Performance Of SOQPSK And Multi-h CPM In The Presence Of Adjacent Channel Interference

Terrance J. Hill
Nova Engineering, Inc.,
Cincinnati, OH

Outline

- Waveform definitions (briefly!)
- Spectral characterizations of telemetry waveforms
- Effects of IF filtering on link performance
- Aggregate effect of adjacent channel interference

Why These Waveforms?

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

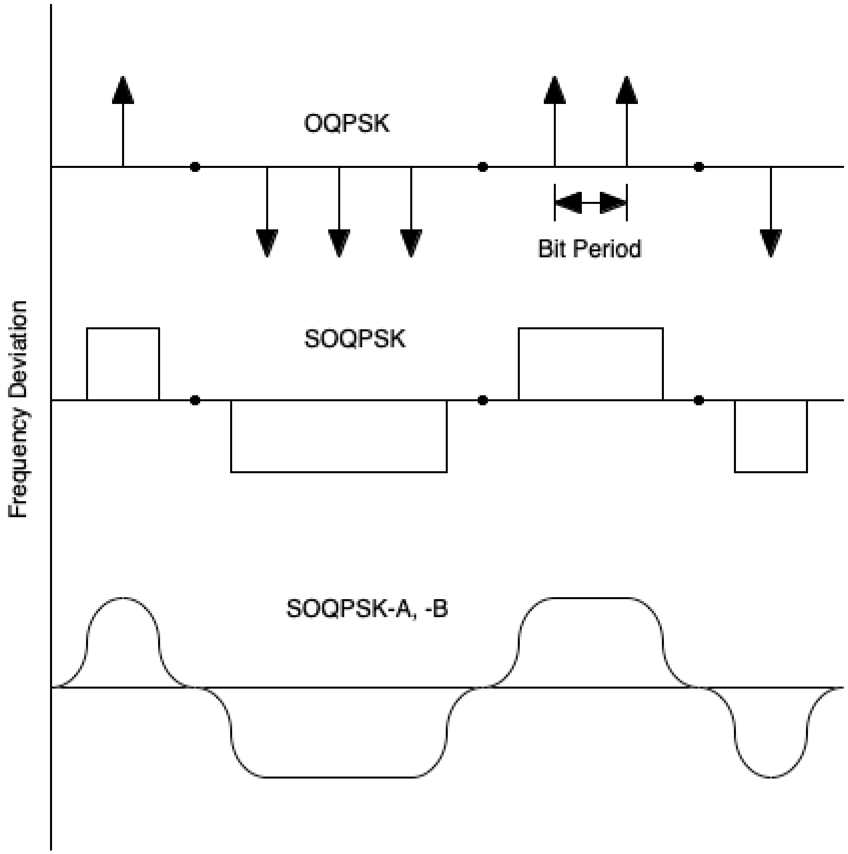
CPM Waveforms

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

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

- Constant envelope, information is carried entirely in the phase
- PSD and BER can be "traded" by
  - Varying h, modulation index
  - Changing g(t), the frequency pulse shape
- FQPSK-B (Revision A1) is not truly a CPM waveform because of its AM component

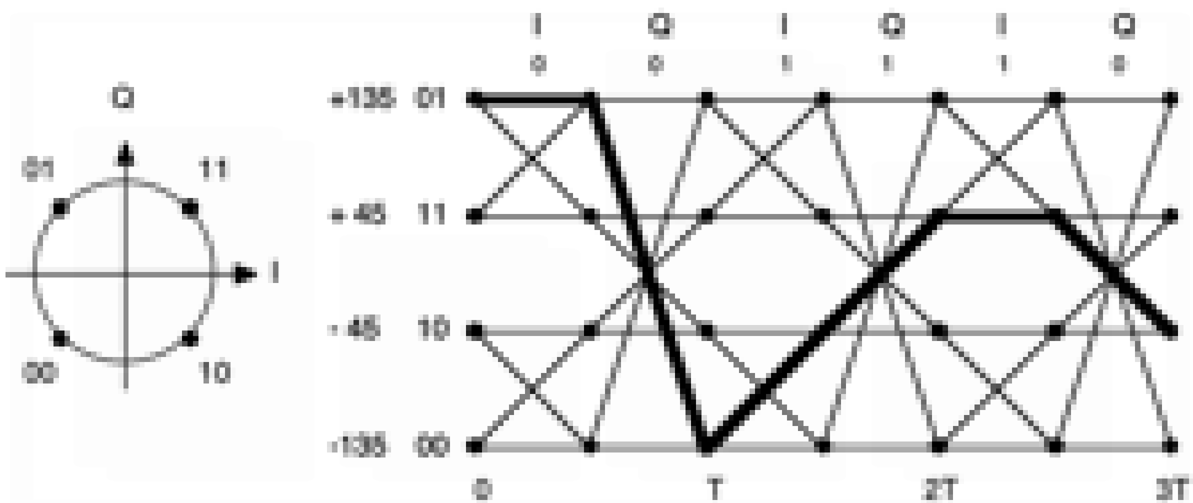
Offset QPSK Variations



- Unshaped
- Rectangular
  - MIL-STD-188-18x
- “Shaped”
  - Arbitrary g(t)

SOQPSK

- MIL-STD-188-181, -182
- Continuous phase modulation, h = 1/4, g(t) = rectangle
- Constant envelope
- Three rates of phase change: 0, $+\Delta f$, $-\Delta f$



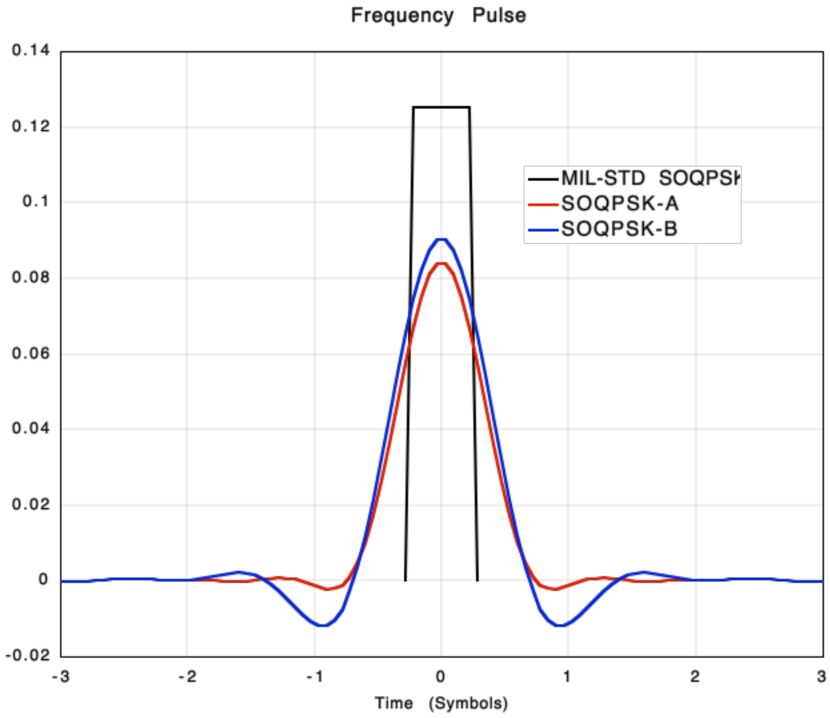
Definition of SOQPSK-A, -B

$g(t) = r(t) * w(t)$, where

$$r(t) = \frac{A\cos(\pi\rho B t/T)}{1 - 4(\rho B t/T)^2} \cdot \frac{\sin(\pi B t/T)}{(\pi B t/T)}$$

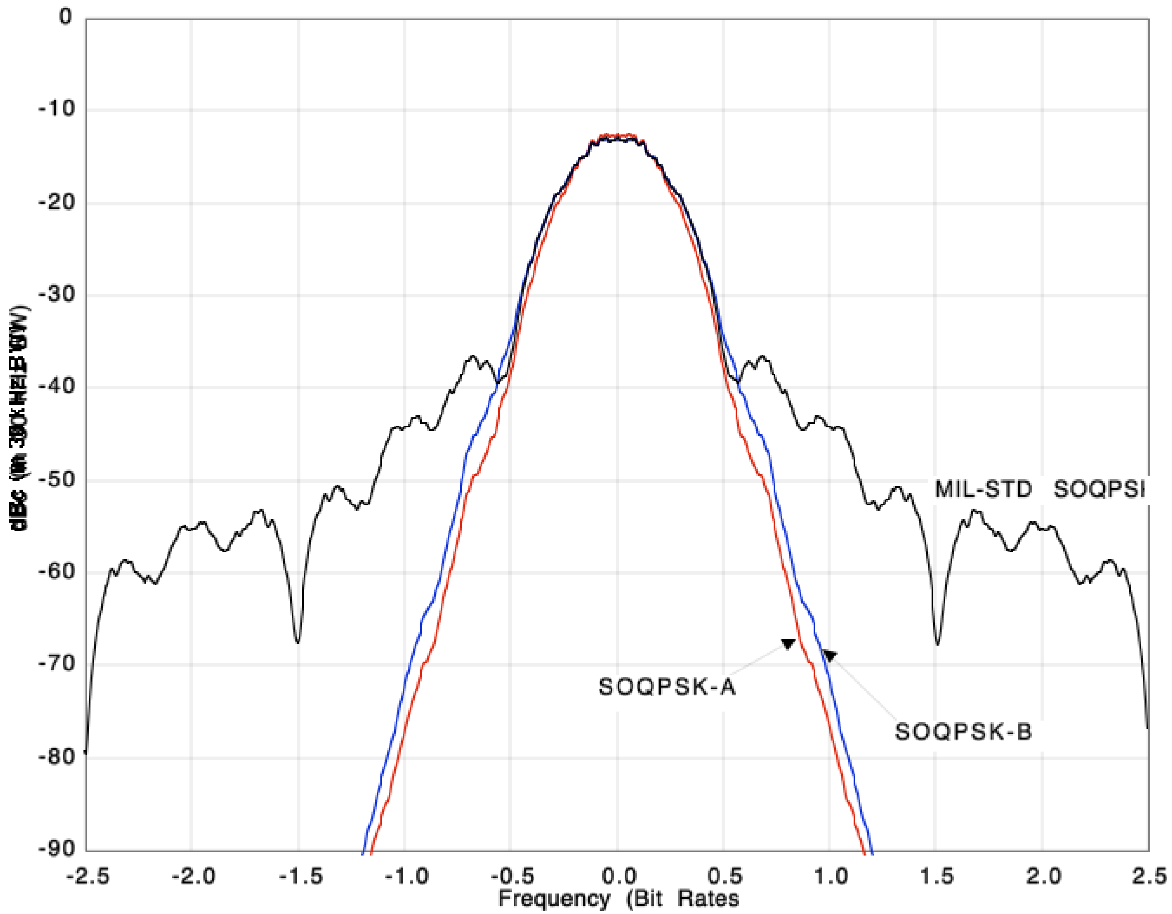
$$w(t) = \begin{cases} 1, & \text{for } |t/T| < T_1 \\ \frac{1}{2} + \frac{1}{2}\cos\frac{\pi(|t/T| - T_1)}{T_2}, & \text{for } T_1 < |t/T| < T_1 + T_2 \\ 0, & \text{for } |t/T| > T_1 + T_2 \end{cases}$$

Frequency Pulse Shape, g(t)

