QAM Multi-path Characterization Due to Ocean Scattering

Richard Swanson, Jeff Dimsdle
Honeywell Federal Manufacturing & Technologies

Tom Petersen, Regina Pasquale, Roger Bracht
Los Alamos National Laboratory

ABSTRACT

A series of RF channel flight characterization tests were recently run to benchmark multi-path performance of high-speed quadrature amplitude modulation (QAM) over the ocean surface. The modulation format was differential-phase/absolute-amplitude two level polar 16 QAM. The bit rate was 100 Megabits per second with a symbol period of 40nS. An aircraft radiated the test signal at 5 different altitudes. It made two inward flights, on two different days, at each altitude with vertical and horizontal polarization, respectively. Receivers, using circular antenna polarization, were in two different locations. Analysis of the resulting data shows flat fading and frequency selective fading effects.

KEY WORDS

Multi-path, frequency selective fading, equalization, QAM modulation, HERT, FQPSK

BACKGROUND

The High Explosive Radio Telemetry (HERT) is a telemetry system that was developed to measure the initial performance of an explosive package in flight. The key period of interest during the explosive event occurs during the first 500 microseconds or less. This requires a telemetry system with accurate, fast time resolution (10 nanoseconds), and the ability to get the data transmitted before the system is destroyed. The telemetry system is designed to affect the resources of the re-entry vehicle (RV) as little as possible by minimizing the size and power requirements. Initially, it is capable of measuring 32 time-of-arrival events into special fiber sensors. This will ultimately be expanded to 64 or more channels. A specially designed QAM modulation is used to enhance the data transmission rate while keeping the required signal-to-noise margin to an acceptable level. To minimize signal dropouts, it was also important to be able to easily recover the signal non-coherently as well as coherently. While the system was designed for end event time of arrival measurements, it is being evaluated for other high-speed general-purpose telemetry needs as well.

This modulation method has been previously used for data transmission from a HERT unit in an RV, but not near the ocean surface. Non-equalized multi-path performance had been calculated by theoretical methods and simulations. This test has allowed us to verify the RF channel characteristics, evaluate the modulation method's viability for high-speed data transmission over the ocean surface, and to help develop multi-path equalization methods, permitting data recovery under even the most severe conditions of frequency dependent fading.

HERT RF MODULATION METHOD

A non-standard method of digital RF modulation and demodulation (covered by one 3/98 and two 4/01 Honeywell KCP invention disclosures) is used, different from any standard QAM, "Differential-Phase/Absolute-Amplitude Polar QAM", which is a hybrid of differential and absolute referencing. As implemented specifically for HERT with a polar 16QAM pseudo-constellation, there are 16 differential phase values and two absolute amplitude level values. An absolute-phase/absolute-amplitude constellation consisting of 32 points is used to generate the 16 differential-phase/absolute-amplitude pseudo-constellation points. For each absolute constellation point sent, the differential phase of the differential-phase/absolute-amplitude symbol being sent is encoded directly into the phase transition from the previous absolute state to the present absolute state. That is, every phase is referenced to the previous phase. The absolute amplitude of the differential-phase/absolute-amplitude symbol being sent is the absolute amplitude level of the present absolute state. Continuous amplitude referencing is accomplished by looking at high to low and low to high amplitude transitions to identify constellation outer circle values, maintaining an average of these values, and using this to scale the data appropriately. One major advantage of this method is that it allows either coherent or non-coherent demodulation. This is an important flexibility to have; in case the signal degradation is such that coherent carrier recovery is not successful, data can still be recovered through non-coherent demodulation. When coherent carrier recovery is possible, however, then coherent demodulation can be done with a significant improvement in BER vs Eb/No over non-coherent demodulation. The method also allows tuning out transmitter hardware constellation errors. The polar format, in addition to allowing phase to be directly differentially encoded, is less sensitive to constellation distortion due to amplifier compression.

TEST DESCRIPTION

In early March of 2002 the authors traveled to Monterey, CA, and joined with Sandia Livermore personnel for a joint airplane flight test of the custom-developed High Explosive Radio Telemetry (HERT) and the latest FQPSK system. HERT transmitted at 100Mbits/sec (40nS symbol period) using Differential-phase/Absolute-amplitude polar 16 QAM. (FQPSK, used by Sandia Livermore, transmitted at 20Mbits/sec.) The focus of the test was multi-path performance over the ocean surface. Operating HERT at this high data rate (40nS symbol period) is much more vulnerable to frequency dependent fading than operating HERT at slower data rates.

