Telemetry Smorgasbord

A Little Taste of Everything

Terry Hill, Quasonix

Spring 2020

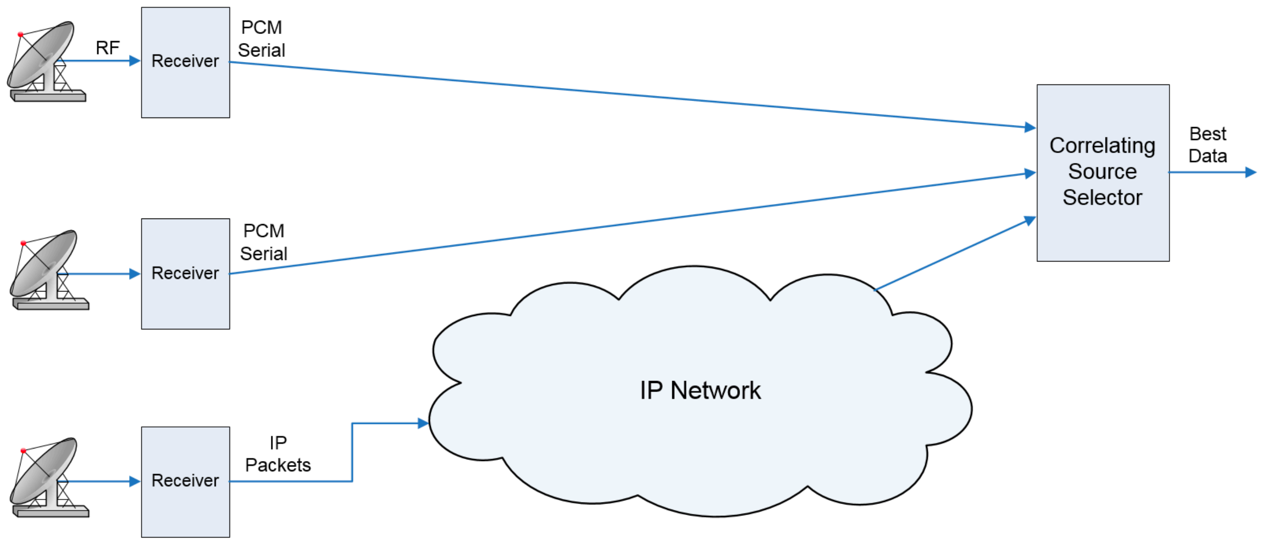
Course Outline – Day 3

- Impairment Mitigation Techniques
  - Adaptive Equalization
  - Best Source Selection
  - Best Channel Selection
  - Space-Time Coding (STC)
  - Low Density Parity Check (LDPC) Coding
  - Auto-Tracking Antennas
- Using All the Tools Together
- Performance Comparison & Summary
- Link Budgets

Best Source Selection

Combining Multiple Sources

- Receive and demodulate the same signal at multiple receive sites
- Funnel all the demodulated data to one central location
- Time align the multiple data streams
- Build a better output stream from the multiple input streams



Selection Algorithms

- Majority vote
  - Reasonably effective with three or more sources
  - Reduces to guesswork with only two sources
  - Sub-optimal for any number of sources
- PCM frame header accuracy
  - Uses only a small fraction of the bits to make an estimate
  - Poor resolution (BER is typically measured as Num_errors ÷ 32)
  - Useless with encrypted data
- Log-likelihood ratio
  - Uses all the bits
  - Works with encrypted data
  - Max-likelihood (optimal) combining scheme
    - Rice, Michael and Perrins, Erik. *"Maximum Likelihood Detection From Multiple Bit Sources"*, Proceedings of the International Telemetering Conference, Las Vegas, NV, USA, 2015.

Why Measure Data Quality?

- Telemetry links suffer from a wide range of impairments
  - Noise
  - Interference
  - Multipath
  - Shadowing
  - Loss of antenna track
- We need a way to asses the impact of *all* these impairments
- We need to compute p_n
  - Quickly
  - Accurately

$$\begin{aligned}
\hat{x} = 0 &\iff \prod_{n\in\mathcal{N}_0} p(y_n|x=0) \prod_{n\in\mathcal{N}_1} p(y_n|x=0) > \prod_{n\in\mathcal{N}_0} p(y_n|x=1) \prod_{n\in\mathcal{N}_1} p(y_n|x=1) \\
&\iff \prod_{n\in\mathcal{N}_0} (1-p_n) \prod_{n\in\mathcal{N}_1} p_n > \prod_{n\in\mathcal{N}_0} p_n \prod_{n\in\mathcal{N}_1} (1-p_n) \\
&\iff \log\left(\prod_{n\in\mathcal{N}_0} (1-p_n) \prod_{n\in\mathcal{N}_1} p_n\right) > \log\left(\prod_{n\in\mathcal{N}_0} p_n \prod_{n\in\mathcal{N}_1} (1-p_n)\right) \\
&\iff \sum_{n\in\mathcal{N}_0} \log(1-p_n) + \sum_{n\in\mathcal{N}_1} \log(p_n) > \sum_{n\in\mathcal{N}_0} \log(p_n) + \sum_{n\in\mathcal{N}_1} \log(1-p_n) \\
&\iff \sum_{n\in\mathcal{N}_0} \log(1-p_n) - \sum_{n\in\mathcal{N}_0} \log(p_n) > \sum_{n\in\mathcal{N}_1} \log(1-p_n) - \sum_{n\in\mathcal{N}_1} \log(p_n) \\
&\iff \sum_{n\in\mathcal{N}_0} \log\left(\frac{1-p_n}{p_n}\right) > \sum_{n\in\mathcal{N}_1} \log\left(\frac{1-p_n}{p_n}\right).
\end{aligned}$$

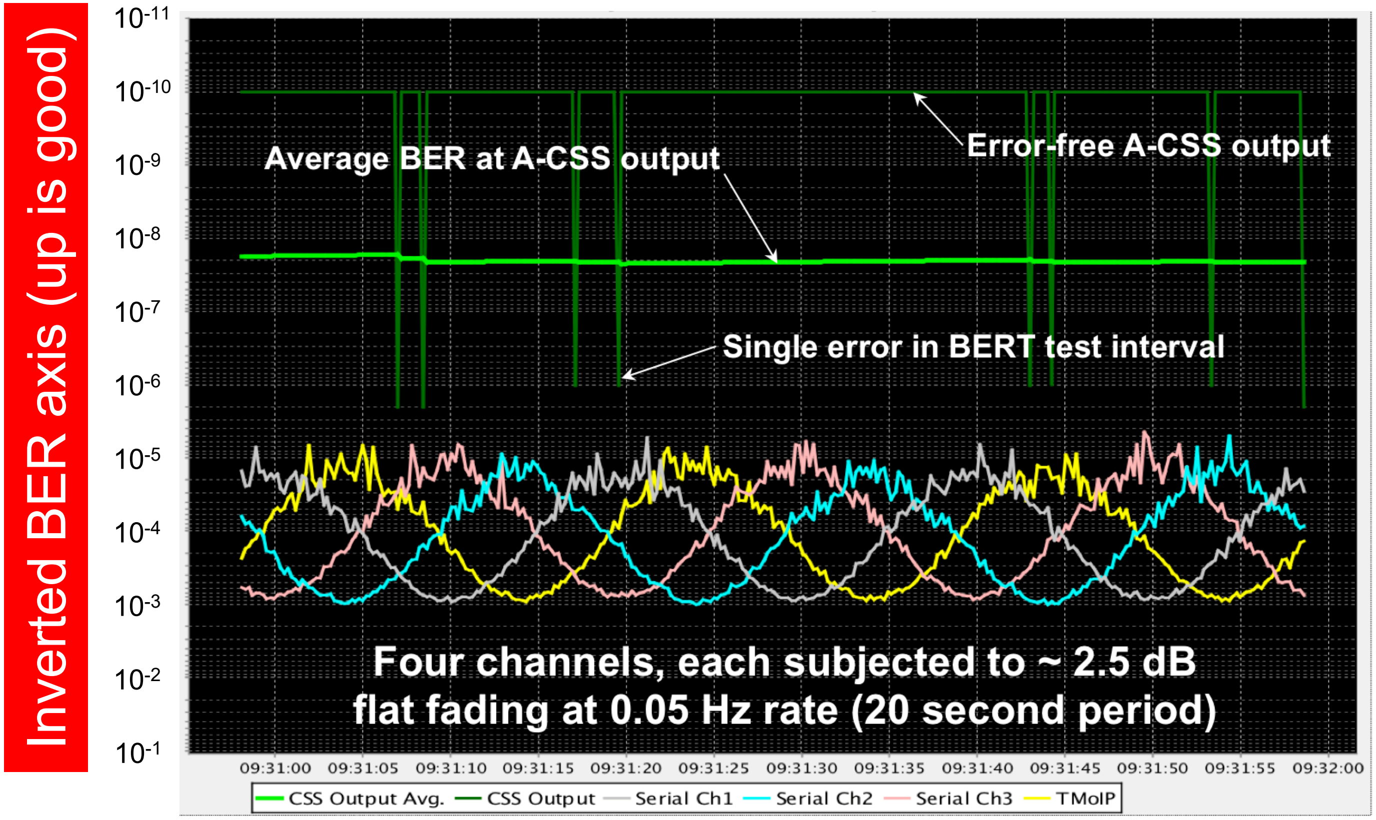
Rice, Michael and Perrins, Erik. "Maximum Likelihood Detection From Multiple Bit Sources", Proceedings of the International Telemetering Conference, Las Vegas, NV, USA, 2015.

Data Quality Encapsulation

- Payload data is bundled with its DQM, to give Best Source Selectors a valid basis for "best"
- Interoperability among vendors requires standards
  - DQM calibration against multiple signal impairments
  - DQE packet structure
- Quasonix has developed and shared an open DQM/DQE format
  - Published at ITC 2015
  - License-free, royalty-free
  - RCC standard as of IRIG 106-17, Chapter 2, appendix G
- Includes test procedures to evaluate DQM accuracy

Does it work?

- Four "poor" channels for input to BSS
- One nearly error-free output from BSS



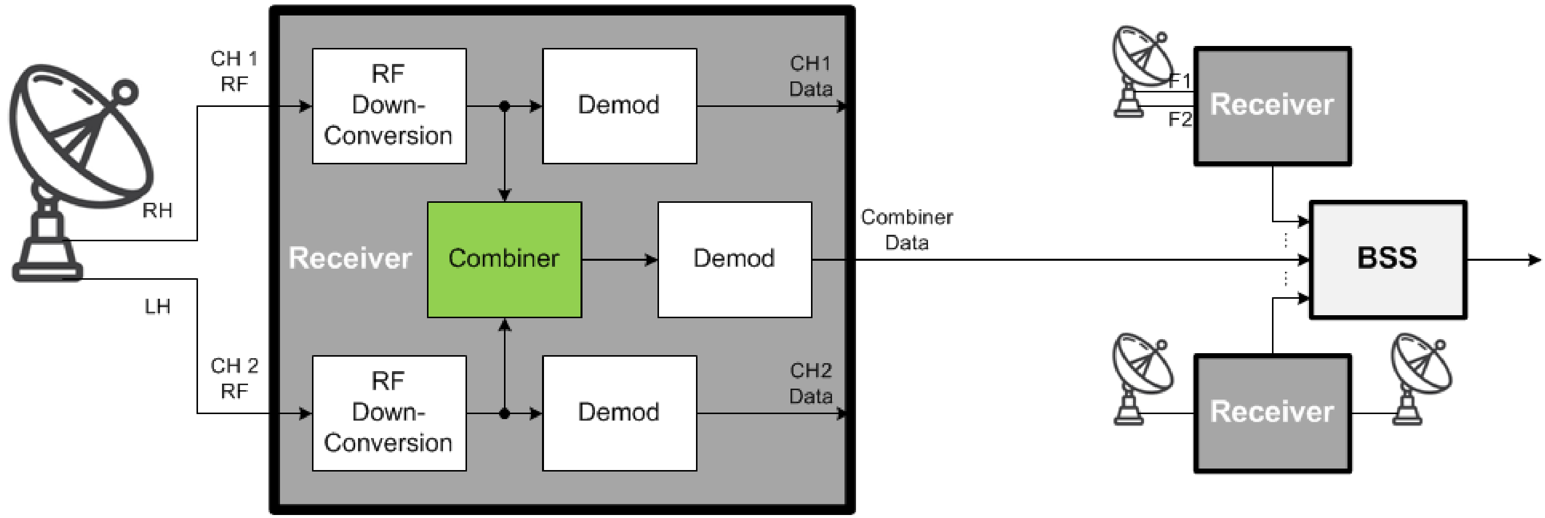
BSS Summary

- Correlating (time-aligning) source selectors deliver output data that is better than any single input stream
- Combats *all* forms of signal impairment
  - Noise
  - Multipath
  - Interference
  - Shadowing
  - Loss of antenna track
- Diversity can be in any form
  - Polarization
  - Frequency
  - Spatial
- DQE / DQM equip the BSS to make optimal decisions

Best Channel Selector (BCS)

Handling the “Un-Combinable” Signals

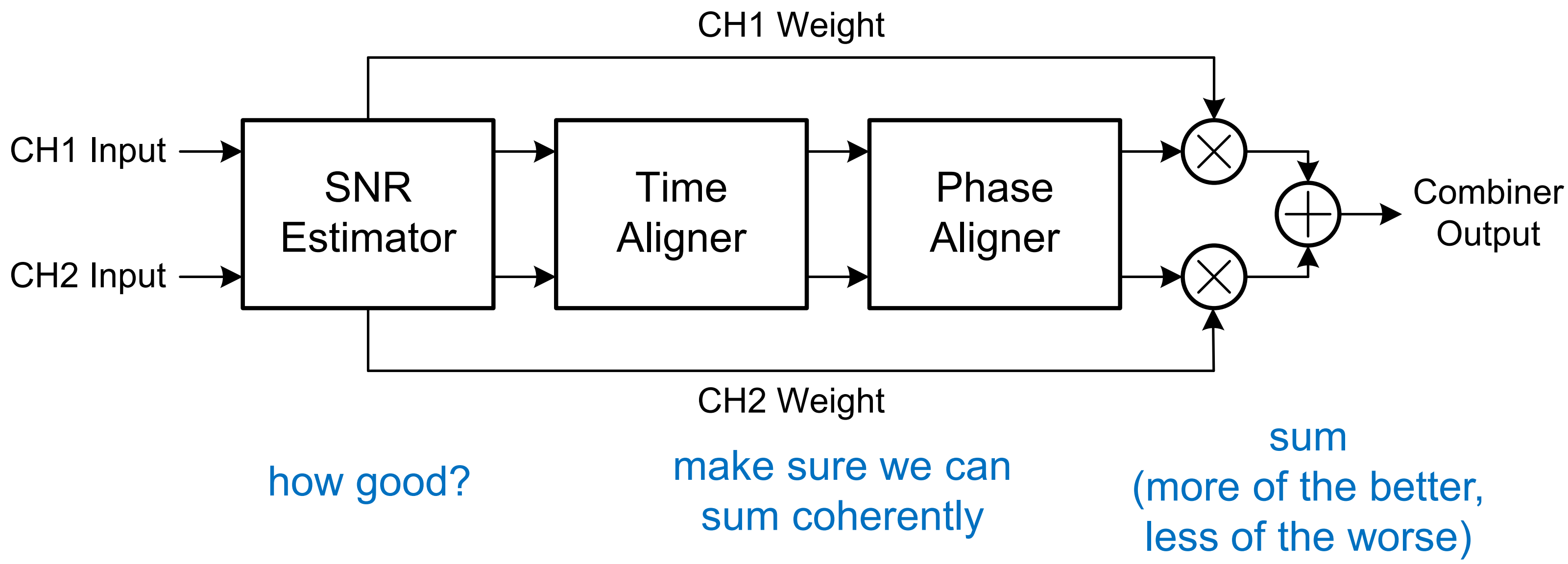
Receive Diversity – Combiner



- Polarization, frequency, or short-range spatial diversity
- Maximal Ratio Combiner sums input channels proportional to their SNR
  - Optimal in additive white Gaussian noise (AWGN) – up to 3 dB gain
  - Use as only receiver output?

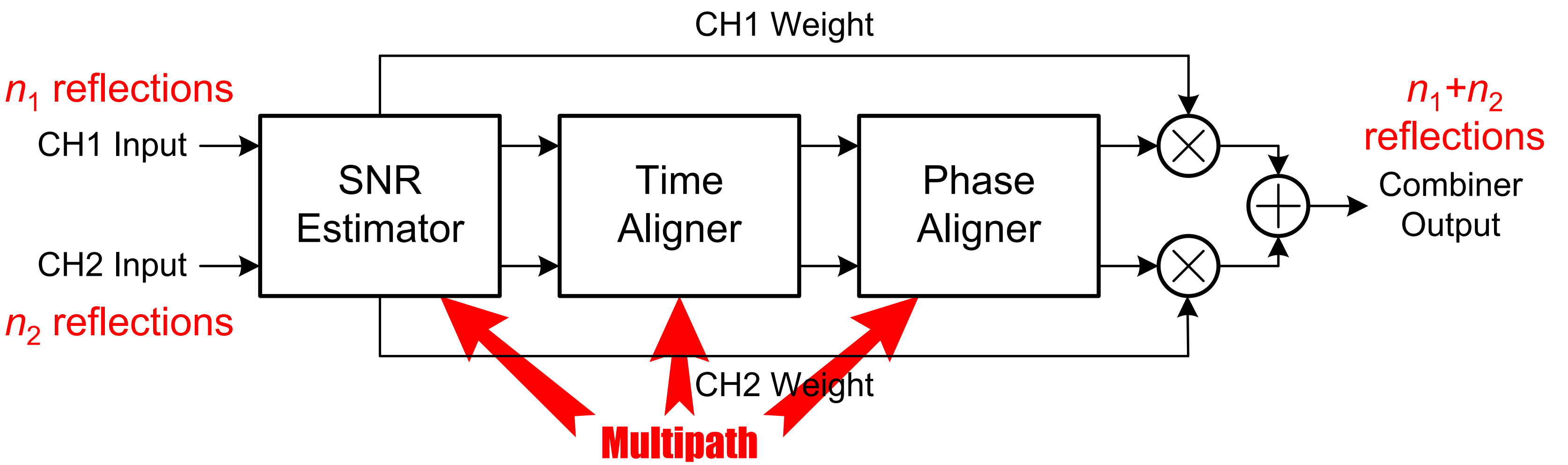
Combiner Structure

- Maximal ratio combining



Combiner Performance

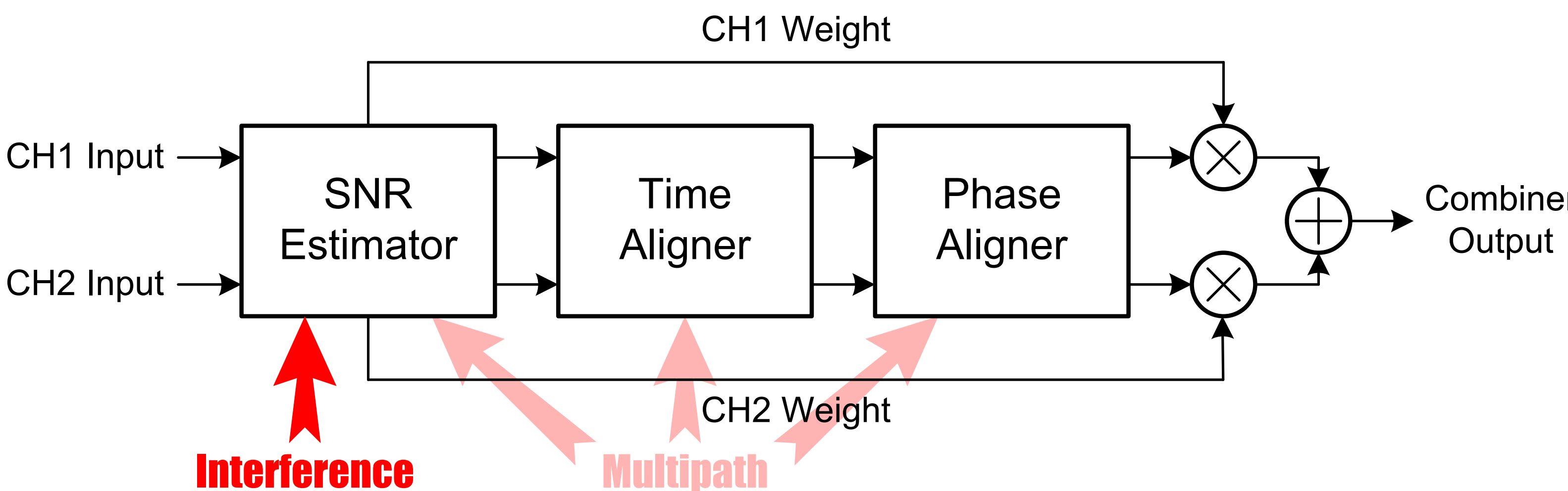
- Maximal ratio combining issues



  - Inaccurate SNR estimation: multiple signal copies, little or no noise
  - Degraded time and phase alignment
  - *Downstream demodulator must deal with **all** received reflections*

