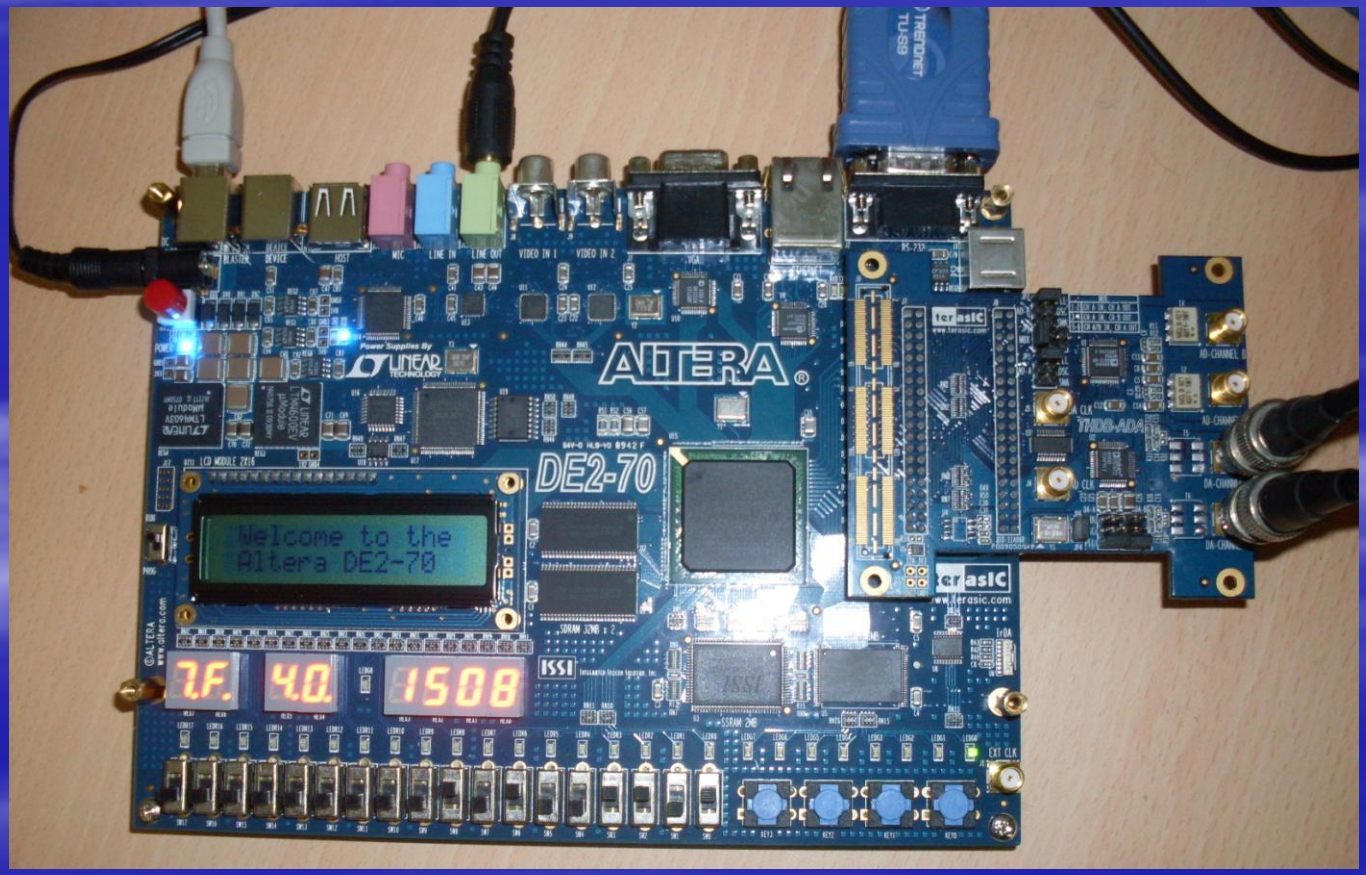
Teaching Digital Communications in a Developing Country using a Low Cost Software Defined Radio Laboratory

Dr. Yair Linn

Ph.D. University of British Columbia, Vancouver, Canada



A little background…..