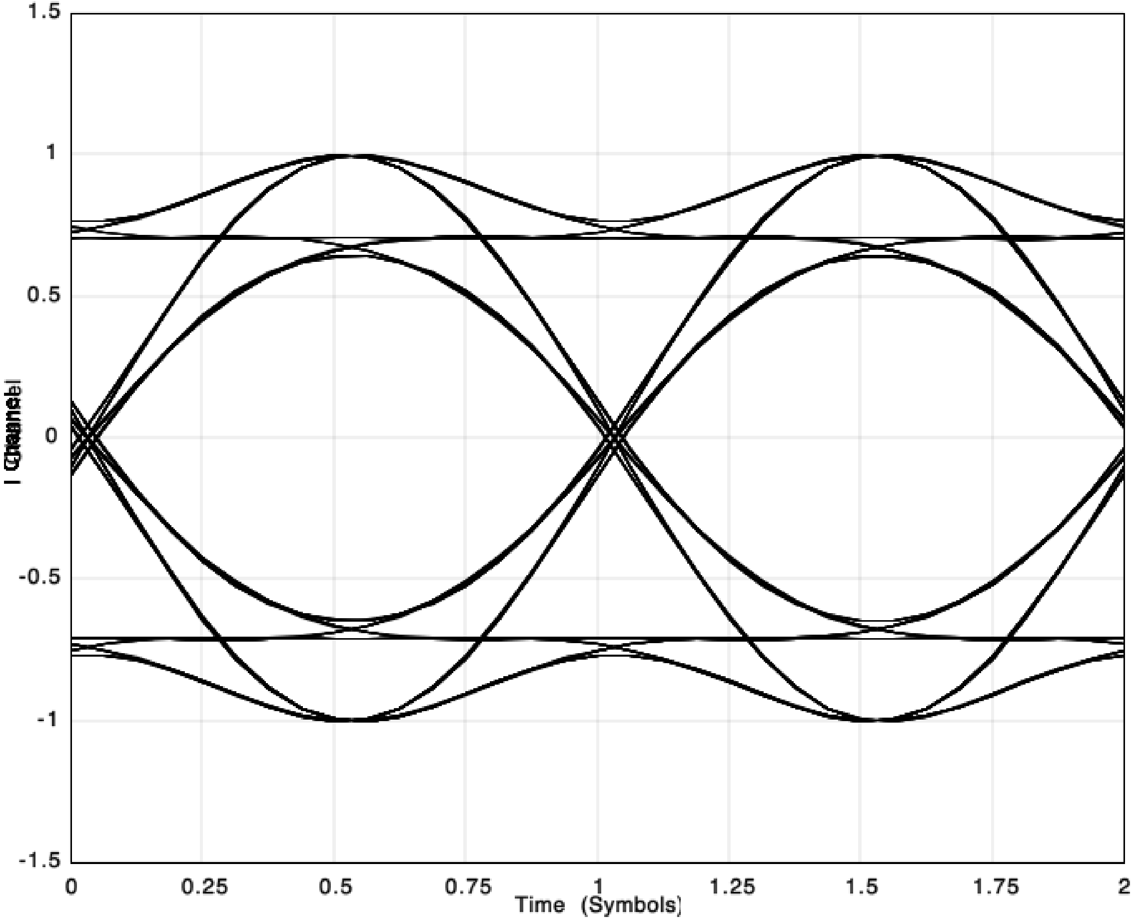


Parameter	SOQPSK-A	SOQPSK-B
ρ	1.0	0.5
B	1.35	1.45
T_1	1.4	2.8
T_2	0.6	1.2

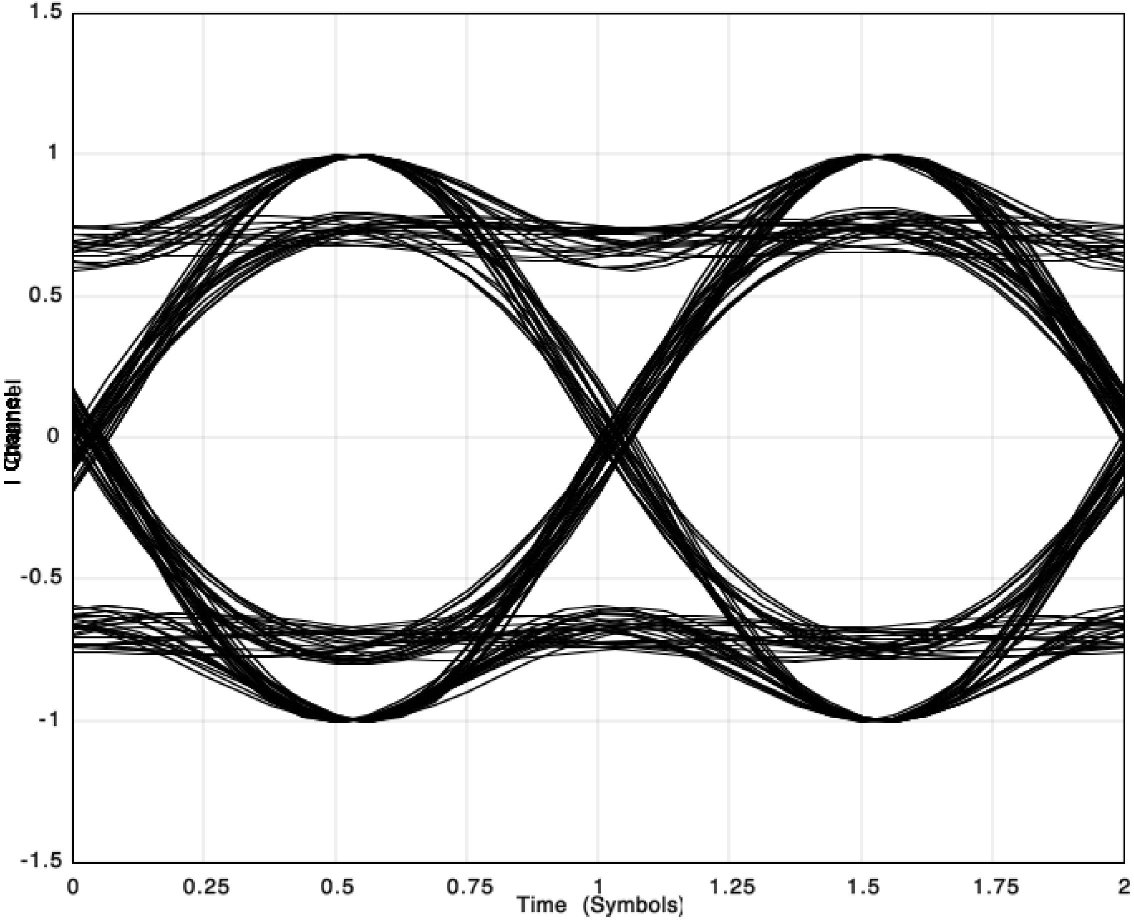
Power Spectral Density



SOQPSK-A Eye Pattern



SOQPSK-B Eye Pattern



Definition of Multi-h CPM

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

Modulating Phase using Frequency Pulses

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

Modulating Phase using Phase Pulses

$$q(t) = \int_{-\infty}^{t} g(\tau)d\tau$$

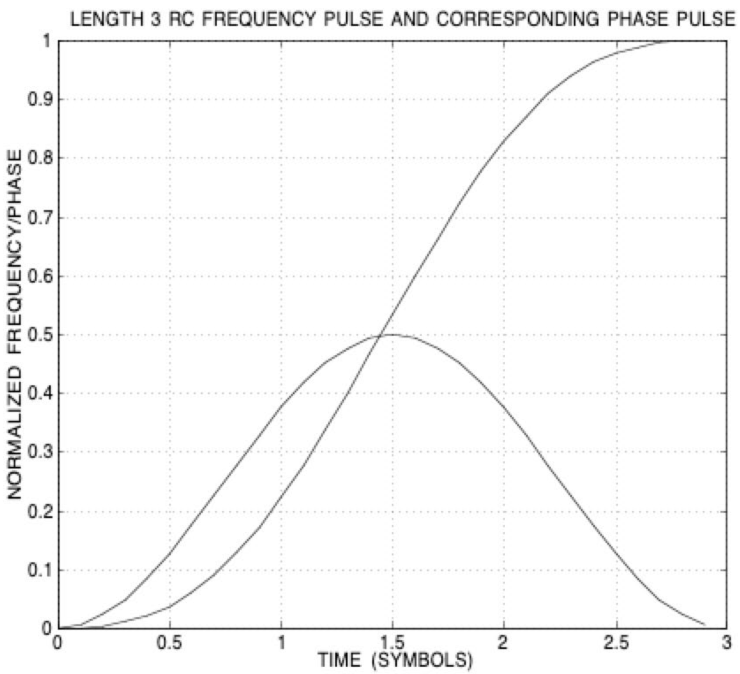
$$\phi(t,\overline{\alpha}) = 2\pi h \sum_{i=-\infty}^{+\infty} \alpha_i q(\tau - iT)$$