Combiner Performance

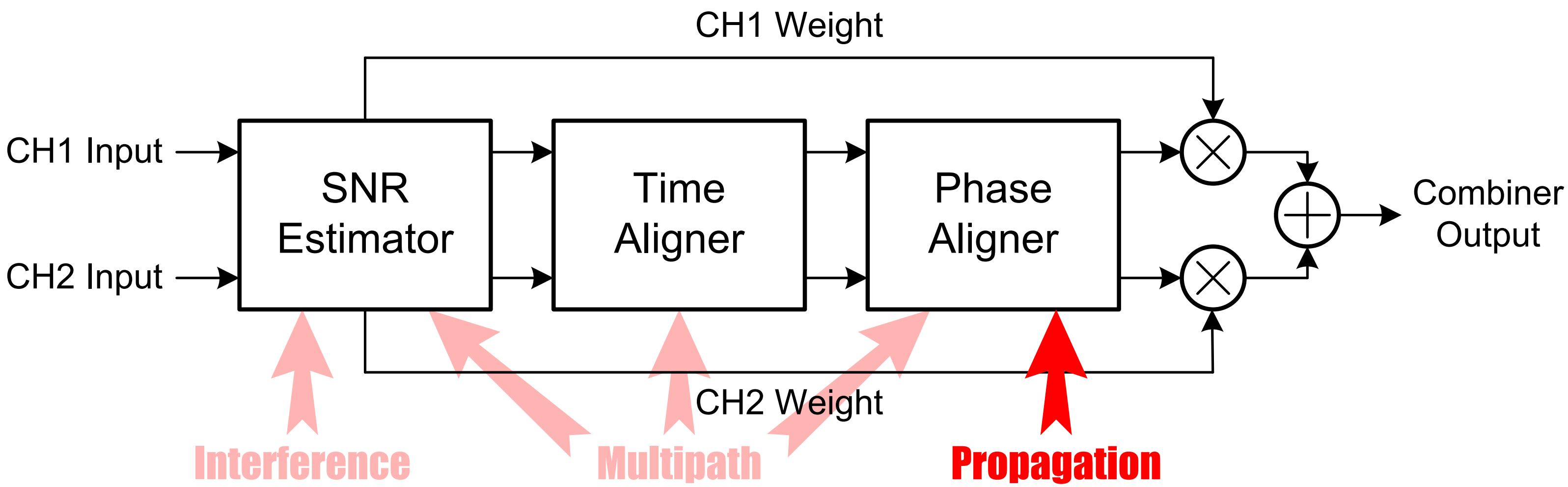
- Maximal ratio combining issues



- Inaccurate SNR estimation: overwhelm estimator with strong *undesired* signal

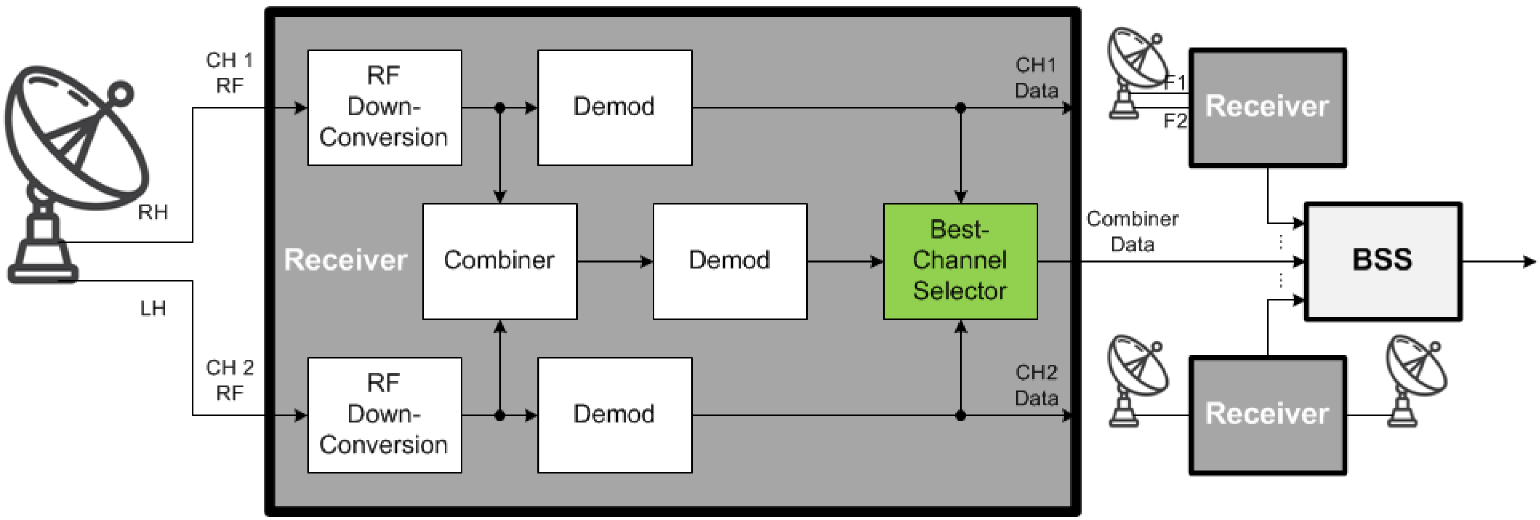
Combiner Performance

- Maximal ratio combining issues



  - Propagation effects may result in non-combinable signals

Receive Diversity – BCS

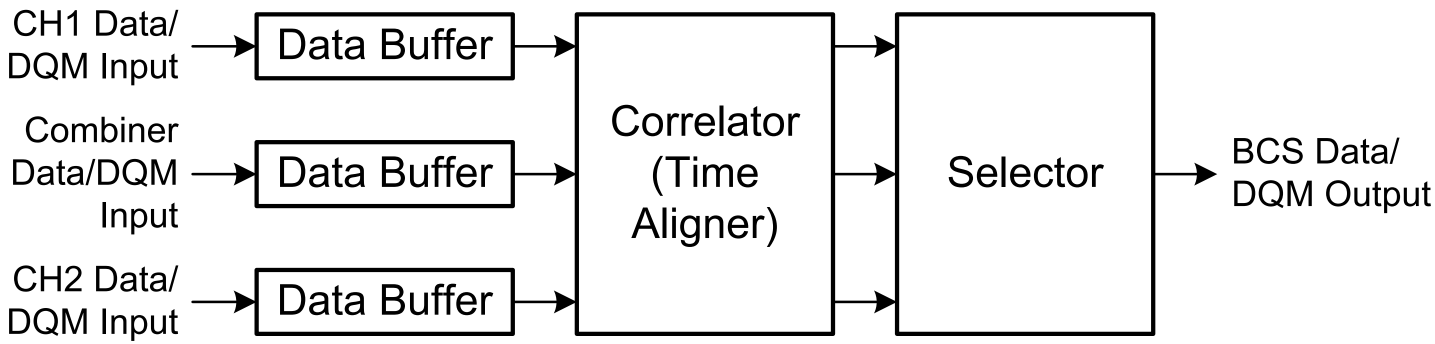


- Like a mini-BSS *inside the receiver*
- Selects and outputs best data from just three sources (Channel 1, Channel 2, and Combiner)
- Optimized for this narrowly scoped role

BCS Structure

- 3-channel correlating selection

"hit-less" – no dropped or duplicated bits

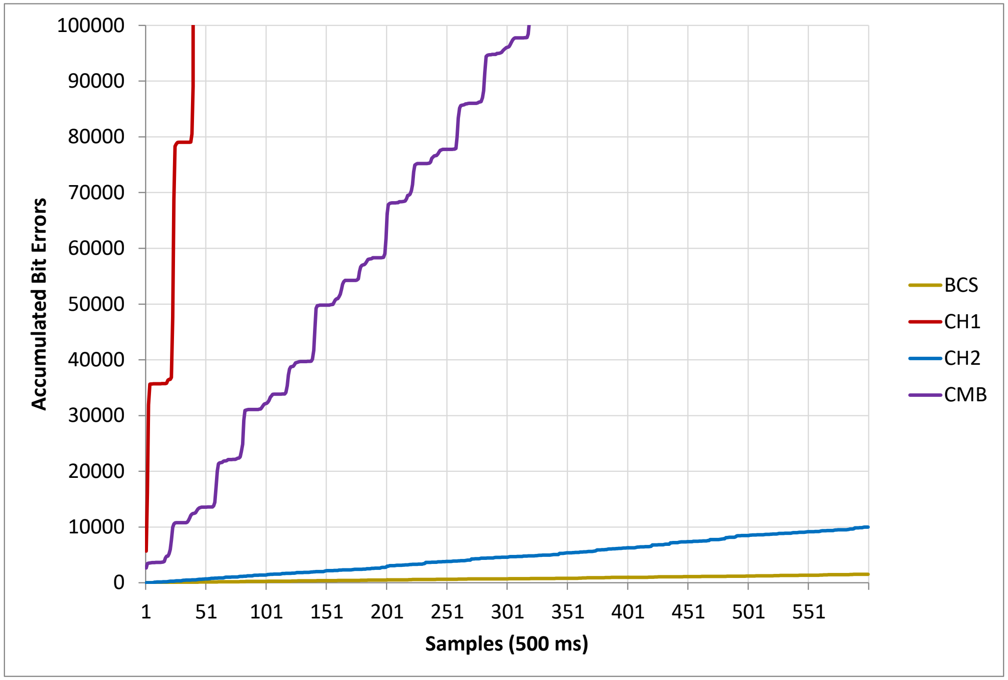


line up bits from all channels

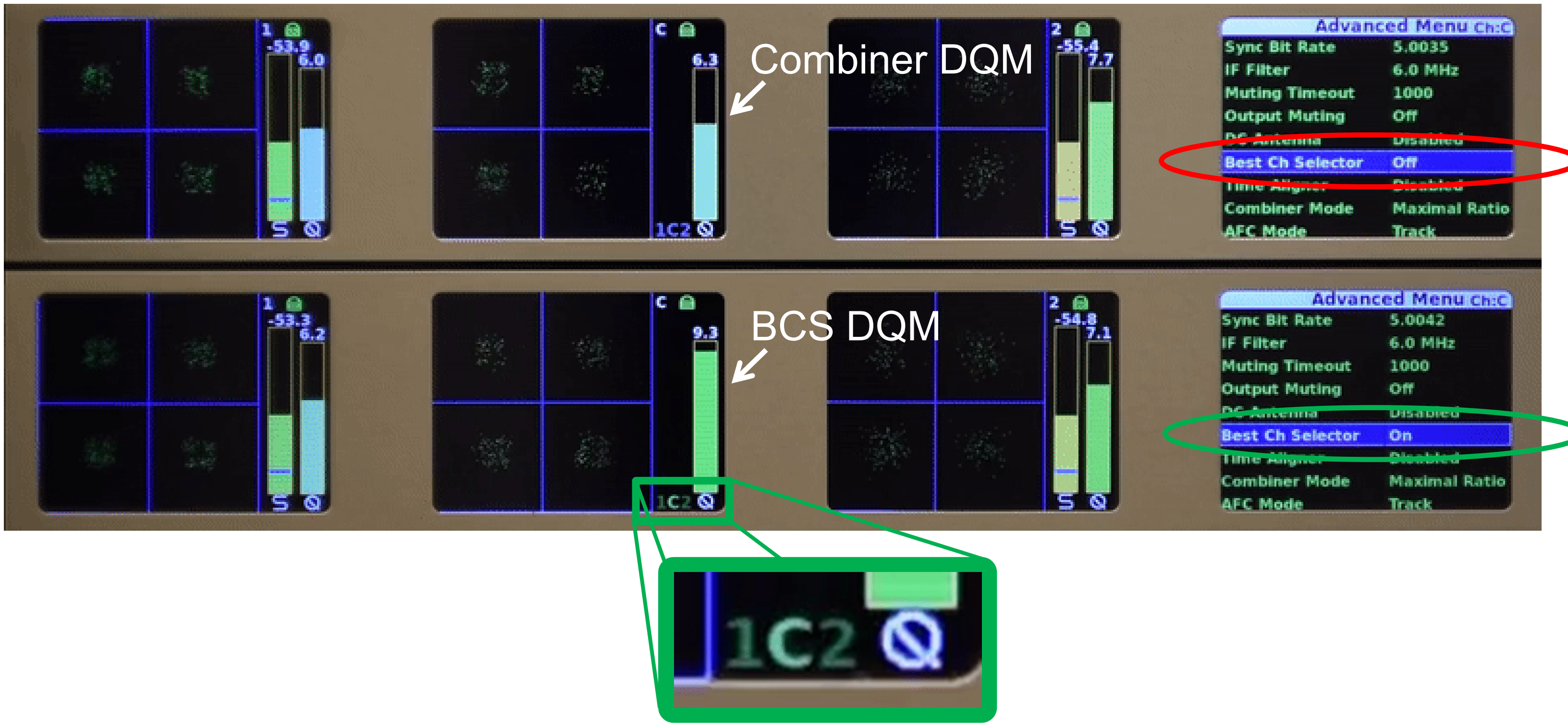
select best bit
based on
best DQM

BCS Test – Multipath

- Apply severe multipath, engage adaptive equalization
- BCS outperforms all channels



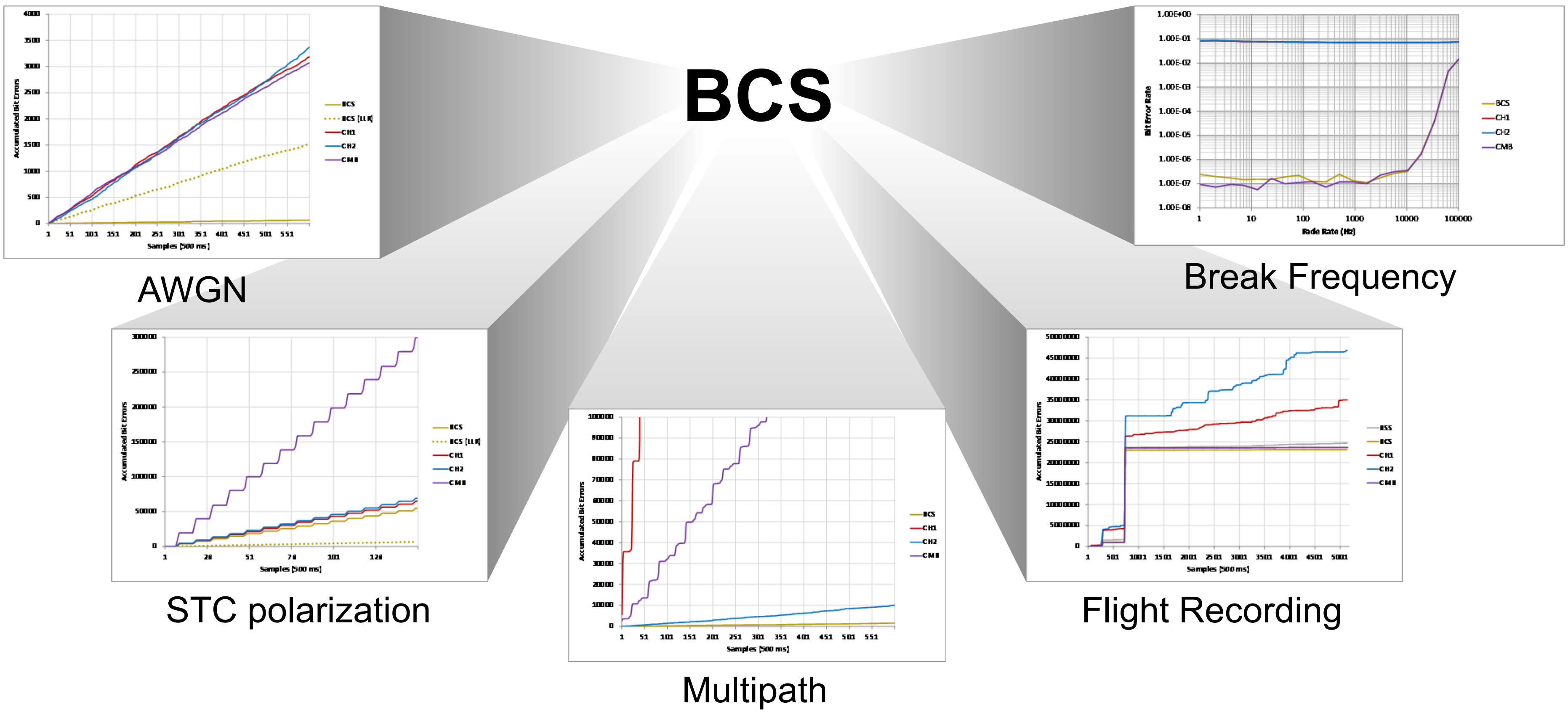
BCS Test – Multipath



- DQM reduction of 1 = BER increase of 10x (!)
- BCS selection > 1000x faster than display

BCS Test – Summary

- Uniformly equals or exceeds best channel's performance



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Conclusions

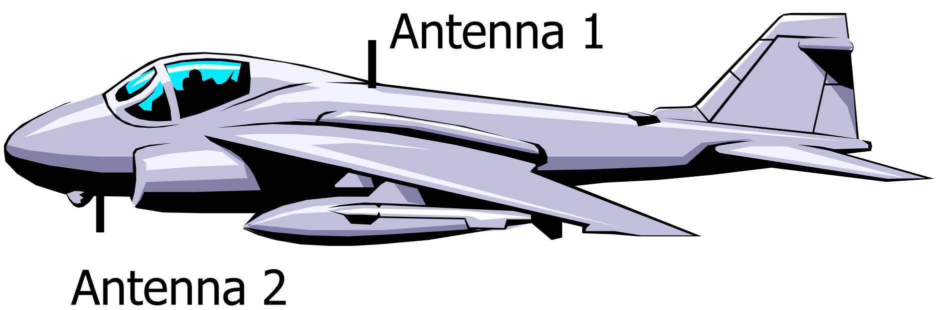
- Combiner best most of the time, but not always
- BCS mitigates cases where Combiner falls short
  - Uses DQM to form reliable selection criterion
  - Dynamically selects best data from Channel 1, Channel 2, or Combiner
    - Preserves combiner gain in AWGN
    - Supplements combiner in multipath, interference, etc.
  - Generates output with accurate composite DQM
  - **Provides single output from dual-channel receiver that reliably supplies data superior to best channel, including Combiner**
- BCS does not replace BSS
  - BCS has great performance local to one receiver
  - BSS extends performance range-wide with multiple receive sites

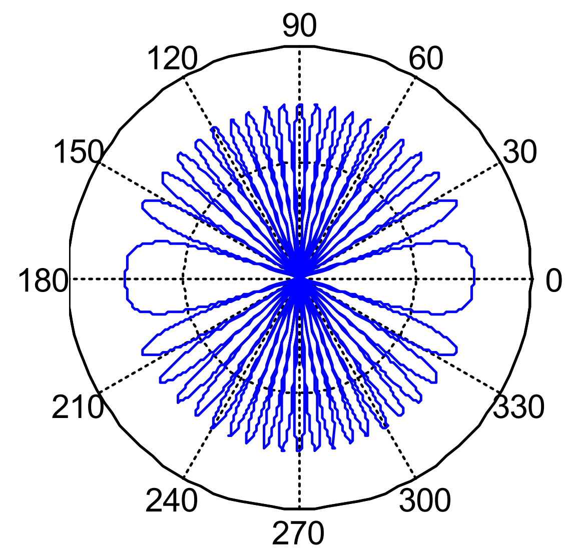
Space-Time Coding

Eradicates Porcupines!