- In 2007 I graduated with a Ph.D. in Electrical and Computer Engineering from the University of British Columbia, Canada.
- In 2008 I accepted the post of Visiting Professor at the Universidad Pontificia Bolivariana in Bucaramanga, Colombia.
- I'm not really sure why…..
- My salary is half what I got as a scholarship as a Ph.D. student in Canada….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Valencia
La Victoria
Santa Teresa
El Carmen de Bolivar
Barquisimeto
Tinaquillo
Lorica
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Ciudad de Panamá
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El Vigía
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San Cristóbal
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Puerto Ayacucho
Tunja
Yopal
Manizales
Zipaquirá
Pereira
Bogota
Ibagué


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Chigorodó
El Bagre
Zaragoza
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Pamplona
Barranca Bermeja
Bucaramanga
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San Vicente de Chucurí
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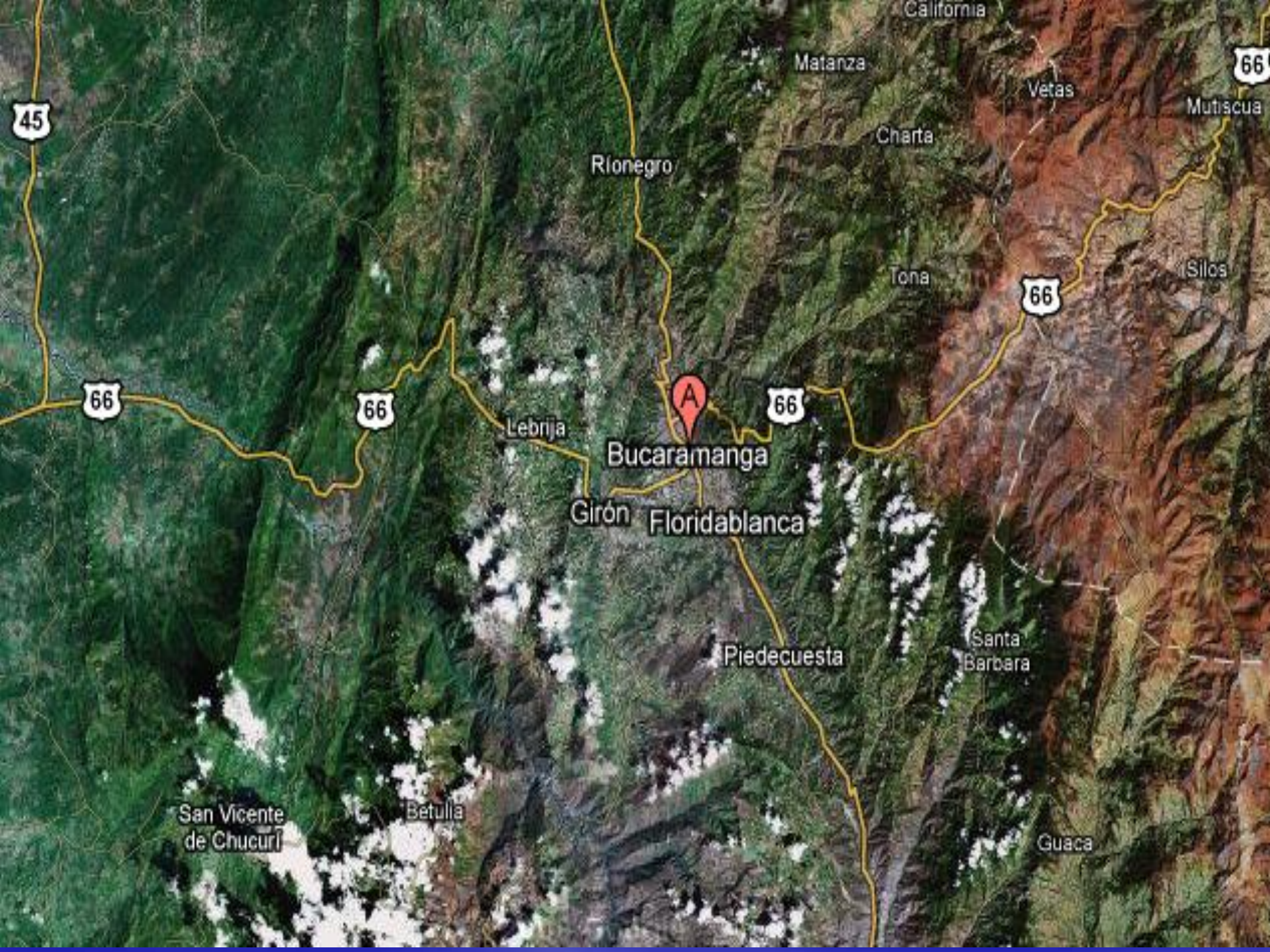
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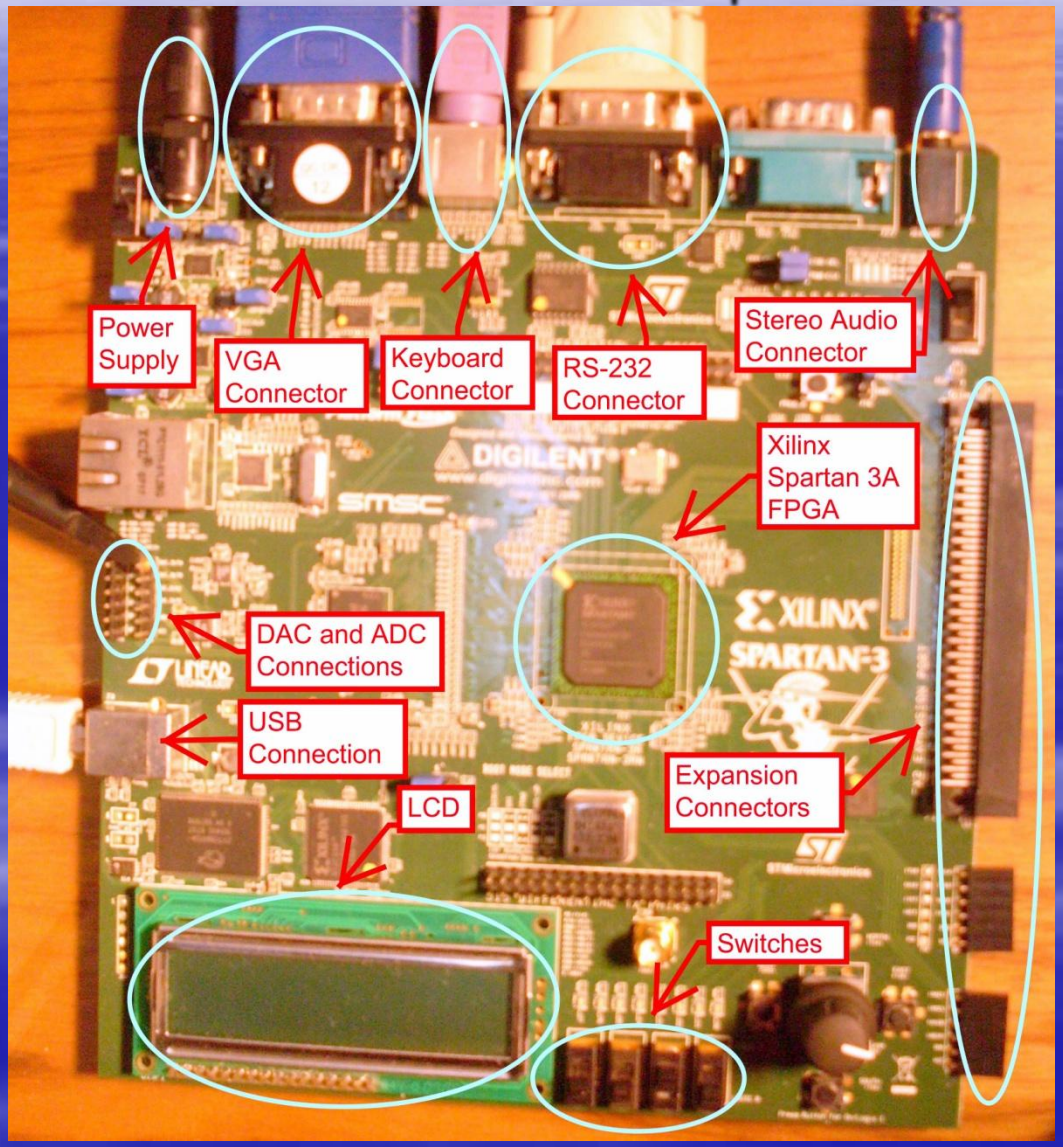
de Chucurí
Betulia
Guaca

