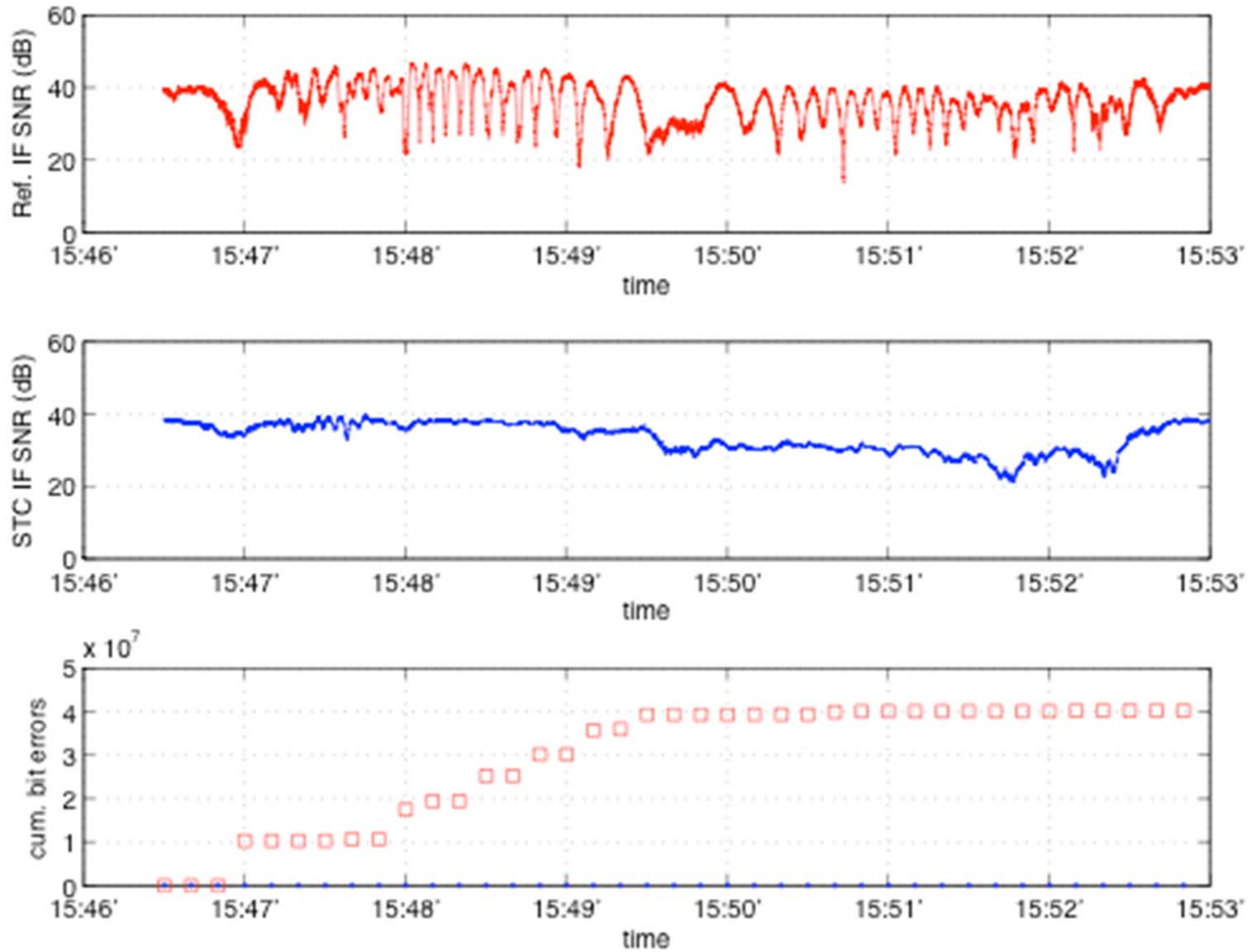
STC Video Clip



M1: Left-Hand Turn @ 10° bank

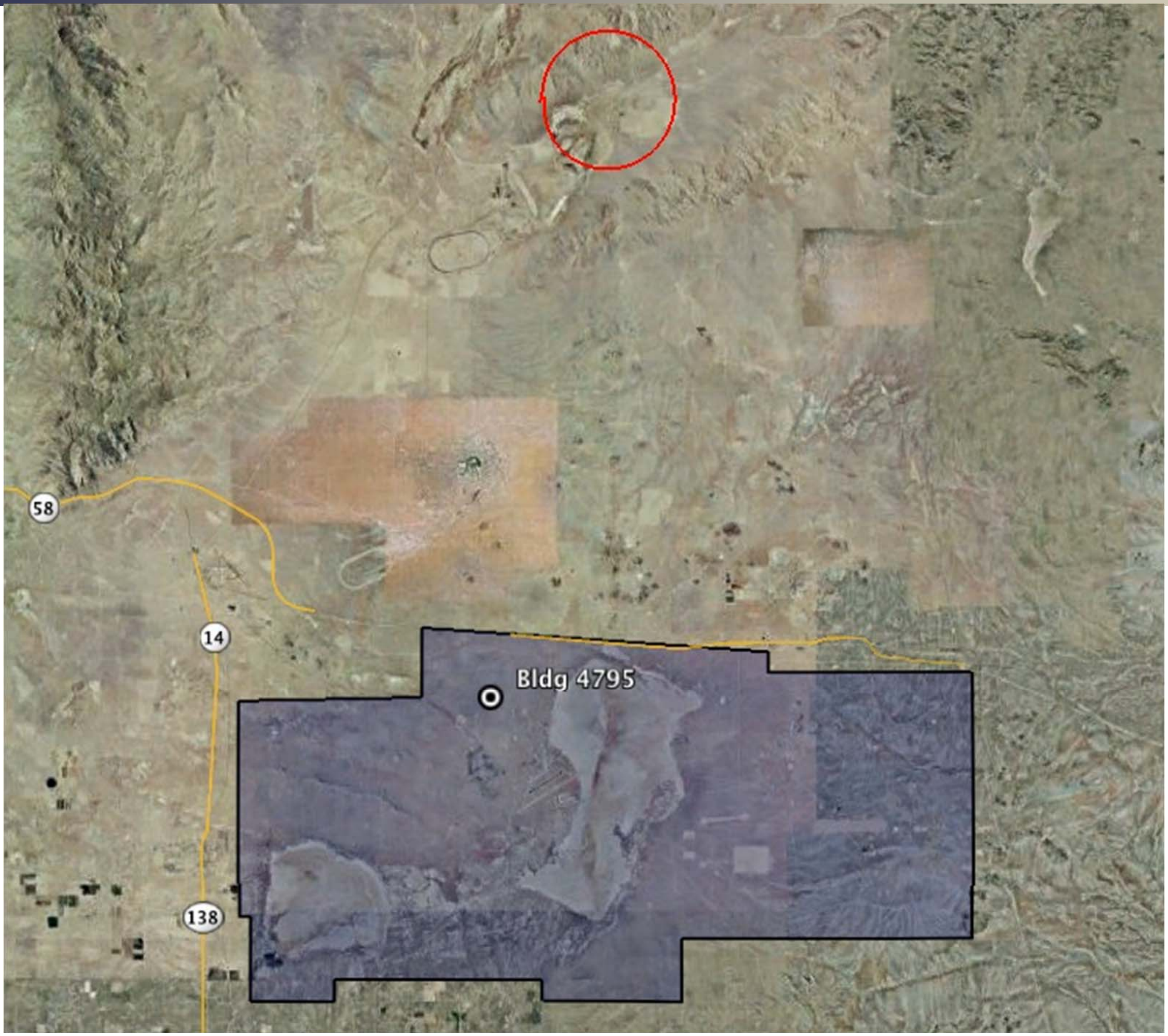
BYU

M1: Test Results



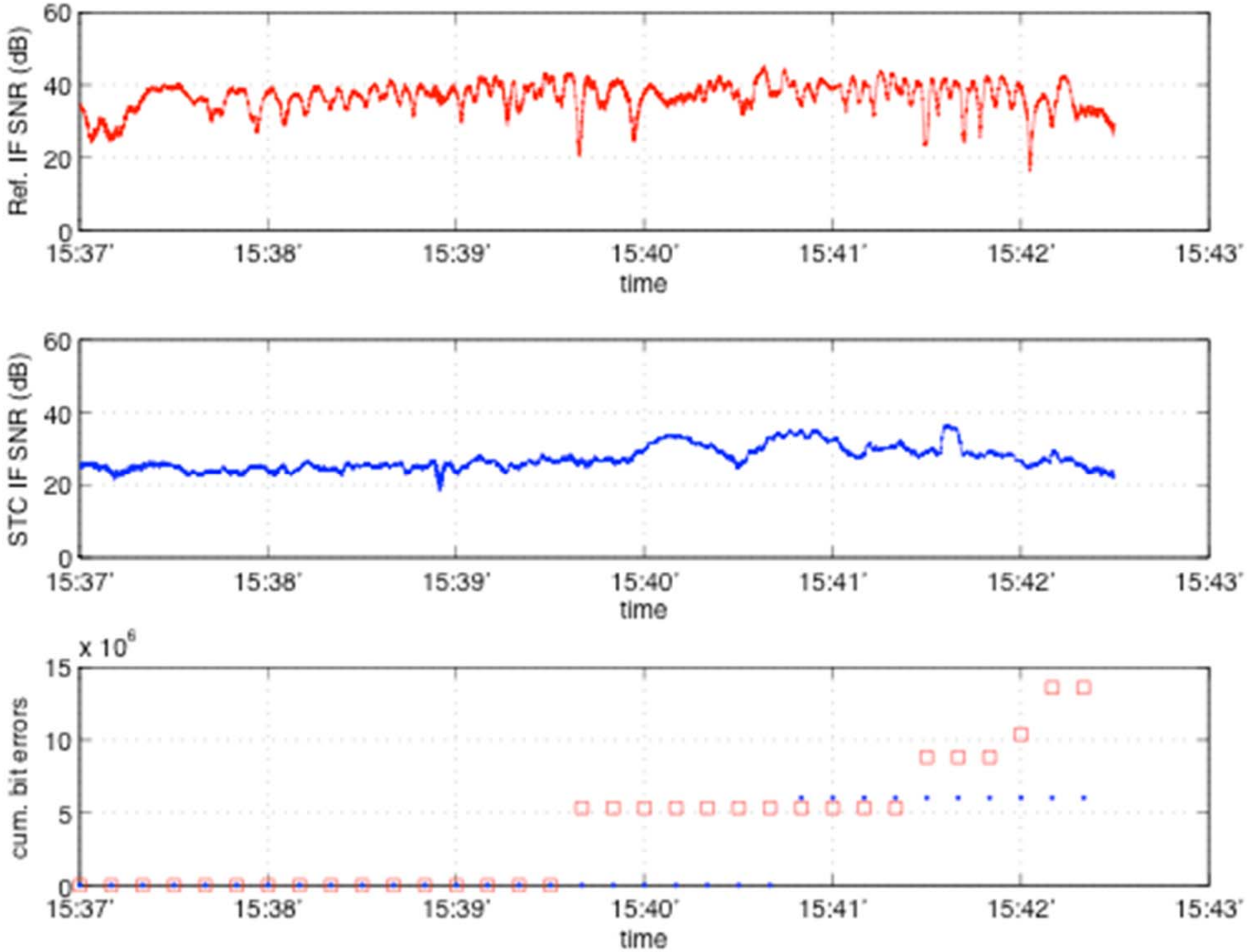
M2: Right-Hand Turn @ 10° bank

BYU



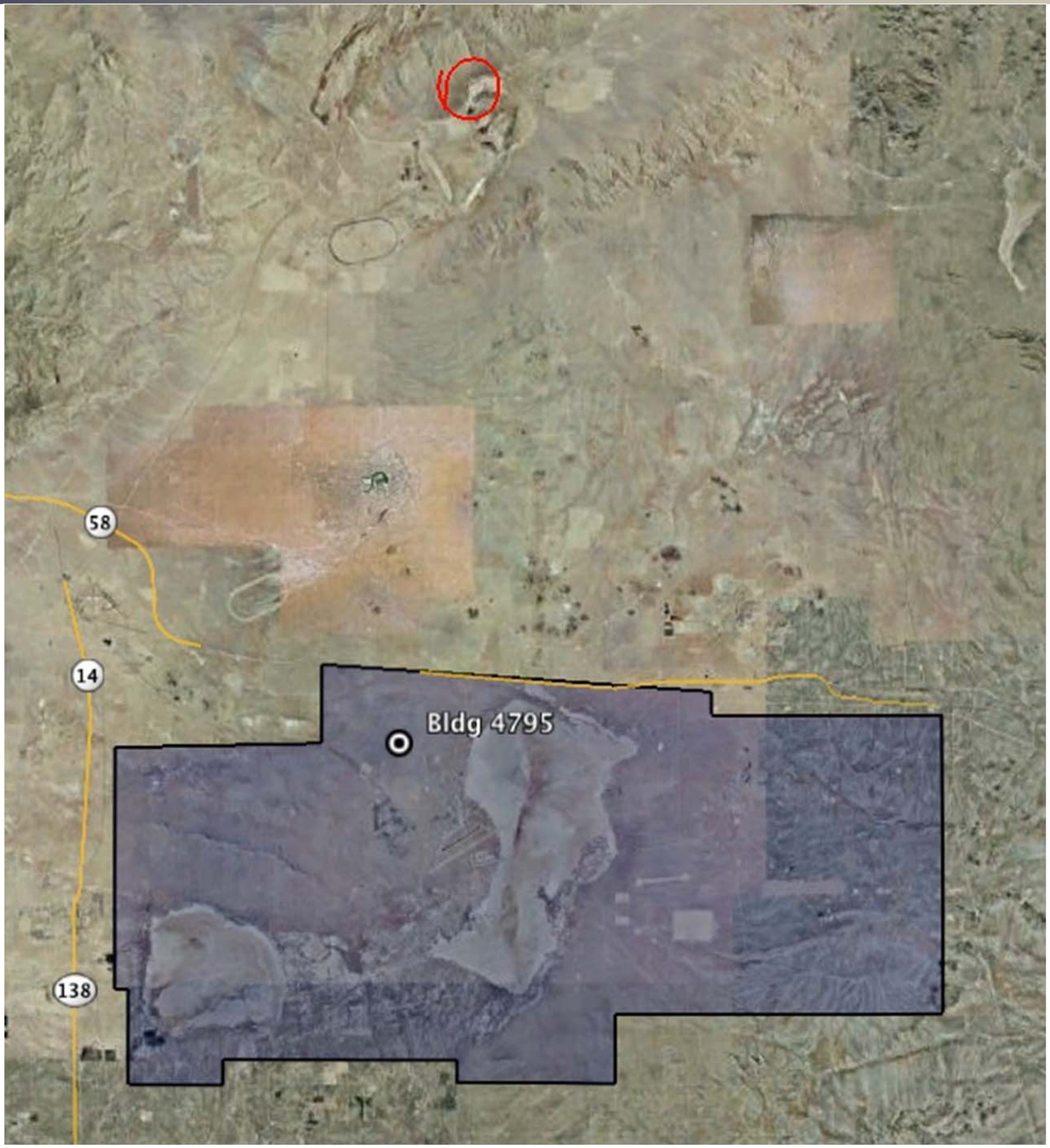
M2: Test Results

BYU



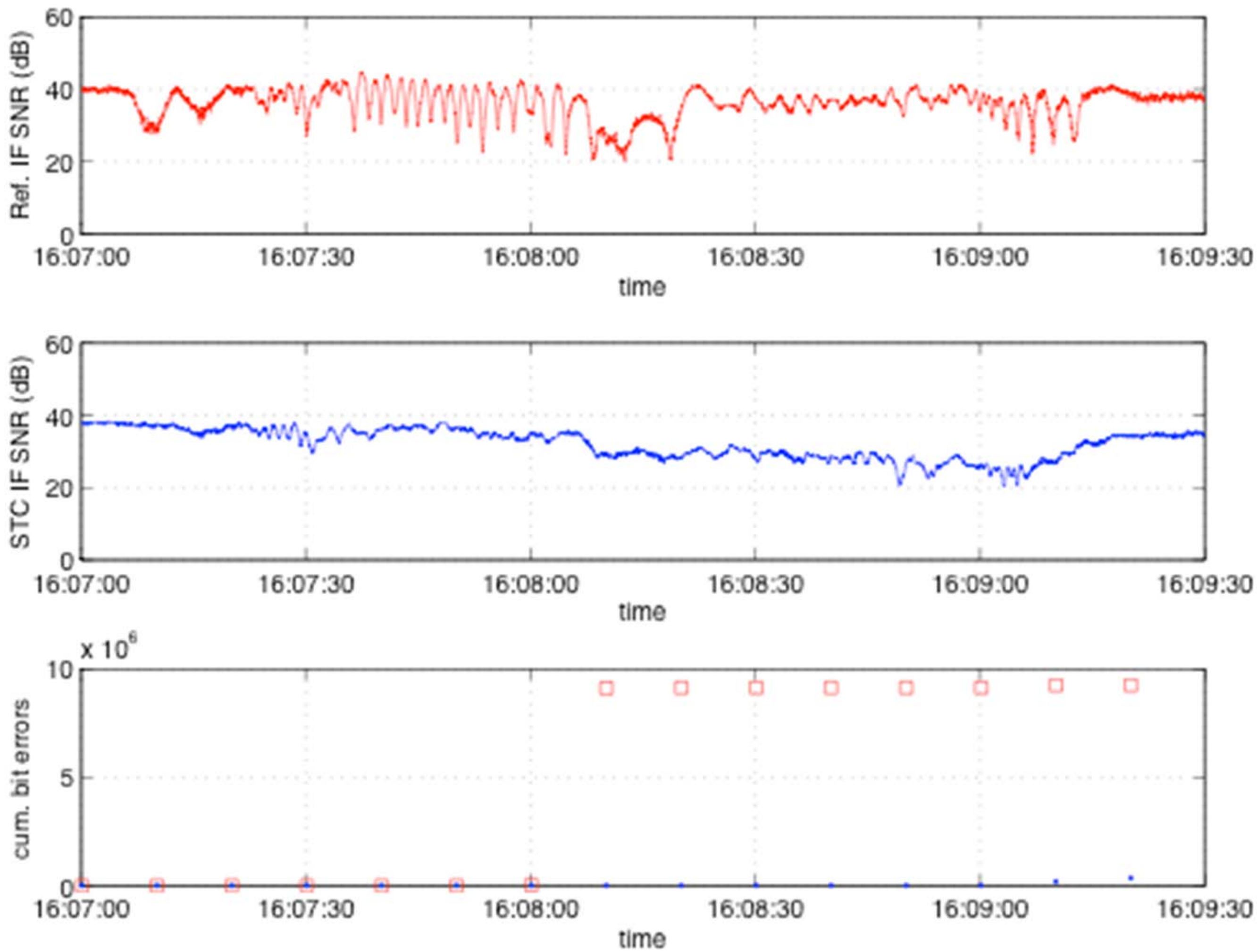
M3: Left-Hand Turn @ 30° bank

BYU



M3: Test Results

BYU

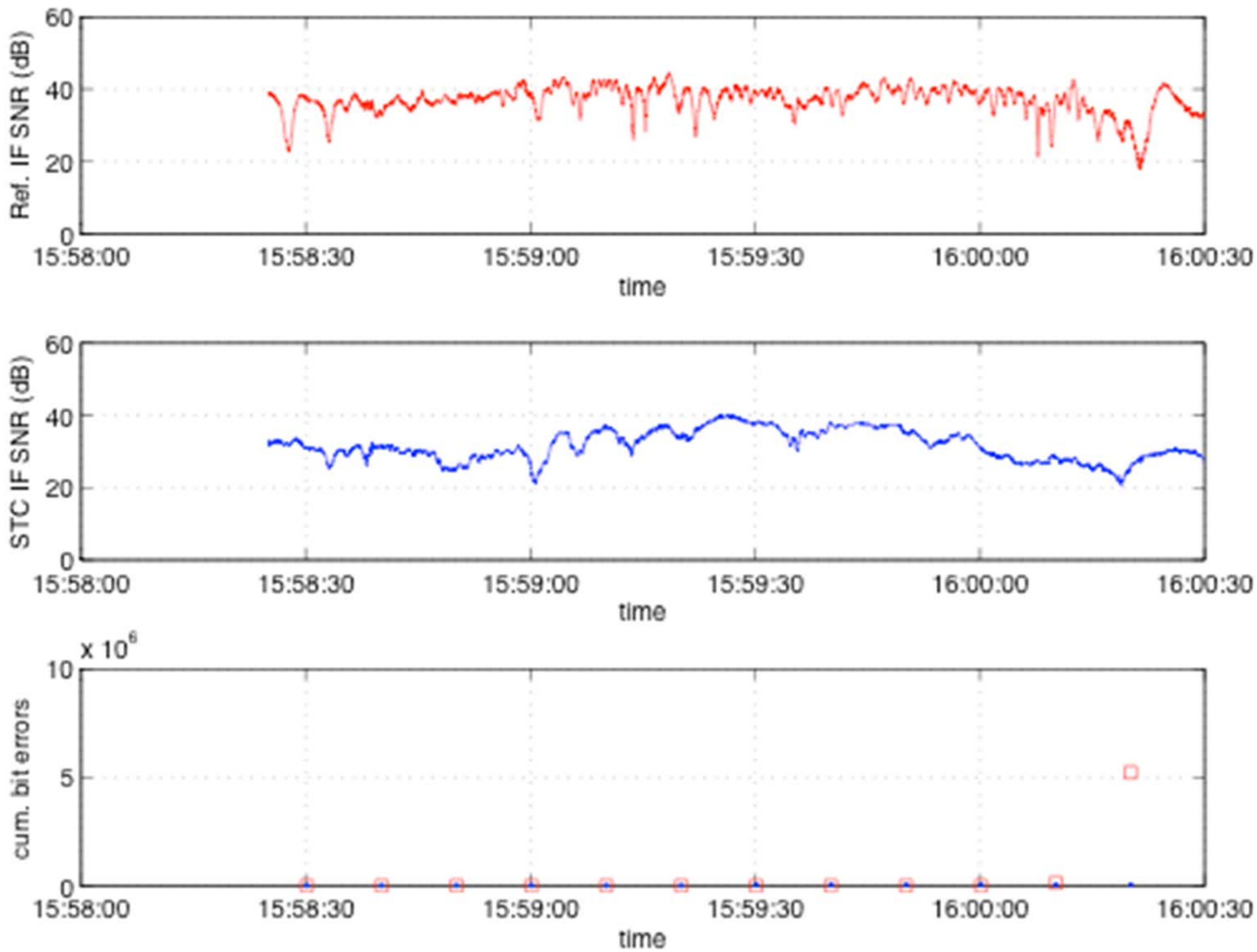