One receiver was placed at Point Sur lighthouse at an altitude of 230 feet above the ocean surface and the other on a boat with the antenna placed just up off of the ocean surface. The Point Sur lighthouse location simulated a tower receiver located at a much greater distance from an RV entry path, either on a ship or land. Point Sur was chosen because it significantly juts out into the ocean away from land objects that could add to the multi-path clutter. Additionally, the lighthouse provided a convenient place to set up receiving equipment directly overlooking the ocean. The boat antenna simulated buoy telemetry receiver configurations that will be used in the future near RV splashdown sites. This test was run over two different days to provide for some variation in sea state conditions. Luckily, the first day was very calm and the second day of testing was a very rough sea. Thus, multi-path data was captured for evaluation under these two very extreme conditions. This information helps us evaluate the effectiveness of this novel modulation scheme for missile telemetry and event telemetry applications.

The airplane flew with both test transmitters, through various altitudes and distances from the boat and lighthouse, corresponding to points along an RV flight path. HERT data was transmitted in 33uS bursts with one burst every 40mS. Operation of receiver hardware, effects on demodulation, and methods for equalization were evaluated. Data was collected over multiple wavelength changes in the difference between the line of sight and the ideal reflected multi-path ray. The real time signal strength variation was recorded as well.

Additional data was taken by testing HERT signal transmission from lighthouse to boat during a rain storm, and from Hurricane Point (across the bay) to lighthouse.

GENERAL TEST RESULTS

The following results were observed after analysis of the HERT data collected during these Point Sur transmission tests conducted on a Tuesday and a Friday, with sea conditions being much calmer on Tuesday than Friday:

1.) The boat data was received without significant problems for all altitudes and both polarizations. On Friday some data segments had degradation not present on Tuesday's data, apparently due to rough sea causing the antenna to point down into the waves as the boat was often tossed about, with the transmitted signal shadowed by waves. Mostly flat fading was observed on the boat data. Some frequency dependent fading was occasionally observed as well and is thought to be due to reflections from the ship radar mast into the receive antenna. This is because the multi-path delays for boat frequency dependent fading were consistently 40nS, corresponding to the approximate distance from the receive antenna to the ship radar mast.

2.) Lighthouse data received from aircraft was unfortunately degraded due to:

> a.) In-band interference from commercial satellite radio signals in bands 2341.3 to 2345 MHz (-8.7 to -5 MHz from the HERT center frequency used of 2350MHz) and 2332.5 to 2336.2 (-17.5 to -13.8 MHz from HERT center frequency). The interference strength relative to the HERT signal varied but was severe in many cases. The interfering signals can be clearly seen by looking at the spectrum of the HERT signal during its pilot CW: The observed interferers' frequency bands correspond exactly with the listed commercial satellite radio bands.

  b.) Frequency dependent multi-path, which was successfully equalized in all of the selected data files.

3.) The transmission from the lighthouse to boat exhibited in-band interference from satellite radio signals and frequency dependent fading, which was successfully equalized in all of the files tested.

4.) The transmission across the bay from Hurricane Point to the Point Sur lighthouse did not exhibit significant interference. Only frequency dependent multi-path was observed, which was successfully equalized in all of the files tested.

The aircraft-to-boat and Hurricane Point-to-lighthouse data was relatively free of satellite radio interference while the aircraft-to-lighthouse and lighthouse-to-boat data exhibited interference apparently due to the different directions that the receive antenna was pointing in each case.

EQUALIZATION

In most cases, the frequency dependent multi-path was successfully equalized by modeling ocean multi-path as consisting of the line-of-sight (LOS) signal plus a single additional multi-path signal and running the received signal complex envelope, $s_k=I_k+jQ_k$ through a single pole auto-regressive (AR) filter: $1/[1+Ae^{jP}z^{-(D+1)}]$, where A is fractional amplitude of 2nd multi-path signal relative to LOS signal, P is relative angle, and D is relative delay-1. The filter is always stable in this form as long as $A<1$. In the case in which $A>1$, then the filter must be put into the following moving average (MA) form, which converges for $A>1$: $z^{-ND} - z^{(1-N)D}/(Ae^{jP})+ z^{(2-N)D}/(Ae^{jP})^2 - z^{(3-N)D}/(Ae^{jP})^3 + z^{(4-N)D}/(Ae^{jP})^4 \ldots (-1)^n z^{(n-N)D}/(Ae^{jP})^n \ldots (-1)^N/(Ae^{jP})^N$, where N=# terms in series-1. (Indices correspond to original digitized IF sample points, not symbol sample points.)