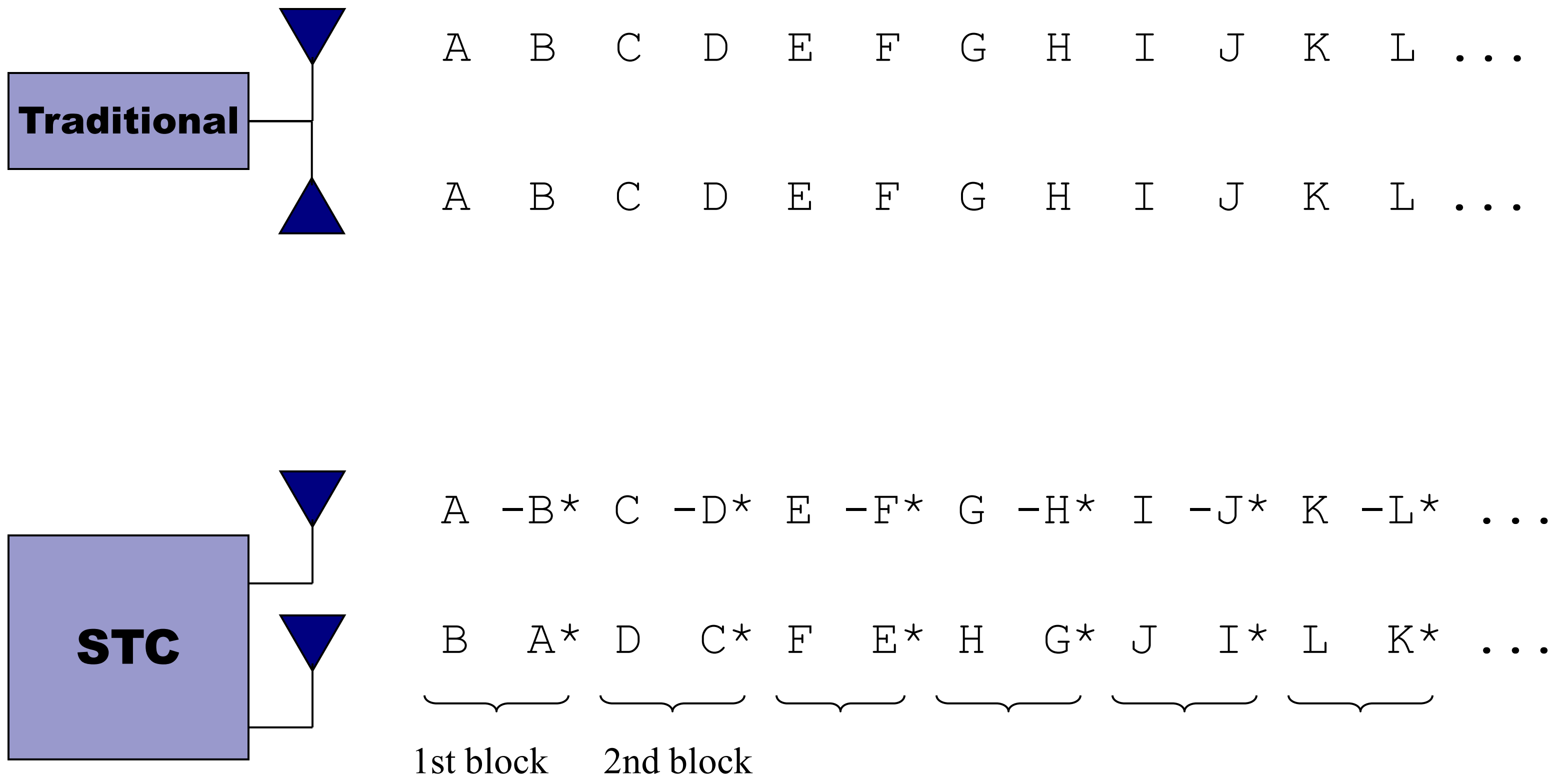
Difficulties with TX Diversity

Spatially Separated Antennas Create Interference Pattern





Alamouti Space-Time Coding (STC)



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

Antenna Pattern Interpretation

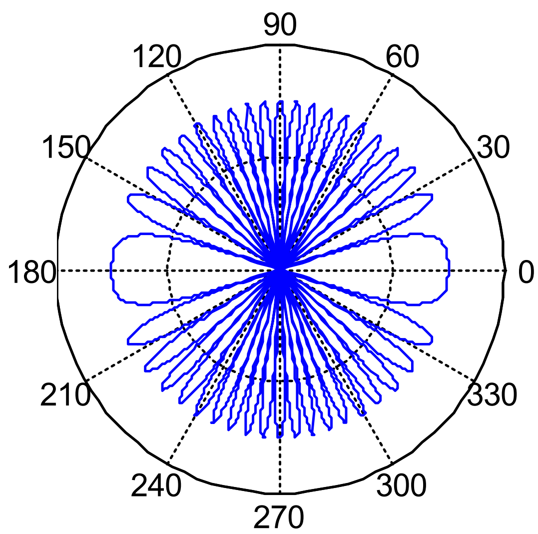
Consider BPSK Signaling and Assume $s_1 = s_2 = 1$

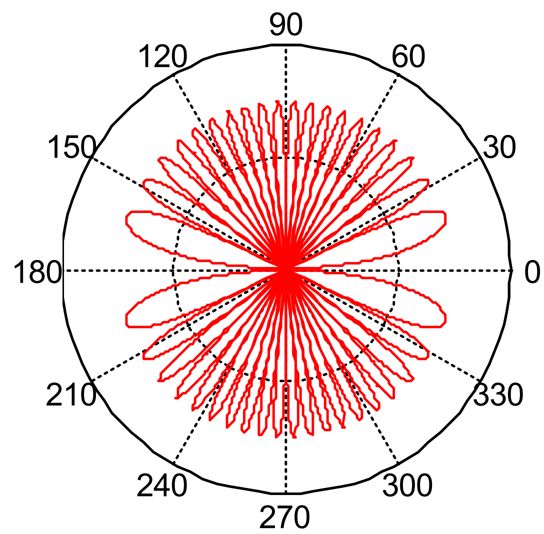
Time Slot 1:

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

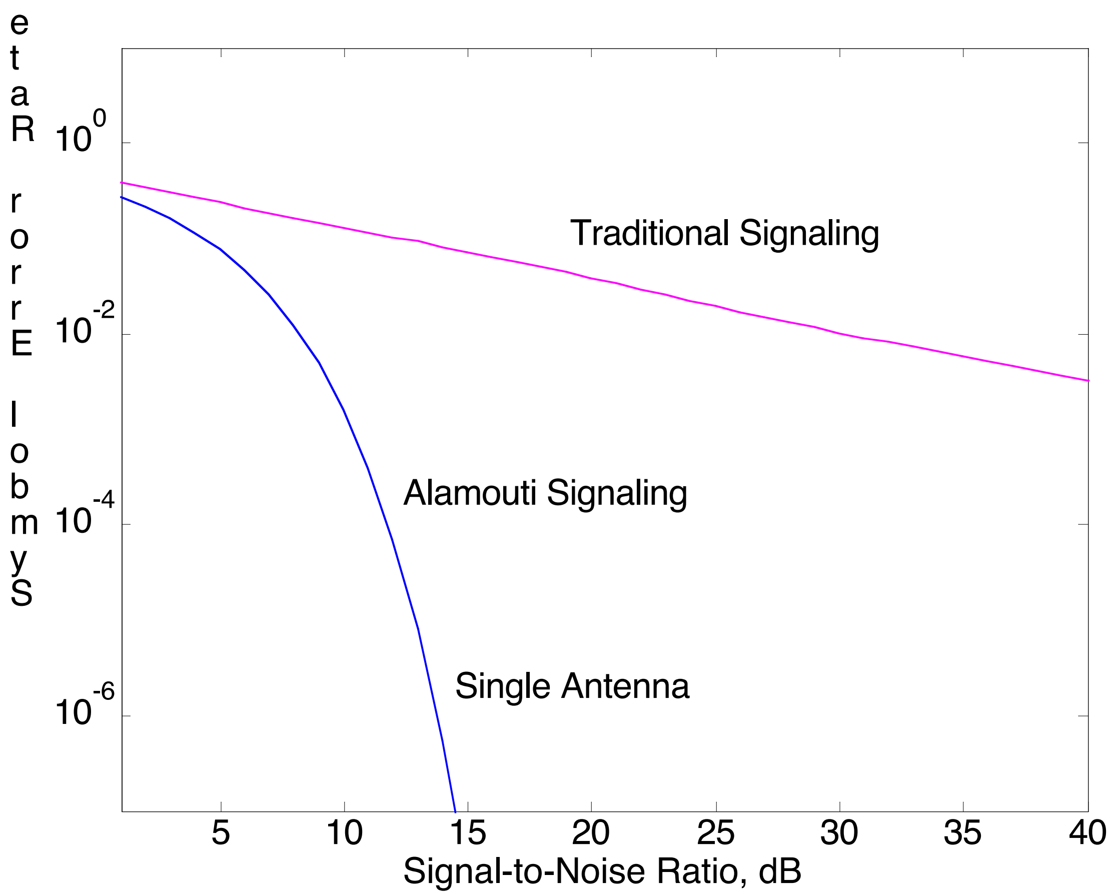
Time Slot 2:

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





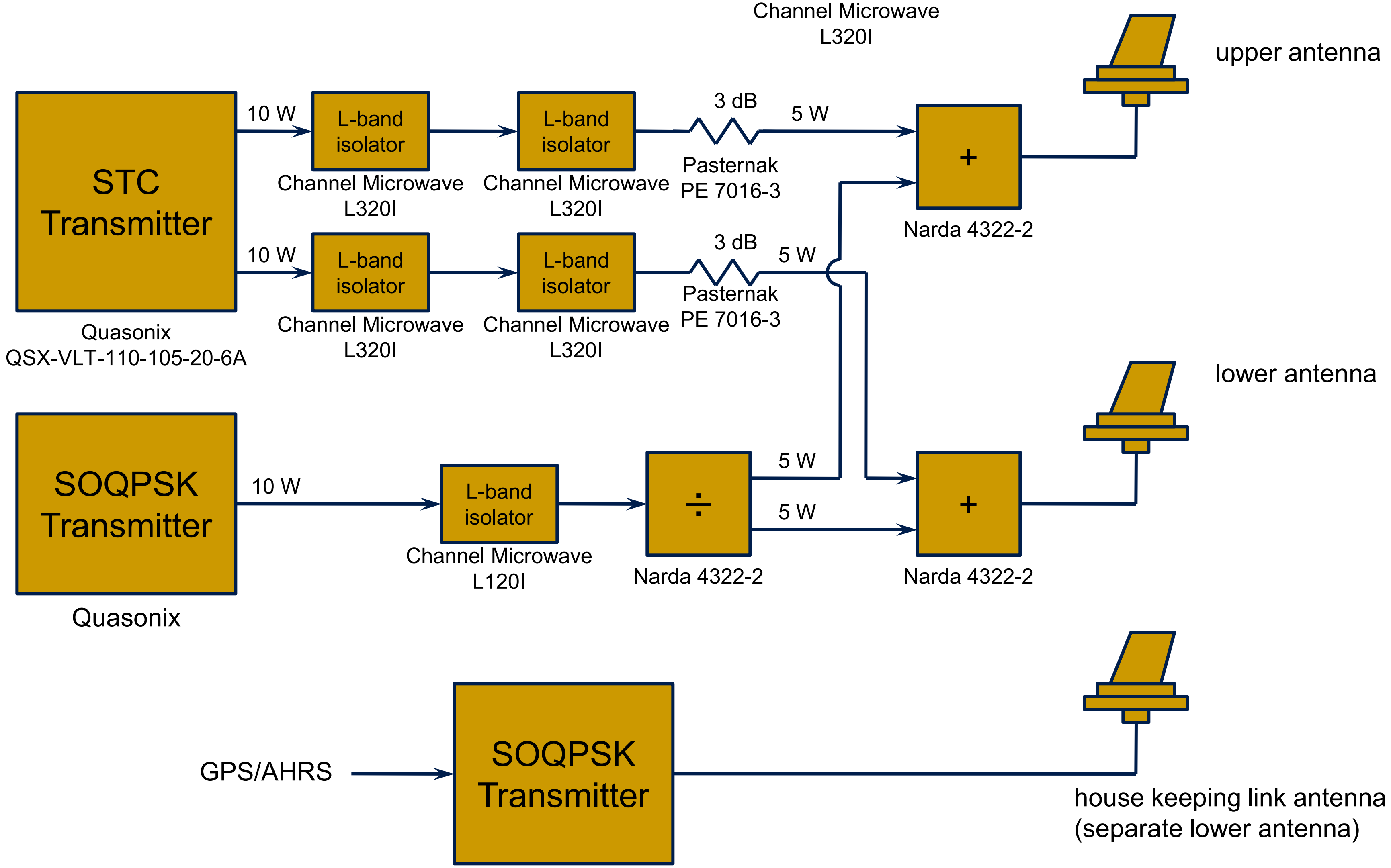
SER Simulations



Circular Polarization Diversity Reception

Results Identical to Single Receive Antenna System

Flight Tests: Airborne Configuration



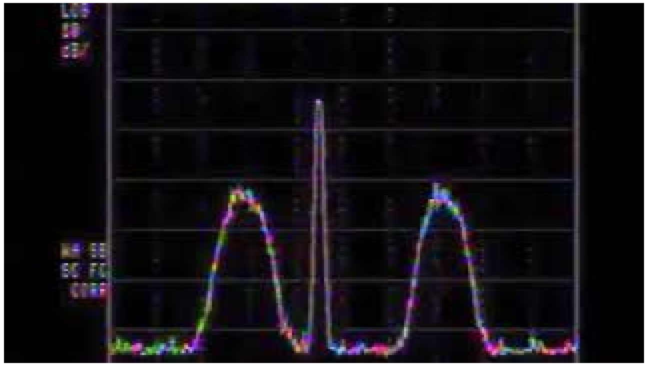
C-12 Beechcraft: Airborne Platform

BYU

STC Video Clip

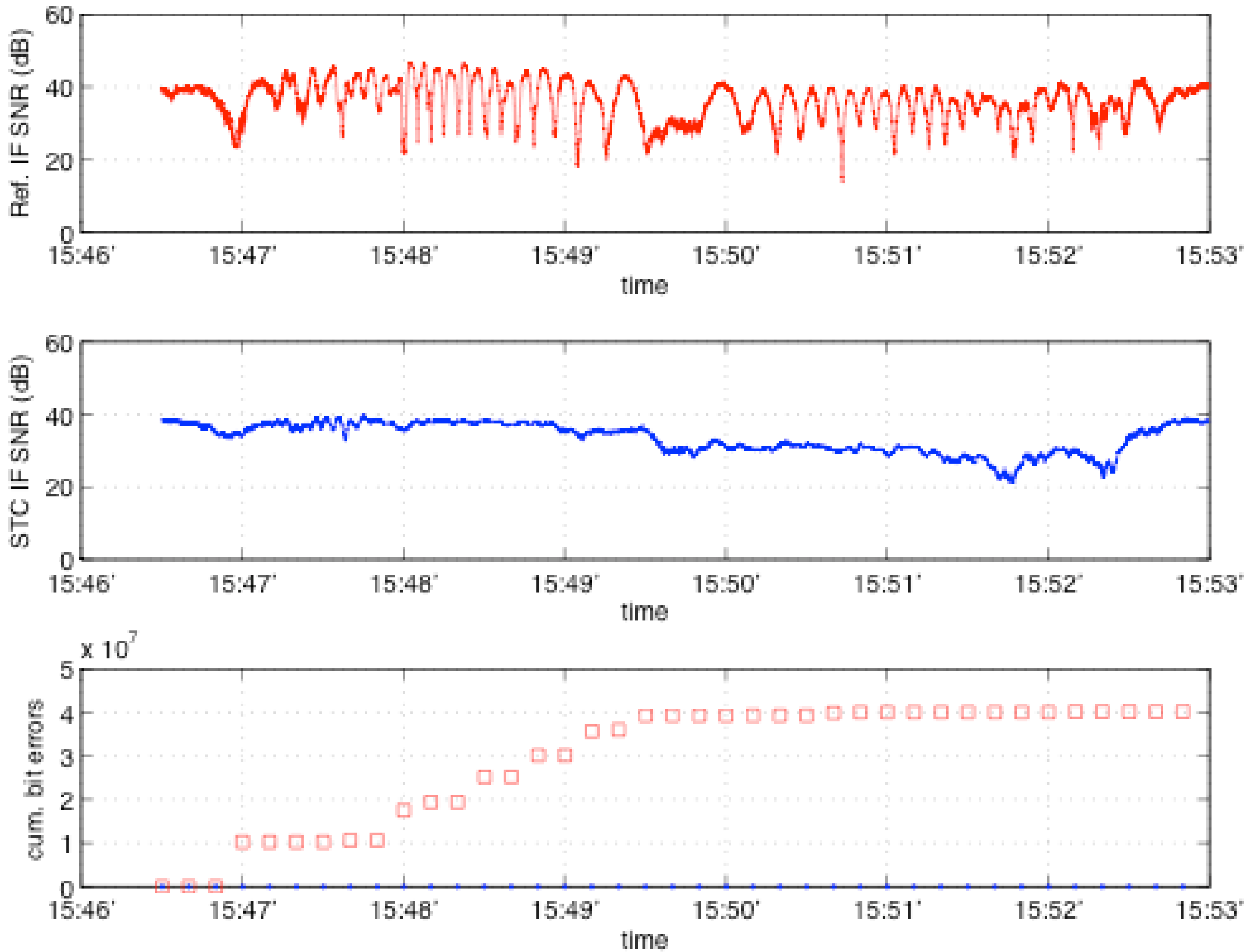
BYU

- Jump to file: stc-video.mp4
  - Or, click to view on our website: STC vs Two-Antenna Video