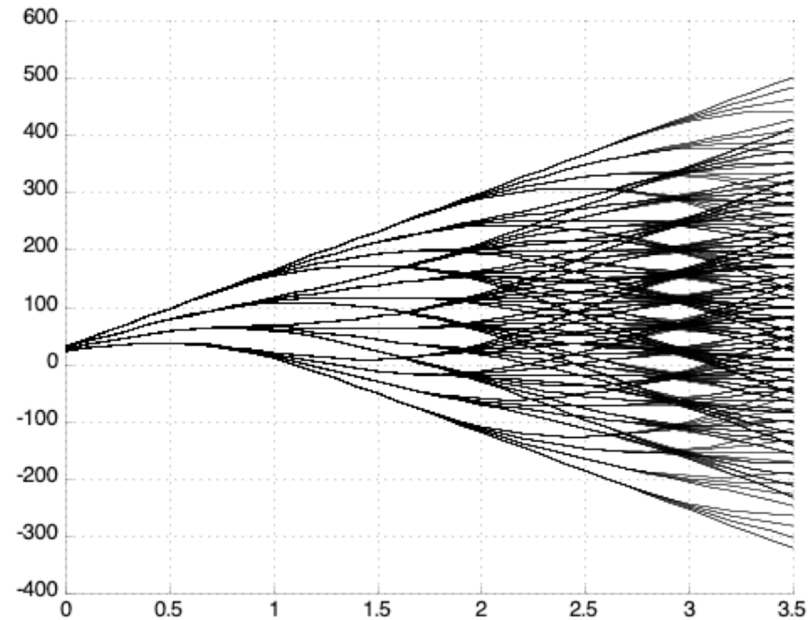
Key CPM Parameters

- 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

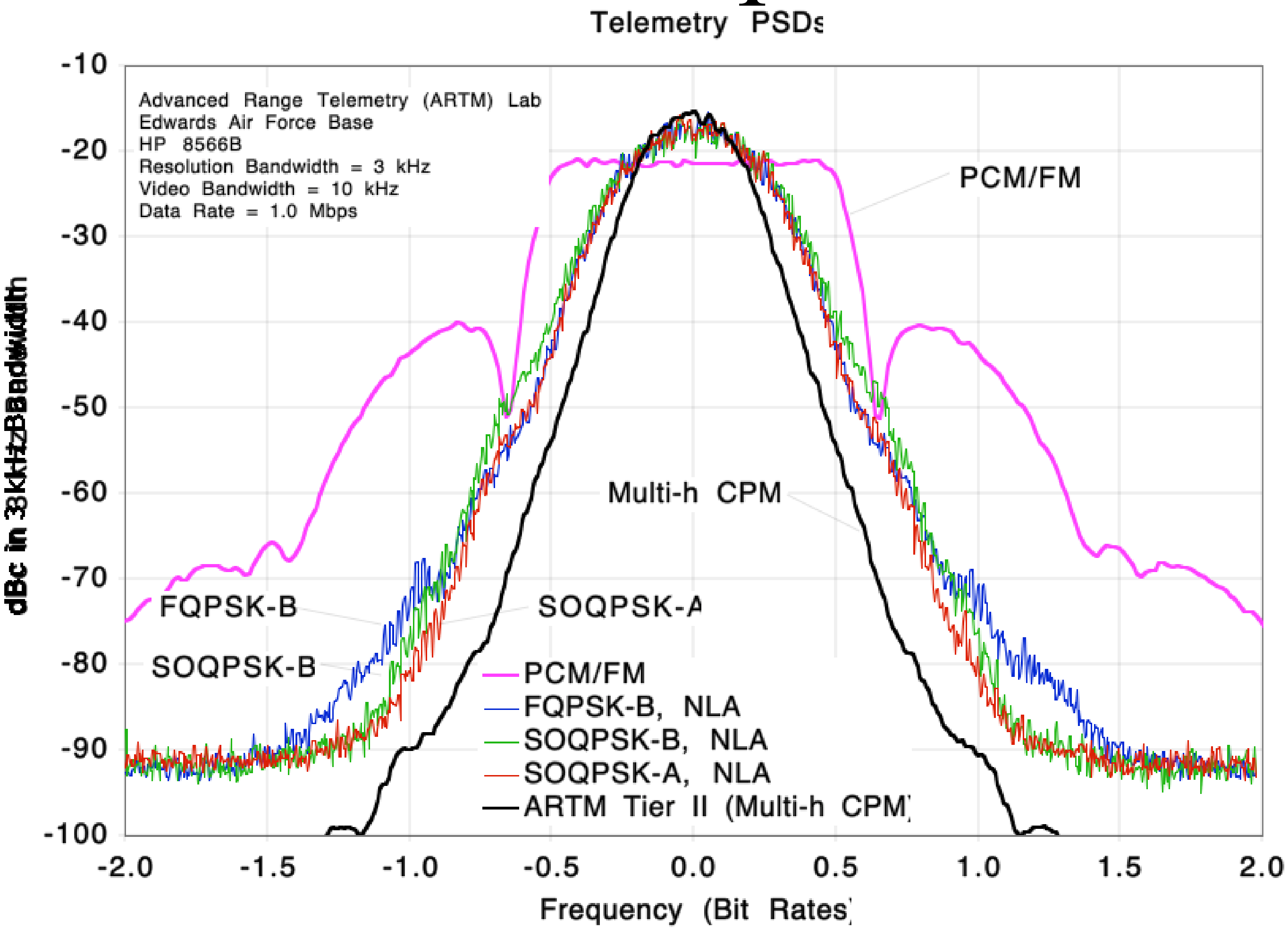
- **Results here are for M=4, L=3RC, h1 = 4/16, h2 = 5/16**