Some further improvement was found to be possible by taking the signal so equalized and determining a second equalizer filter pole, independent of the first pole. More equalizer poles can be added independently in this manner as desired. Ideally, all poles would be determined simultaneously, but doing so would quickly add an excessive number of simultaneous search parameters.

On data without appreciable satellite radio interference, just multi-path, such as that received at the lighthouse from Hurricane Point across the bay, the original signal could be recovered with equalization. When only multi-path was degrading the signal, parity errors could be reduced to zero or very near zero. In cases in which improvement was limited after equalization, there were other sources of degradation such as interference from satellite radio or a very weak signal.

A trigger consisting of a sequence of either 24 or 64 known pseudo-random symbols was transmitted with each burst. When two peaks of the response of a software transversal filter (based on ideal trigger) to the actual received trigger were clearly visible, the optimal delay found for the equalization filter corresponded fairly closely to the separation between them. In some cases the separation was too close, or the 2nd multi-path signal too low, to clearly observe two peaks, although the multi-path was still significant enough to degrade the received signal.

For data with significant satellite radio interference, the multi-path could be equalized with parity errors reduced and constellation spread decreased, but limited by the amount of interference. After equalization, any 2nd peak of the transversal filter response was eliminated and any notches in the spectrum, some quite deep, were also eliminated.

EQUALIZATION METRICS

One of the metrics used to determine this QAM recovery margin involves a term we have labeled “spread.” The definition of this constellation spread is: $\sqrt{[\sum_i(D_i^2)]}$, where $D_i^2=(I_{Ci}-I_{Si})^2+(Q_{Ci}-Q_{Si})^2$, (I_{Si}, Q_{Si})=symbol sample constellation point vector received, and (I_{Ci}, Q_{Ci})=ideal constellation point vector closest to S_i. That is, D_i is the distance between the sampled constellation point received and the nearest ideal constellation point. The outer constellation amplitude is normalized to a value of 3. A spread of 0.26 roughly corresponds to an E_b/N_o=16dB.

The optimization criteria used by the equalization search routine (to obtain best A, D, and P values) was selectable: maximize magnitude of “correlation of correlation” (Criteria 1) or to minimize 10*(# parity errors)+(constellation spread) (Criteria 2). Short of doing a full demodulation, the “correlation of correlation” metric worked quite well. It is implemented as follows:
“correlation of correlation” scalar optimization criteria=$R_{ST}\bullet R_{TT}^*/||R_{ST}||$
Where,
$R_{ST}(k)=\sum_i S_{i+k}T_i^*$
$R_{TT}(k)=\sum_i T_{i+k}T_i^*$
$||R_{ST}||=\sqrt{(R_{ST}\bullet R_{ST}^*)}$
“•” is the dot product with respective peaks of product terms aligned and each product term reduced to segment just encompassing trigger response area.
T_k is the ideal complex envelope trigger sequence transmitted.
S_k is the actual complex envelope trigger sequence received after trial equalization.
The indices correspond to original digitized IF sample points (not symbol sample points).
“Trigger sequence” refers to a known set of pseudo-random symbols that were transmitted each burst. This is required by the “correlation of correlation” criteria, but not by the 10*(# parity errors)+(constellation spread) criteria.
(Some aspects of the equalization technique used are covered by a Honeywell KCP 5/02 invention disclosure.)

EXAMPLE TEST EQUALIZATION RESULTS

The data was stored as 512 segments per file, each segment corresponding to a data burst. As stated earlier, there is a separation of 40mS between segments (bursts). Note the change in characteristics of multi-path signal in the 40mS between adjacent segments 57 to 58 (file 0) and 30 to 31 (file 1). Hurricane Point was a static test; the only thing changing was wave action. Also note consistent 40nS delay on boat frequency dependent fading apparently due to reflection from boat radar mast into receive antenna. Some example results follow:

Hurricane Point to Lighthouse with Horizontal Transmit Polarization

These results are especially significant because the transmitter was from a stable platform across the bay about 3.5 miles away, and there was no RF interference observed in the received data.