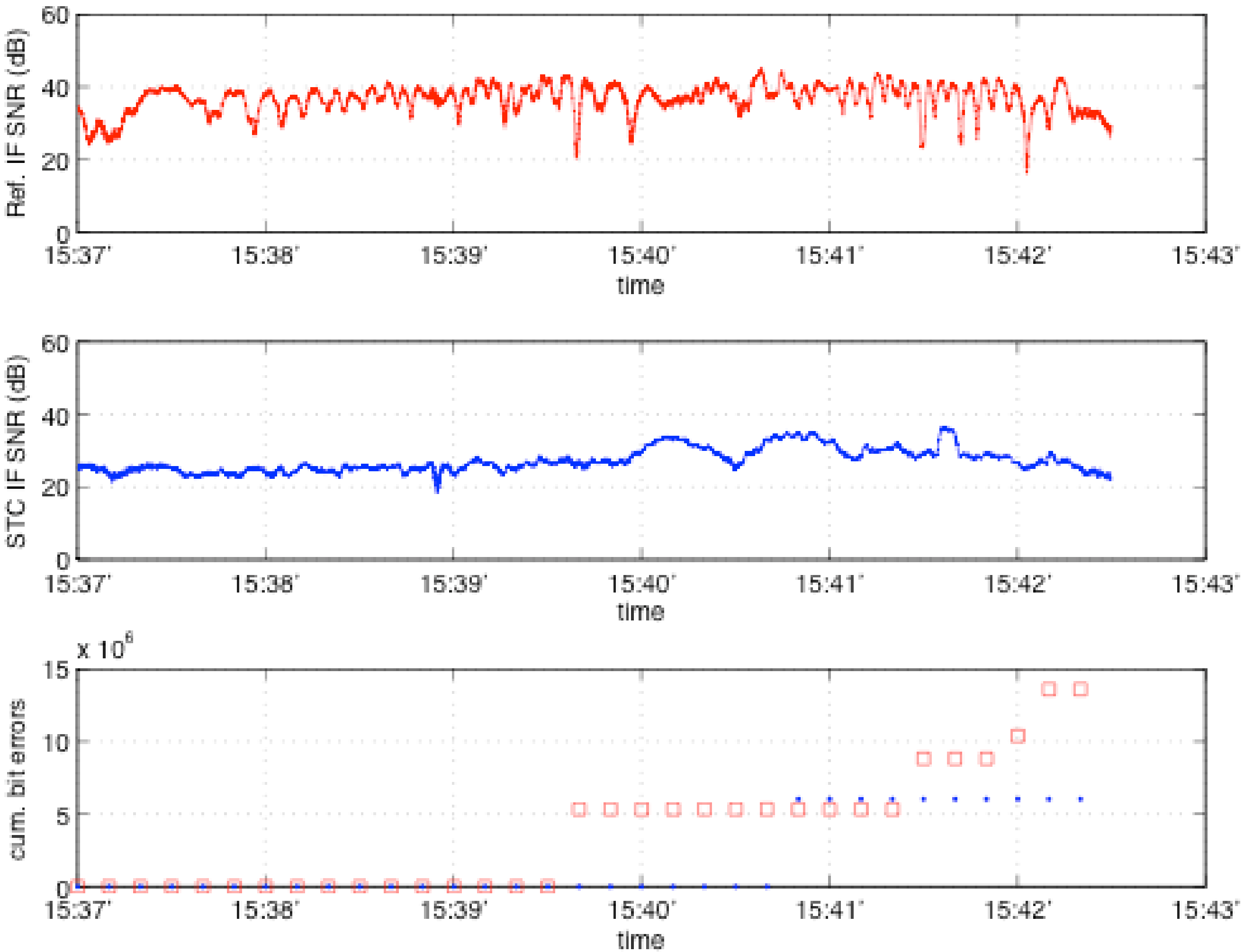
M1: Test Results

BYU

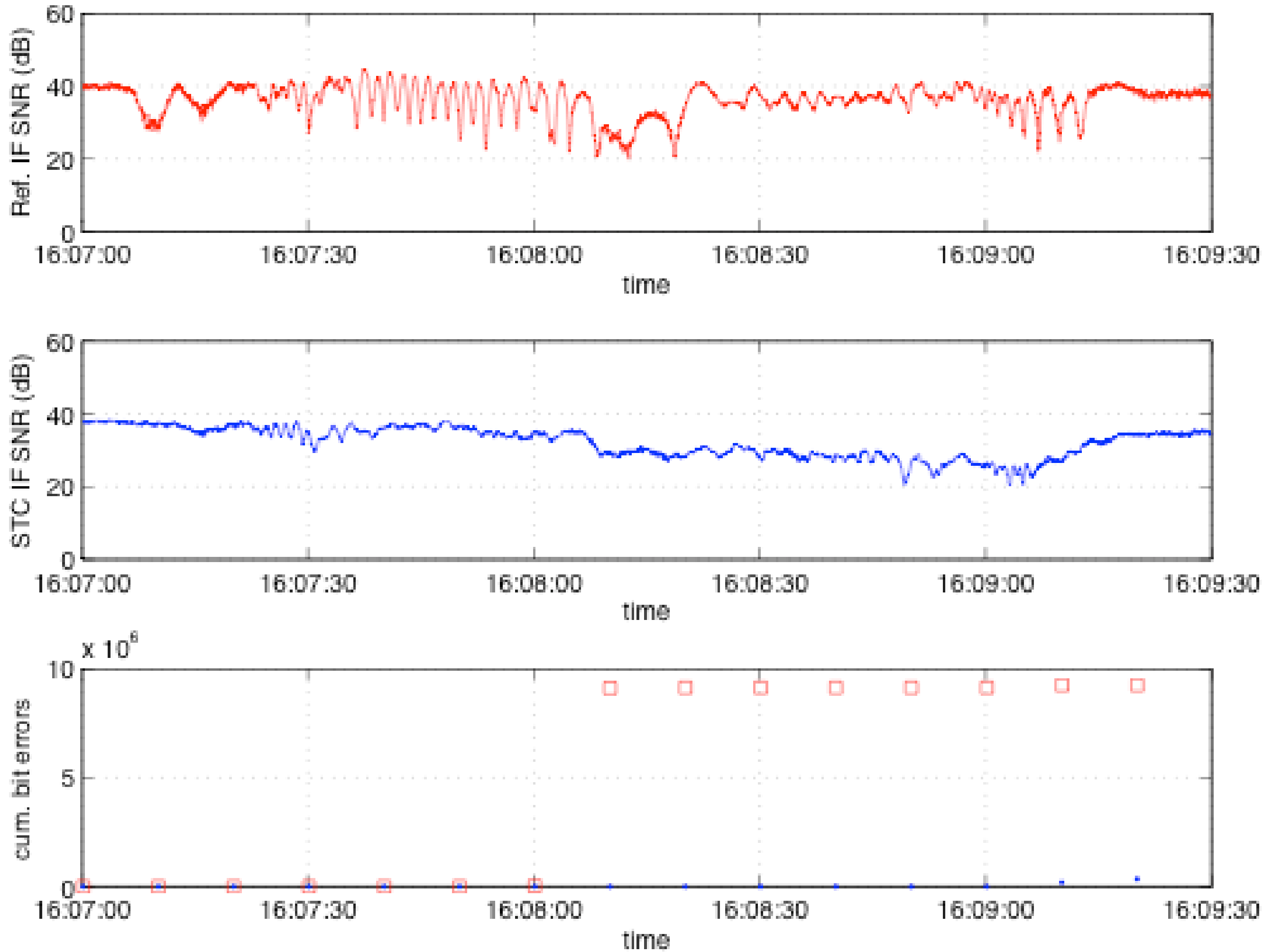


M2: Test Results

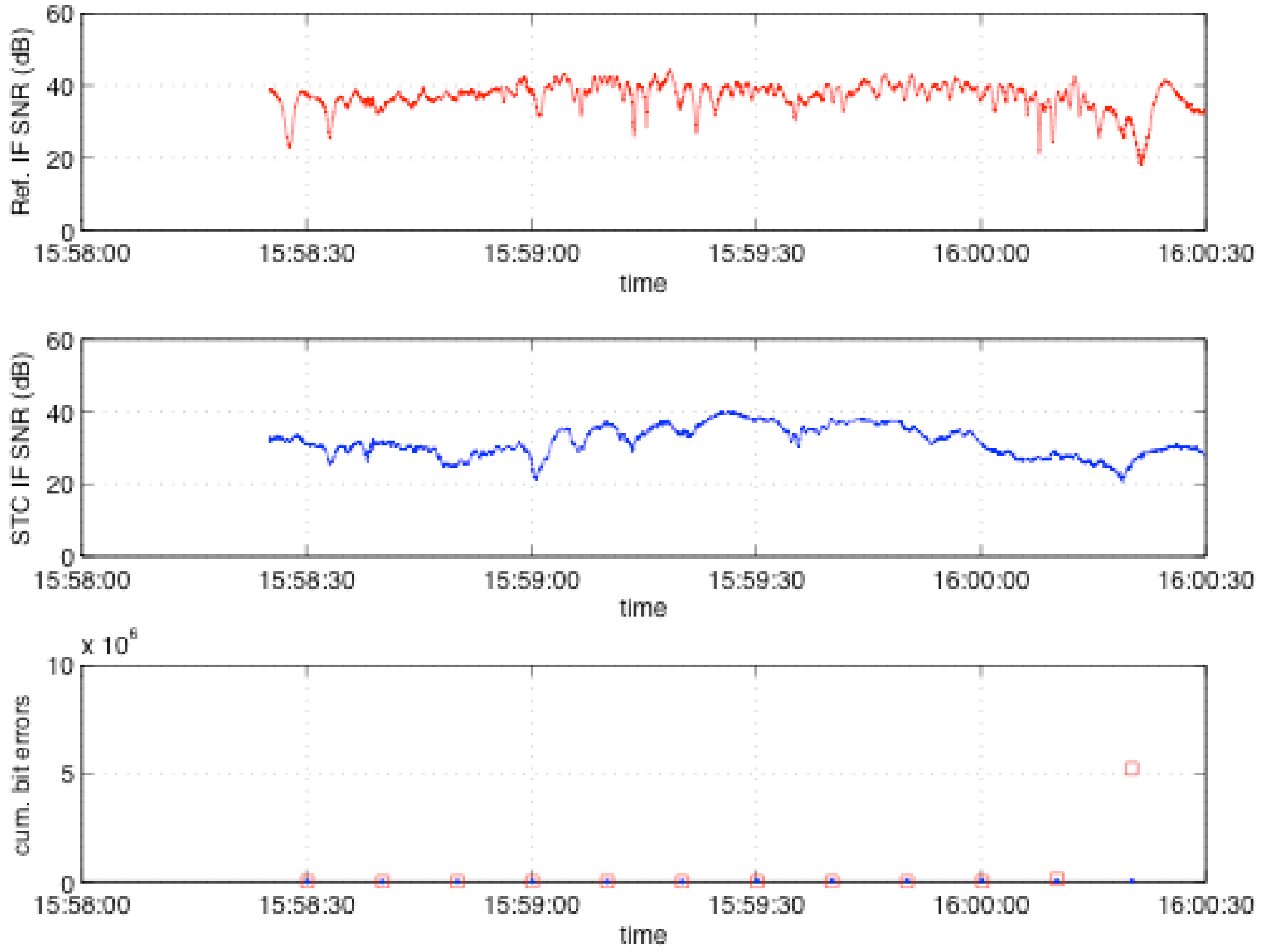
BYU



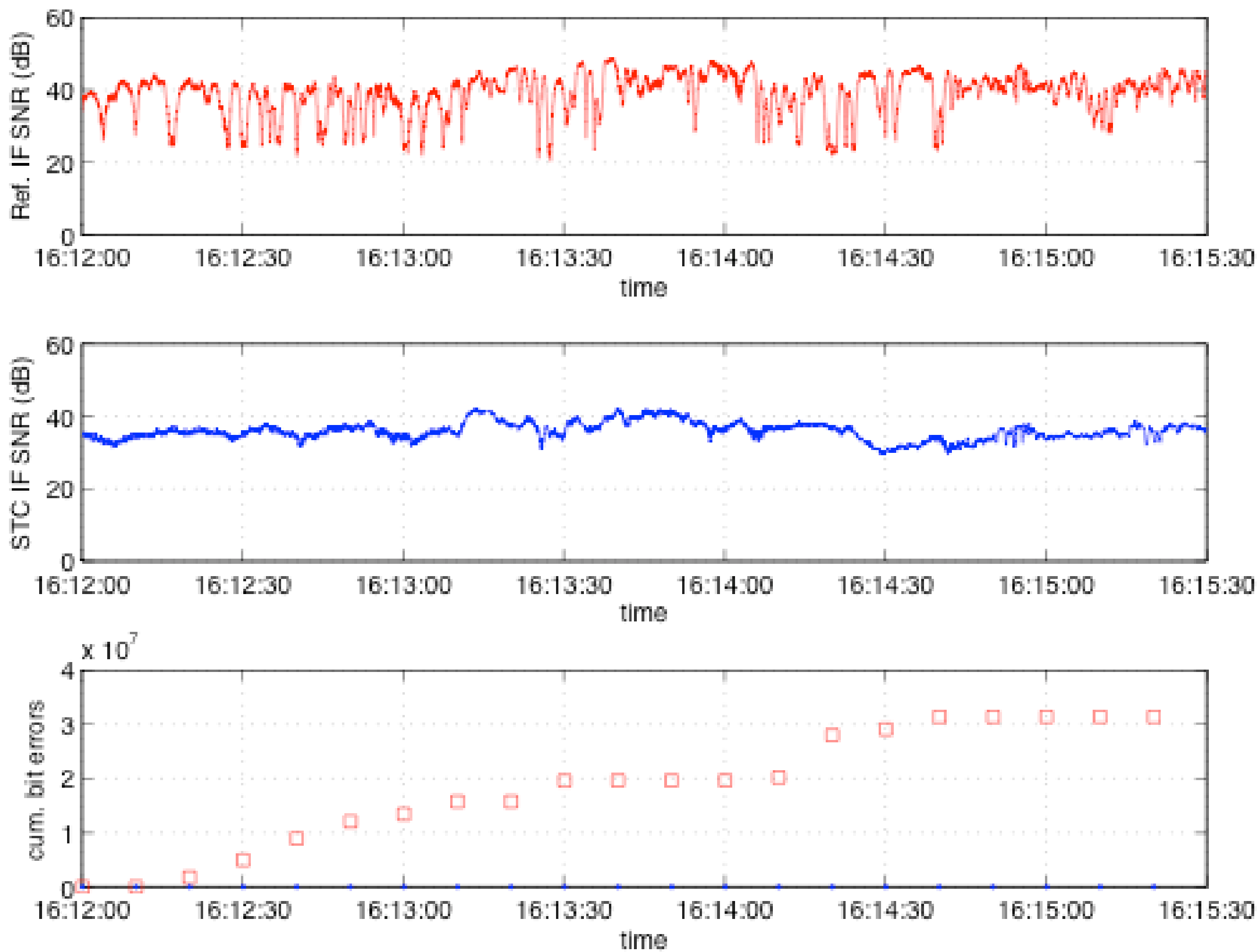
M3: Test Results



M4: Test Results

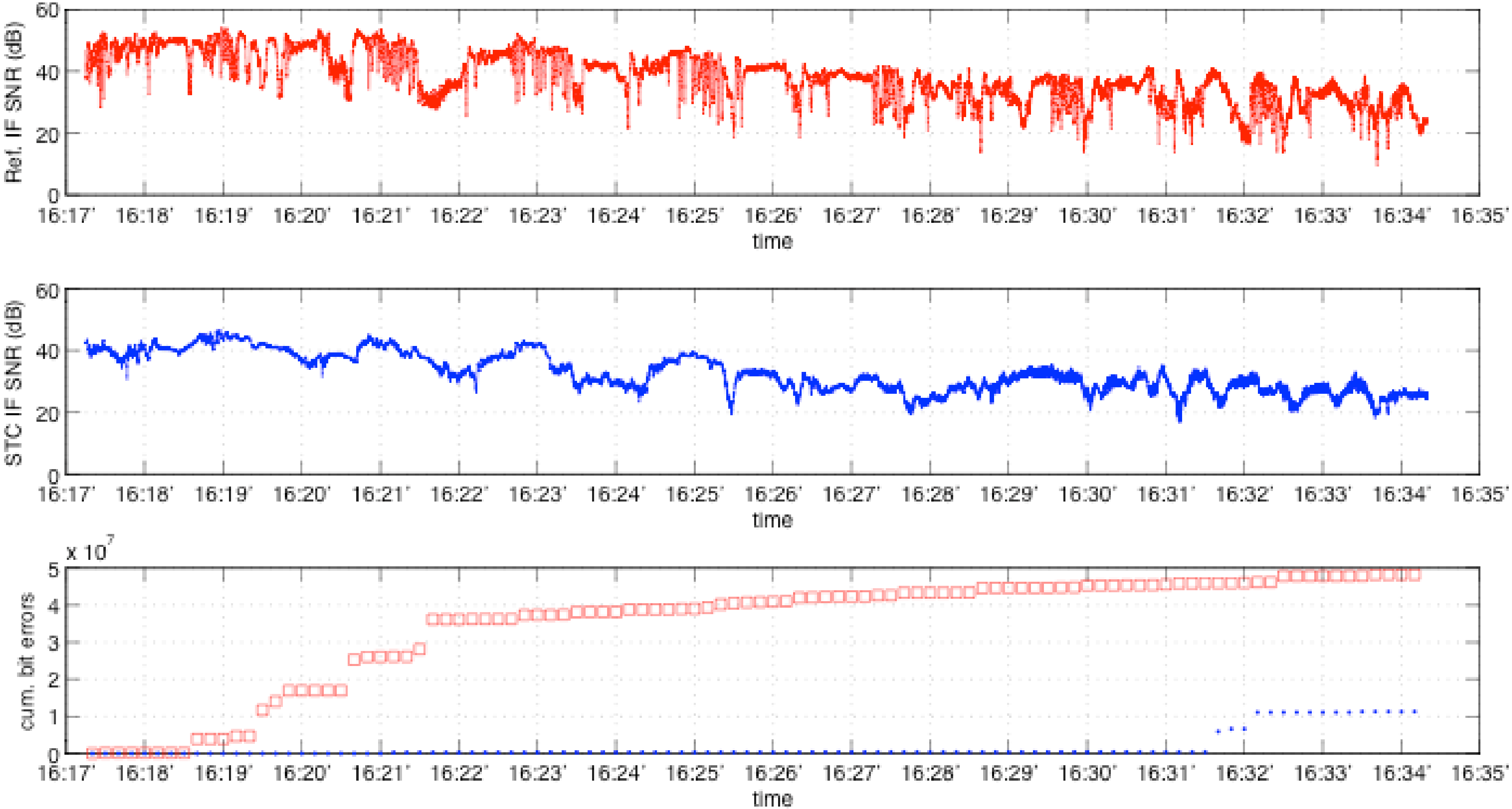


M3 to C2 Transition Test Results



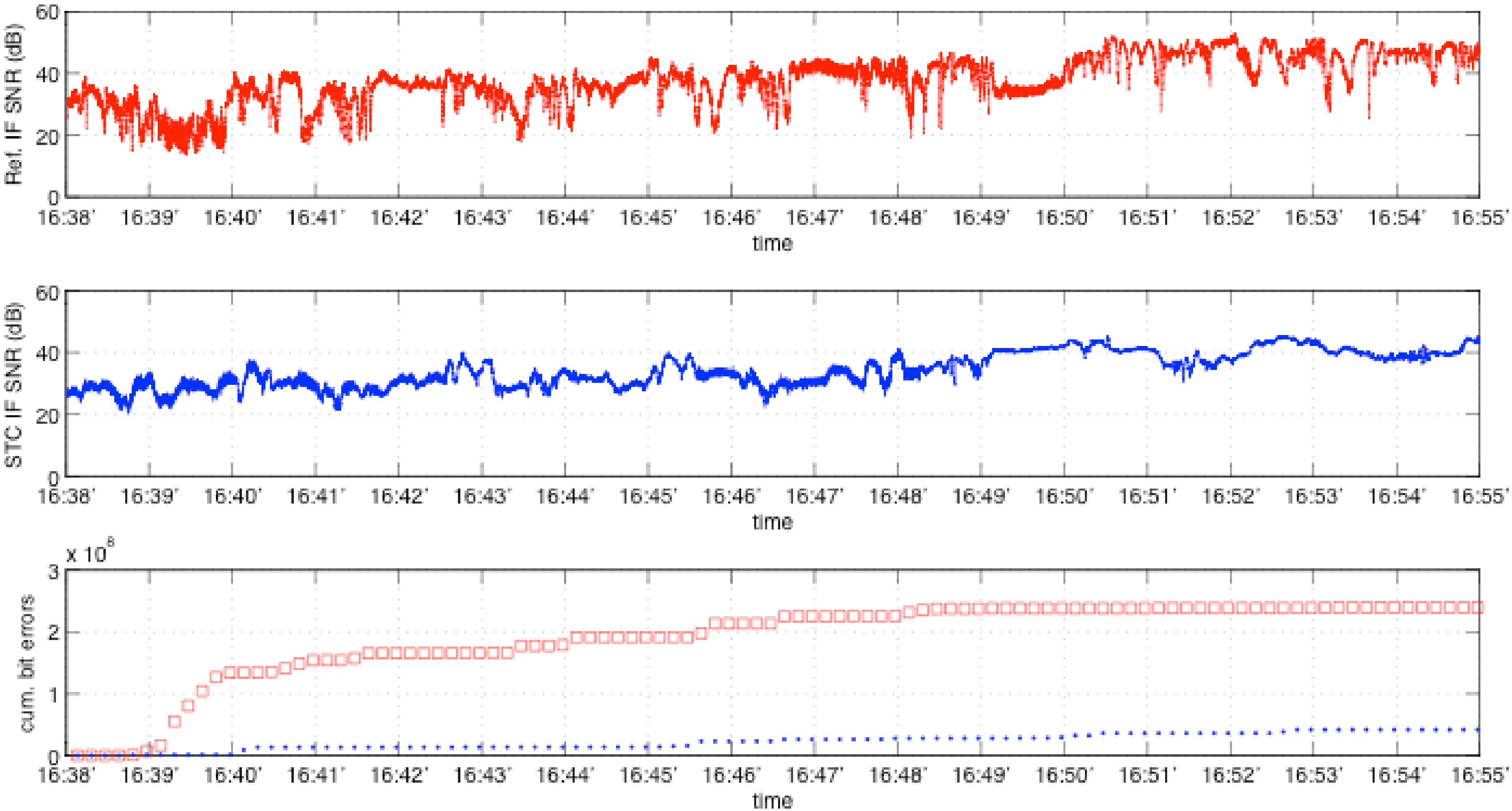
C2: Test Results

BYU



D2: Test Results

BYU



STC Summary

- Dual-Antenna Diversity Scheme
- Removes dropouts 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

Forward Error Correction

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
  - Concatenated codes
    - RS / Viterbi
    - Turbo product codes (TPC)
  - Low Density Parity Check (LDPC)

LDPC Codes - History

- LDPC: Low Density Parity Check
- Linear block codes
  - Some are systematic
- Developed by Robert G. Gallager at M.I.T. in 1960
  - Published by the M.I.T Press as a monograph in 1963
- No practical implementations at that time
- Re-discovered by David J.C. MacKay in 1996
  - Began displacing turbo codes in the late 1990s
- Recent history
  - 2003: LDPC code selected for the new DVB-S2 standard for the satellite digital TV
  - 2006: LDPC code selected for 10GBase-T Ethernet (10 Gbps over twisted-pair cables)
  - 2007: LDPC codes published by CCSDS as an “Orange Book”
  - 2008: LDPC code selected for the ITU-T G.hn standard
  - 2009: LDPC codes adopted for Wi-Fi 802.11 High Throughput (HT) PHY specification
  - 2012: LDPC code selected for integrated Network Enhanced Telemetry (iNET)

LDPC AR4JA Codes

- AR4JA: Accumulate-Repeat-4-Jagged-Accumulate
- Published by CCSDS as an “Orange Book”
  - Low Density Parity Check Codes For Use in Near-Earth and Deep Space Applications
- Defines a family of systematic LDPC codes

Information block length k	Code block length n		
	rate 1/2	rate 2/3	rate 4/5
1024	2048	1536	1280
4096	8192	6144	5120
16384	32768	24576	20480