Some numbers……

- The entire R&D annual budget of the Electronic Engineering Faculty at the UPB is $20,000 (for all profs combined!)
- I wanted to continue my research in SDR
- But all I could get were 6 FPGA boards for an advanced undergraduate FPGA course
- The cards (Spartan 3A Starter Kit) cost $189 each. The FPGA is a small $10 FPGA.
- Making an SDR with such an inexpensive FPGA seemed like a lost cause, but I did it!
- Results of this were presented in SDR'09

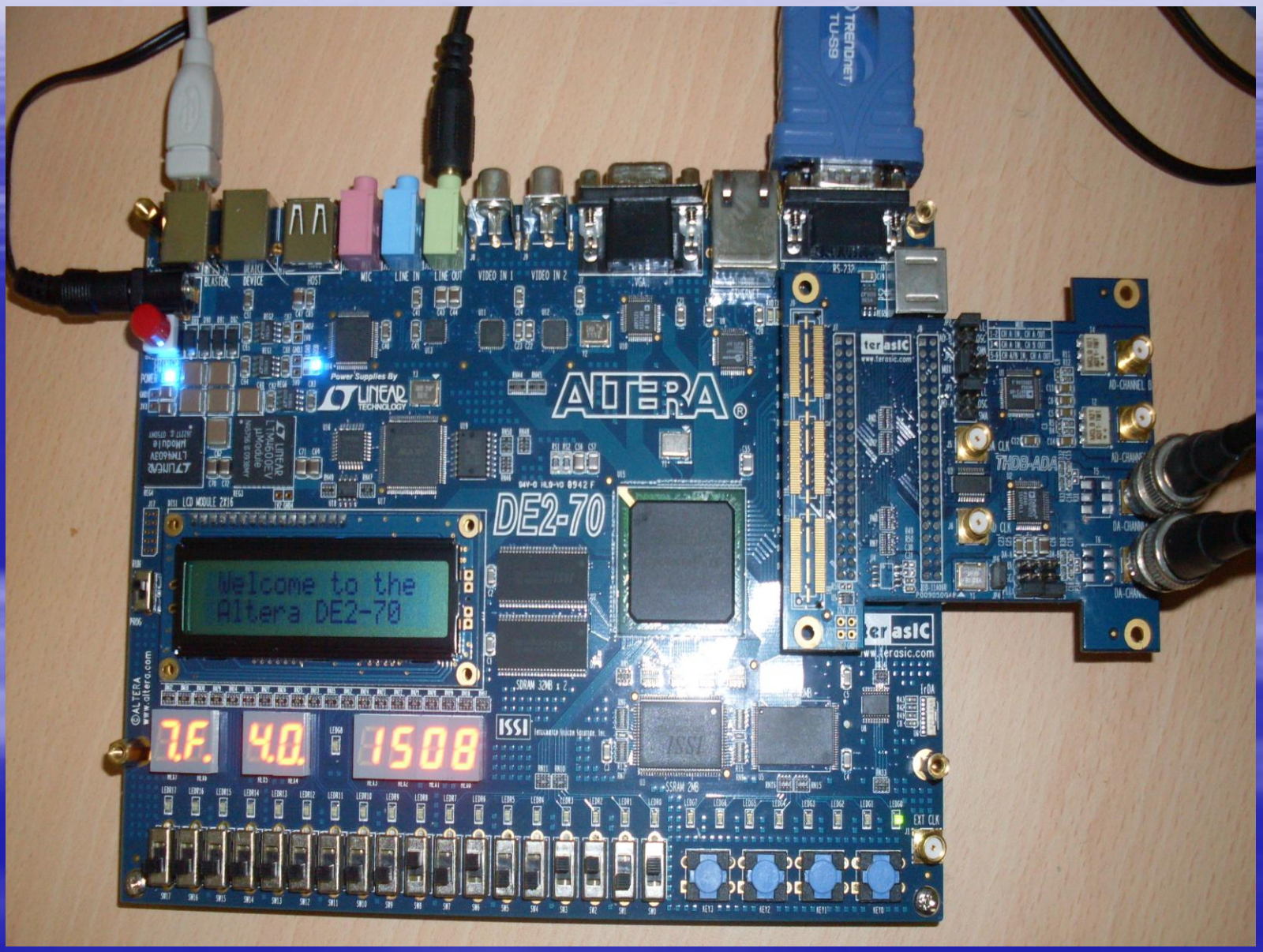
The Laboratory presented in SDR'2009– all for under $200!!!



The laboratory presented in this paper

- The laboratory presented in this paper is a port of the laboratory from SDR'09 to a new FPGA board, the Altera DE2-70 + ADC/DAC daughtercard (total cost: $550)
- The bigger FPGA allows for many improvements and new features.
- In this paper we present the laboratory and we present student survey results that show that the laboratory is highly effective as a teaching aid.