File 0, Seg 57	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)		0.395	0.395	0.06460
Delay(NS)		21	26	67
Phase(deg)		220	220	336
Spread	0.7295	0.3469	0.344	0.2976
Parity Errors	92	4	1	0

File 0, Seg 58	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)		0.486	0.360	
Delay(NS)		13	24	
Phase(deg)		213	223	
Spread	0.7131	0.3175	0.2904	
Parity Errors	92	0	0	

File 1, Seg 30	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)		0.221	0.223	
Delay(NS)		44	35	
Phase(deg)		99	110	
Spread	0.5711	0.255	0.2265	
Parity Errors	63	0	0	

File 1, Seg 31	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)		0.2592	0.268	
Delay(NS)		47	45	
Phase(deg)		109	122	
Spread	0.5406	0.2891	0.2314	
Parity Errors	56	0	0	

File 1, Seg 0	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)		0.3555	0.4	0.10
Delay(NS)		42	46	17
Phase(deg)		150	148	225.5
Spread	0.5735	0.4	0.3682	0.3376
Parity Errors	62	11	1	0

For more results please see the appendix.

CONCLUSIONS

The test was successful and a large amount of data was collected for aircraft-to-boat, aircraft-to-lighthouse, lighthouse-to-boat, and Hurricane Point-to-lighthouse. Multi-path fading was observed and data was analyzed to characterize the nature of ocean multi-path and methods to equalize it. There were no major problems observed for HERT transmission and reception, particularly with regards to the simulated buoy reception, critical for HERT telemetry during actual RV tests. As a result of this test, we can conclude the following:

1.) Ocean multi-path can be adequately modeled as the LOS signal plus one other dominant path signal reflected from the ocean surface, and as such, the received signal can be successfully equalized with a single pole AR filter (or its equivalent MA form).

2.) Some additional improvement to equalization filter can be obtained by independently determining additional poles one at a time, each iteration on the previous step's equalized signal.

3.) Short of actual demodulation of signal for parity errors and constellation spread during each trial, the "correlation of correlation" criteria works acceptably as an optimization criteria for use by the equalization filter parameter search routine.

4.) HERT telemetry signals can usually be recovered even under the most severe environments.

5.) Theoretical calculations presented at the 1998 ITC Conference showed that there would be difficulty with data recovery using this modulation scheme if multi-path reflections amounted to more than –18dB of the main signal. These tests have shown that with equalization, significant multi-path degradation can take place and the data still recovered. The static Hurricane Point examples clearly indicate that data can be recovered with multi-path reflections as high as –6dB. It will take more analysis to determine the actual limit of recovery in light of severe frequency selective multi-path conditions.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of Sandia National Laboratory of Livermore, California, who also provided most of the logistics and air support contacts through CIRPAS that flew the experimental aircraft out of Marina, CA. We also wish to acknowledge the support of personnel at Pt. Sur lighthouse. This work has been funded out of the ESP, Department of Energy, Defense Programs Office. The Los Alamos part of the work was performed under the auspices of the U.S. Department of Energy, Contract W-7405-ENG-36. Honeywell Federal Manufacturing & Technologies is operated for the United States Department of Energy under Contract Number DE-AC04-01AL66850

REFERENCES

R. Bracht, J. Dimsdle, D. Rich, F. Smith: "Radio Frequency Overview of the High Explosive Radio Telemetry Project," *Proceedings of the International Telemetering Conference*, vol. 34 pp. 161-166, San Diego, October 1998.

R. Bracht, T. Crawford, R. Johnson, B. Mclaughlin: "High Explosive Radio Telemetry System," *Proceedings of the International Telemetering Conference*, vol. 34 pp. 167-172, San Diego, October 1998.

M. Rice, E. Law: "Aeronautical Telemetry Fading sources at Test Ranges," *Proceedings of the International Telemetering Conference*, vol. 33 pp. 660-666, Las Vegas, October 1997.

E. Law: "Estimating the Characteristics of the Aeronautical Telemetry Channel during Bit Error Events," *Proceedings of the International Telemetering Conference*, vol. 35 pp. 879-888, Las Vegas, October 1999.

E. Law: "Performance of PCM/FM During Frequency Selective Fading," *Proceedings of the International Telemetering Conference*, vol. 31 pp. 281-289, Las Vegas, October 1995.

H. Leung, T. Lo: "A Spatial Temporal Dynamical Model for Multi-path Scattering from the Sea," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 2, pp. 441-448, March 1995.

B. Ungan, J. Johnson: "Time Statistics of Propagation over the Ocean Surface: A Numerical Study," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 38, No. 4,pp. 1626-1634, July 2000.