- Defines attached sync markers (ASM)
  - Specified in section 6 of CCSDS Recommended Standard CCSDS 131.0-B-1
- Present work based on the (6144, 4096) code

Packet Assembly

- Input 4096 data bits
  - Randomize prior to encoding, if necessary
- Compute and append 2048 parity bits
- Prepend 256-bit attached sync marker (ASM)
  - Yields a 6400-bit packet
  - Each and every code word carries the ASM: A, A, Ā, A
    - A = FCB88938D8D76A4F
    - Ā = 034776C7272895B0
  - Synchronization requires at most one code word

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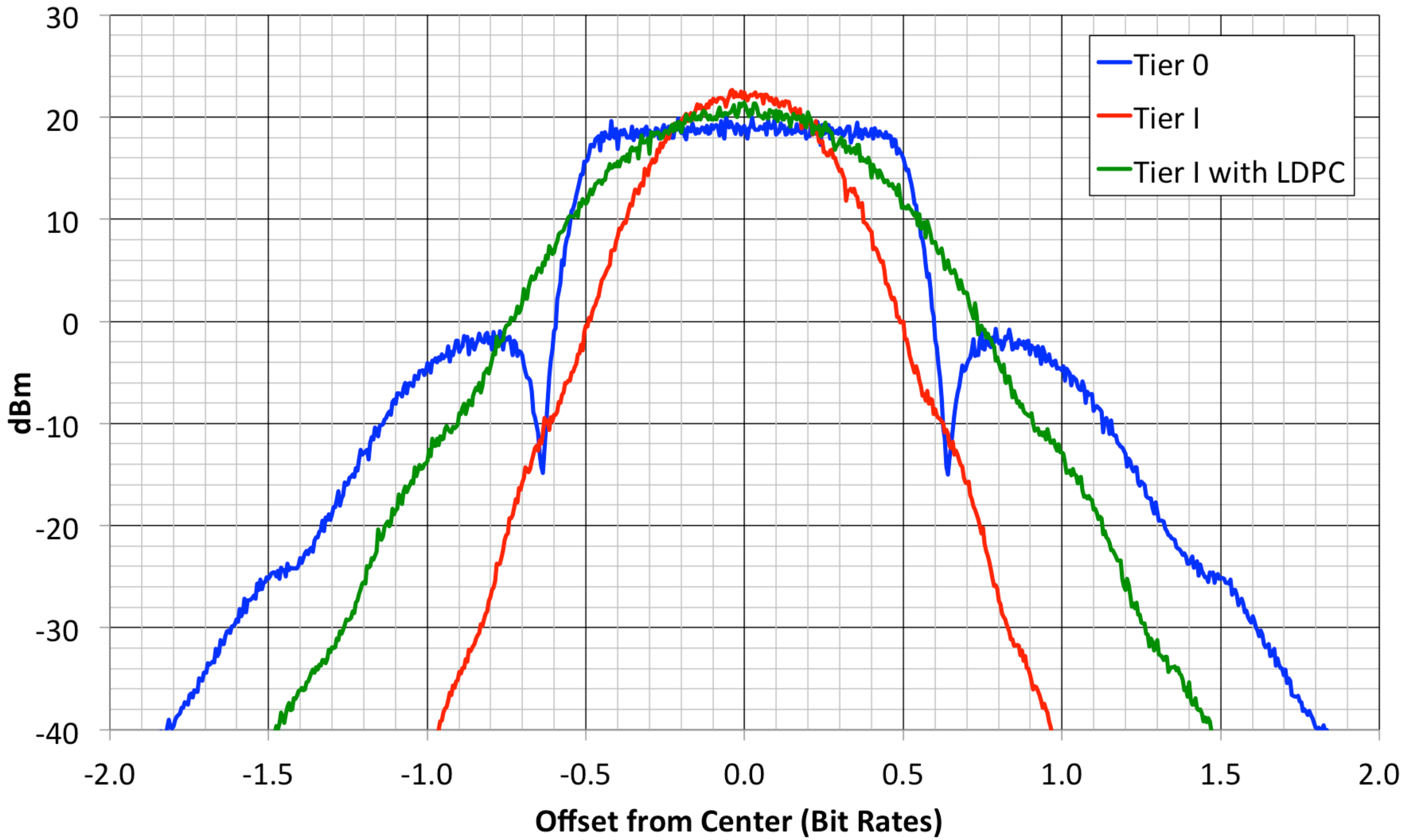
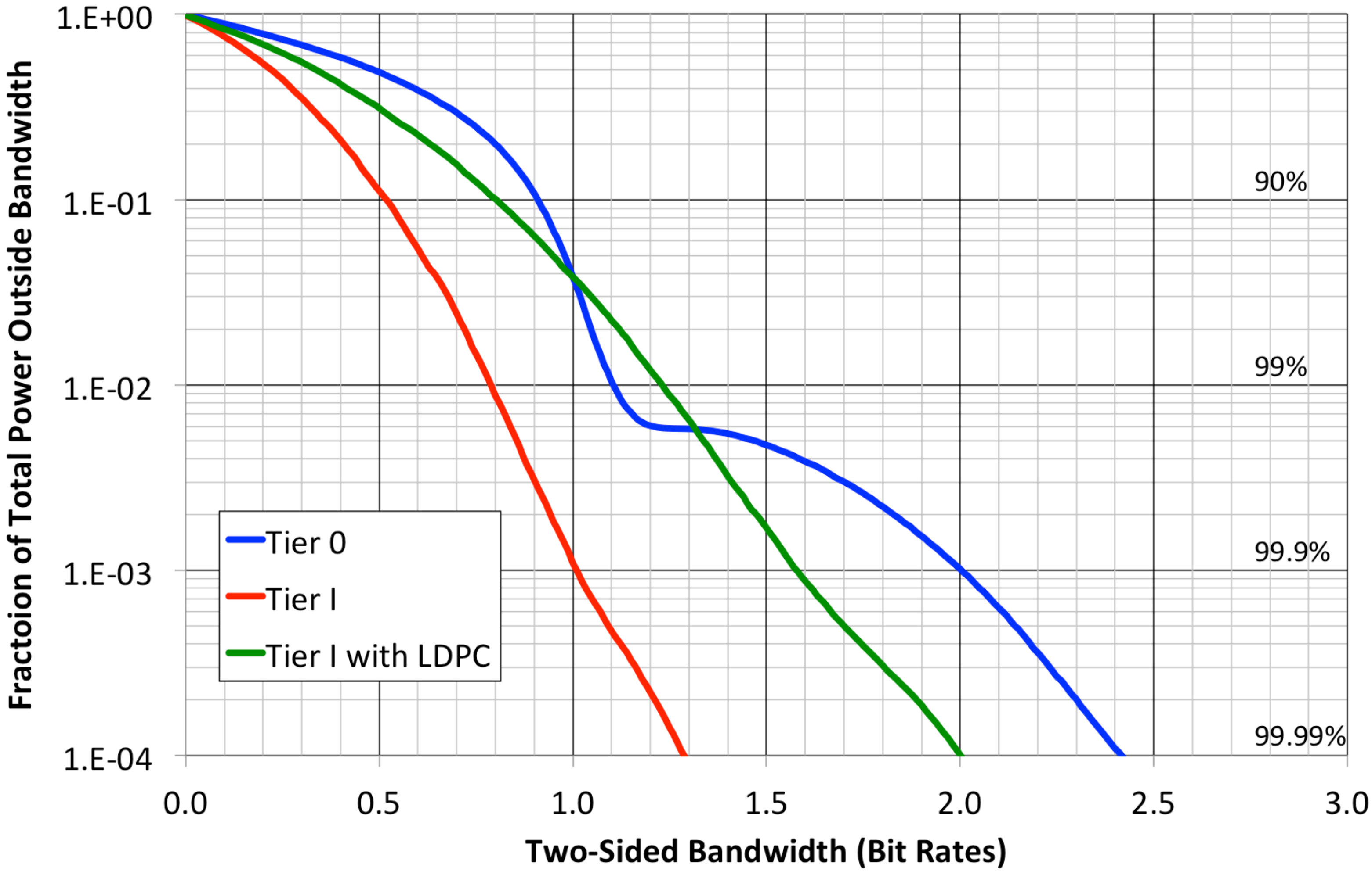
Spectral Characterization



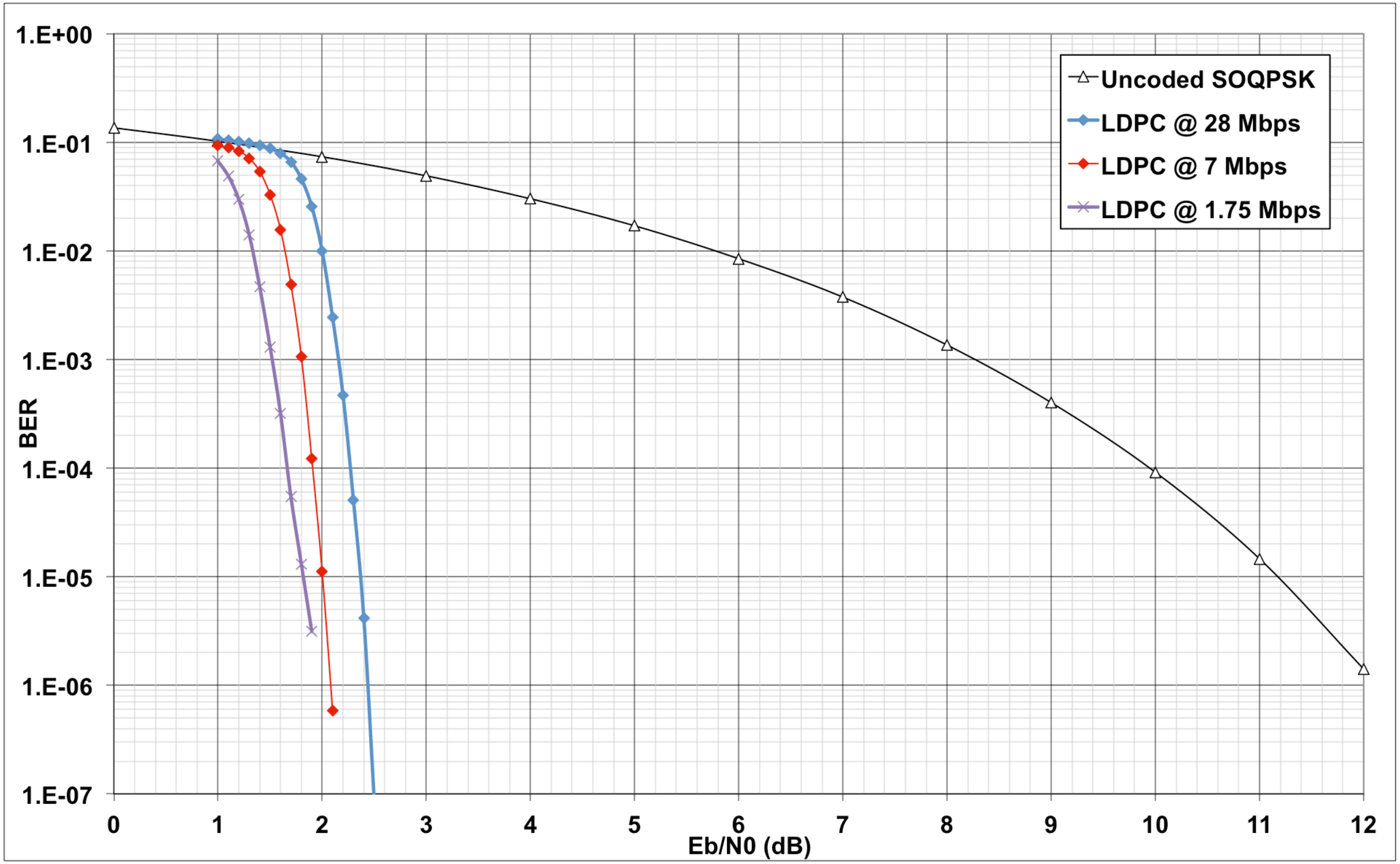
Fractional Out-of-Band Power



Decoder

- Demodulate SOQPSK with soft decisions
  - Implemented 8-bit decisions
    - Iterative decoders work best with high resolution soft decisions
  - Estimate E_b/N_0 for soft decision scaling
- Correlate for ASM with hard decisions
  - Resolves the 4-ary phase ambiguity in SOQPSK
  - Virtually certain sync at E_b/N_0 = 0 dB
- Initialize decoder
- Execute decode iterations until next code word
  - Coding gain varies with bit rate

Measured BER Results



LDPC from Appendix 2-D

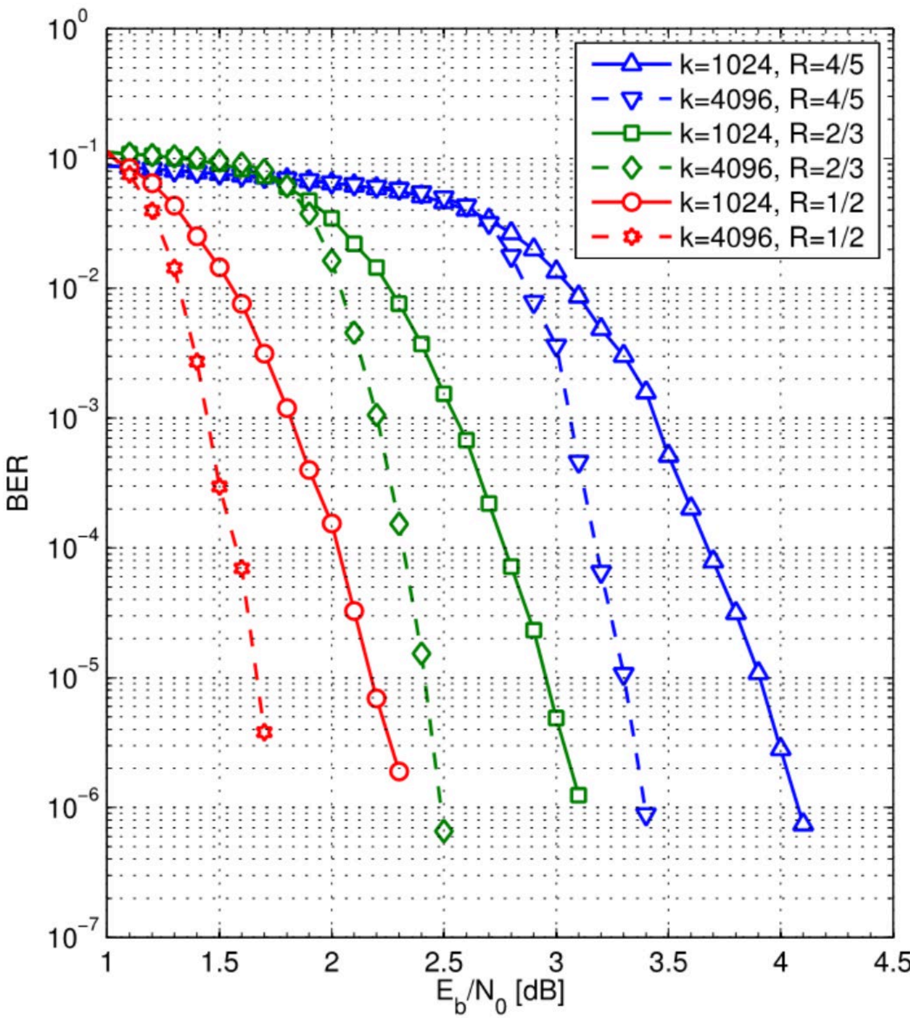
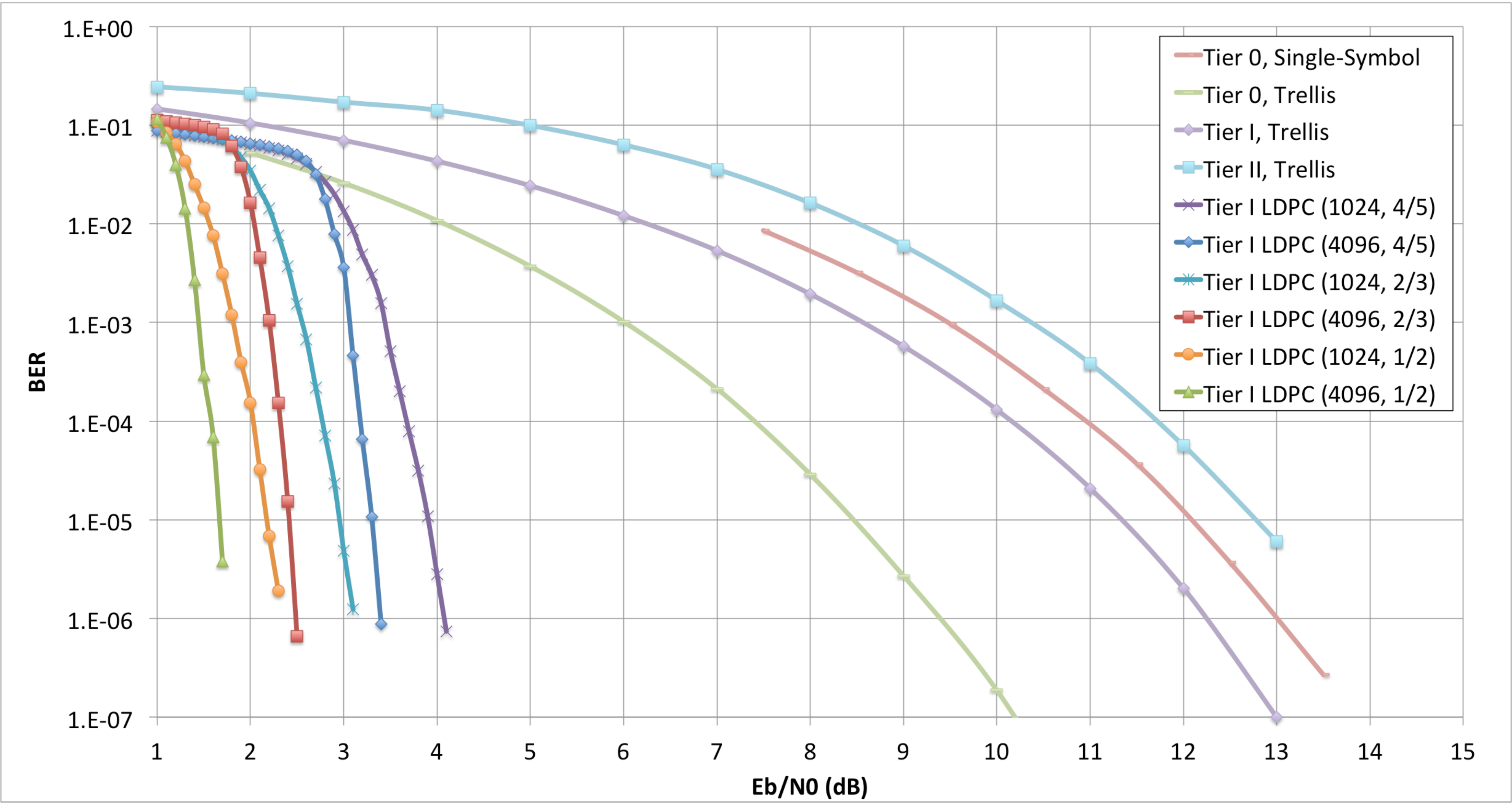


Table D-11. Bandwidth Expansion Factor

Information Block Length, *k*	Bandwidth Expansion Factor		
	Rate 1/2	Rate 2/3	Rate 4/5
1024	33/16	25/16	21/16
4096	33/16	25/16	21/16