Frequency Pulse and Phase Tree



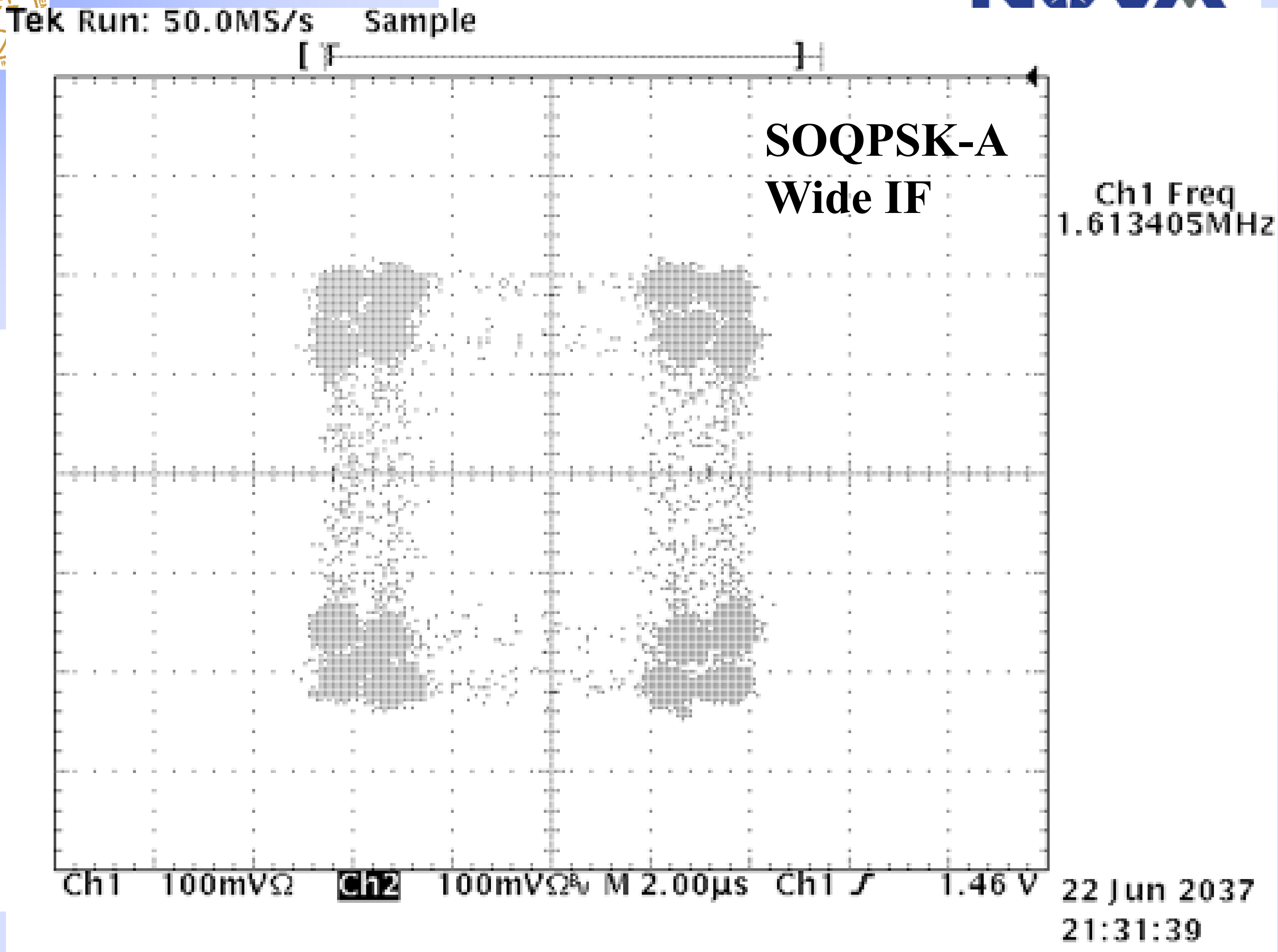


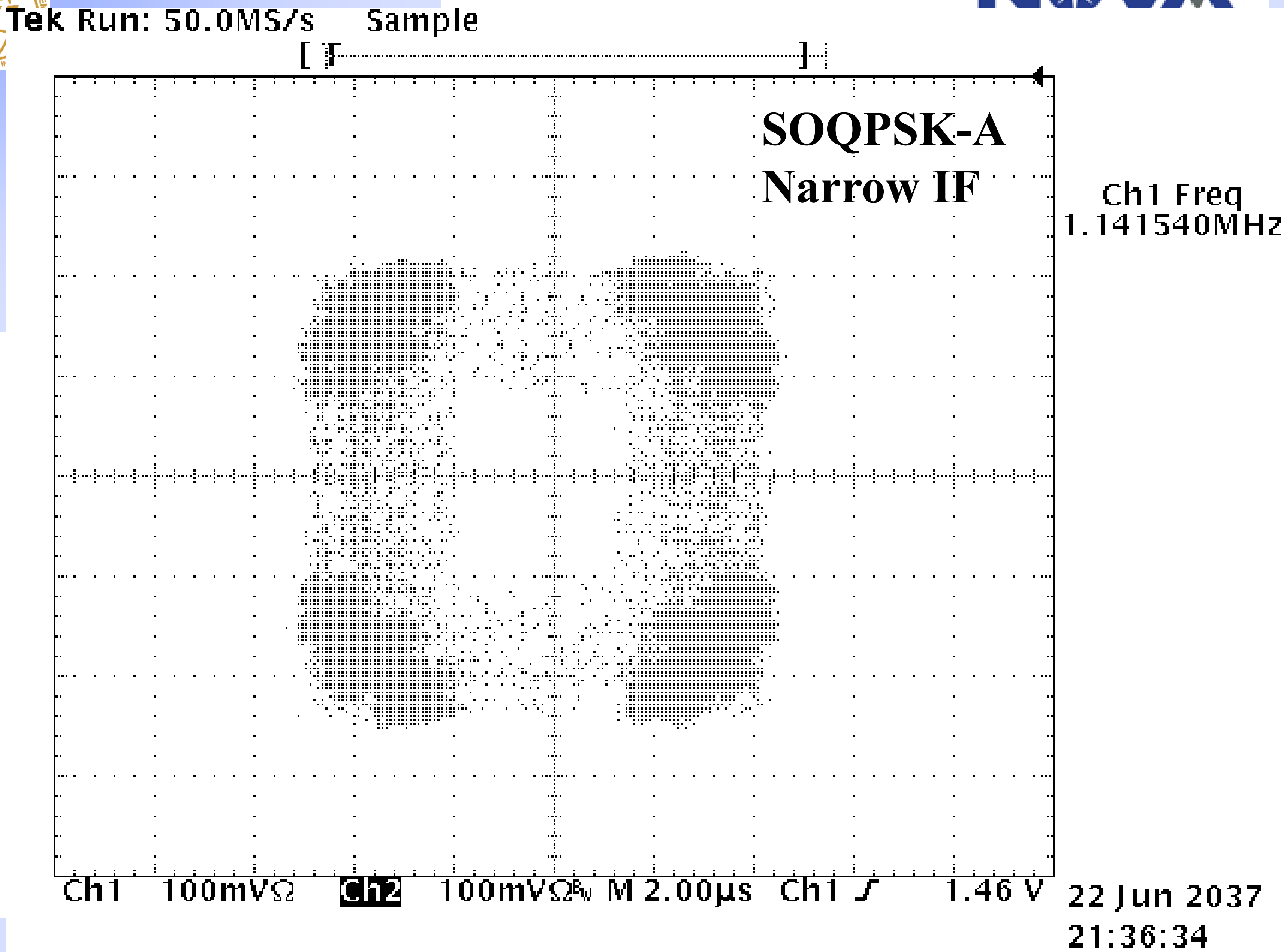
PSD Comparison

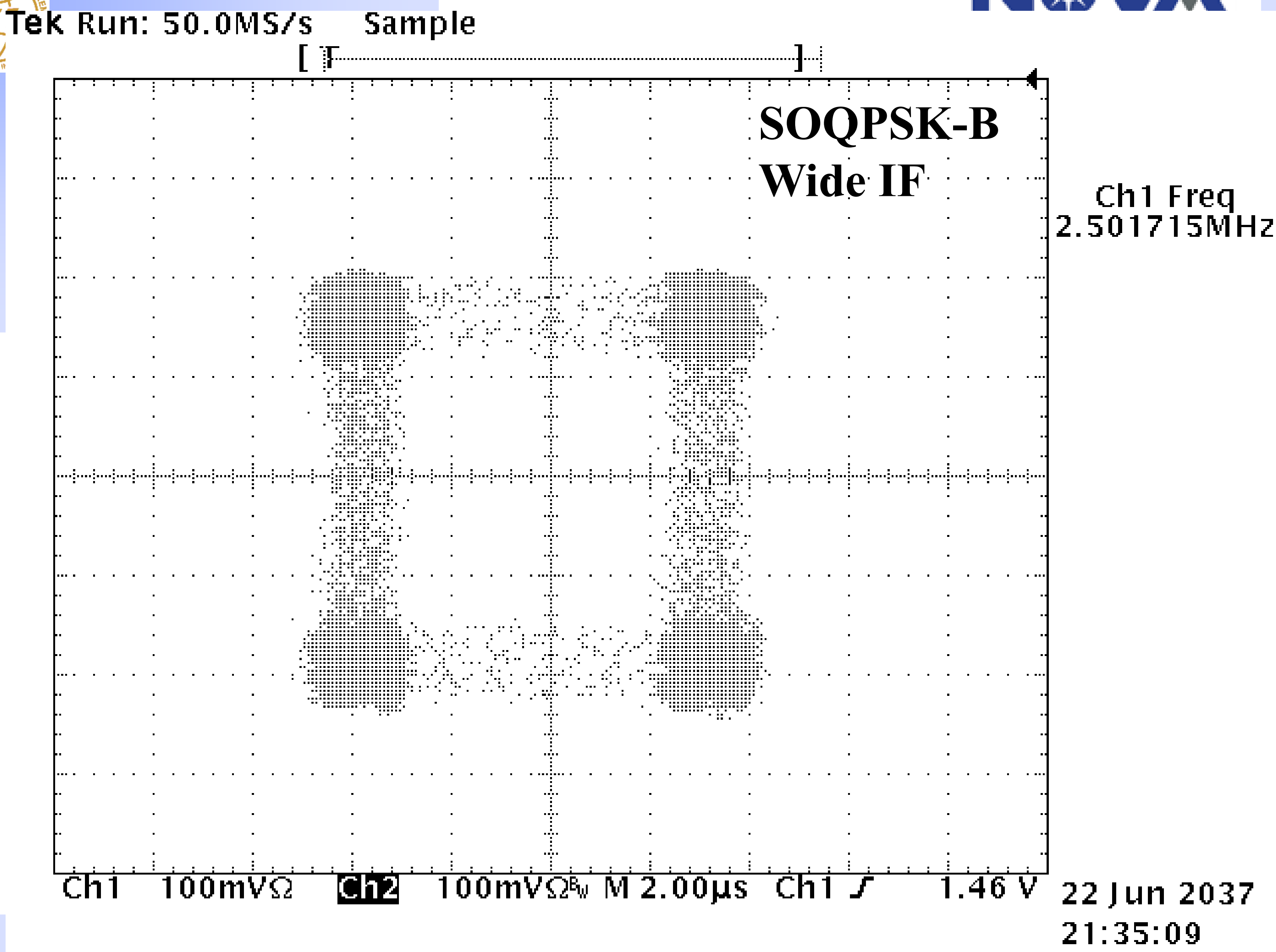


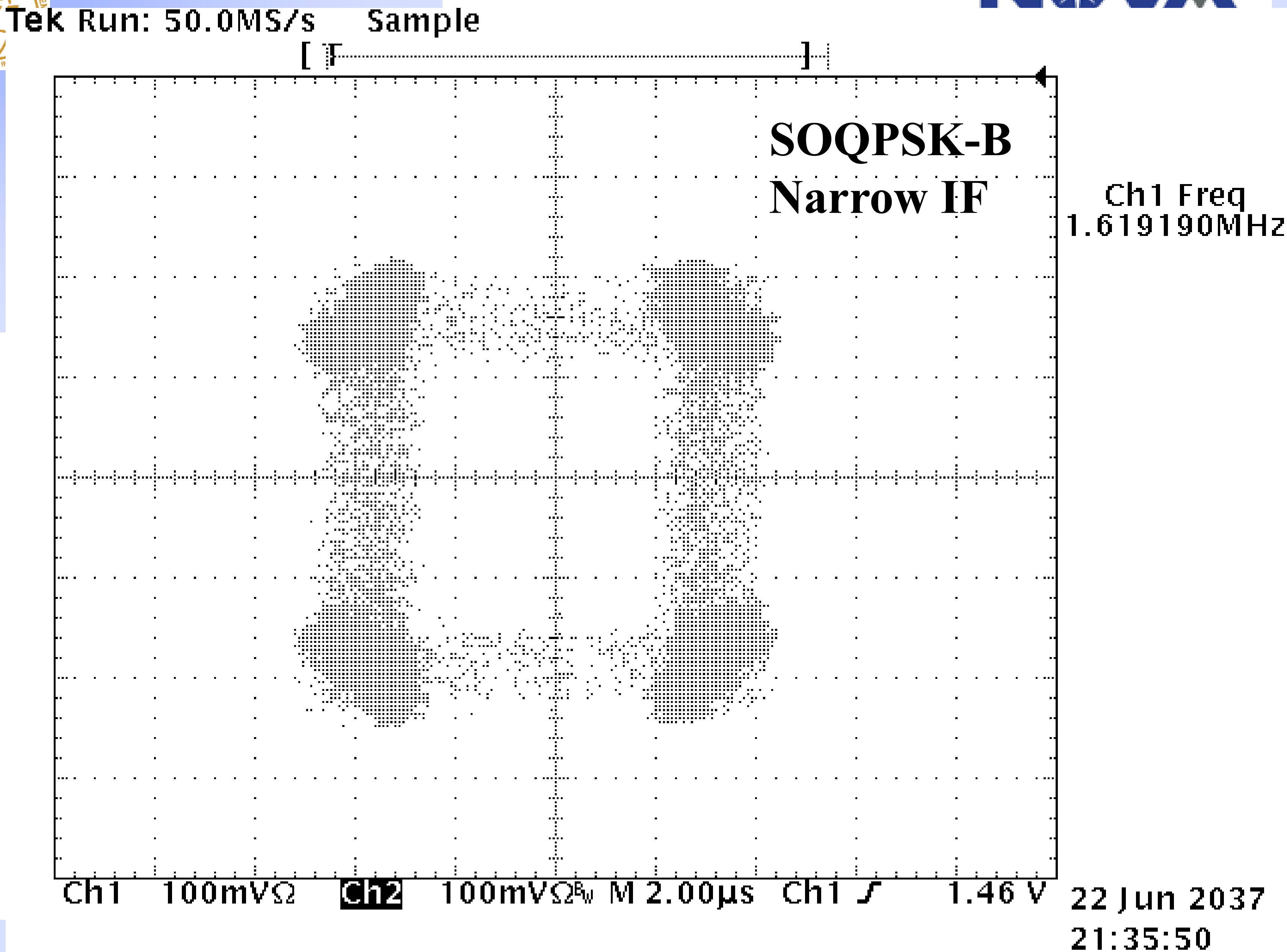
PSD is Half the Story

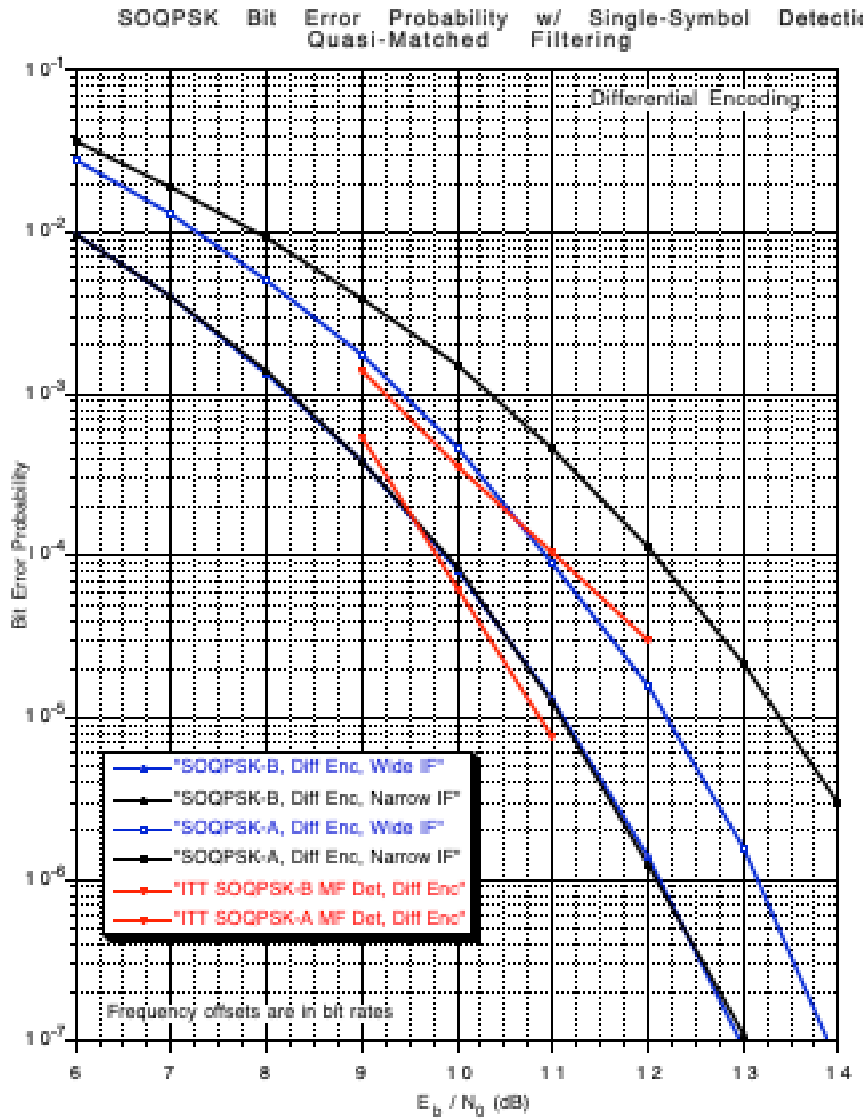
- Overall spectral efficiency is determined by spacing between channels
- Receiver selectivity affects channel spacing
- A valid comparison must account for both transmitted spectrum and “tolerable” receiver filtering
- Not all modulations are equally “tolerant” of IF filtering


Tek Run: 50.0MS/s Sample
SOQPSK-A
Wide IF
Ch1 Freq
1.613405MHz
Ch1 100mVΩ Ch2 100mVΩ M 2.00µs Ch1 ƒ 1.46 V
22 Jun 2037
21:31:39

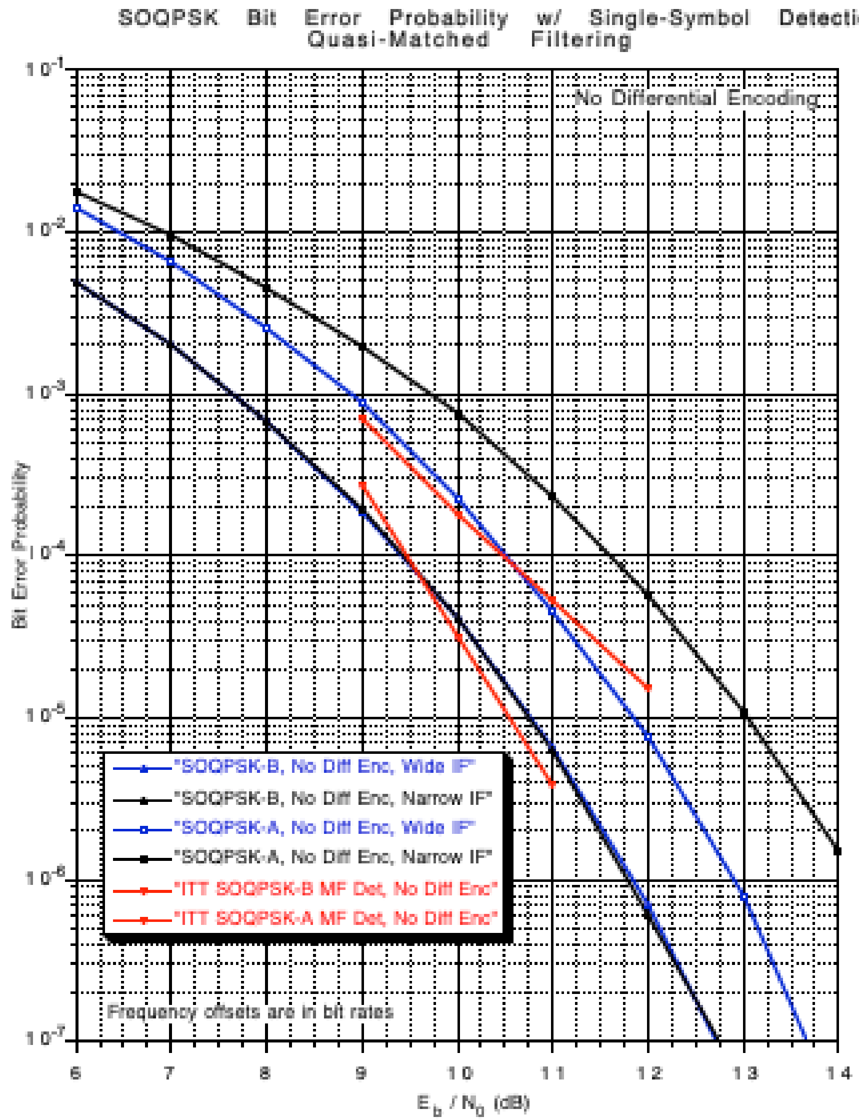

Tek Run: 50.0MS/s Sample
SOQPSK-A
Narrow IF
Ch1 Freq
1.141540MHz
Ch1 100mVΩ Ch2 100mVΩ M 2.00µs Ch1 ƒ 1.46 V
22 Jun 2037
21:36:34