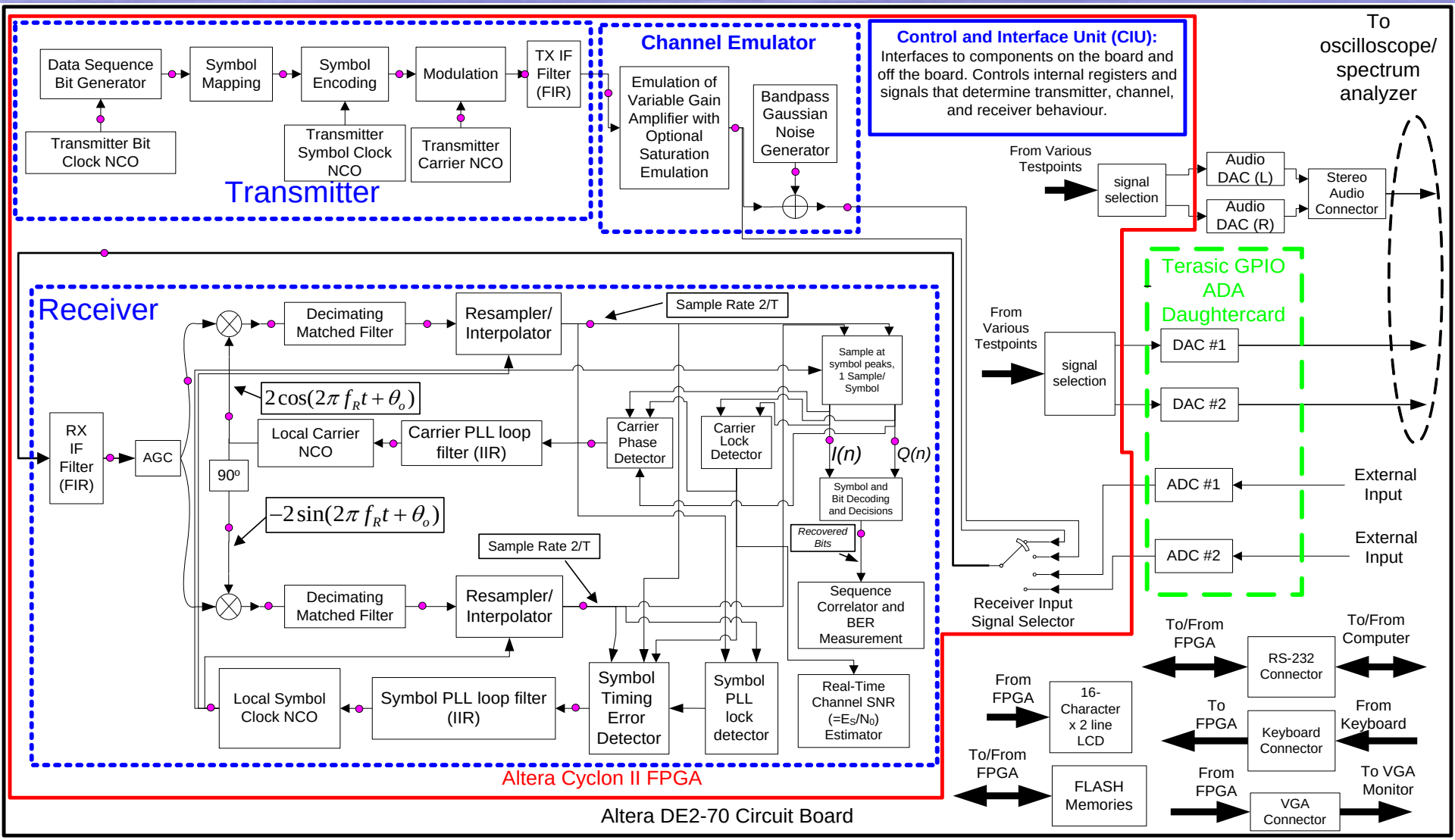
DE2-70 Card + ADC/DAC



DE2-70 Card Components

- 70,000 Logic Element Altera Cyclone II FPGA
- USB connection
- 2-Mbyte SSRAM
- Two 32-Mbyte SDRAM8-Mbyte Flash memory
- SD Card Socket
- 4 Pushbutton Switches
- 18 Toggle switches
- 50-Mhz and 28.63-Mhz Oscillators
- 9 Green + 18 Red LEDs
- VGA output
- 24-bit audio CODEC with line-in, line-out, and microphone-in
- 10/100 Ethernet Controller with a connector
- 2 TV Decoder (NTSC/PAL) and TV-in connector
- RS-232 transceiver and 9-pin connector
- USB Host/Slave Controller
- IrDA transceiver
- PS/2 mouse/keyboard connector
- Two 40-pin Expansion Headers

Laboratory – functional diagram



Cost

- Lab is based on COTS cards, costs under $550
- Available worldwide
- Same card can be used for courses in digital logic, microprocessors, networking, FPGA design, etc.
- Audio output allows oscilloscope and spectrum measurements to be done using PC, with freeware programs
- Thus, incremental cost of the laboratory can approach $0
- Ideal for teaching in developing countries, but also useful for teaching in developed countries
- Simple yet robust laboratory that is also very useful for research

Features

- Transmitter
- Channel Emulation (AWGN), slow fading also supported
- Ability to compress or saturate TX amplifier
- Receiver
- Modulations (currently supported, more on the way!):
  - BPSK
  - QPSK (=4-QAM)
  - 8-PSK
  - 16-PSK
  - D-BPSK
  - D-QPSK
  - D-8-PSK
  - D-16-PSK
  - QAM-16
  - QAM-64
  - QAM-256
  - pi/4-QPSK, pi/8-8PSK,
  - pi/4-DQPSK, pi/8-D8PSK
  - Offset QPSK
  - Offset 8-PSK
  - Offset 16-PSK
  - MSK
  - GMSK (TX only, so far)
  - Offset-QAM-16
  - Offset-QAM-64
  - Offset-QAM-256
  - Pulse shaping
    - Rectangular
    - SRRC rolloff = 0.35
    - SRRC rolloff = 0.85
    - Half Sinusoid
    - Gaussian (various BT)
    - User defined
  - Lots of other wierd modulation combinations