BER – All Modes



Conclusions

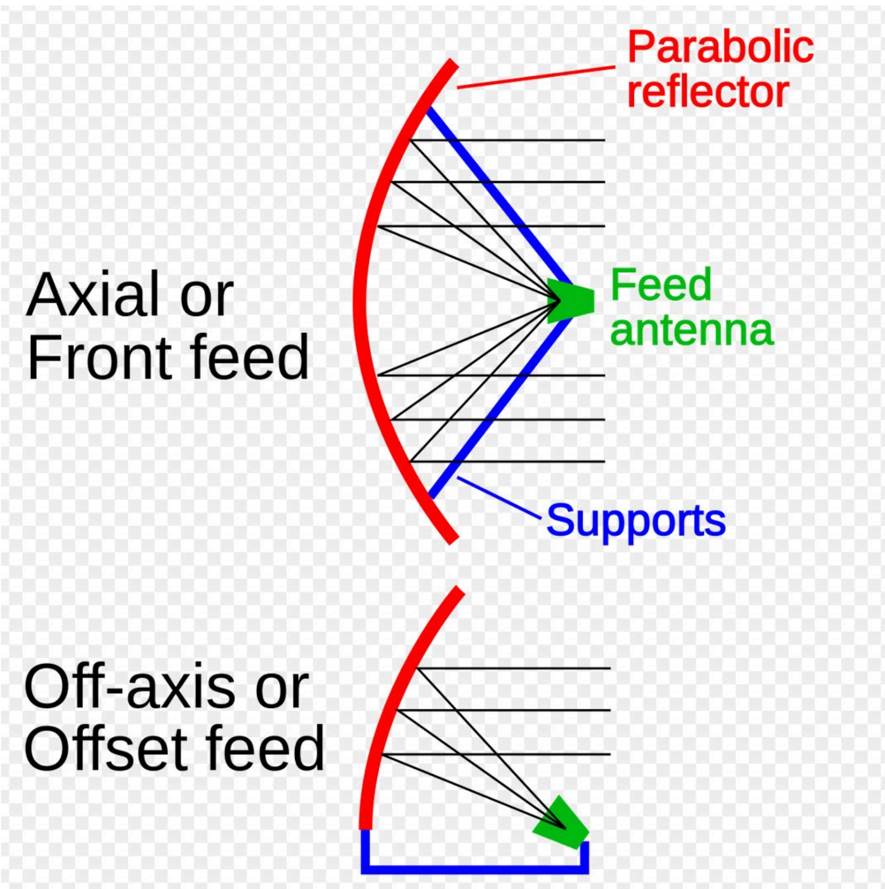
- Rate 2/3 LDPC code yields ≈9 dB coding gain relative to uncoded SOQPSK
  - ±0.5 dB, depending on data rate
- 256-bit ASM provides reliable, fast synchronization at Eb/N0 < 0 dB
  - Synchronization is consistently achieved in < 4096 data bits
- Bandwidth expansion of 25/16
  - Still 22% less bandwidth than legacy PCM/FM
- SOQPSK with LDPC offers a reasonable trade of spectral efficiency for a significant gain in detection efficiency
- 5 other LDPC codes offer similar trade of bandwidth for BER performance

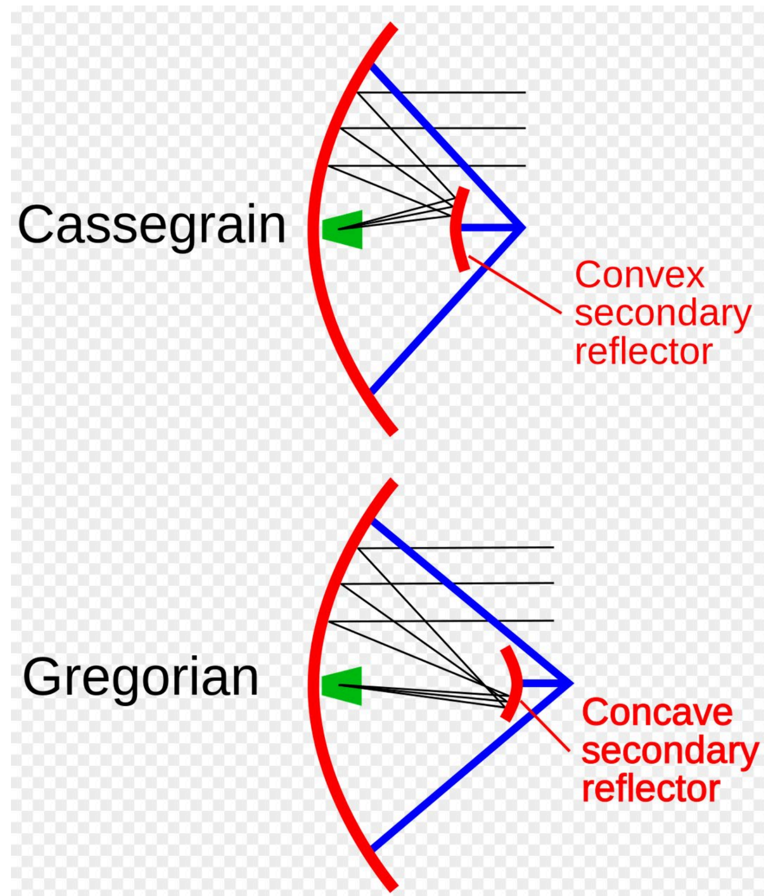
Auto-Tracking Antennas

Can You Hear Me NOW?

- Reflectors focus energy on the feed
- Bigger reflectors capture more energy
- Bigger reflectors see a smaller spot in the sky

House of Mirrors



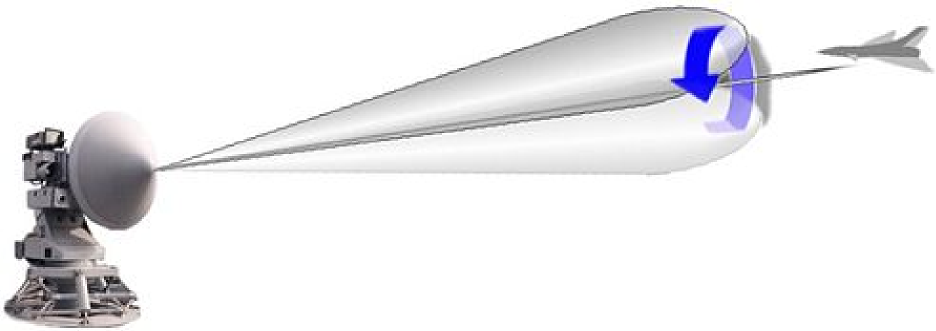


Antenna Gain

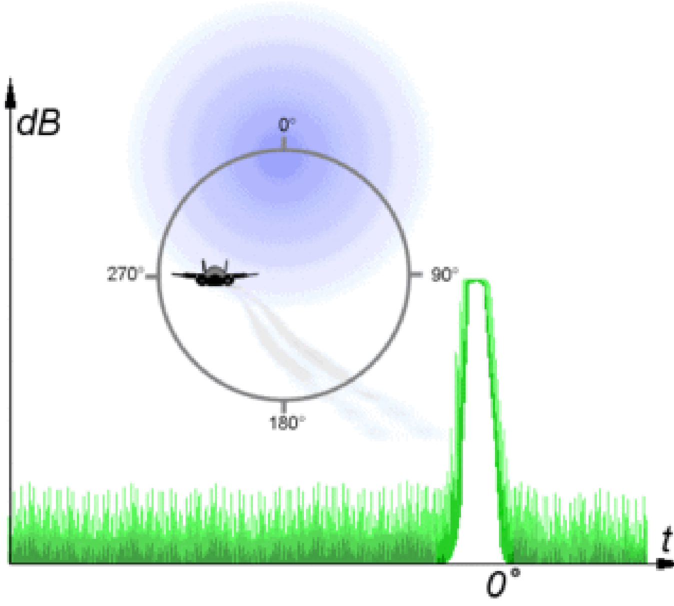
$$G = \frac{4\pi A}{\lambda^2} e_A = \left(\frac{\pi d}{\lambda}\right)^2 e_A$$

- A is the area of the antenna aperture, that is, the mouth of the parabolic reflector. For a circular dish antenna, $A = \pi d^2/4$, giving the second formula above.
- d is the diameter of the parabolic reflector, if it is circular
- λ is the wavelength of the radio waves.
- e_A is a dimensionless parameter between 0 and 1 called the *aperture efficiency*.

Autotracking Antennas

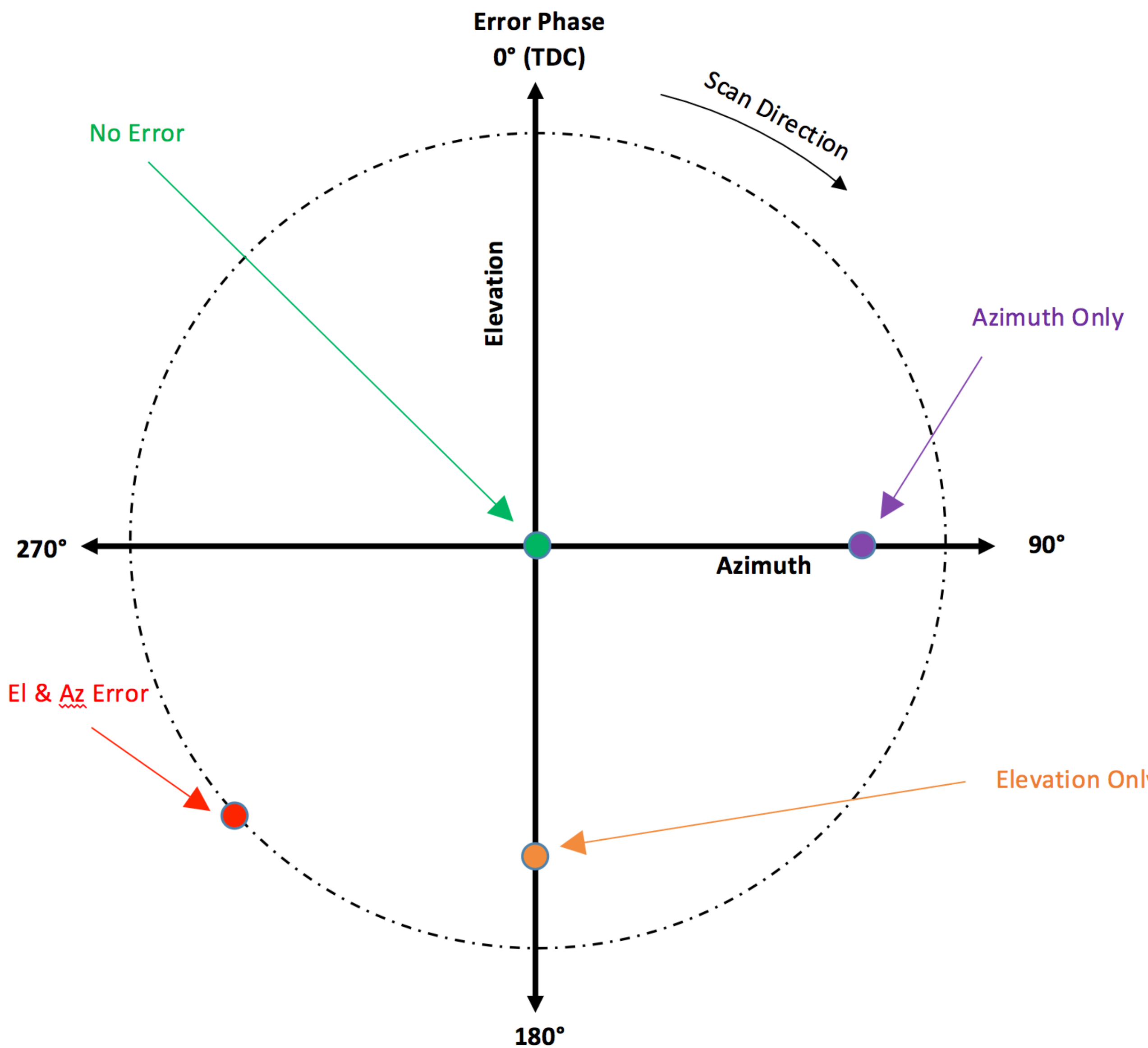


- Tracking antennas steer the receiving beam through space, producing amplitude modulation (AM) on the RF signal.
- For a Con-Scan system this is done by mechanically nutating a waveguide, resulting in a continuous AM error signal.
- For a Monopulse system this is done by electronically switching the RF difference signal and coupling it into the RF sum channel, resulting in a stepped AM signal.
- AM allows the receiving antenna to follow the target with minimal or no operator interaction.



Pointing Error Calculation

- Phase of the AM with respect to top dead center timing mark determines target location…



Quasonix

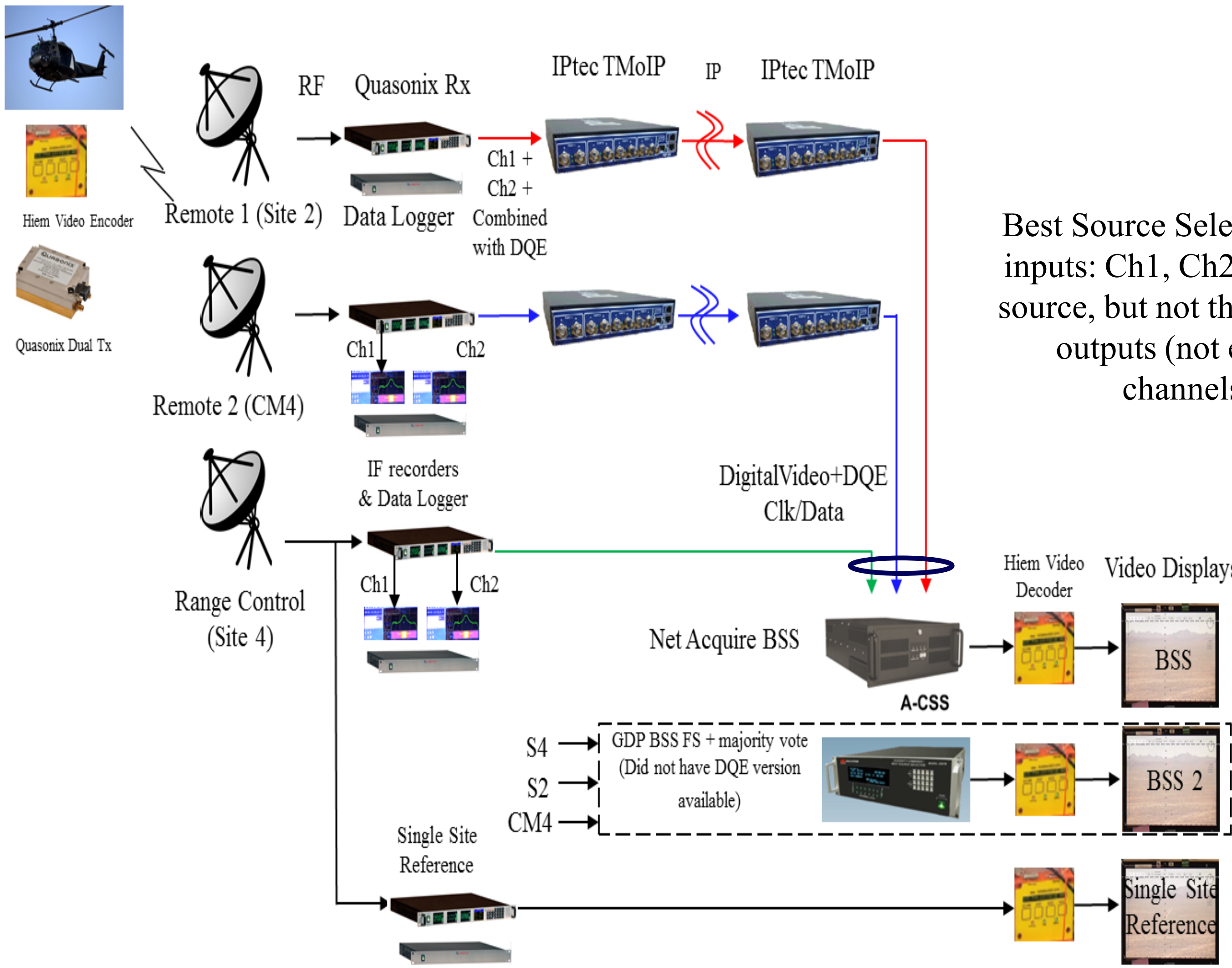
How Well Does It All Work Together?

Yuma Proving Grounds, AZ
Feb 8-11, 2016

Recipe for Delivering Every Bit

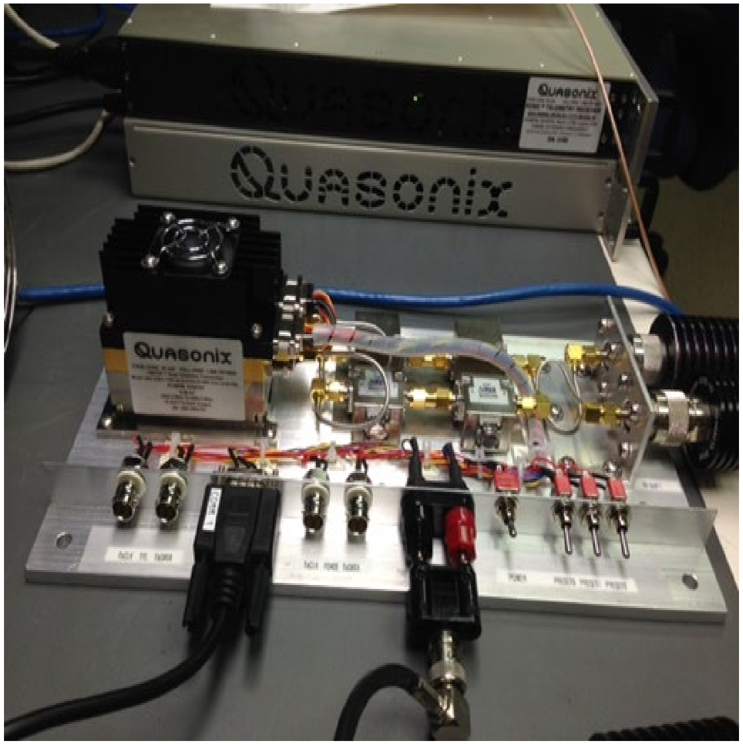
- Space Time Coding (STC)
  - Eliminates aircraft pattern nulls
- Low Density Parity Check (LDPC) coding
  - Improves margin, stops “dribbling errors”
- Adaptive Equalization (for non-STC signals)
  - Mitigates multipath
- Spatial diversity with correlating source selection
  - Eliminate coverage-based dropouts
  - Requires DQE/DQM for optimal operation
  - TMoIP makes delivery easy

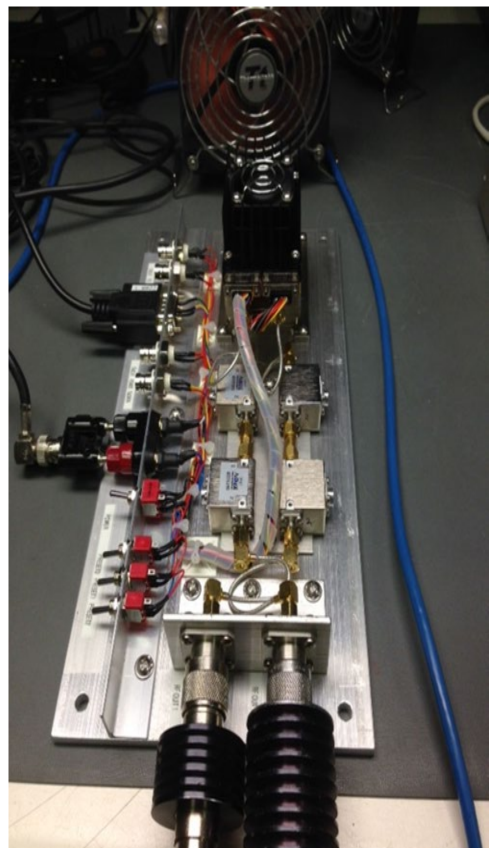
Multiple Receiving Sites



Best Source Selector used 6 inputs: Ch1, Ch2 from each source, but not the combiner outputs (not enough channels).