Tek Run: 50.0MS/s Sample
SOQPSK-B
Wide IF
Ch1 Freq
2.501715MHz
Ch1 100mVΩ
Ch2 100mVΩ
M 2.00µs Ch1
1.46 V
22 Jun 2037
21:35:09

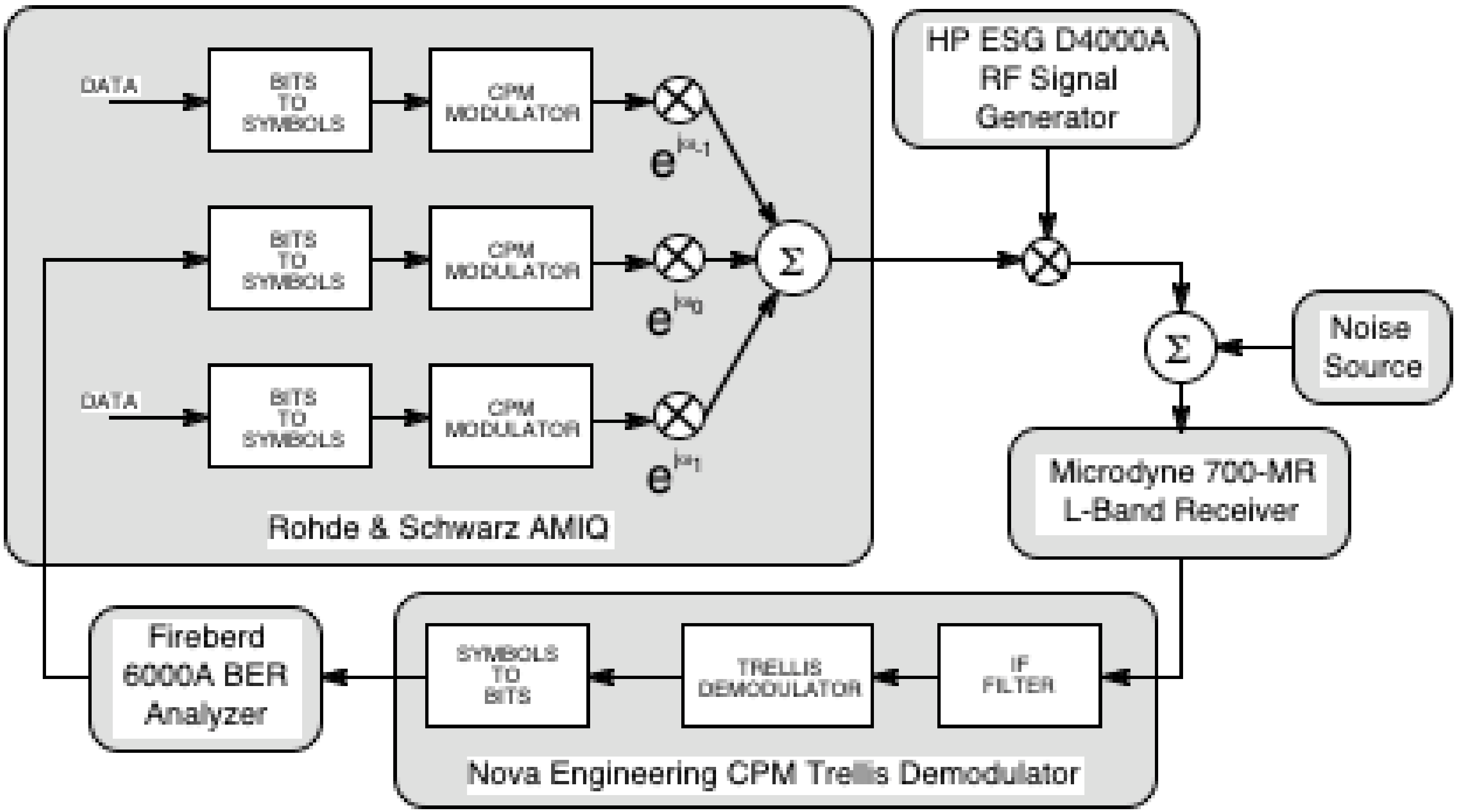

Tek Run: 50.0MS/s Sample
SOQPSK-B
Narrow IF
Ch1 Freq
1.619190MHz
Ch1 100mVΩ
Ch2 100mVΩ
M 2.00µs
Ch1 1.46 V
22 Jun 2037
21:35:50

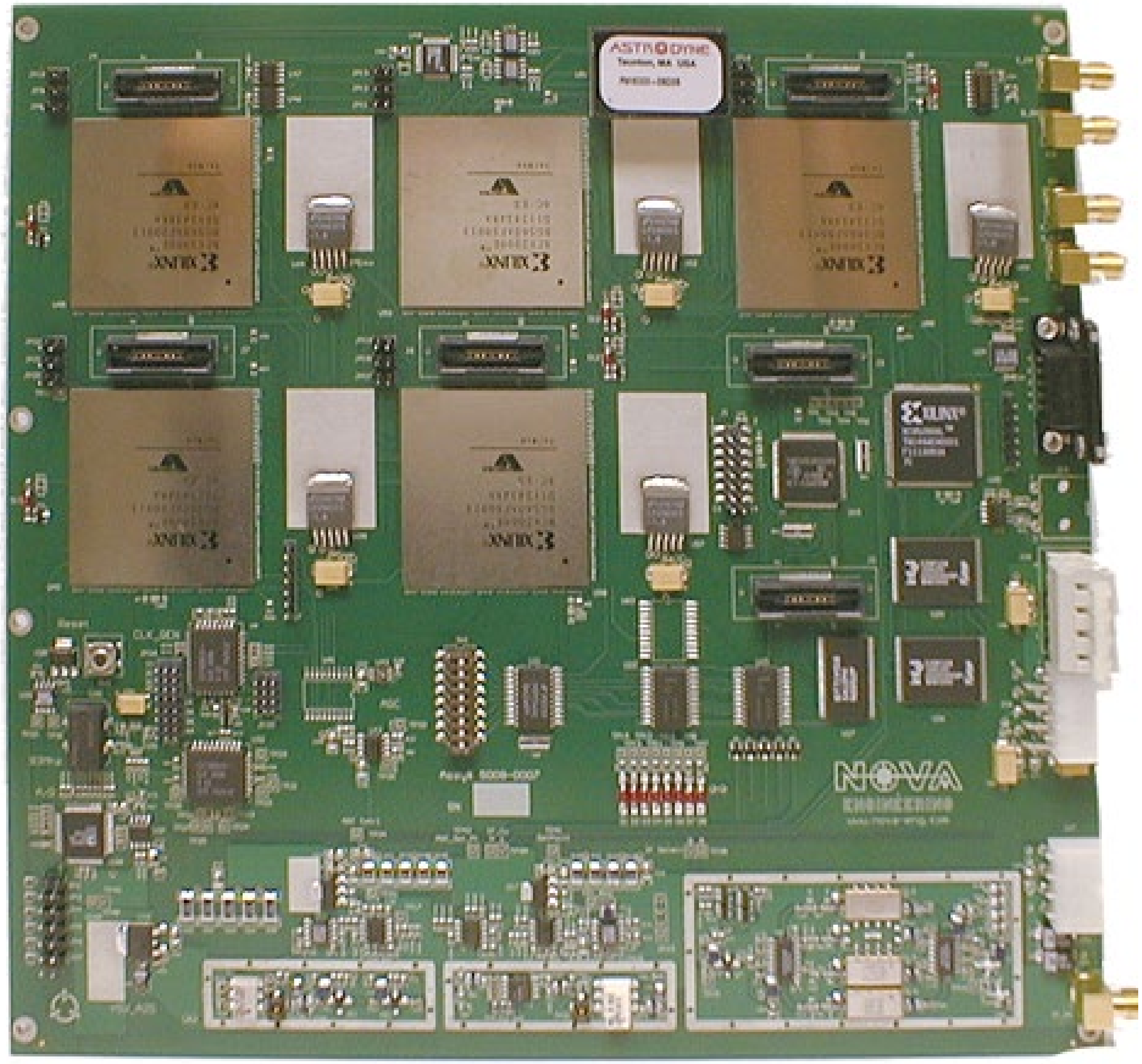


SOQPSK Bit Error Probability w/ Single-Symbol Detecti
Quasi-Matched Filtering
Differential Encoding
Bit Error Probability
"SOQPSK-B, Diff Enc, Wide IF"
"SOQPSK-B, Diff Enc, Narrow IF"
"SOQPSK-A, Diff Enc, Wide IF"
"SOQPSK-A, Diff Enc, Narrow IF"
"ITT SOQPSK-B MF Det, Diff Enc"
"ITT SOQPSK-A MF Det, Diff Enc"
Frequency offsets are in bit rates
E_b / N_0 (dB)