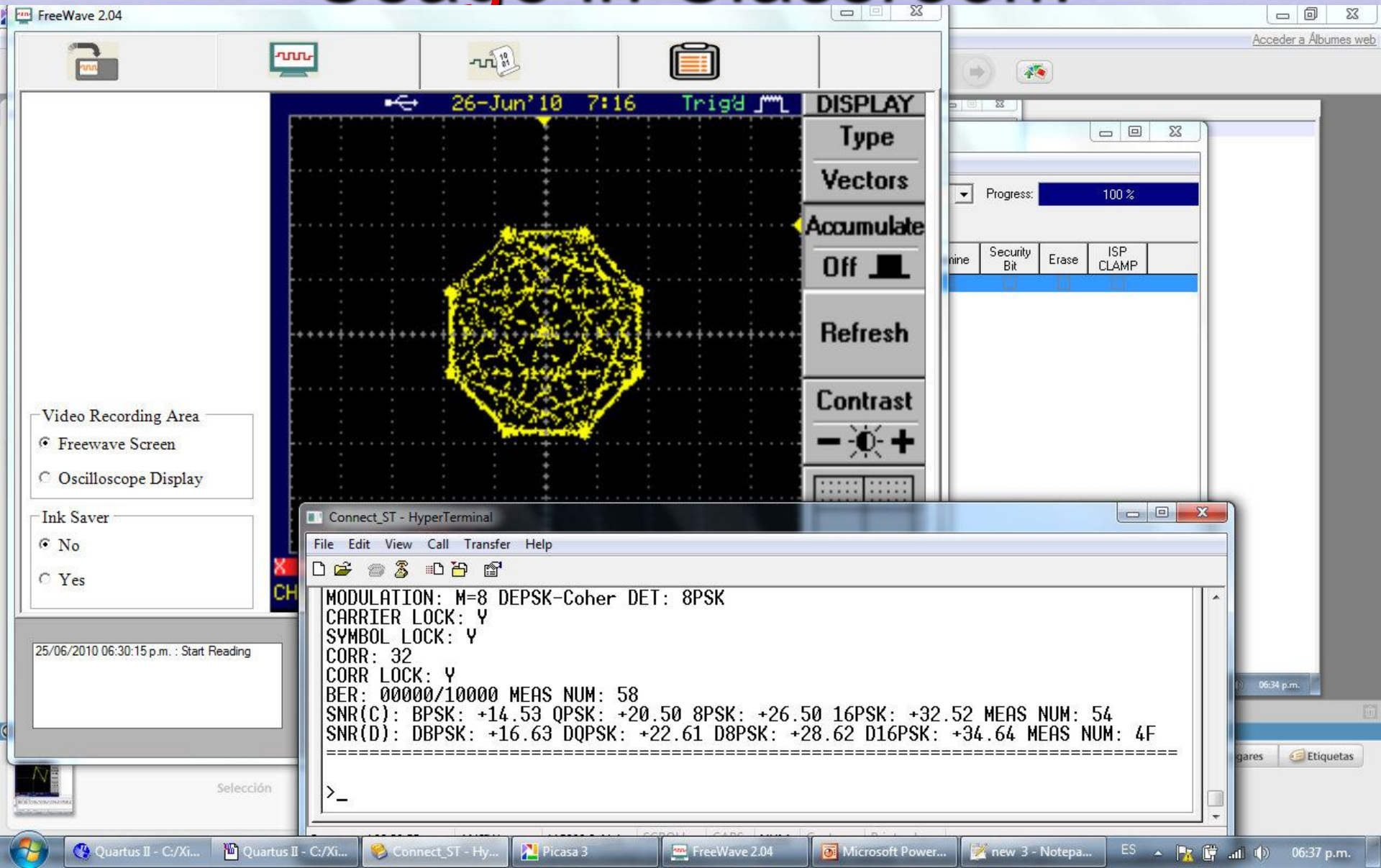
Features (Cont.)

- Coding: differential and gray coding
- Receiver:
  - Coherent
  - Differential
- Control loops:
  - Carrier PLL
  - Symbol PLL
  - 2 AGC loops
- Carrier lock detector
- Symbol lock detector
- Real-time SNR measurements (two methods)
- Real-time BER measurements
- Pseudo-random bit streams or user supplied data transmission
- Ability to probe within multirate upconversion and downconversion chains (new DUC and DDC architectures)
- Ability to generate symbol SNRs of up to 40 dB
- Much better quantization performance (possible due to larger FPGA)

Features (cont.)