M4: Right-Hand Turn @ 30° bank

BYU

M4: Test Results

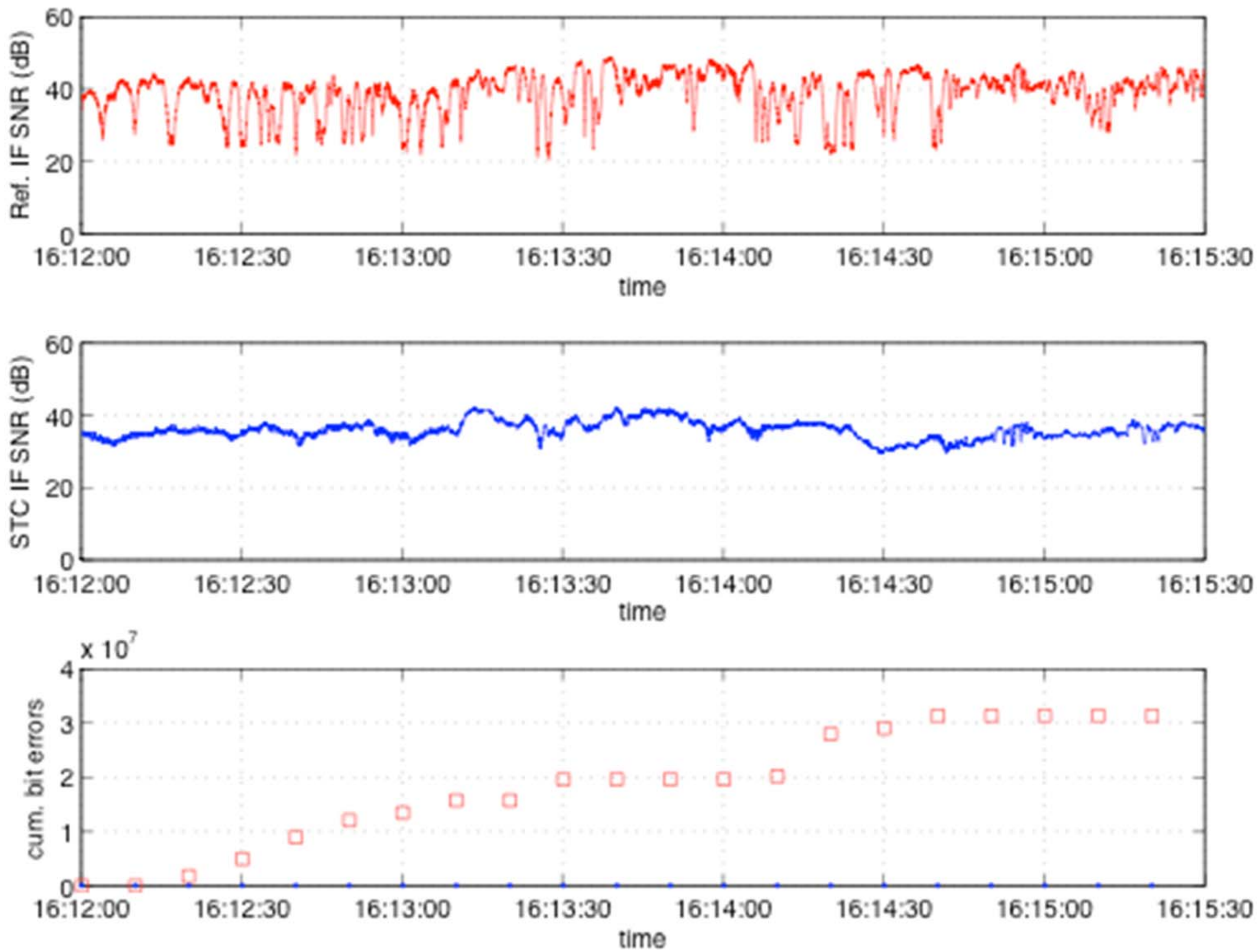
BYU



M3 to C2 Transition

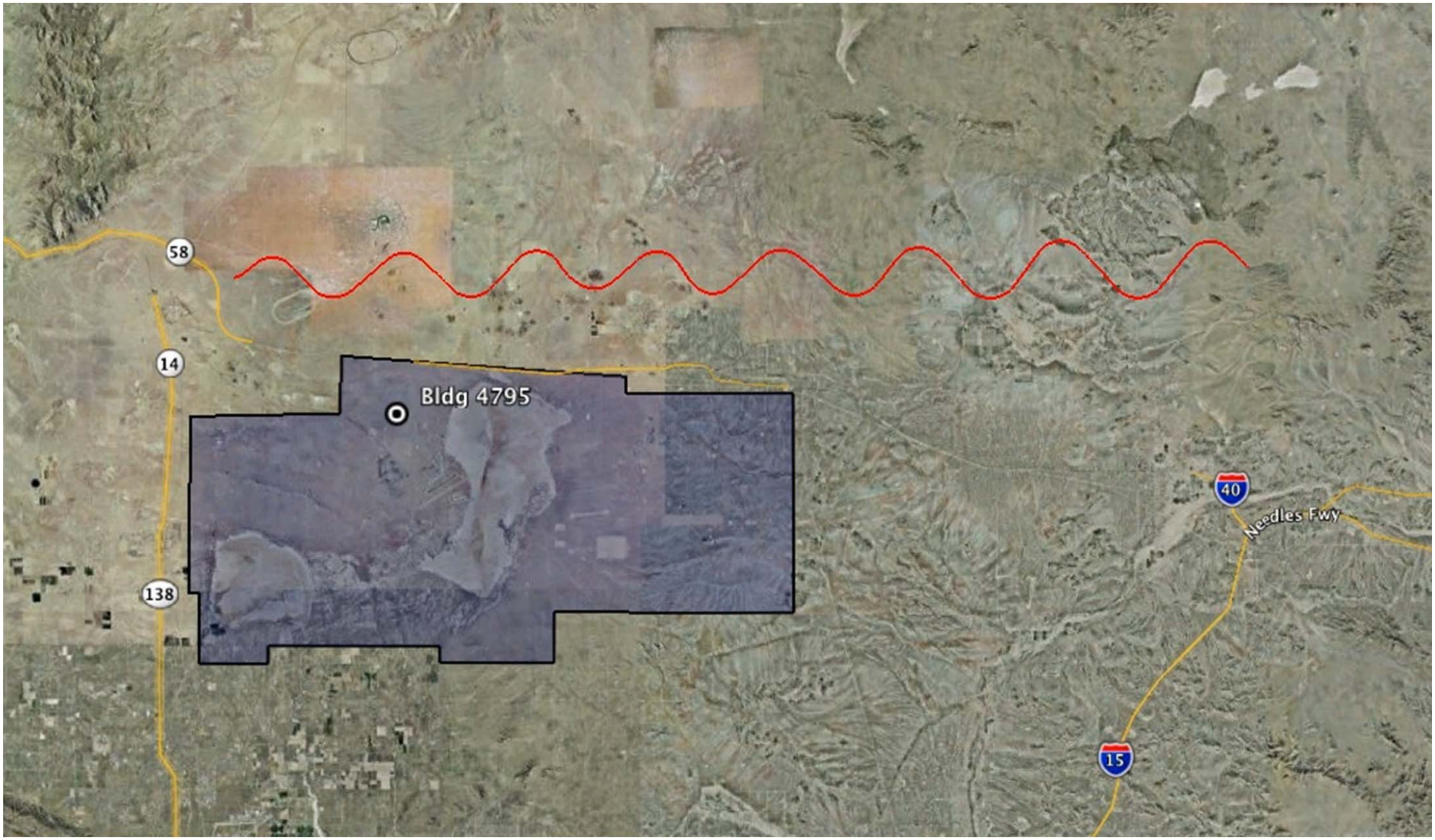
BYU

M3 to C2 Transition Test Results



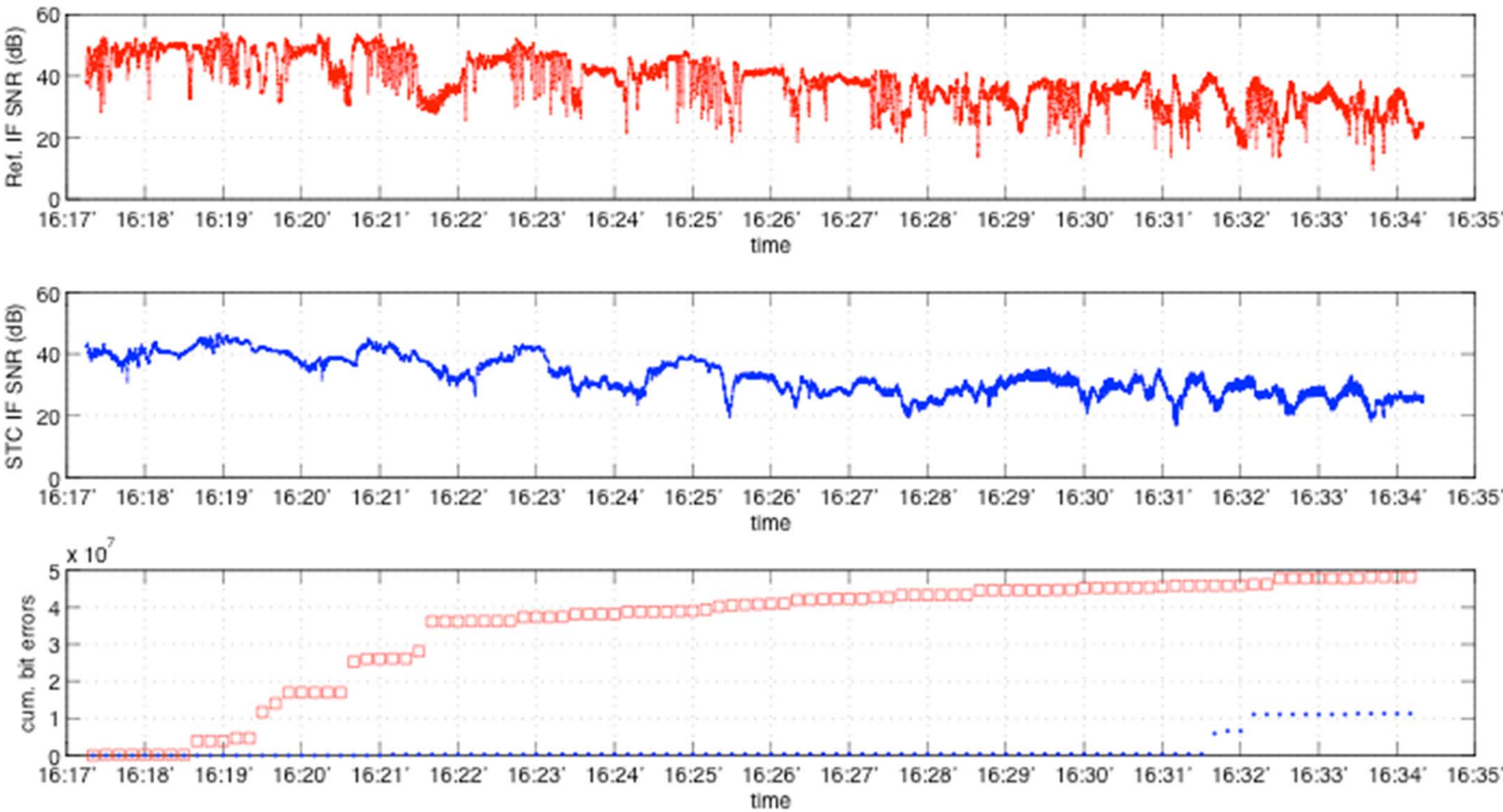
C2: Cords Road West-to-East

BYU



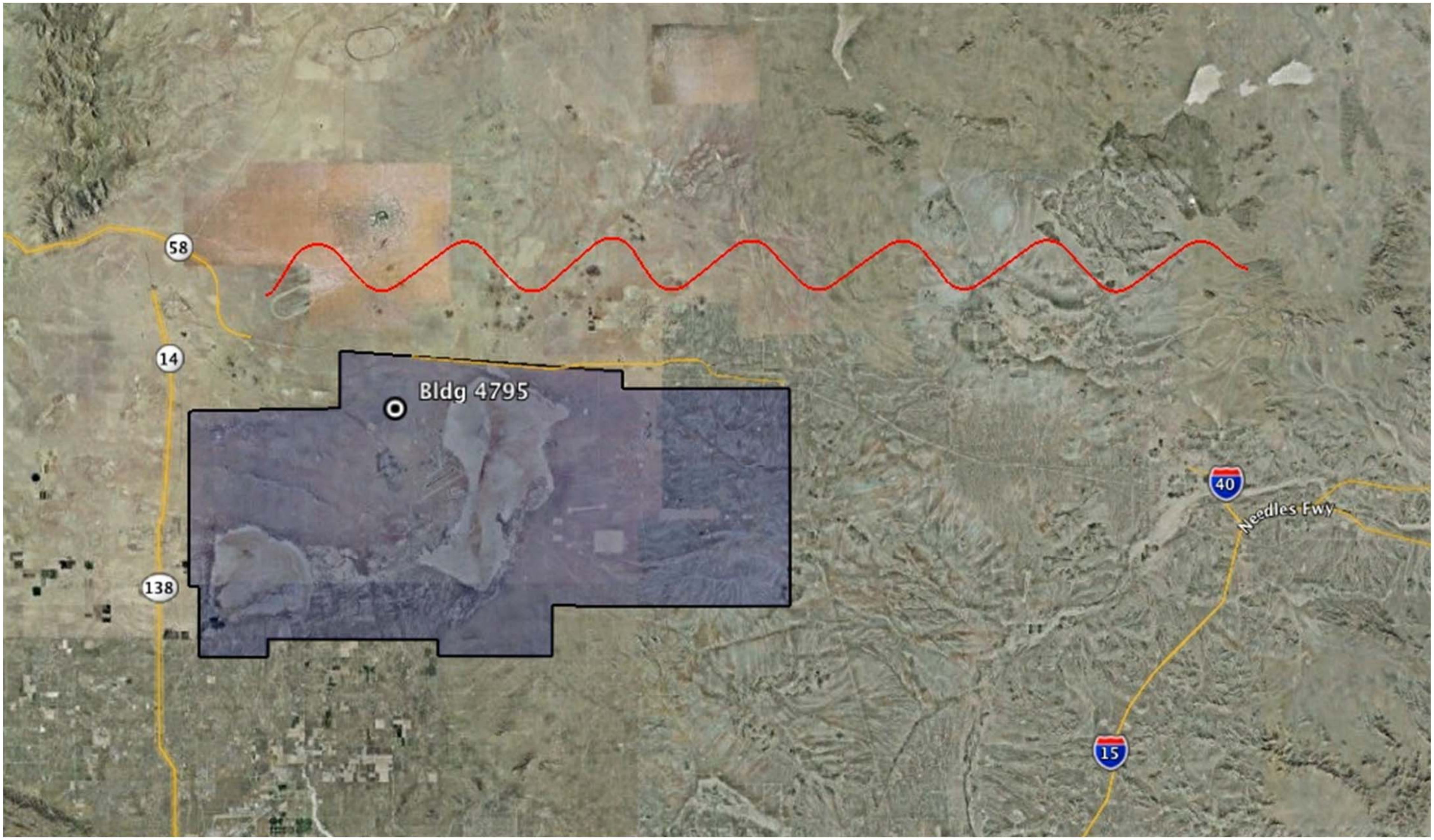
C2: Test Results

BYU

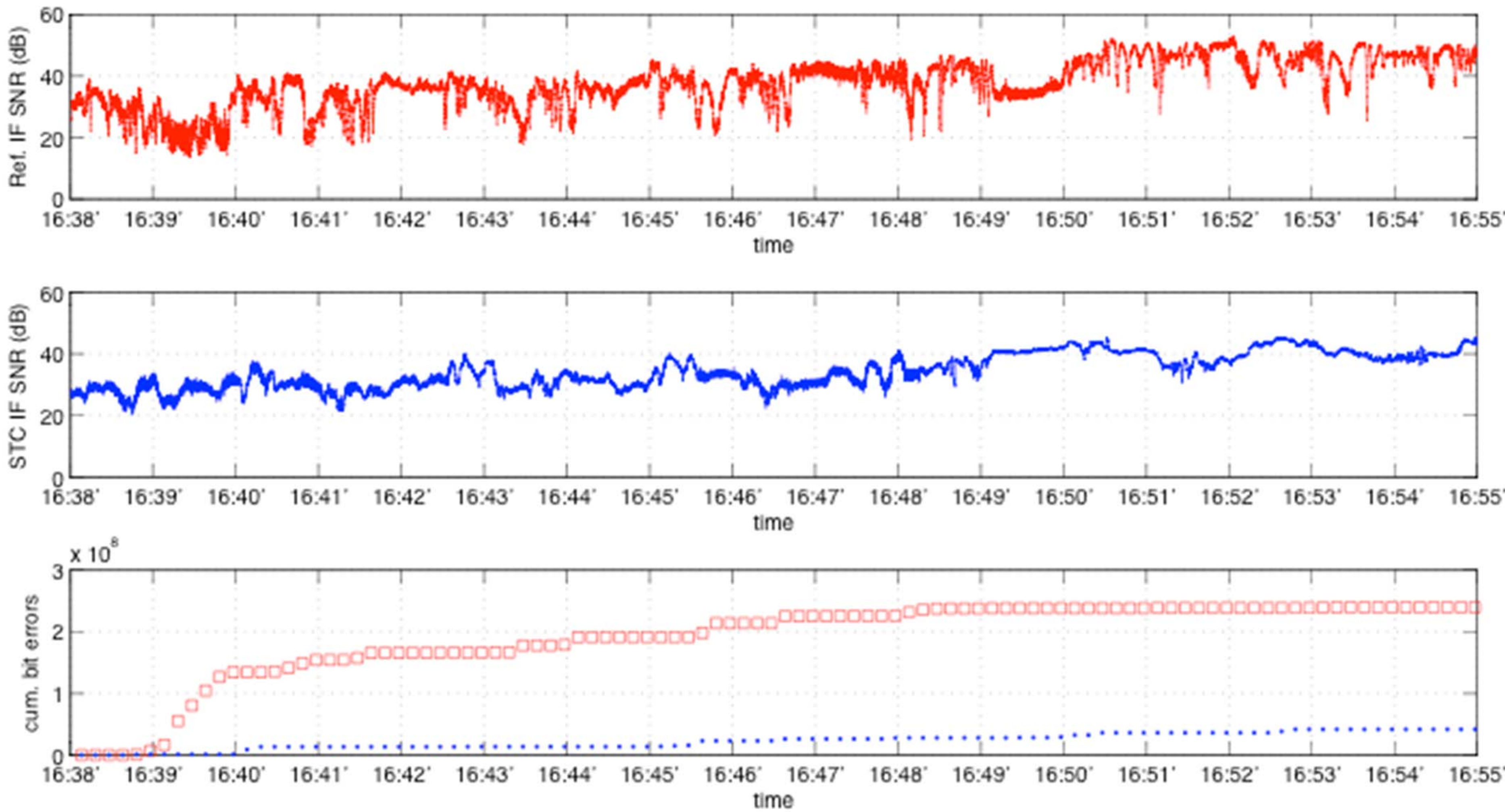


D2: Cords Road East-to-West