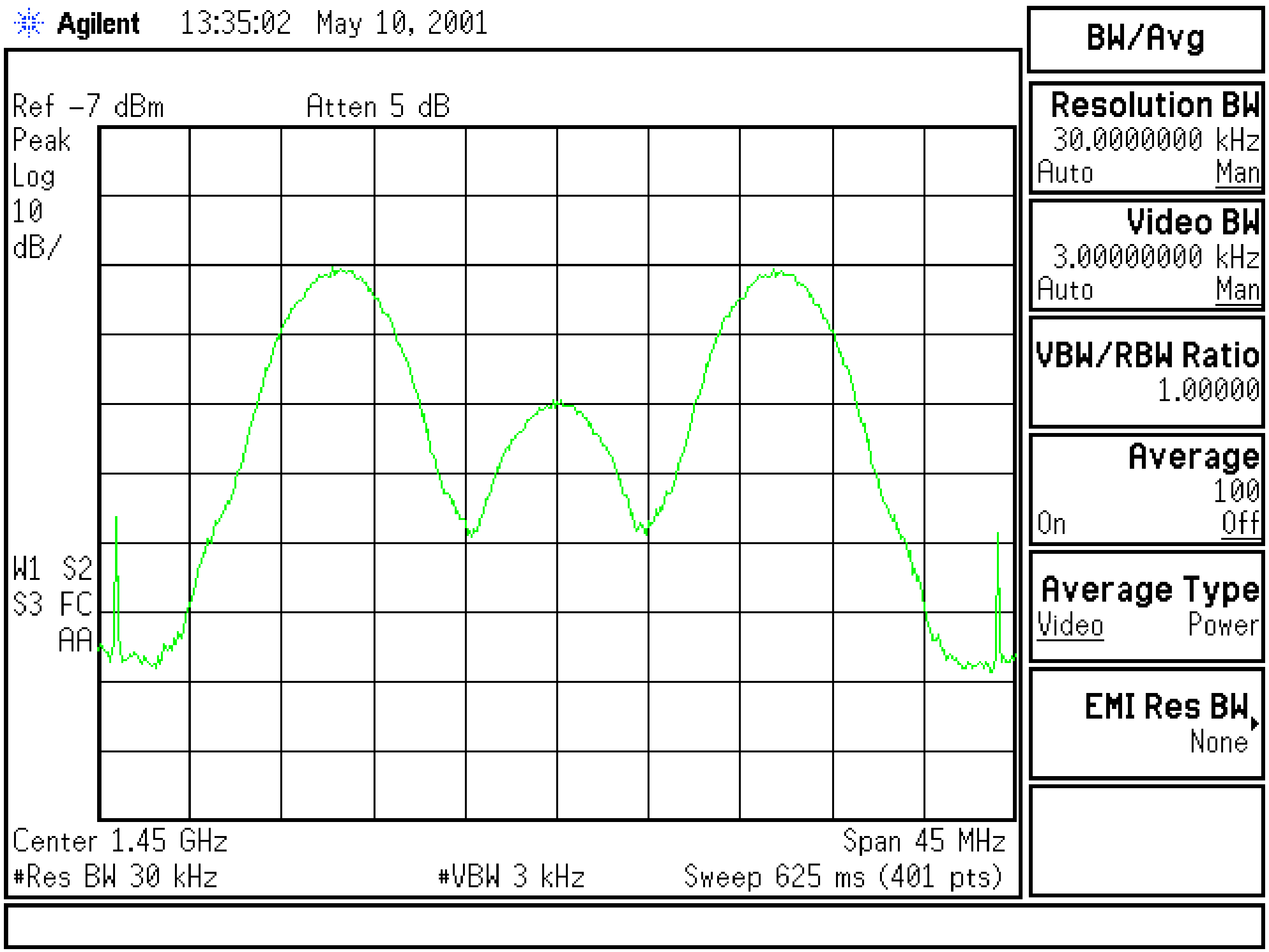

SOQPSK Bit Error Probability w/ Single-Symbol Detectic
Quasi-Matched Filtering
No Differential Encoding
Bit Error Probability
"SOQPSK-B, No Diff Enc, Wide IF"
"SOQPSK-B, No Diff Enc, Narrow IF"
"SOQPSK-A, No Diff Enc, Wide IF"
"SOQPSK-A, No Diff Enc, Narrow IF"
"ITT SOQPSK-B MF Det, No Diff Enc"
"ITT SOQPSK-A MF Det, No Diff Enc"
Frequency offsets are in bit rates
E_b / N_0 (dB)