- Audio output for interface to PC-based oscilloscope and spectrum analyzer software
- 2 DAC outputs for oscilloscope use
- 2 ADC inputs
- Can be used for interface to RF components, however channel emulation makes this unneccesary
- Interface via keyboard and VGA
- Interface via hyperterminal and RS-232
- All of the above are very simple to do in developing countries, and also is useful for developed countries for students to buy their own laboratory
- In a unified curriculum, students can buy card and

Usage in Classroom



Survey Results

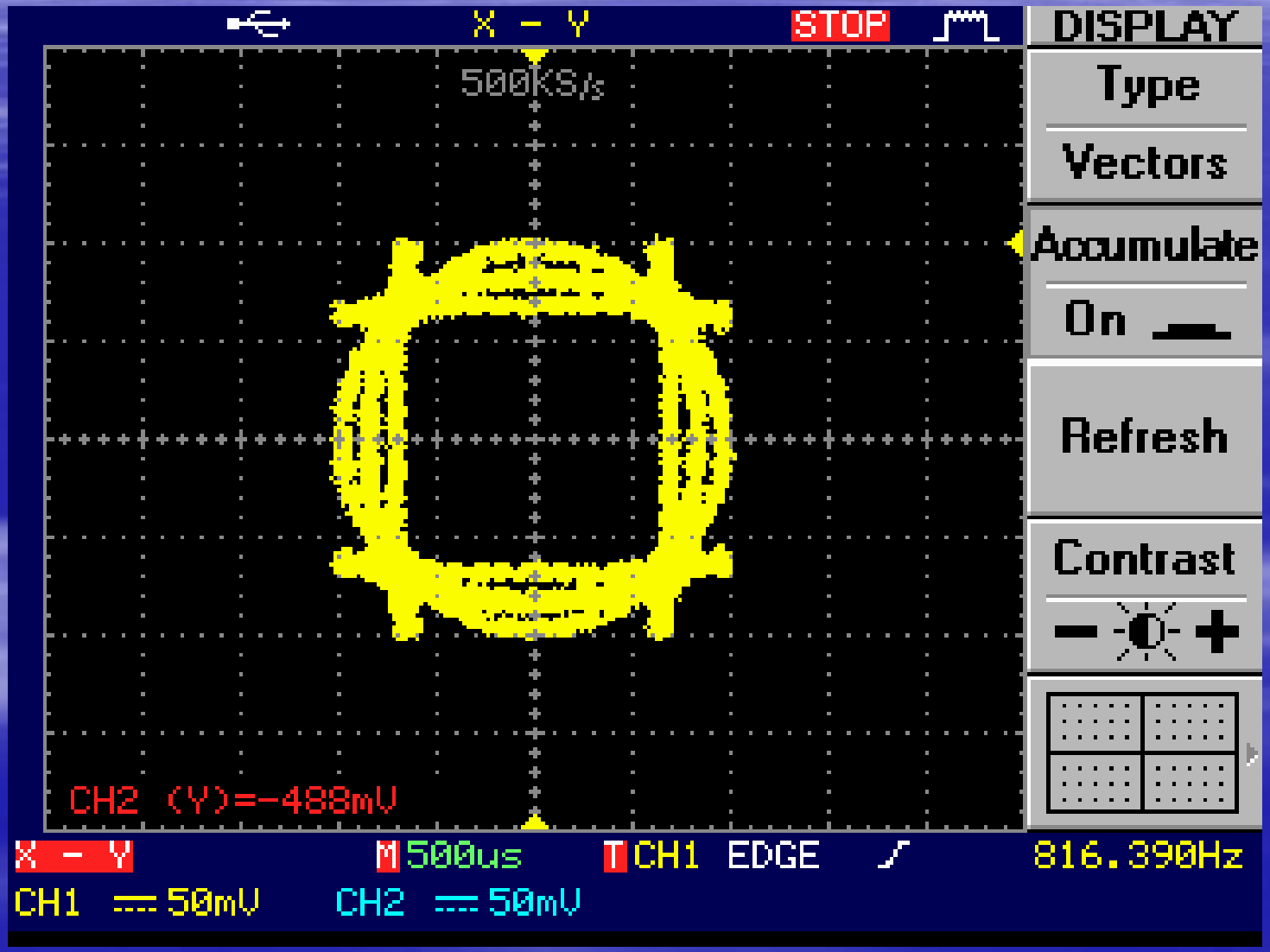
Table 2 - Survey results. The first group is of 40 students and used the laboratory [1] presented in SDR'09. The second group is of 30 students and used the new laboratory presented in this paper.