BYU



D2: Test Results



STC Summary

Dual-Antenna Diversity Scheme

- Removes interference created by multiple transmit antennas
  - SNR equivalent to single antenna transmission
  - Multi-antenna scheme alleviates masking during maneuvering
  - Can be used with diversity reception
- Realtime hardware flight tested at Edwards AFB and showed substantial performance benefit

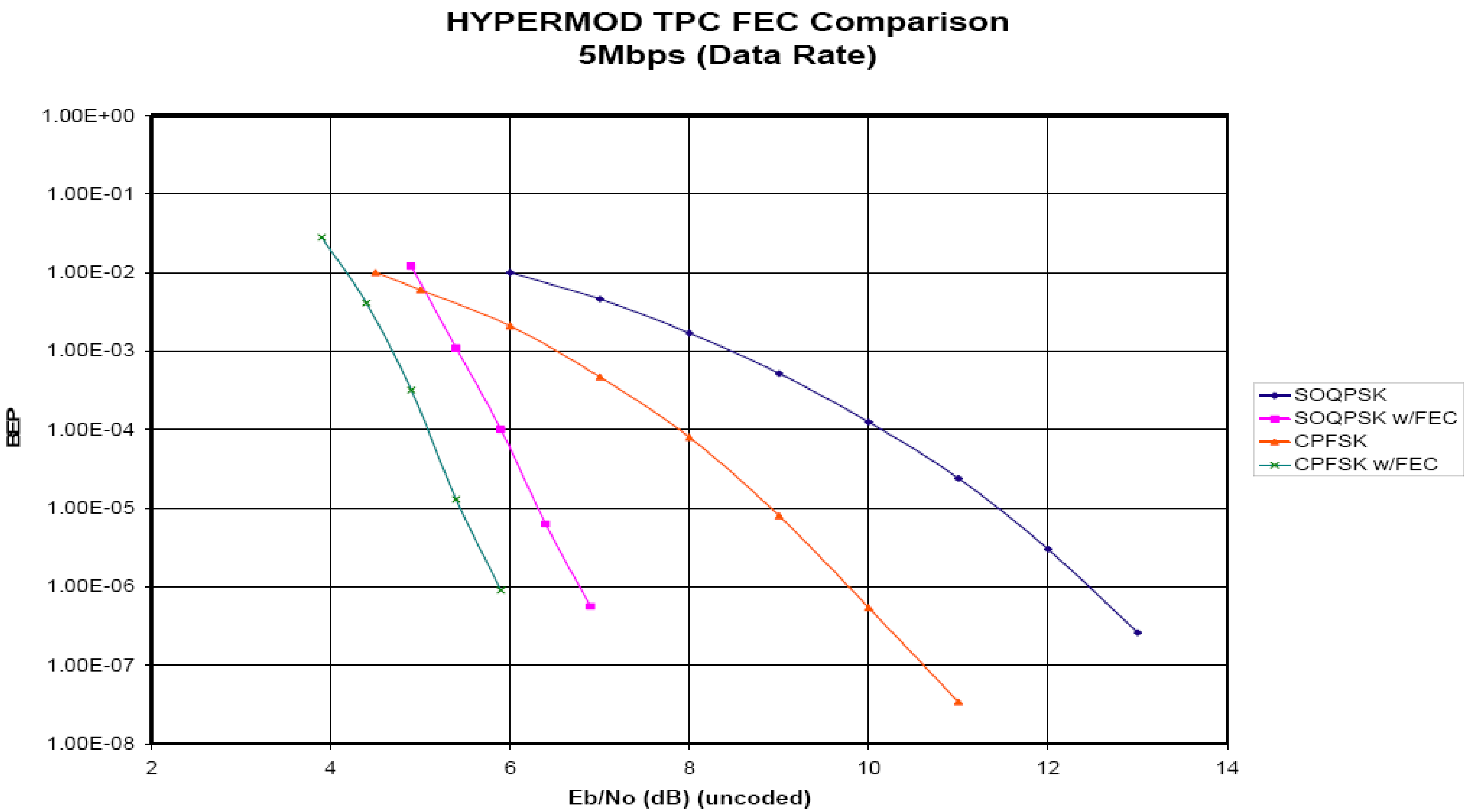