Experimental Setup

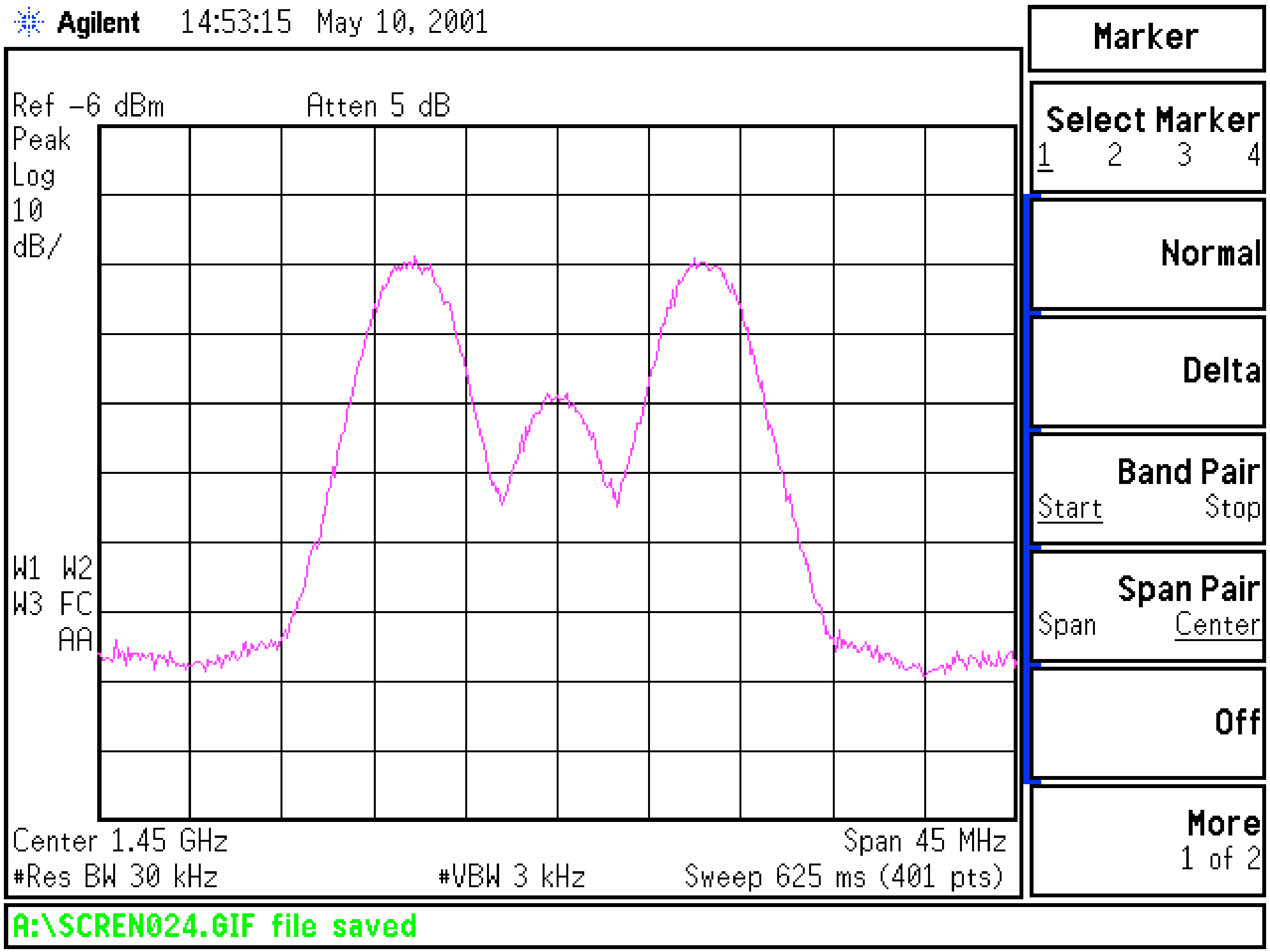


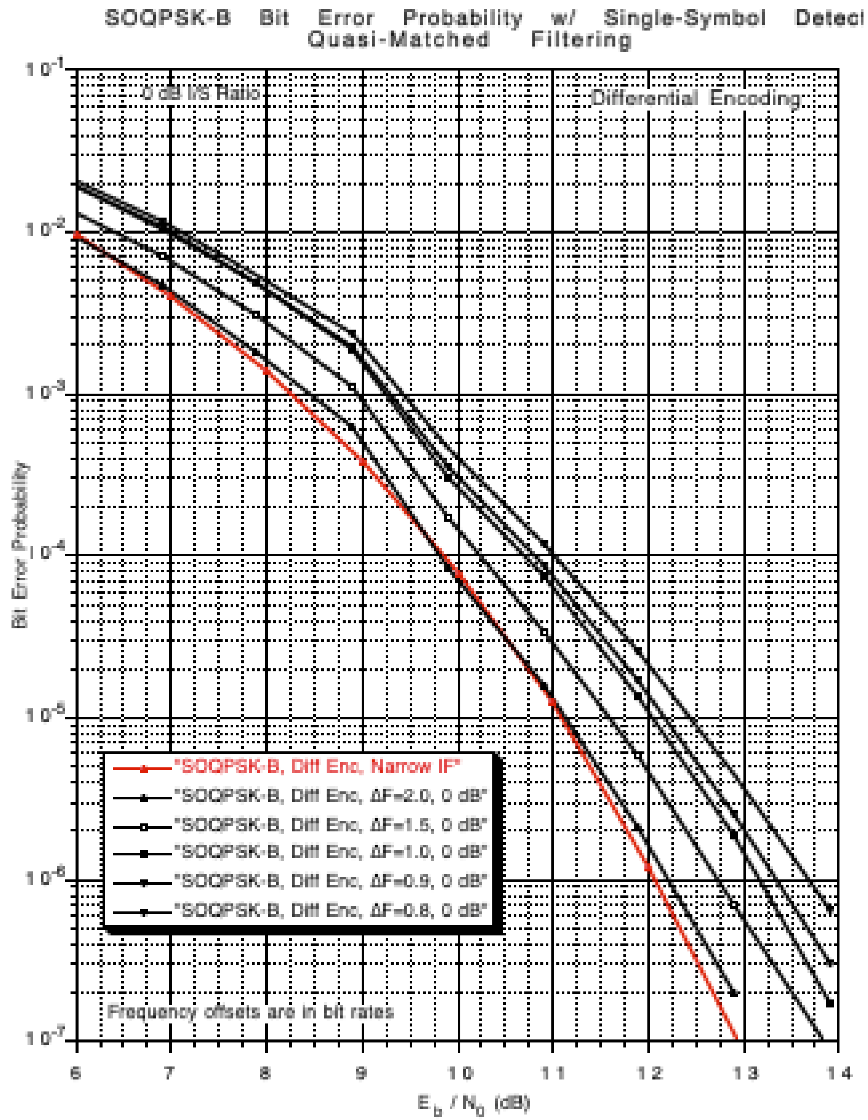

ASTRODYNE
XILINX
NOVA
ENGINEERING

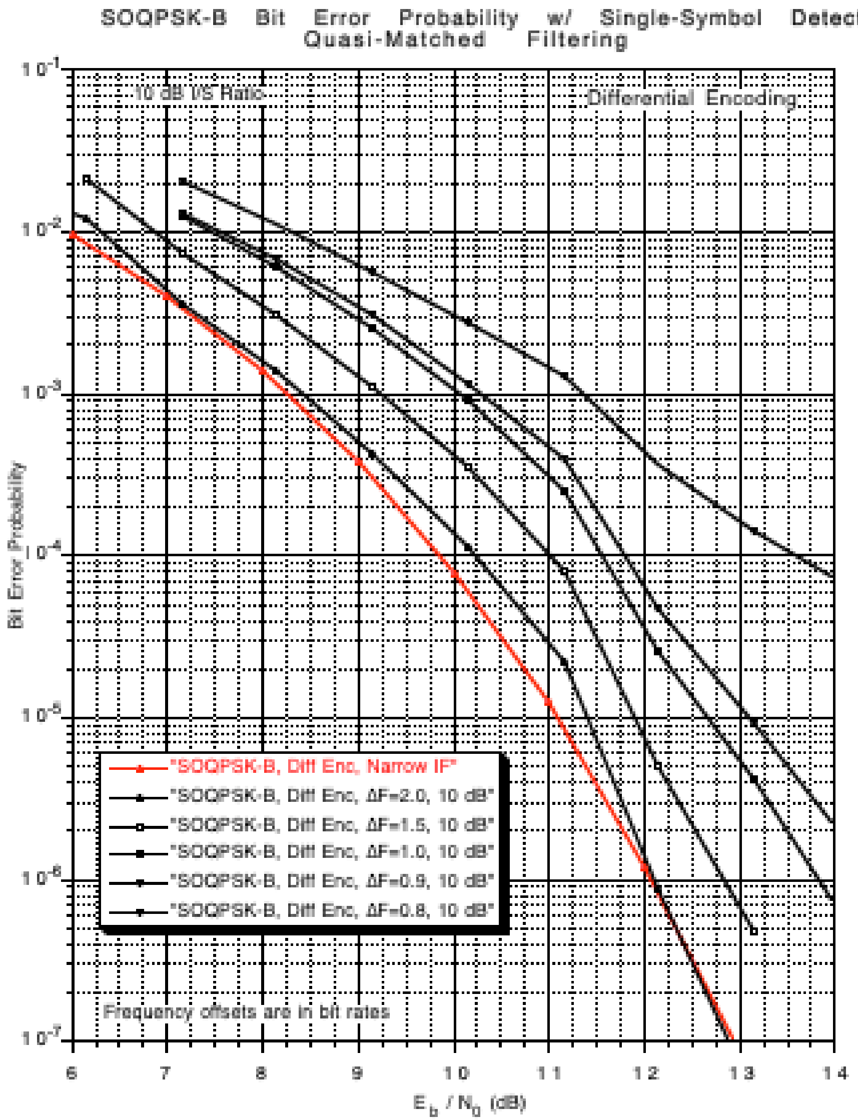
9 Mbps SOQPSK-A, Multichannel

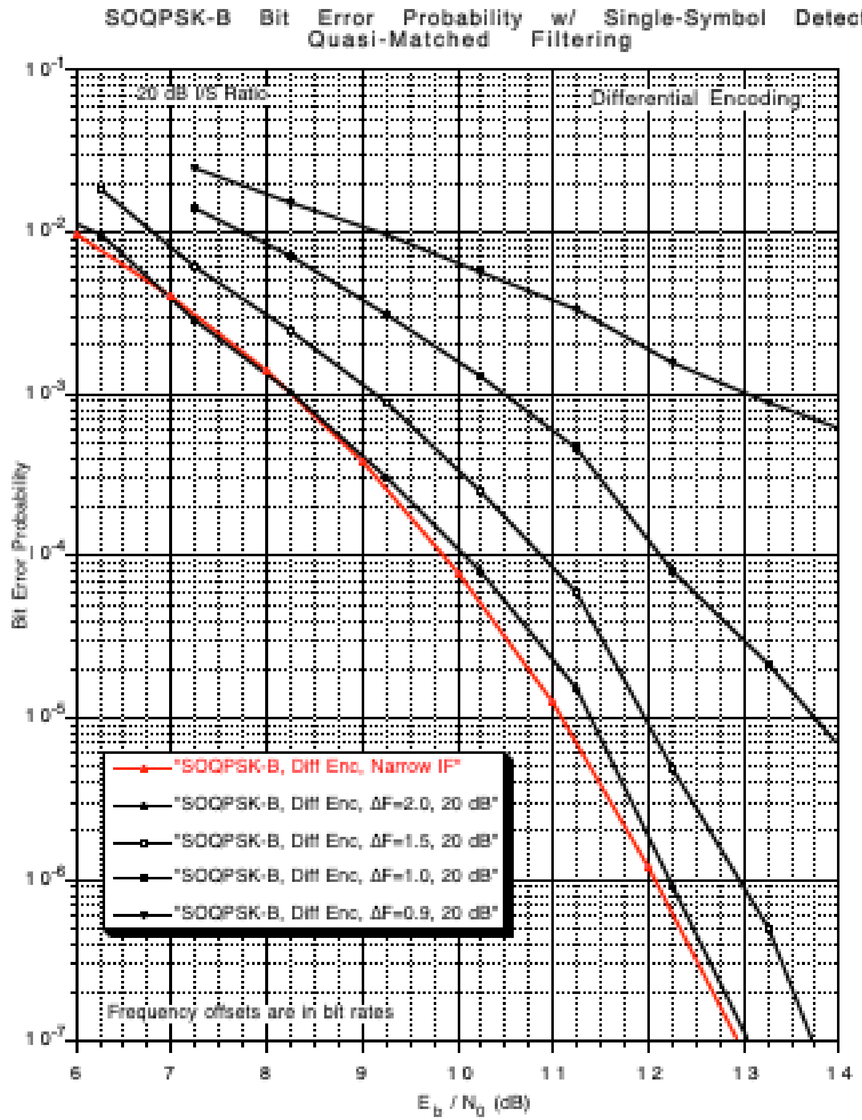


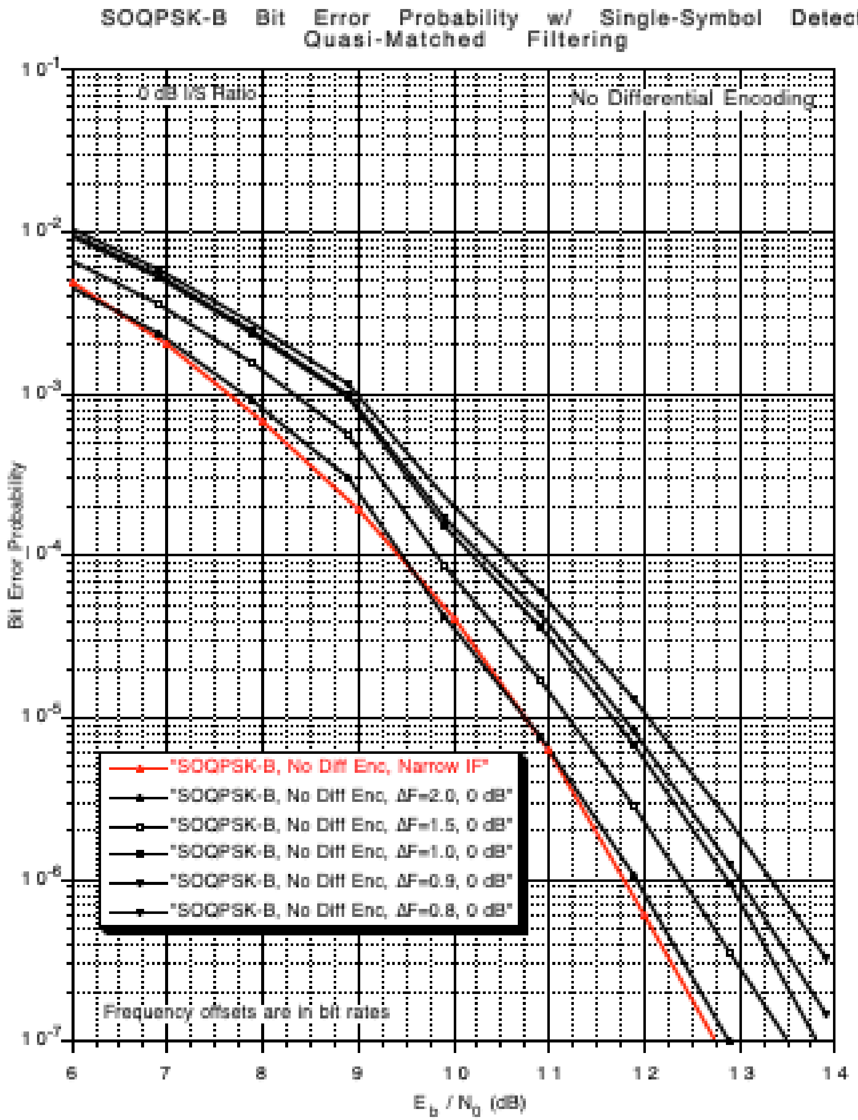
9 Mbps Multi-h CPM, Multichannel

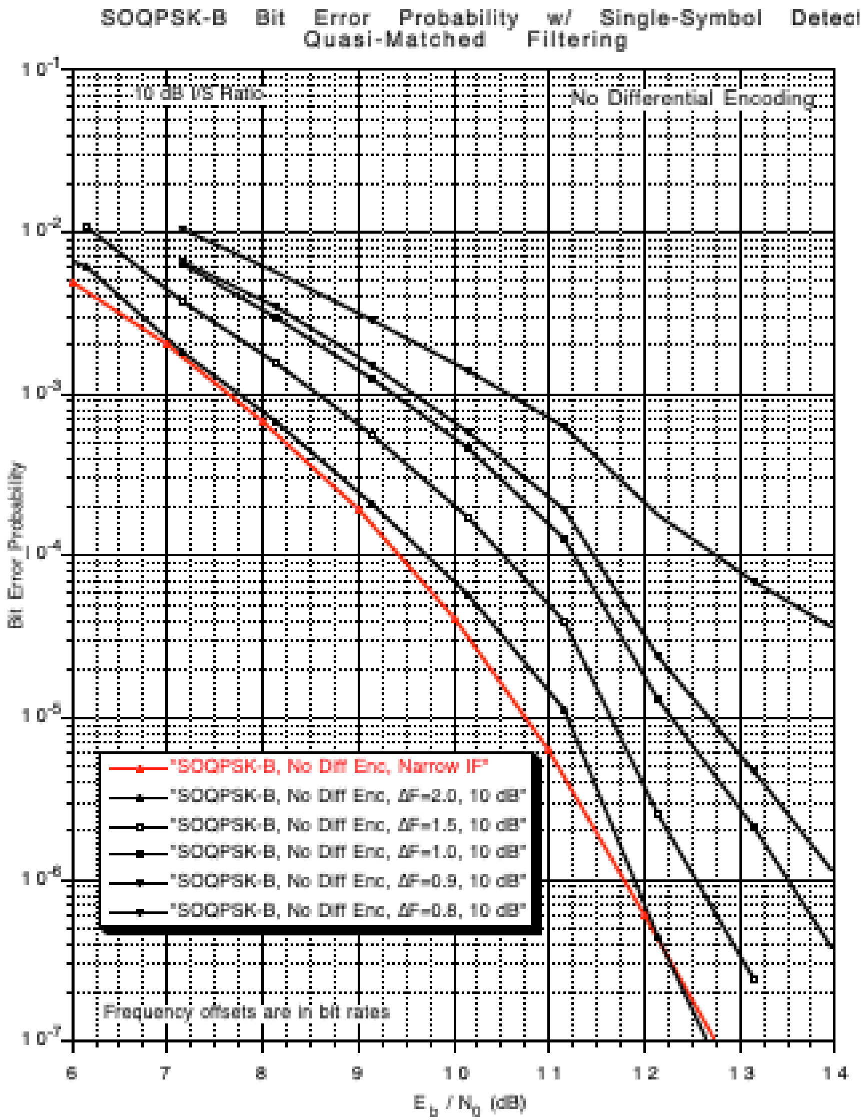



SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
0 dB I/S Ratio
Differential Encoding
Bit Error Probability
"SOQPSK-B, Diff Enc, Narrow IF"
"SOQPSK-B, Diff Enc, ΔF=2.0, 0 dB"
"SOQPSK-B, Diff Enc, ΔF=1.5, 0 dB"
"SOQPSK-B, Diff Enc, ΔF=1.0, 0 dB"
"SOQPSK-B, Diff Enc, ΔF=0.9, 0 dB"
"SOQPSK-B, Diff Enc, ΔF=0.8, 0 dB"
Frequency offsets are in bit rates
E_b / N_0 (dB)