R. Dye, L. Horne: "*Parameter Characterization on a Telemetry Channel Including the effects of the Specular Ray,*" *Proceedings of the International Telemetering Conference*, vol. 31 pp. 314-332, Las Vegas, October 1995.

M. Rice, D. de Gaston, A. Davis, G. German, C. Bettwieser: "ARTM Channel Sounding Results an Investigation of Frequency Selective Fading on Aeronautical Telemetry Channels," *Proceedings of the International Telemetering Conference*, vol. 35 pp. 889-910, Las Vegas, October 1999.

APPENDIX

Aircraft to Boat Friday 6000’ Horizontal Transmit Polarization

This is one of few boat data segments on Friday where there was a problem, apparently due to rough sea, causing antenna to point down into waves occasionally as boat was tossed about with transmitted signal shadowed by waves.

File2, Seg 117	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.382	
Delay(NS)			40	
Phase(deg)			256	
Spread	0.6828		0.3666	
Parity Errors	90		6	

Aircraft to Boat Friday 3000’ Horizontal Transmit Polarization

These are examples of a few boat data segments on Friday where there was a problem, apparently due to rough sea, causing antenna to point down into waves occasionally as boat was tossed about with transmitted signal shadowed by waves.

File 2, Seg 317	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.8	
Delay(NS)			2	
Phase(deg)			192	
Spread	0.7062		0.5112	
Parity Errors	90		42	

File 2, Seg 111	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.4	
Delay(NS)			40	
Phase(deg)			279	
Spread	0.676		0.5909	
Parity Errors	91		56	

This example is particularly interesting since the LOS signal was weaker than the multi-path off the boat mast.

File 2, Seg 334	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			1.141	0.44
Delay(NS)			39	11
Phase(deg)			117.94	207.96
Spread	0.7818		0.5896	0.5136
Parity Errors	92		51	27

Aircraft to Lighthouse Friday 1500’ Vertical Transmit Polarization

These had in-band satellite radio interference which limited possible improvement.

File 0, Seg 44	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.35	
Delay(NS)			36	
Phase(deg)			244	
Spread	0.7219		0.3289	
Parity Errors	90		1	

This example showed a deep notch in center of spectrum. The trigger response showed two distinct returns 44nS apart, with second return relative amplitude of 0.74.

File 0, Seg 440	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.63077	
Delay(NS)			42	
Phase(deg)			153	
Spread	0.7954		0.5737	
Parity Errors	97		52	

Aircraft to Lighthouse Friday 6000’ Horizontal Transmit Polarization

These had in-band satellite radio interference which limited possible improvement.

File 2, Seg 19	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.3	
Delay(NS)			28	
Phase(deg)			158	
Spread	0.6340		0.6023	
Parity Errors	90		62	

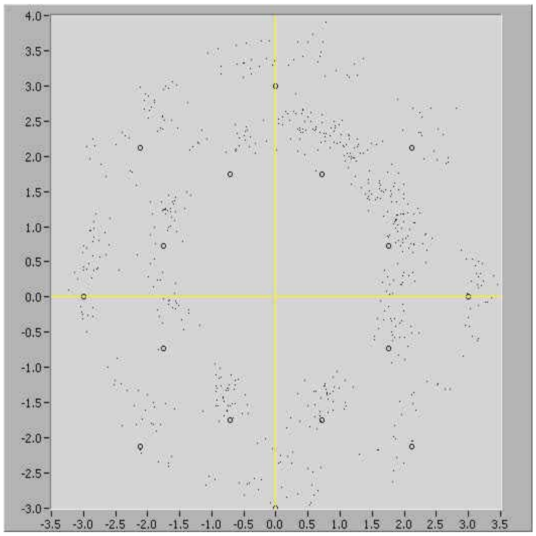
File 2, Seg 100	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.10	
Delay(NS)			74	
Phase(deg)			135	
Spread	0.5759		0.5058	
Parity Errors	61		40	

Lighthouse to Boat

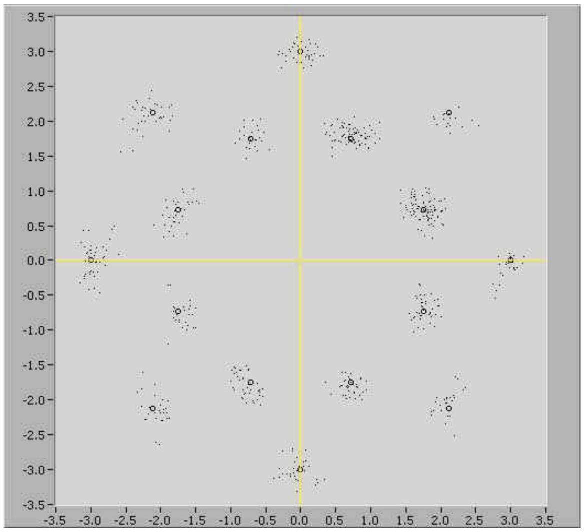
This had in-band satellite radio interference which limited possible improvement.