Course Outline

- Historical Perspective
- Performance Metrics
- Modulation Universe
- Life on the Unit Circle
  - ARTM Tier 0
  - ARTM Tier I
  - ARTM Tier II
- Demodulation
- Diversity Combining
- Channel Impairments & Mitigation
  - Adjacent Channel Interference
  - Multipath Propagation
    - Adaptive Equalization
    - Space-Time Coding
  - Forward Error Correction (FEC)
- Performance Comparison & Summary

Forward Error Correction

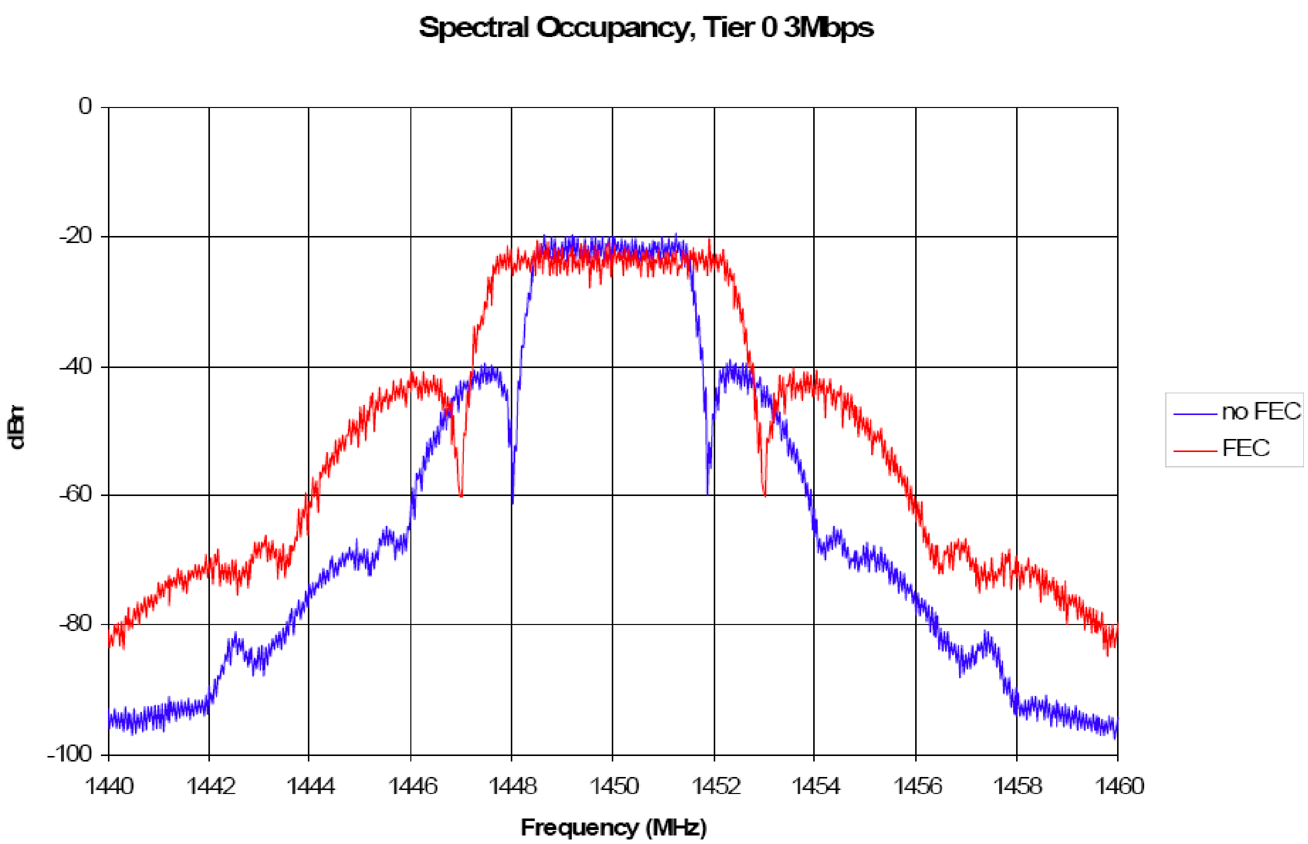
- Basic premise
  - Insert redundant bits into transmitted stream
  - Use known relationships between bits to correct errors
- Countless schemes have been developed
  - Convolutional code / Viterbi decoder
  - Block codes
    - BCH
    - Reed-Solomon
  - Low Density Parity Check (LDPC)
  - Concatenated codes
    - RS / Viterbi
    - Turbo product codes (TPC)