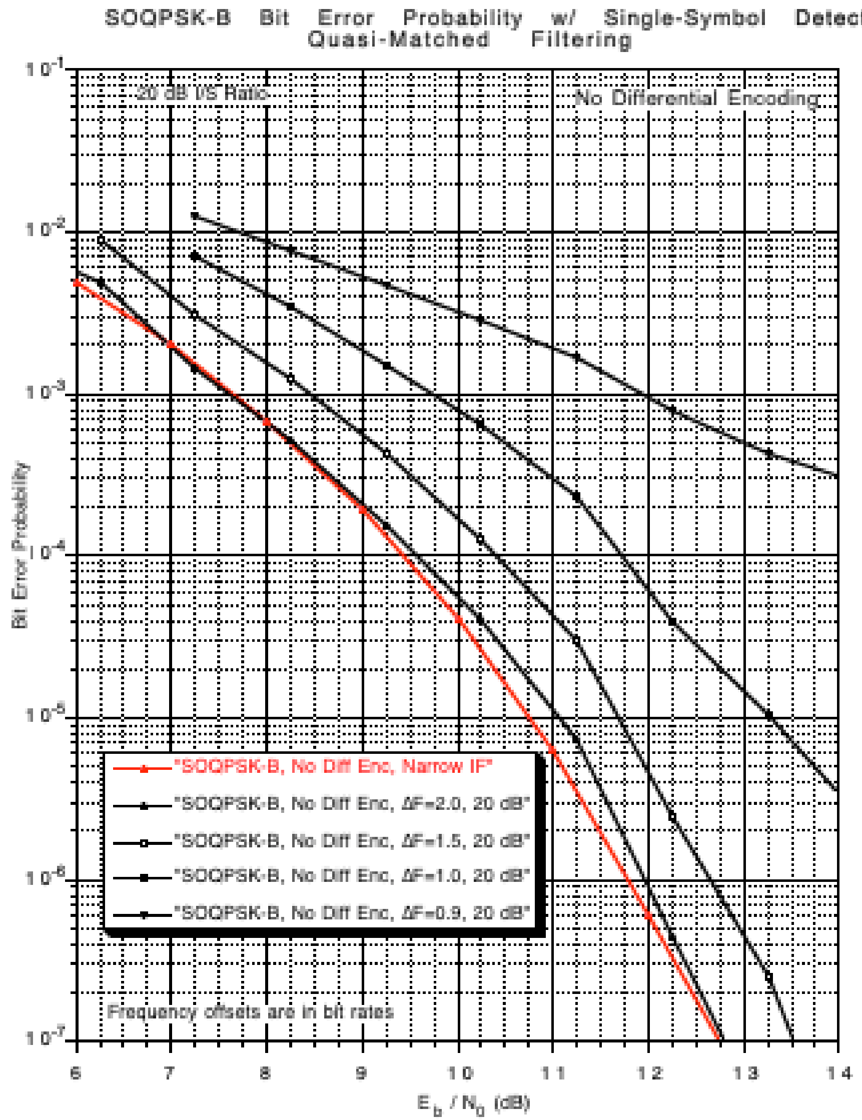

SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
10 dB I/S Ratio
Differential Encoding
Bit Error Probability
E_b / N_0 (dB)
"SOQPSK-B, Diff Enc, Narrow IF"
"SOQPSK-B, Diff Enc, ΔF=2.0, 10 dB"
"SOQPSK-B, Diff Enc, ΔF=1.5, 10 dB"
"SOQPSK-B, Diff Enc, ΔF=1.0, 10 dB"
"SOQPSK-B, Diff Enc, ΔF=0.9, 10 dB"
"SOQPSK-B, Diff Enc, ΔF=0.8, 10 dB"
Frequency offsets are in bit rates


SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
20 dB I/S Ratio
Differential Encoding
Bit Error Probability
E_b / N_0 (dB)
"SOQPSK-B, Diff Enc, Narrow IF"
"SOQPSK-B, Diff Enc, ΔF=2.0, 20 dB"
"SOQPSK-B, Diff Enc, ΔF=1.5, 20 dB"
"SOQPSK-B, Diff Enc, ΔF=1.0, 20 dB"
"SOQPSK-B, Diff Enc, ΔF=0.9, 20 dB"
Frequency offsets are in bit rates

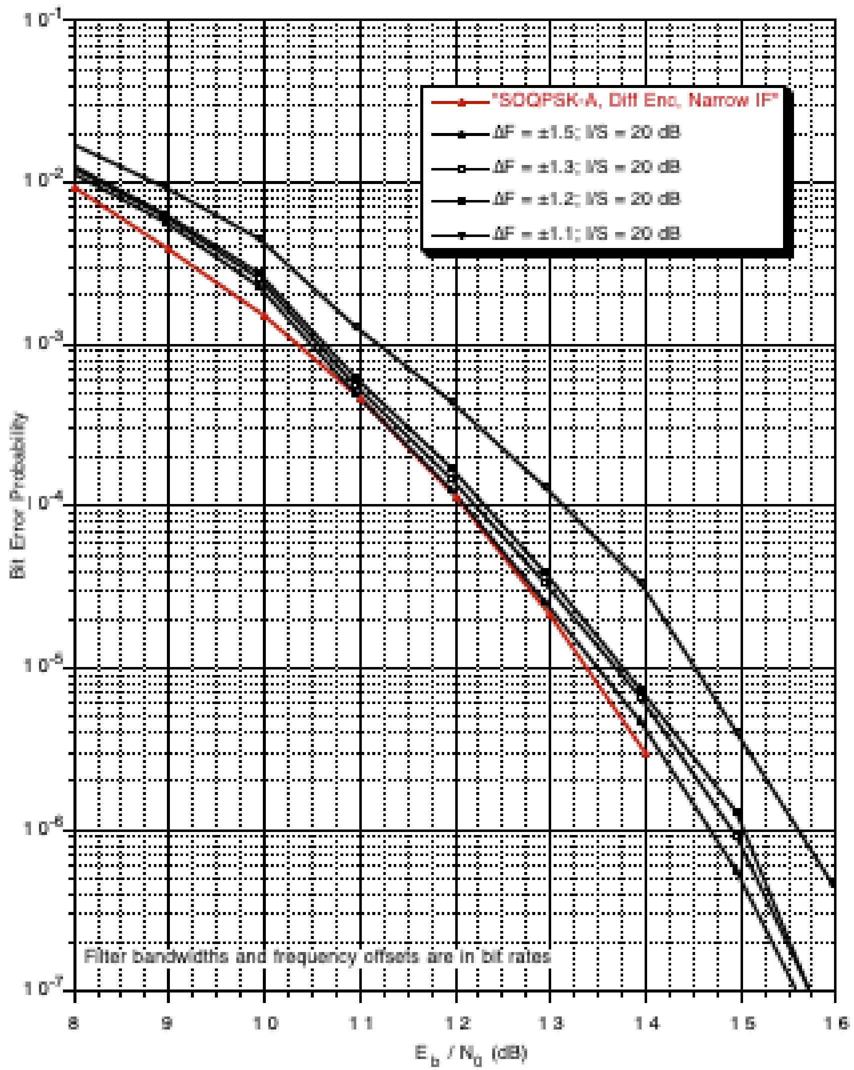

SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
0 dB I/S Ratio
No Differential Encoding
"SOQPSK-B, No Diff Enc, Narrow IF"
"SOQPSK-B, No Diff Enc, ΔF=2.0, 0 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.5, 0 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.0, 0 dB"
"SOQPSK-B, No Diff Enc, ΔF=0.9, 0 dB"
"SOQPSK-B, No Diff Enc, ΔF=0.8, 0 dB"
Frequency offsets are in bit rates
Bit Error Probability
E_b / N_0 (dB)

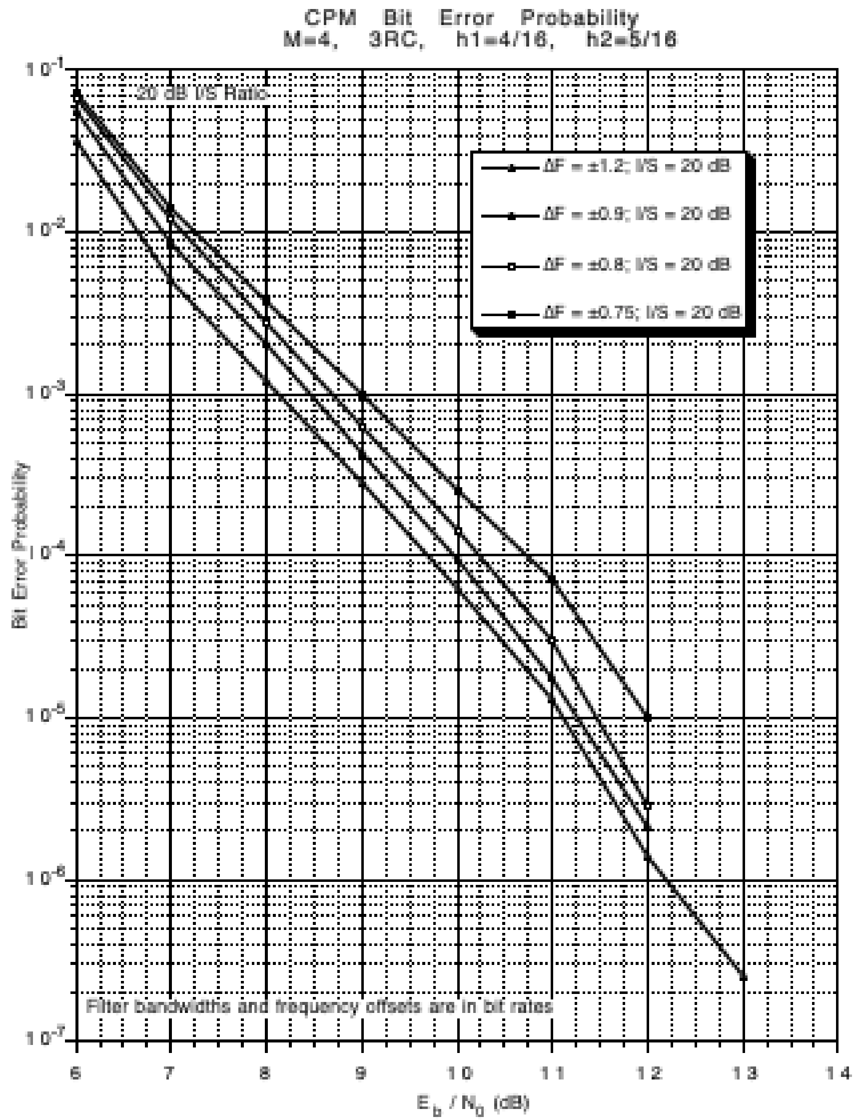


SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
10 dB I/S Ratio
No Differential Encoding
"SOQPSK-B, No Diff Enc, Narrow IF"
"SOQPSK-B, No Diff Enc, ΔF=2.0, 10 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.5, 10 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.0, 10 dB"
"SOQPSK-B, No Diff Enc, ΔF=0.9, 10 dB"
"SOQPSK-B, No Diff Enc, ΔF=0.8, 10 dB"
Frequency offsets are in bit rates
Bit Error Probability
E_b / N_0 (dB)


SOQPSK-B Bit Error Probability w/ Single-Symbol Detect
Quasi-Matched Filtering
20 dB I/S Ratio
No Differential Encoding
Bit Error Probability
"SOQPSK-B, No Diff Enc, Narrow IF"
"SOQPSK-B, No Diff Enc, ΔF=2.0, 20 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.5, 20 dB"
"SOQPSK-B, No Diff Enc, ΔF=1.0, 20 dB"
"SOQPSK-B, No Diff Enc, ΔF=0.9, 20 dB"
Frequency offsets are in bit rates
E_b / N_0 (dB)

SOQPSK-A Bit Error Probability




CPM Bit Error Probability
M=4, 3RC, h1=4/16, h2=5/16
20 dB I/S Ratio
ΔF = ±1.2; I/S = 20 dB
ΔF = ±0.9; I/S = 20 dB
ΔF = ±0.8; I/S = 20 dB
ΔF = ±0.75; I/S = 20 dB
Filter bandwidths and frequency offsets are in bit rates
Bit Error Probability
E_b / N_0 (dB)

Summary

Modulation	Channel spacing for 1 dB loss at I/S ratio = 0 dB	Channel spacing for 1 dB loss at I/S ratio = 10 dB	Channel spacing for 1 dB loss at I/S ratio = 20 dB	Eb/N0 for BER = 1.0e-5, with I/S ratio = 20 dB
SOQPSK-A	-	-	1.11 bit rates	14.5 dB
SOQPSK-B	1.0 bit rates	1.4 bit rates	1.50 bit rates	12.0 dB
Multi-h CPM	-	-	0.77 bit rates	12.0 dB

Conclusions

- SOQPSK and Multi-h CPM offer substantial reduction in bandwidth over PCM/FM, with little or no penalty in BER.
- SOQPSK-B is largely insensitive to IF filtering, while SOQPSK-A is more “delicate”
- SOQPSK-B offers better detection efficiency than SOQPSK-A, at the expense of slightly greater bandwidth
- Multi-h CPM offers almost 50% more bps / Hz than SOQPSK-A, <u>and</u> 2.5 dB better detection efficiency.
- Multi-h CPM nearly doubles the bps / Hz of SOQPSK-B, with the same detection efficiency.