Dual Transmitter – S band – 10 W each output





Installed in UH-1 (Huey) helicopter with top and bottom blade antennas

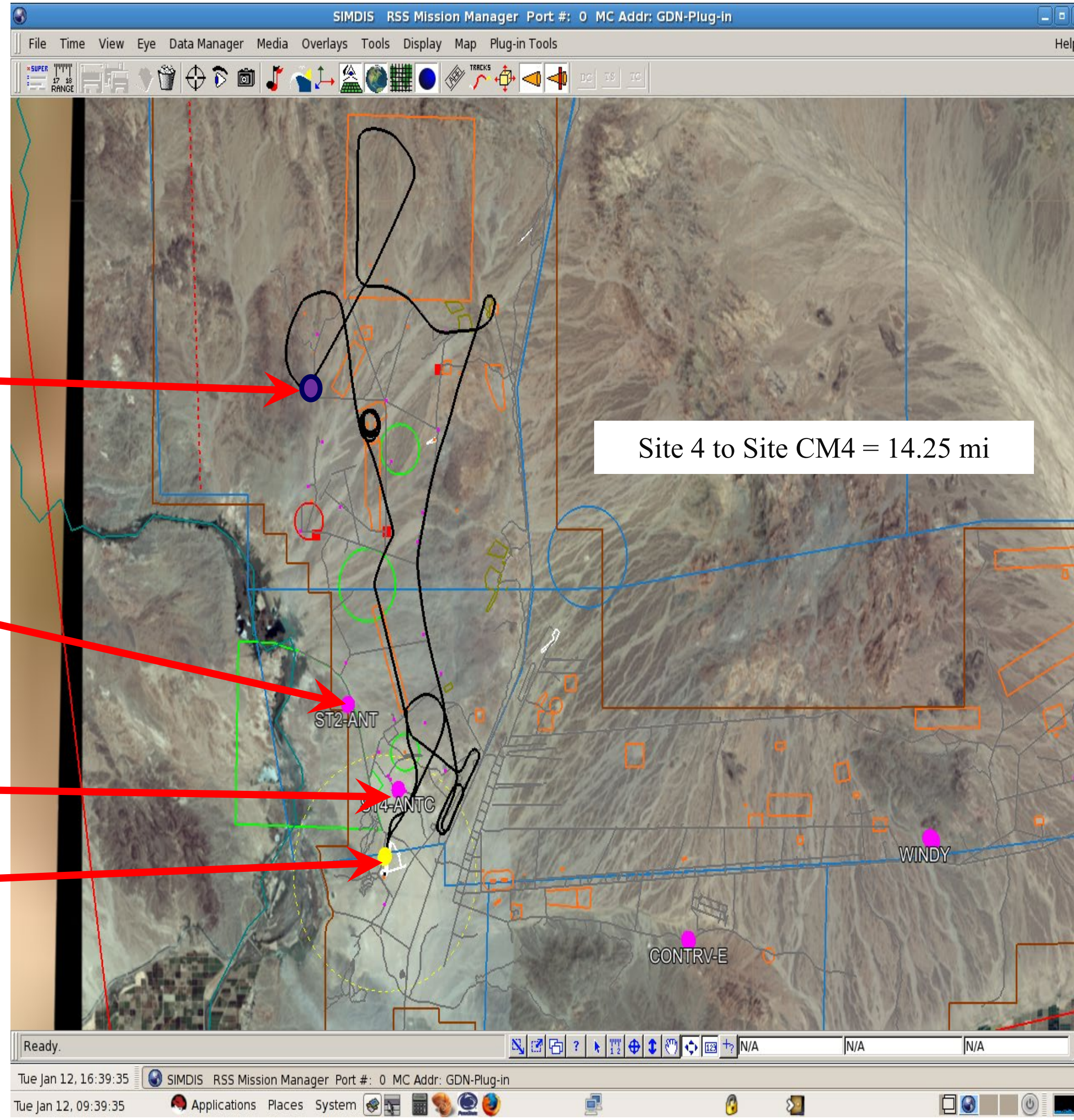
YPG Test Sites

Site CM4

Site 2

Site 4

Laguna Airfield



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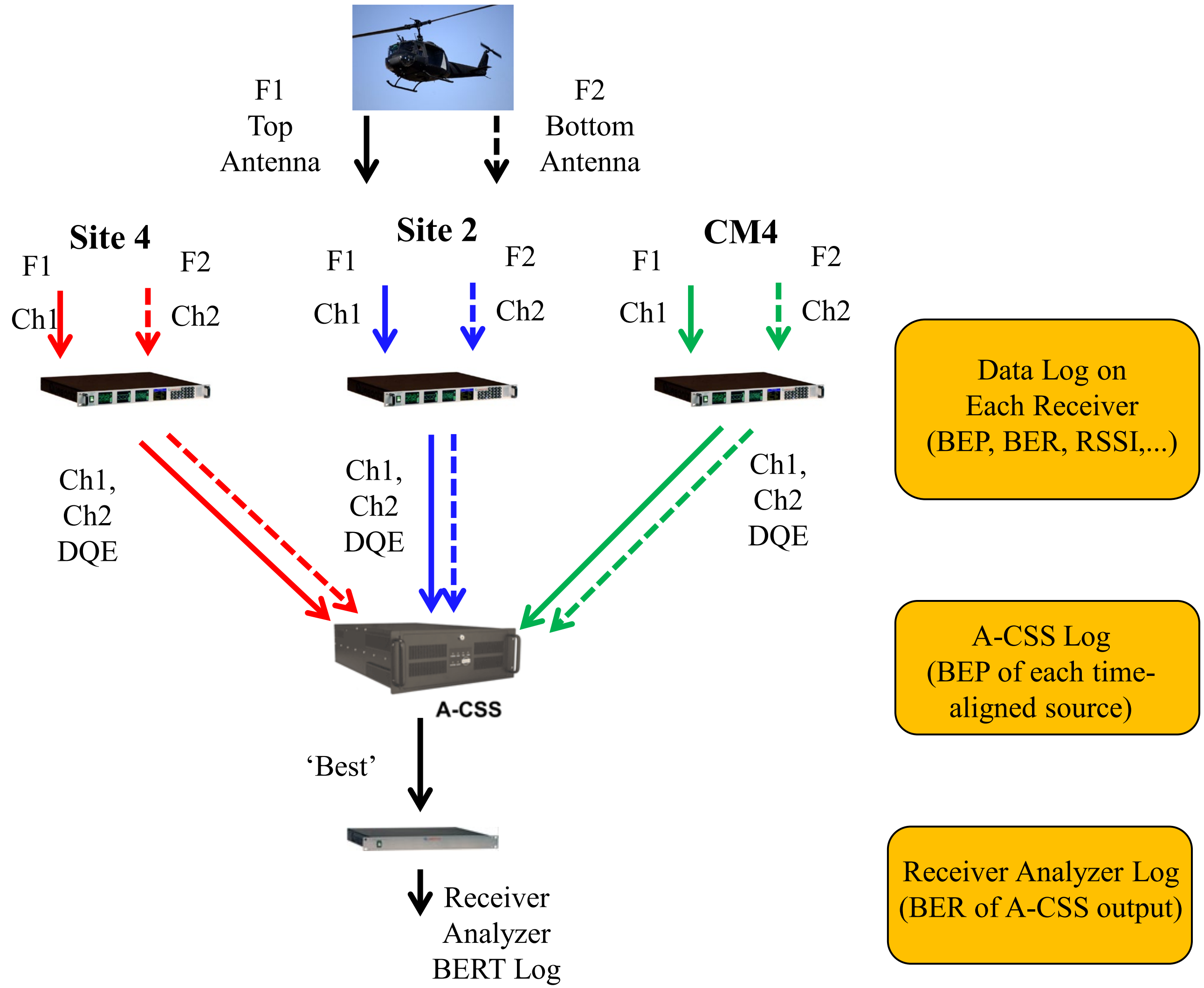
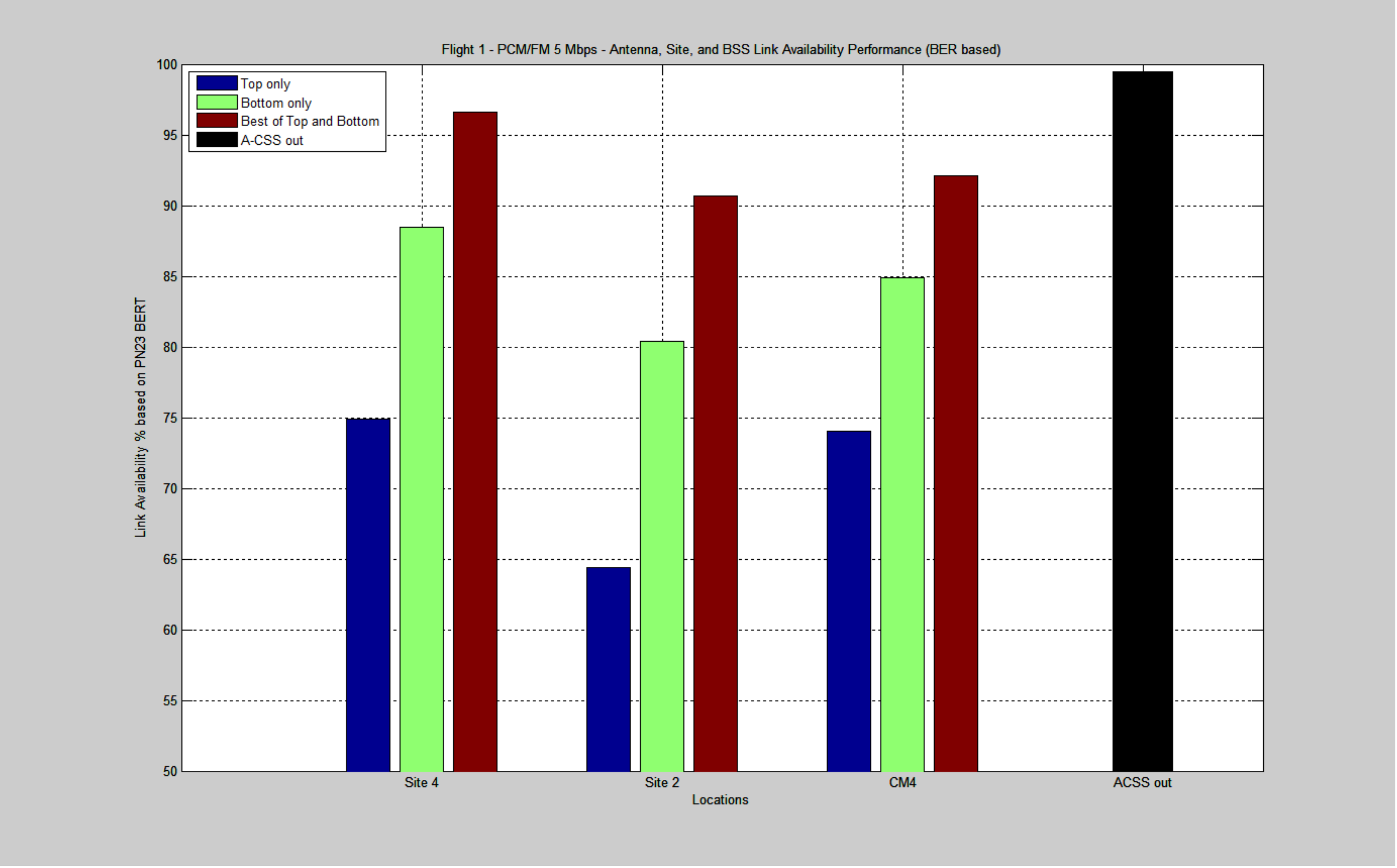
Analysis using Data Logs

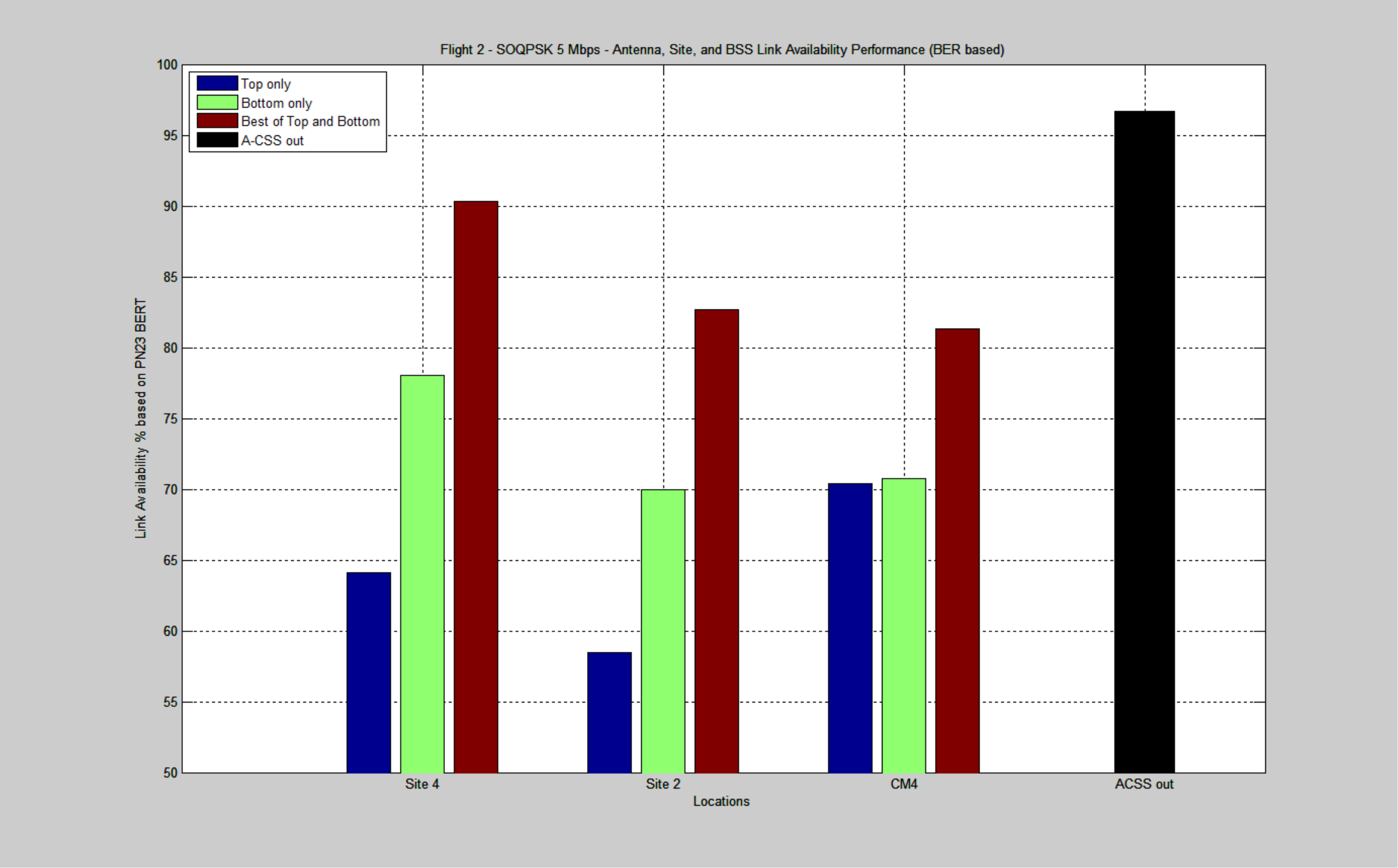


- Transmit F1-Top, F2-Bottom
- 3 Receive Sites
- 6 Clock & Data streams provided to A-CSS with Data Quality Encapsulation (DQE)
- DQE = Receiver inserts periodic estimate of instantaneous BEP
- Items of interest
  - Top vs Bottom Antenna
  - Individual Site Performance
  - Source Selector Performance

Flight 1 – PCM/FM 5 Mbps
Link Availability Summary (PN23 BER)



Flight 2 – SOQPSK 5 Mbps
Link Availability Summary (PN23 BER)



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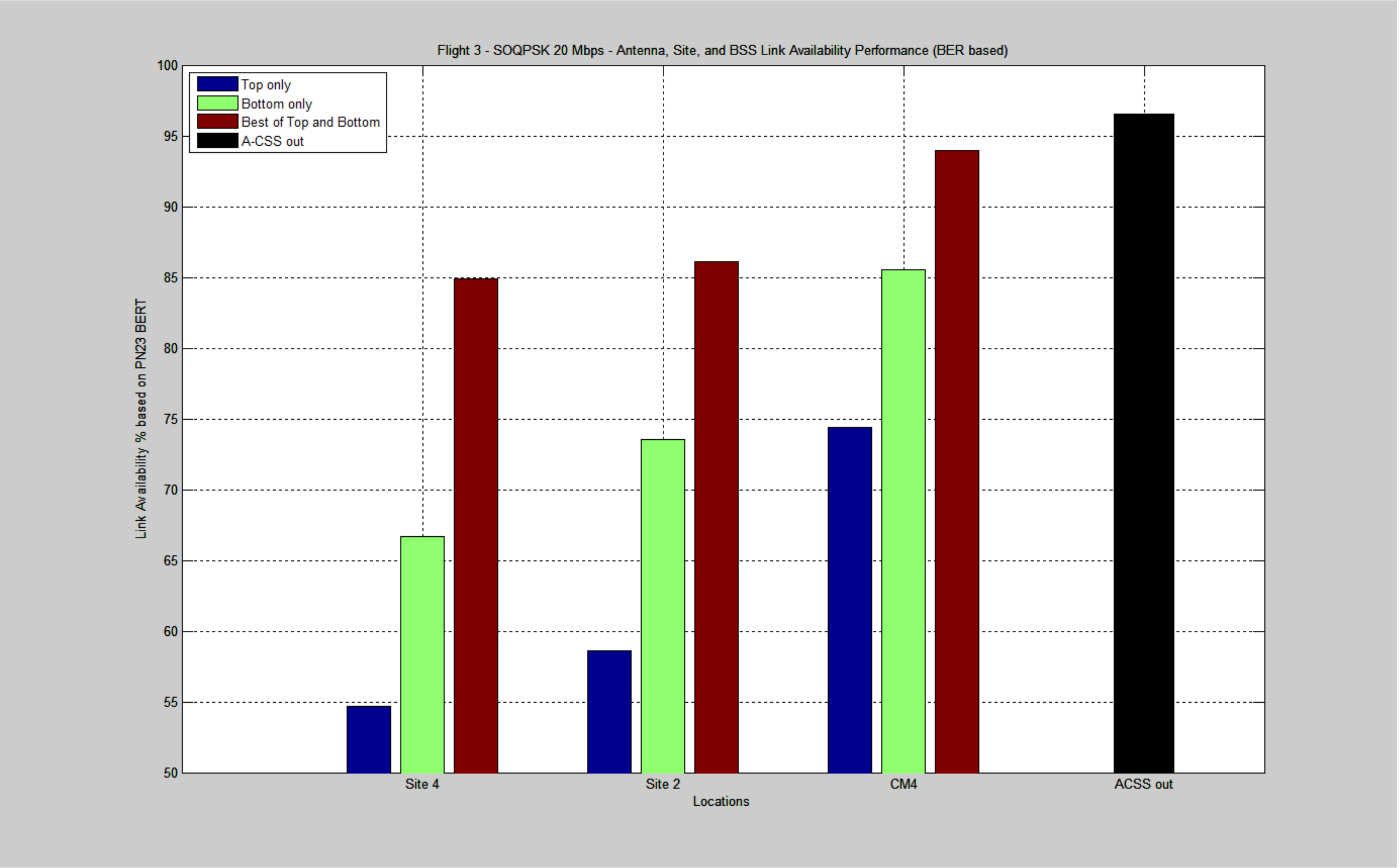
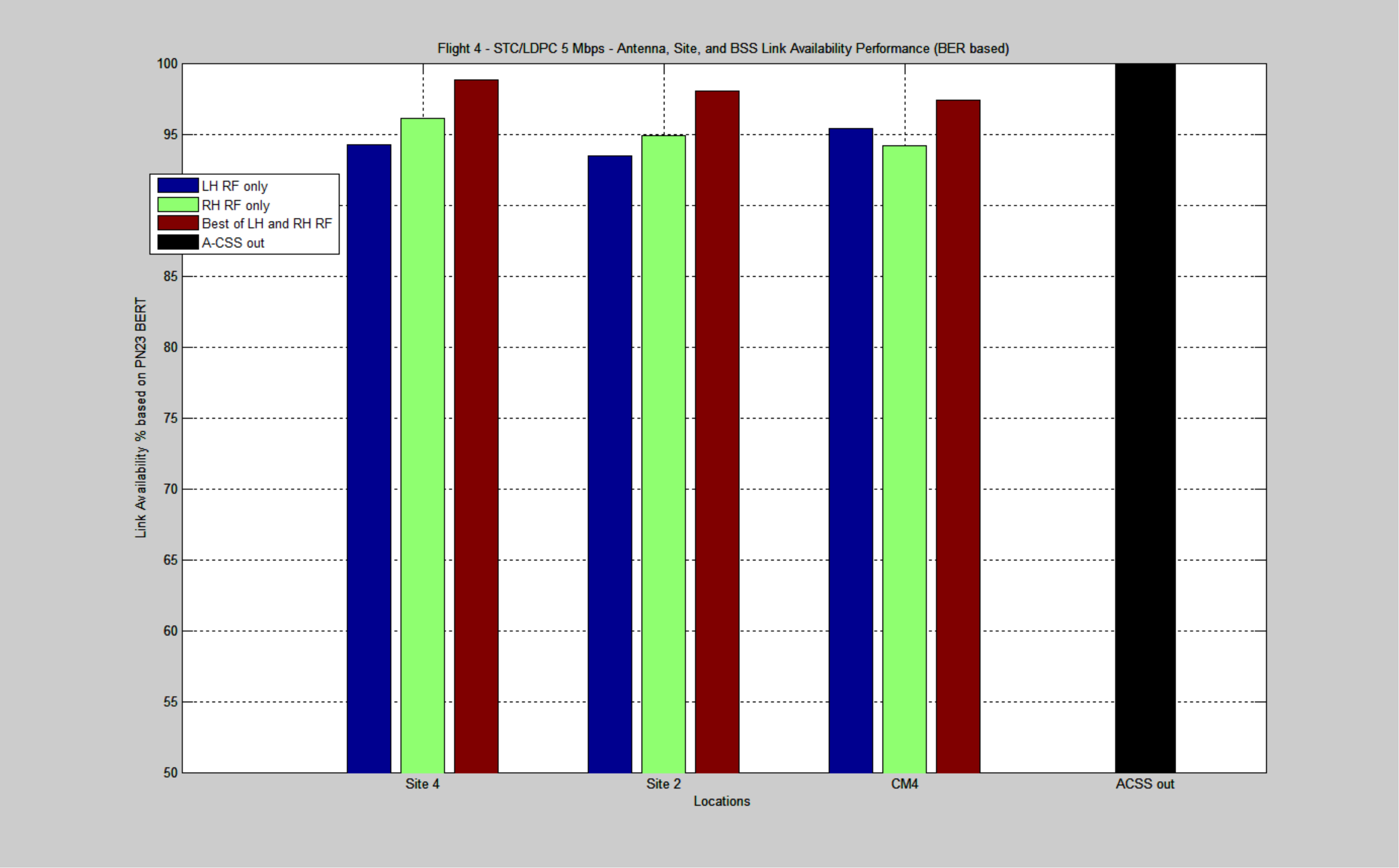
Flight 3 – SOQPSK 20 Mbps Link Availability Summary (PN23 BER)