BER with TPC

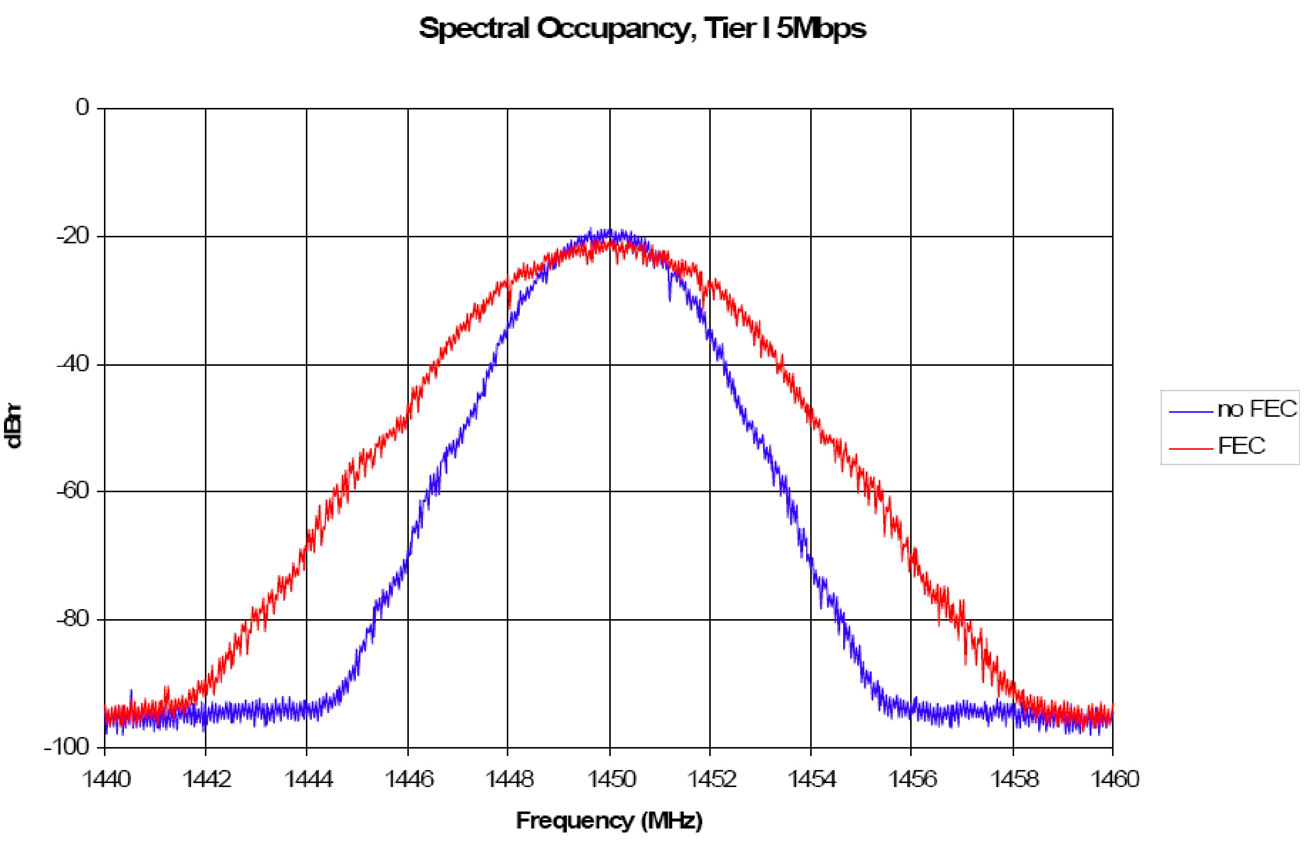


HYPERMOD TPC FEC Comparison
5Mbps (Data Rate)
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
BEP
2
4
6
8
10
12
14
Eb/No (dB) (uncoded)
SOQPSK
SOQPSK w/FEC
CPFSK
CPFSK w/FEC

Spectral Expansion - Tier 0

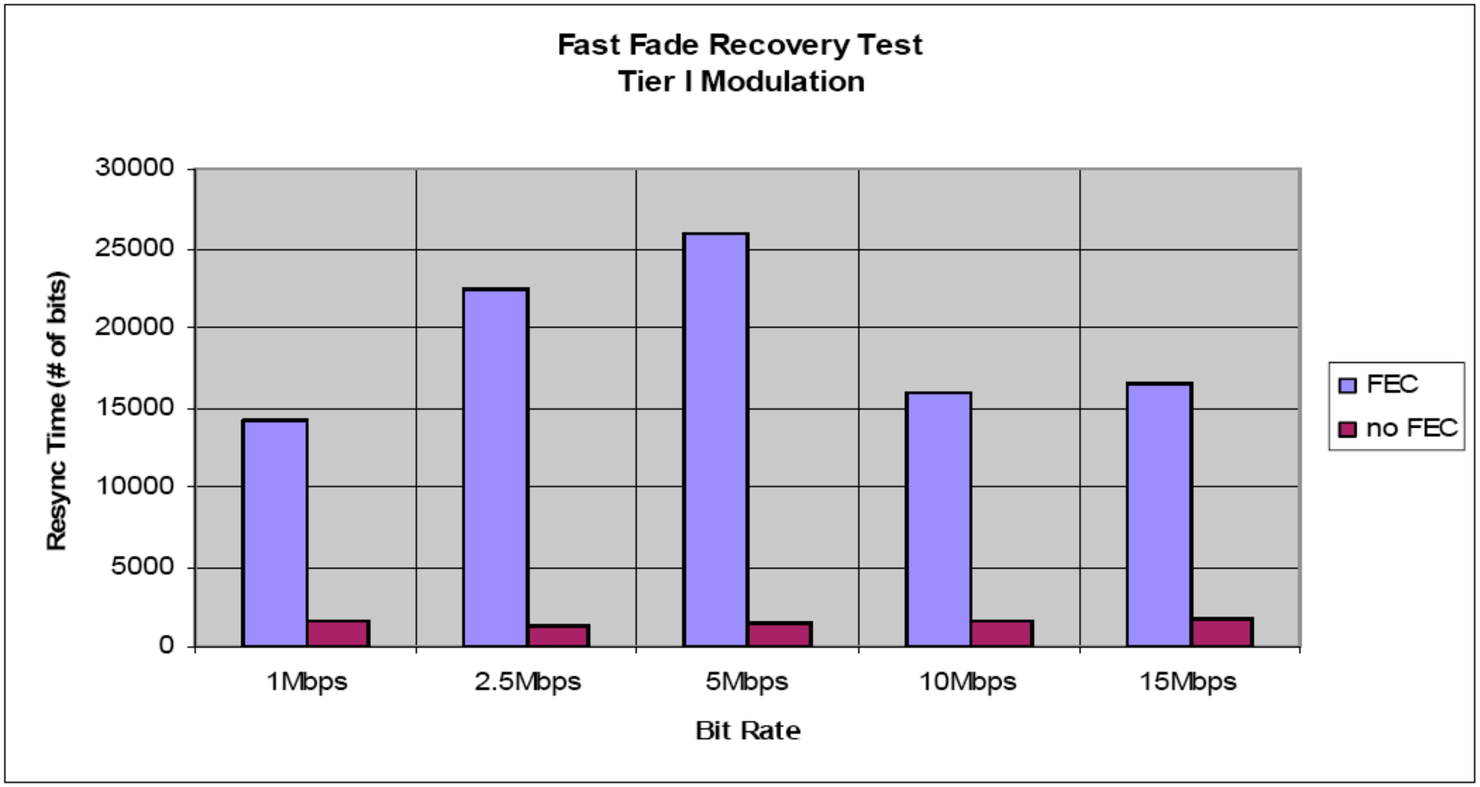


Spectral Expansion - Tier I



Quasonix

Sync Time with FEC



Cumulative Error Results

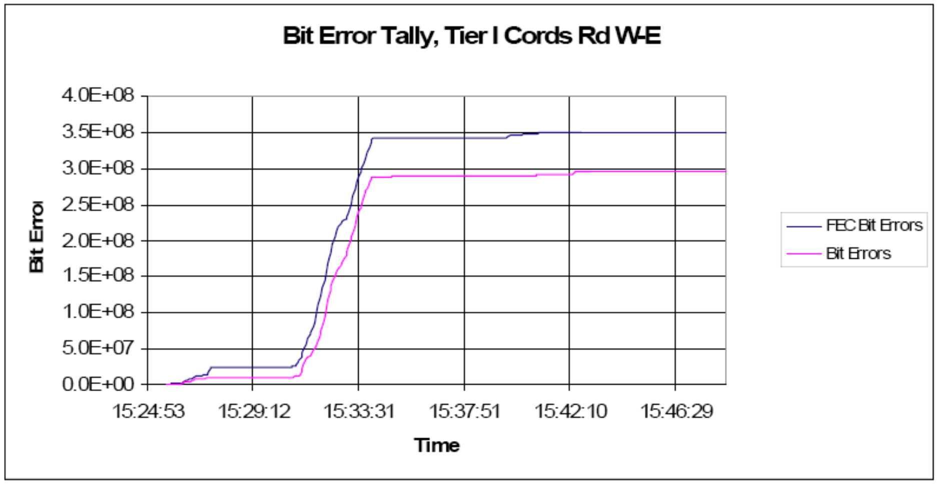
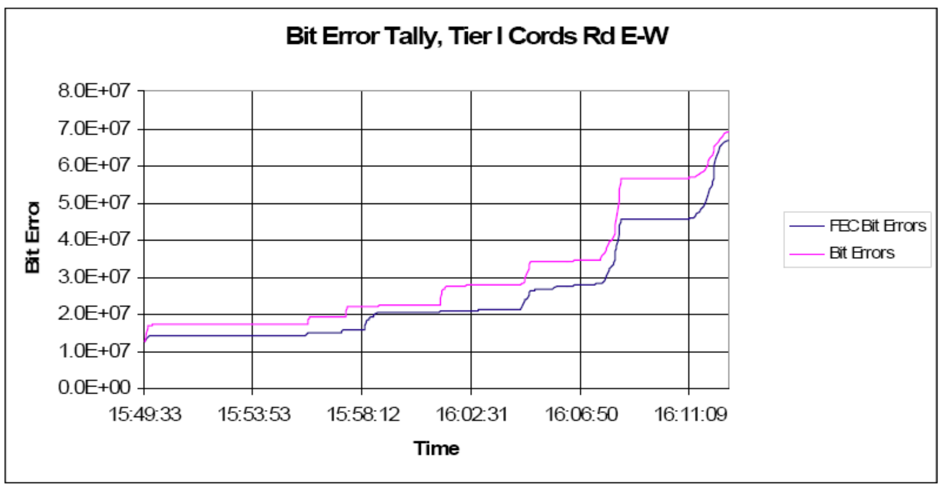


Figure 14 – Accumulated Bit Errors, Cords Rd W-E



Does FEC help?