File 5, Seg 19	No Equalization	Criteria 1	Criteria 2	Criteria 2 + 2nd pole
Ampl (ratio)			0.6875	
Delay(NS)			14	
Phase(deg)			313	
Spread	0.6281		0.5518	
Parity Errors	80		37	

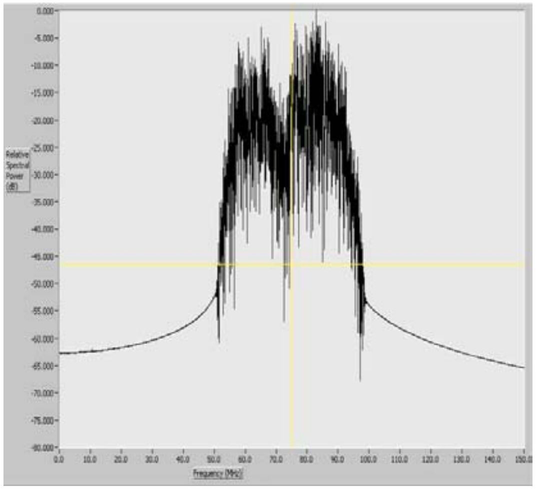
TYPICAL EQUALIZATION RESULTS



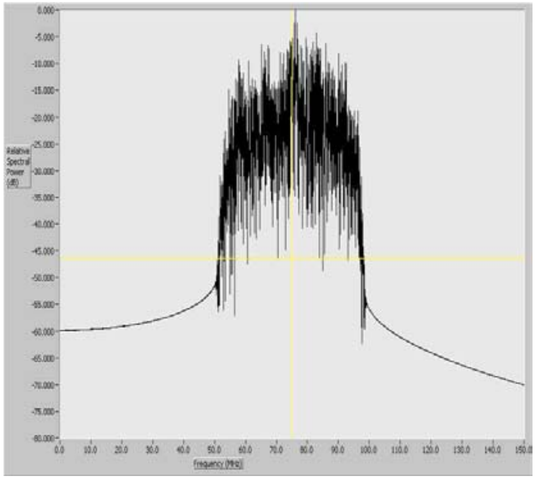
Constellation Before Equalization



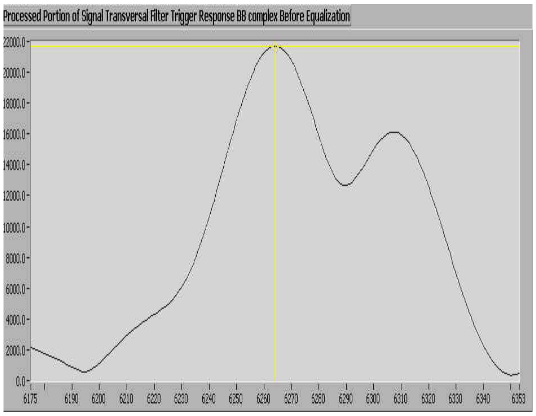
Constellation After Equalization



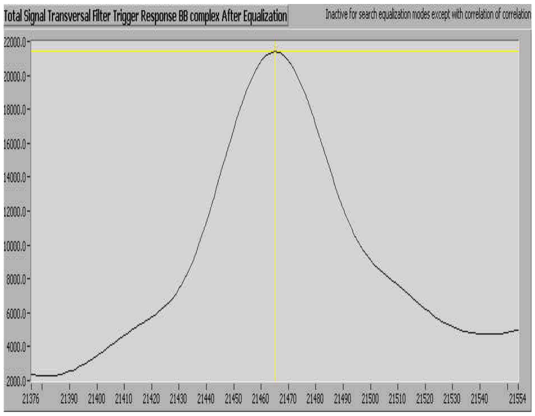
Spectrum Before Equalization



Spectrum After Equalization



Trigger Response Before Equalization



Trigger Response After Equalization