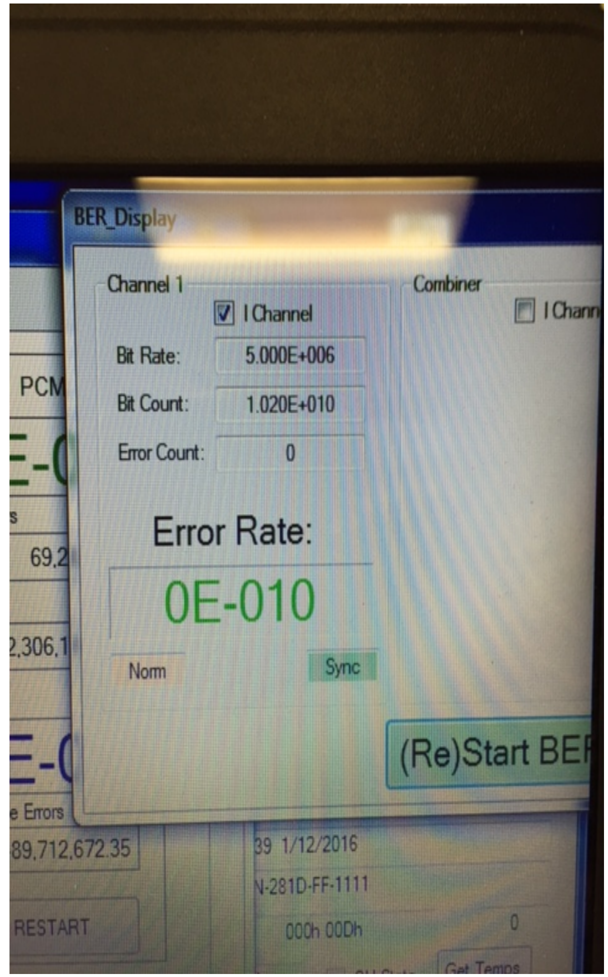
April 2020 TM Smorgasbord
Terry Hill - thill@quasonix.com

Flight 4 – STC/LDPC 5 Mbps Link Availability Summary (PN23 BER)



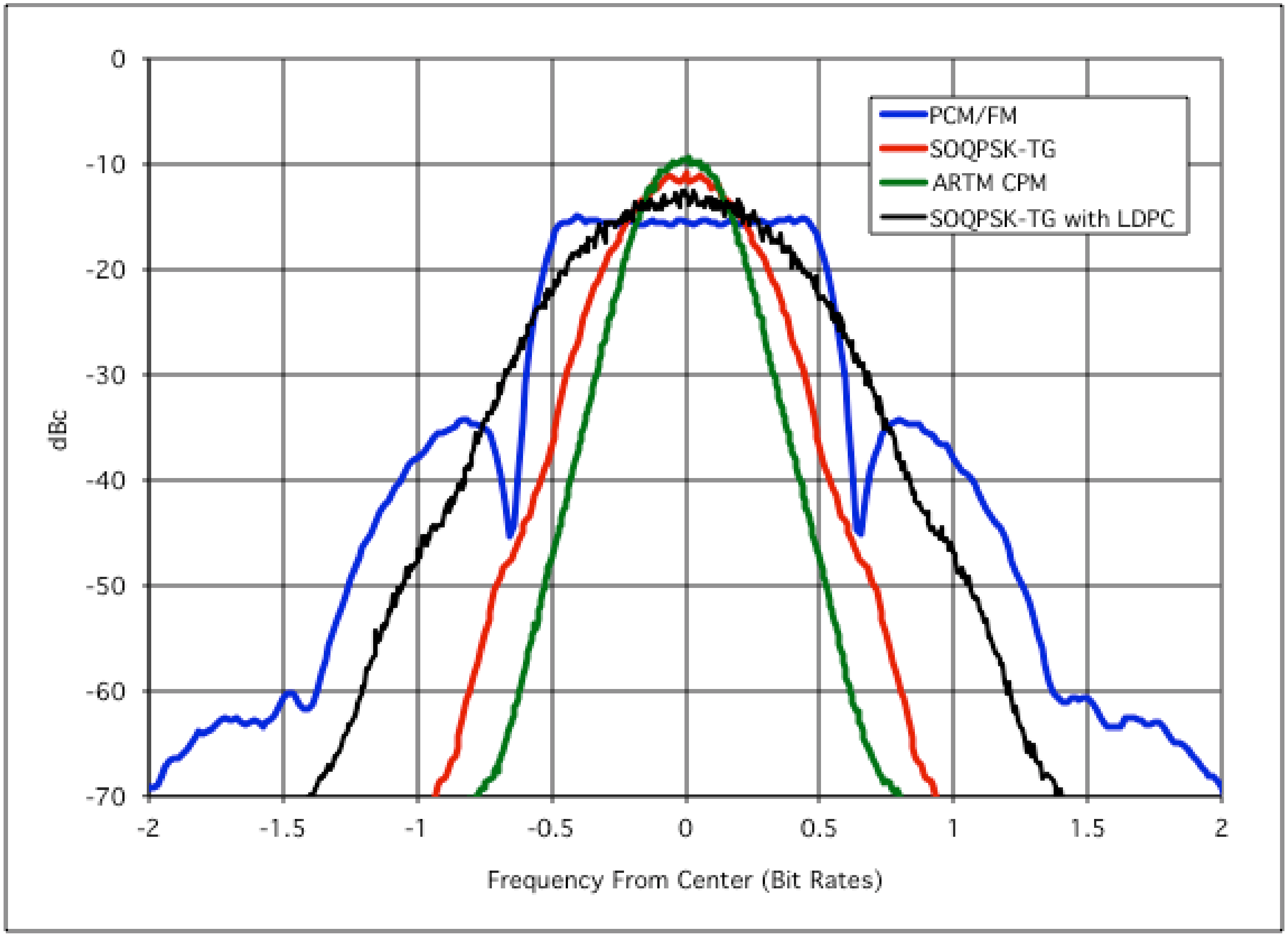
The elusive zero-error link.....

- STC/LDPC from 3 sites at 5 MBPS
- 1st pass PN23 -- 34 minutes of helicopter flight across YPG…
- Error-free!
- 2nd pass video with no freeze ups or blackouts!

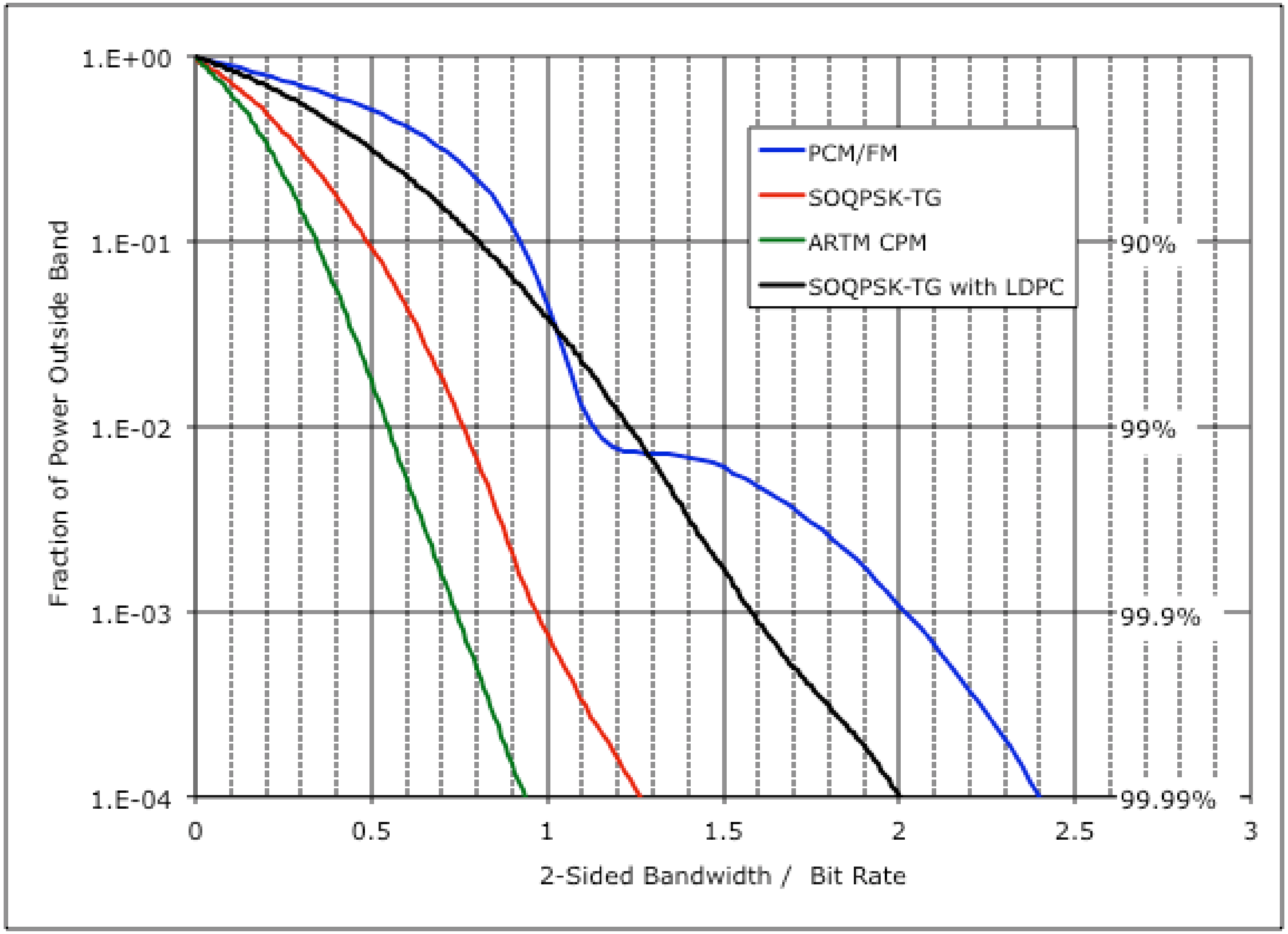


Performance Comparison and Summary

Power Spectral Densities

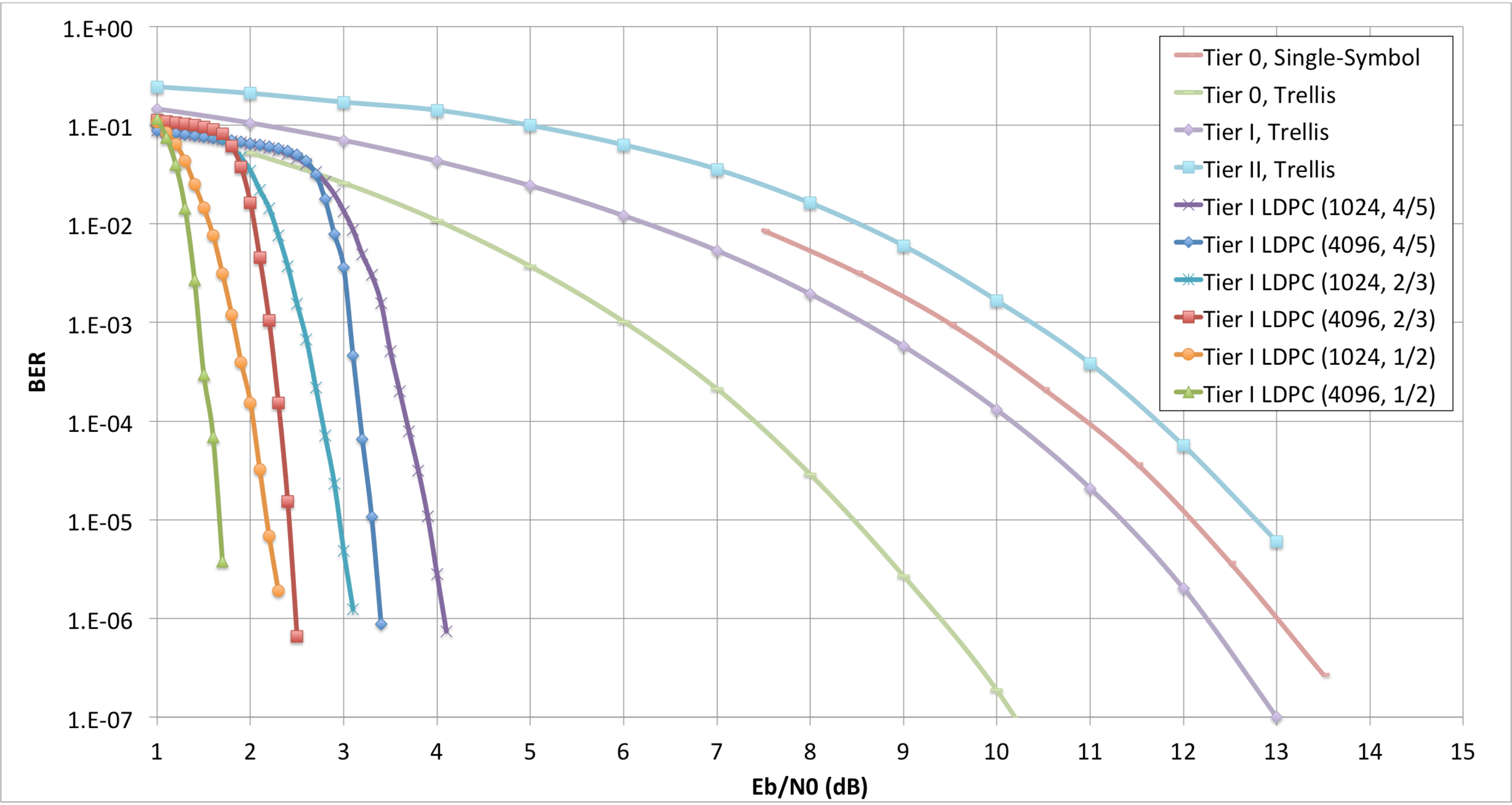


Out-of-Band Power

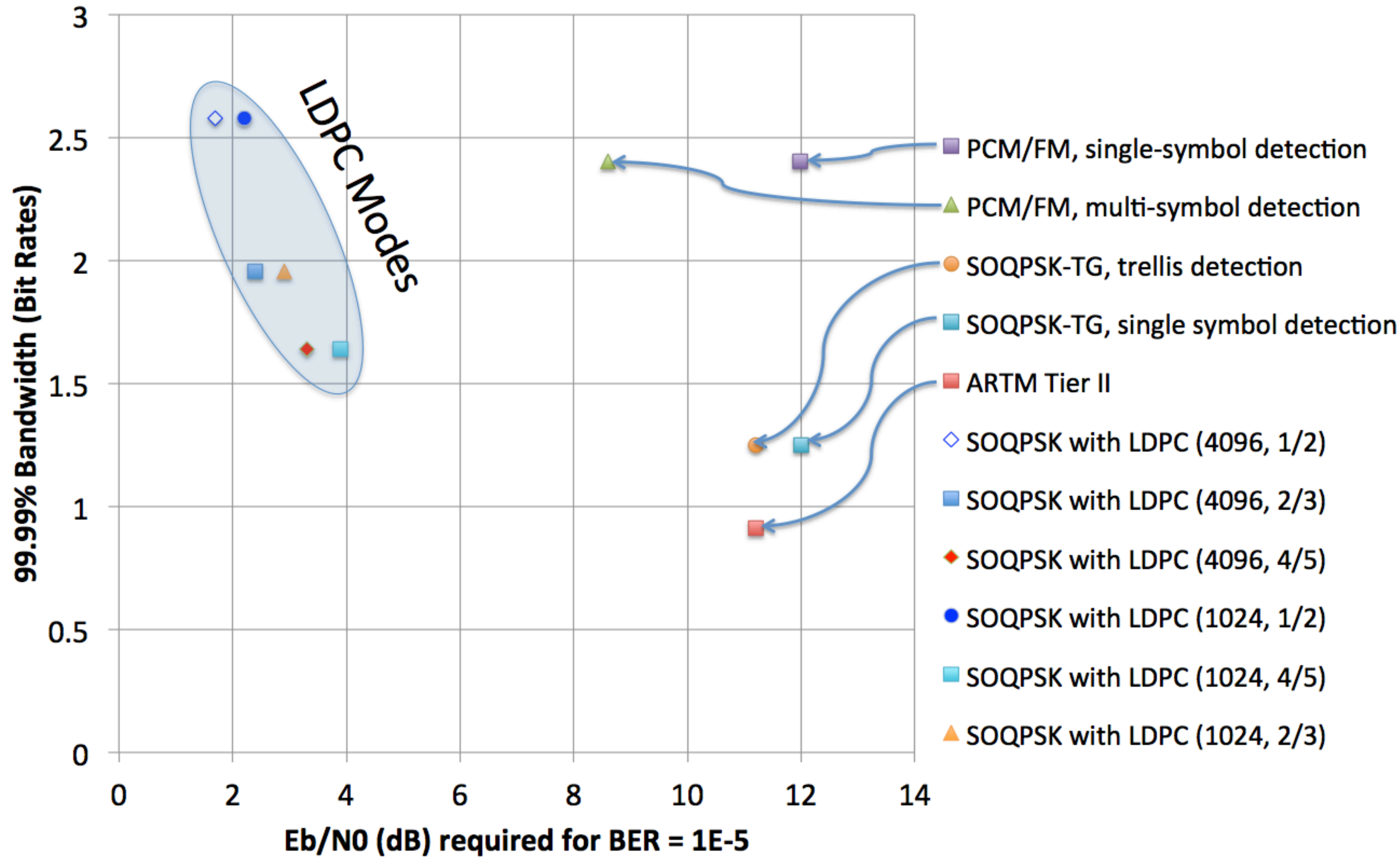


Terry Hill - thill@quasonix.com

BER Performance Comparison



Bandwidth-Power Plane



Stitching it all Together

Link Budget

	A	B	C	E	F	G	H
1	Data entry in Yellow cells						
2							
3	Transmit Power	37	dBm				
4	Transmit Losses (cable, etc.)	1	dB				
5	Transmit Antenna Gain	-1	dBi				
6	Net Transmit EIRP	35	dBm				
7				Wavelength (meters)			
8	Carrier Frequency	2300	MHz	0.130			
9	Transmit/Receiver Range	100	miles				
10	FREE SPACE Path Loss	143.8	dB				
11	Polarization loss	3	dB	Assumes linear to circular			
12	Total path loss	146.8	dB				
13				Dish diameter (meters)	Efficiency	Beamwidth (degrees)	
14	Receive Antenna Gain	24.26	dBi	1.00	46%	9.13	
15	Receive Losses (cable, etc.)	0.3	dB				
16	Tracking Loss (dB)	0	dB				
17	Received Signal Power	-87.9	dBm	One polarization only. Combiner gain below.			
18							
19	Receive System Noise Figure	1	dB	75.1	°K, Assumes feed LNA has enough gain to overcome cable losses		
20	Boltzmann's Constant x 290 K	-173.98	dBm/Hz	5.21	G/T in dB/K, FYI only. Not used in calculation		
21	C/kT	85.1	dB/Hz				
22							
23	Data Rate	1.00E+06	bps	This is the USER PAYLOAD rate (not including the FEC parity bits)			
24	Data Rate	60	db-Hz				
25	Combiner gain	3	dB				
26	Eb/N0 Achieved	28.1	dB				
27	Eb/N0 Required for BER = 1e-5	8.6	dB	Insert correct value from BER plots (next tab)			
28							
29	**Link Margin**	**19.5**	**dB**				

Acknowledgements

- Mark Geoghegan, Quasonix
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- Kip Temple, ARTM, Edwards AFB
- Gene Law, NAWCWD, Pt. Mugu
- Vickie Reynolds, White Sands Missile Range

Questions/Comments