- FEC is certainly effective in the AWGN channel
  - Reduces number of errors
- FEC certainly increases the sync time of the receiving system
  - Increases number of errors
- Net effect depends on your channel
  - If your channel is always in sync but has isolated one-at-a-time bit errors, FEC helps
  - If your link has dropouts (due to multipath, shadowing, interference, etc.), FEC may do more harm than good

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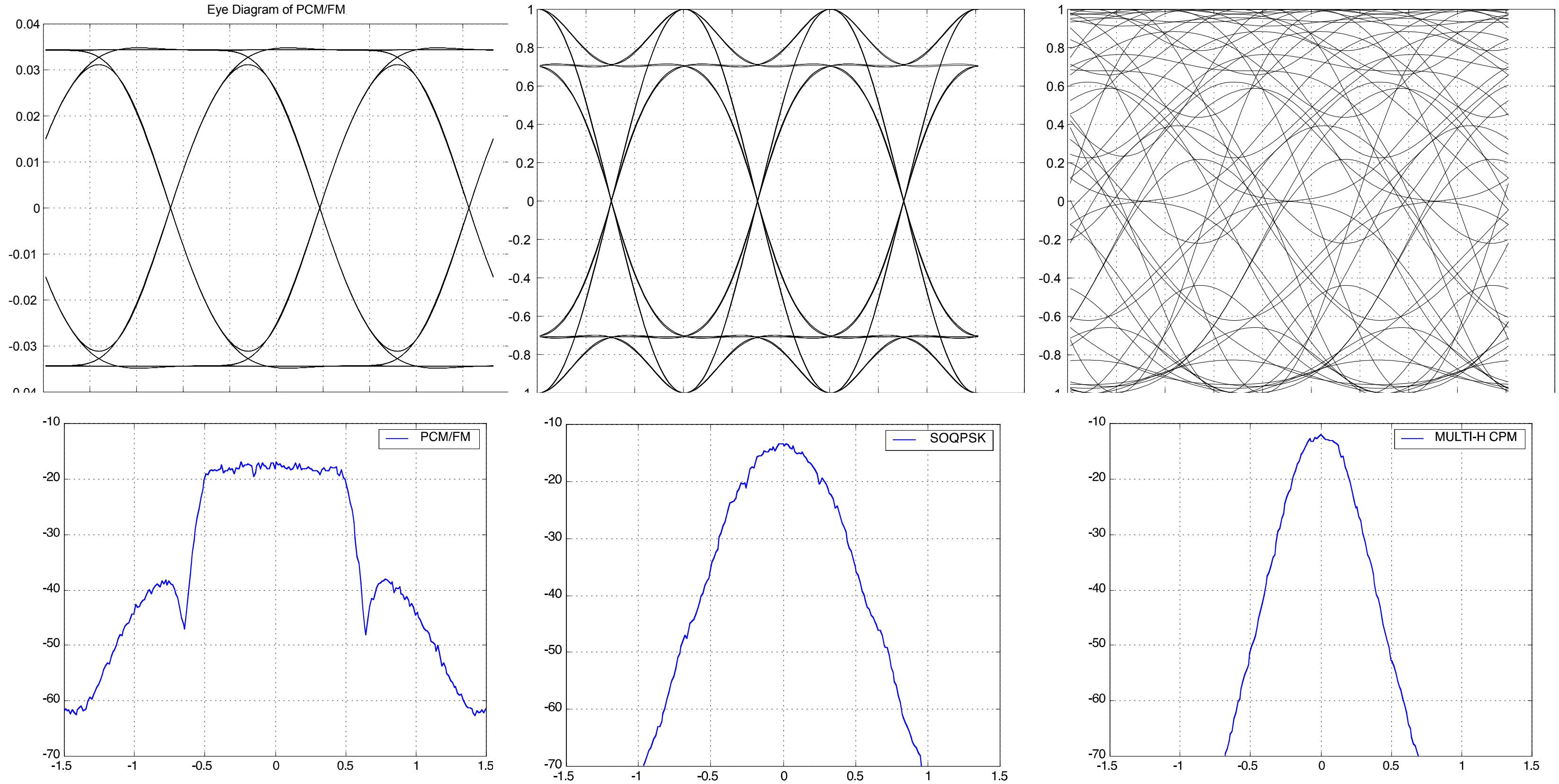
Waveform Comparison

PCM/FM (1x) SOQPSK (2x) Multi-h CPM (2.5x)



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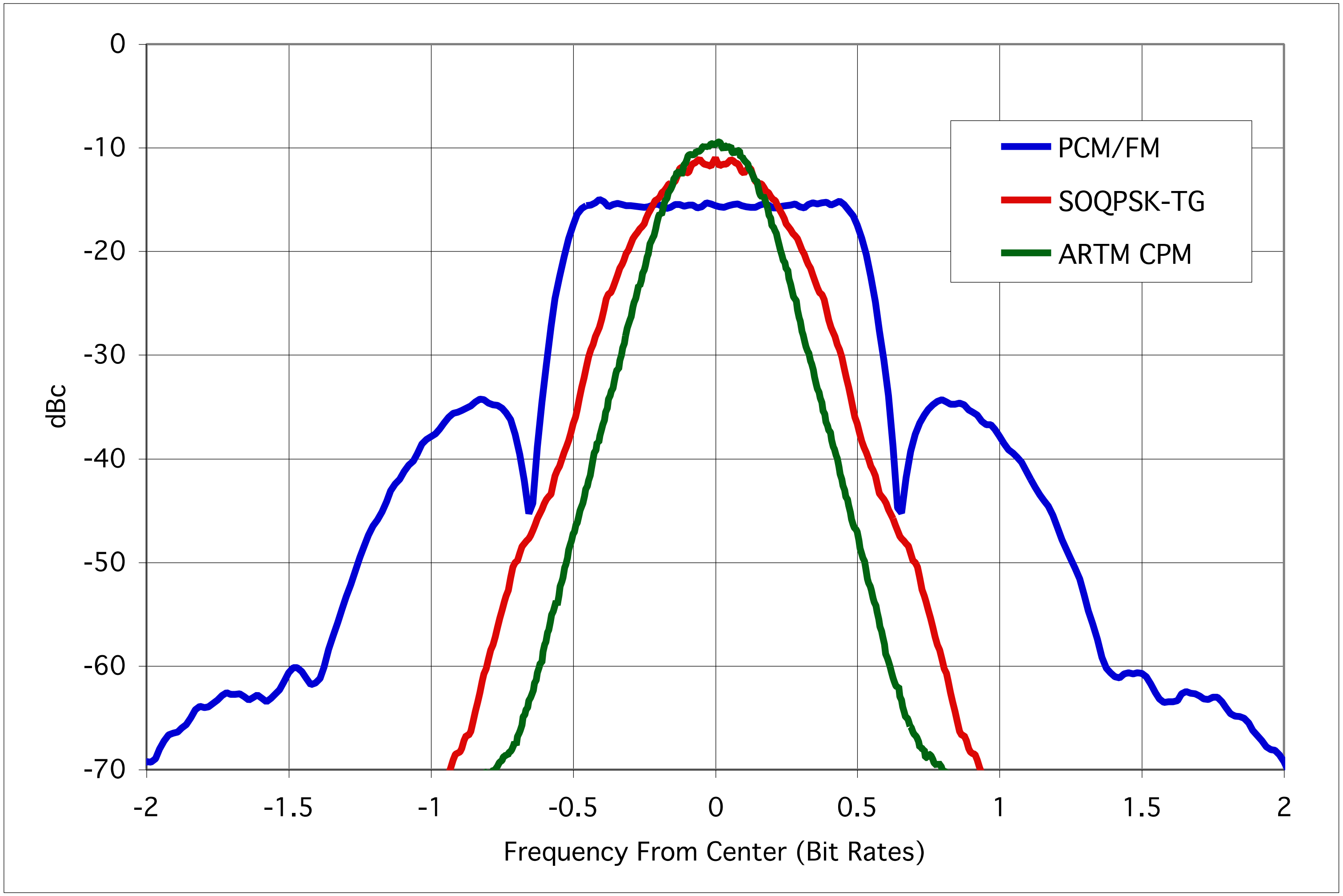
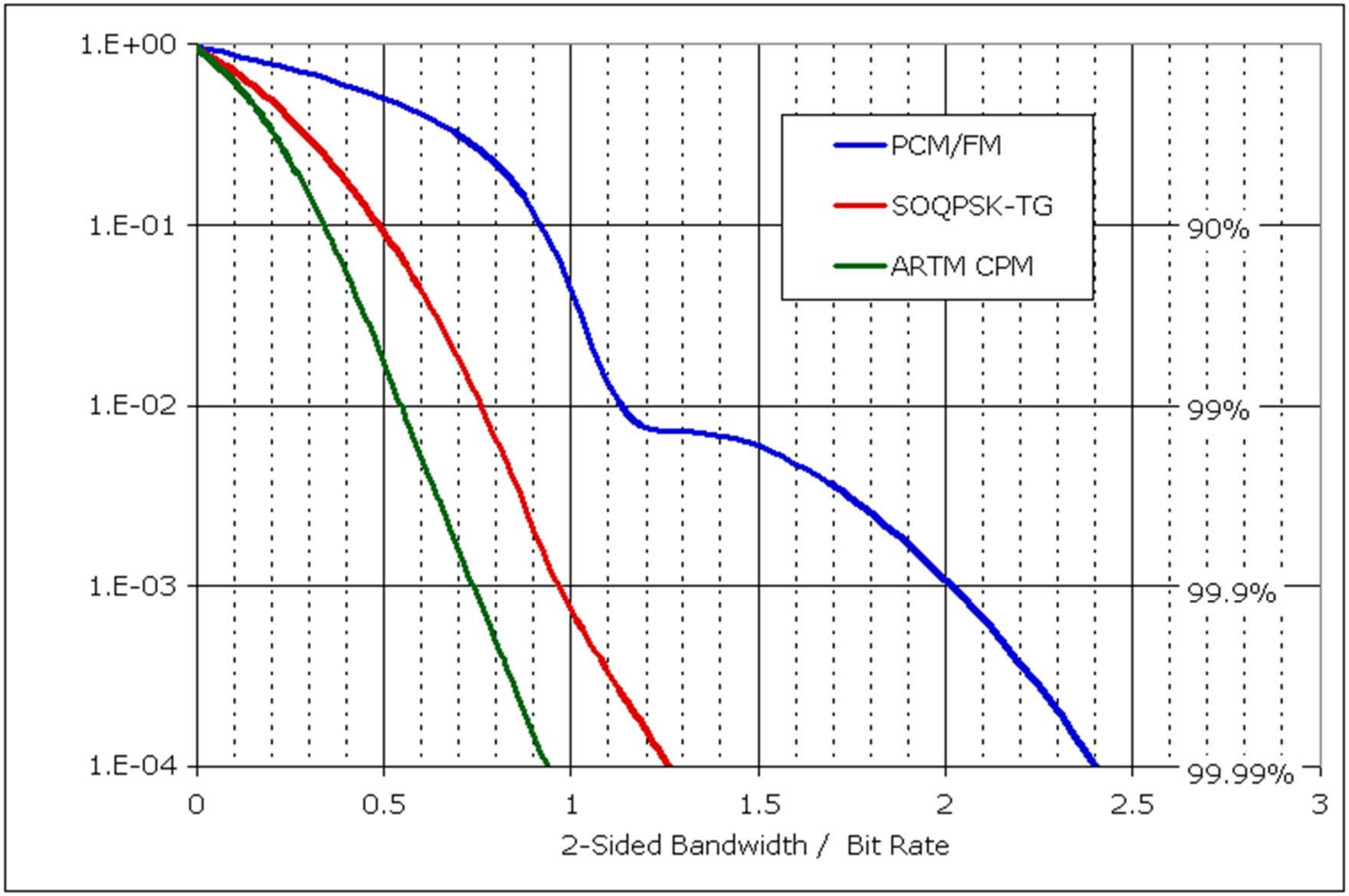
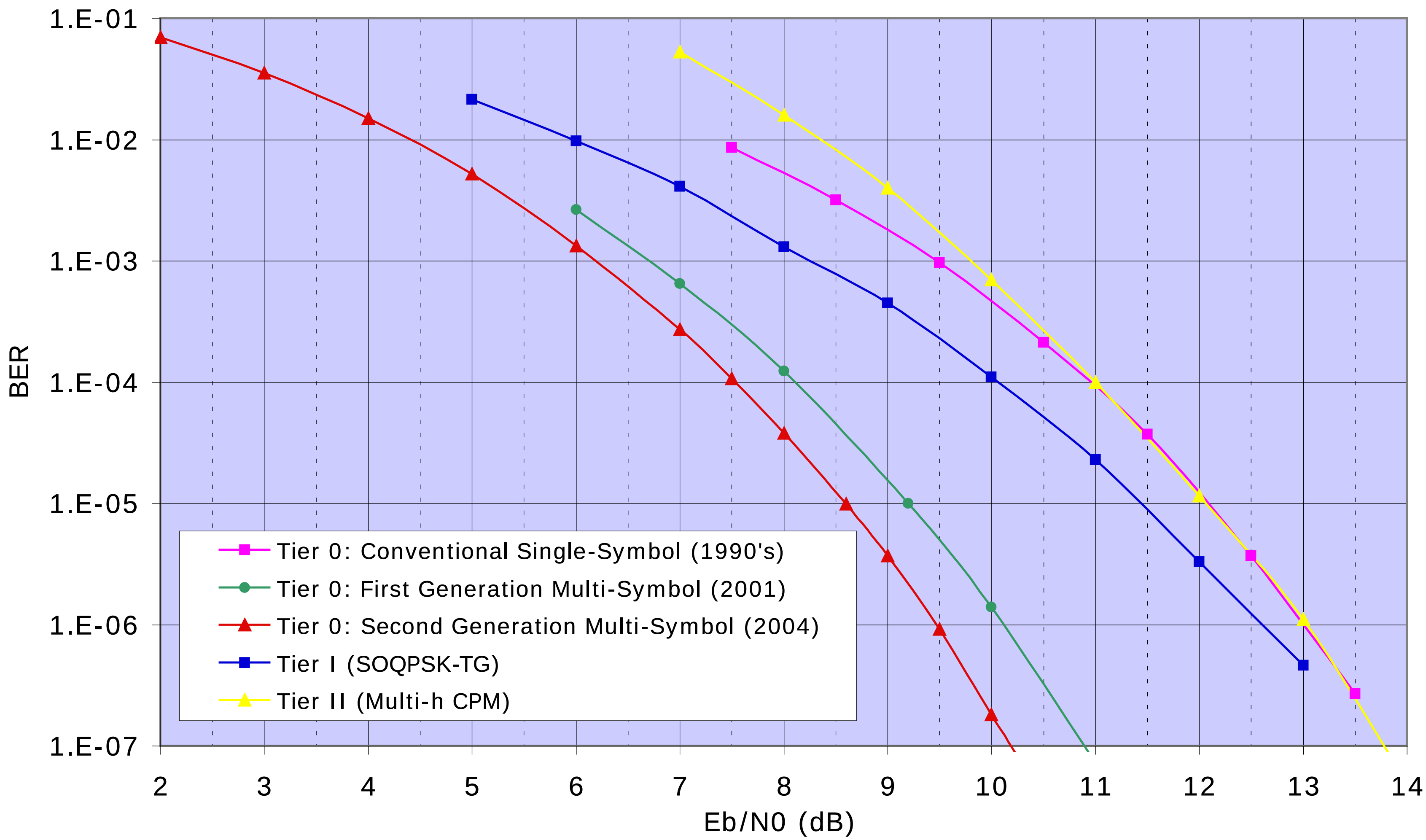
Power Spectral Densities



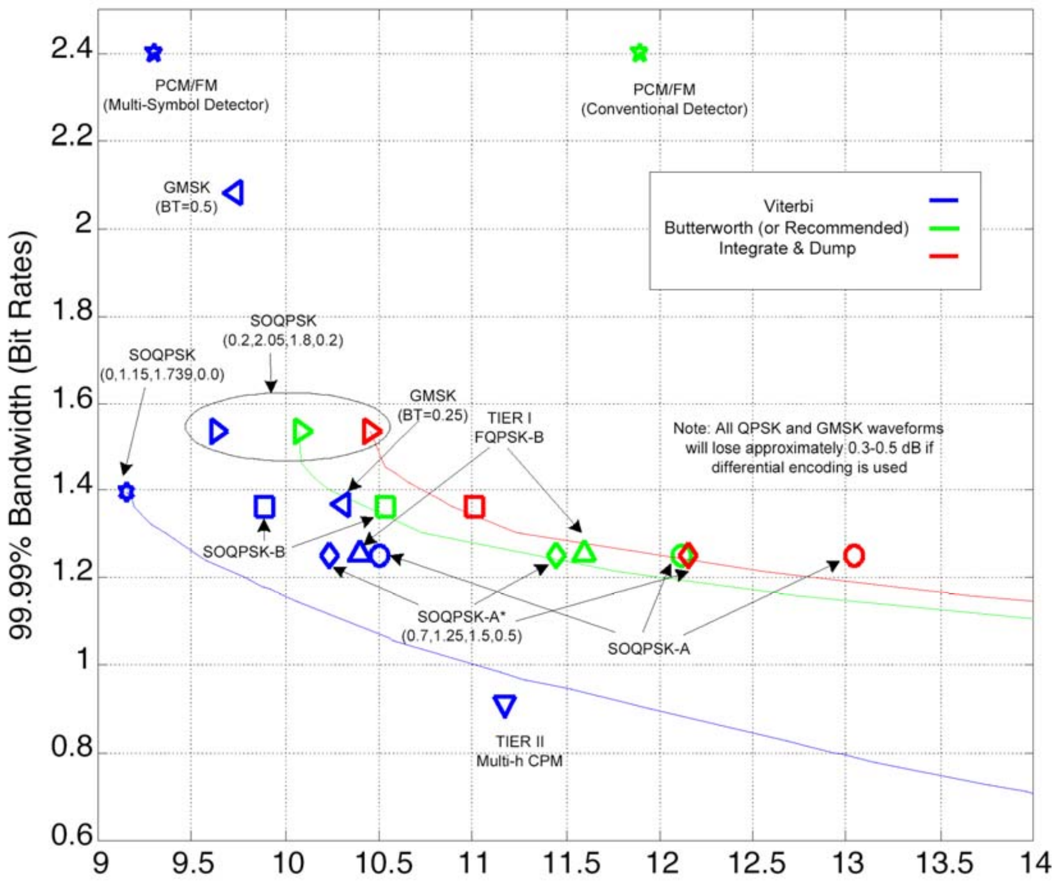
Out-of-Band Power



BER Performance Comparison



Bandwidth-Power Plane



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- Dr. Bernard Sklar
- Kip Temple, ARTM, Edwards AFB
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- Vickie Reynolds, White Sands Missile Range

Questions/Comments