Question	SDR'09 Lab Average	SDR'09 Lab Std. Dev.	SDR'10 Lab Average	SDR'10 Lab Std. Dev.
The demonstrations done with the laboratory helped me understand the course material	3.83	0.93	4.27	1.01
Seeing the signals graphically using the laboratory is more useful than reading the course textbook	4.18	0.78	4.43	0.86
The demonstrations using the laboratory were clear	3.48	0.99	4.03	0.85
The demonstrations using the laboratory were useful	3.83	0.84	4.47	1.01
The activities and demonstrations using the laboratory were fun	3.18	1.08	3.73	0.78
The demonstrations using the laboratory incentivized me to further explore the subject of digital communications	3.70	0.94	3.77	1.10
I recommend using a similar laboratory for other courses in electronics in order to help in the teaching process	4.20	0.85	4.47	0.97
I learned more from the laboratory demonstrations than from the theoretical exposition on the blackboard	3.63	0.95	3.50	1.11
The use of this laboratory as a teaching aid must be made obligatory for teaching of this course in the future	4.10	0.84	4.43	1.10
The demonstrations using the laboratory were pretty	3.35	0.92	3.87	1.04
I like the subject of digital communications	3.93	0.86	4.03	0.85
The professor Yair Linn taught the course well	3.55	1.06	4.33	0.92
Average	**3.75**	**0.92**	**4.10**	**0.96**

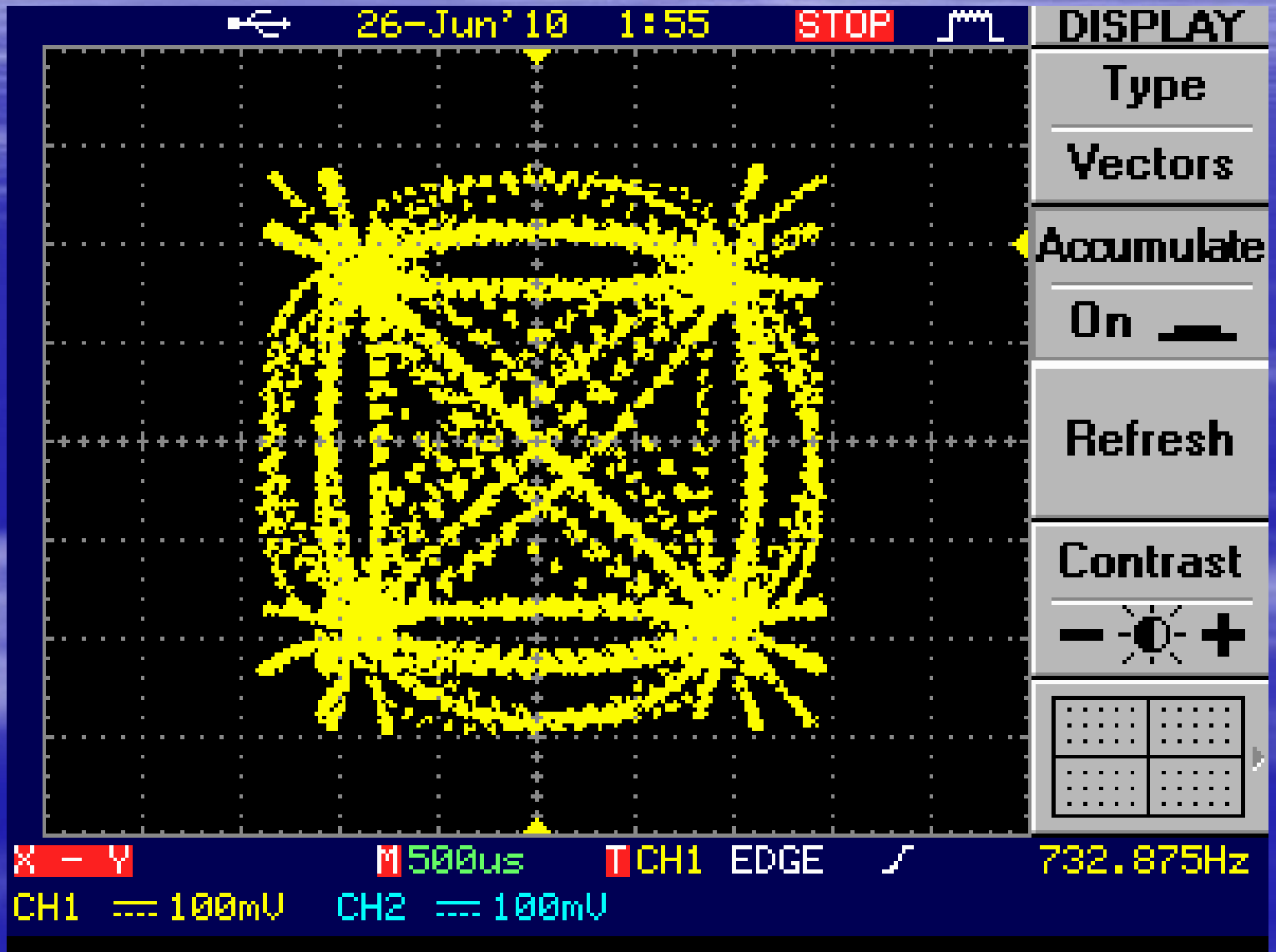
A Picture is worth a thousand words……

And now for some nice pictures!!!

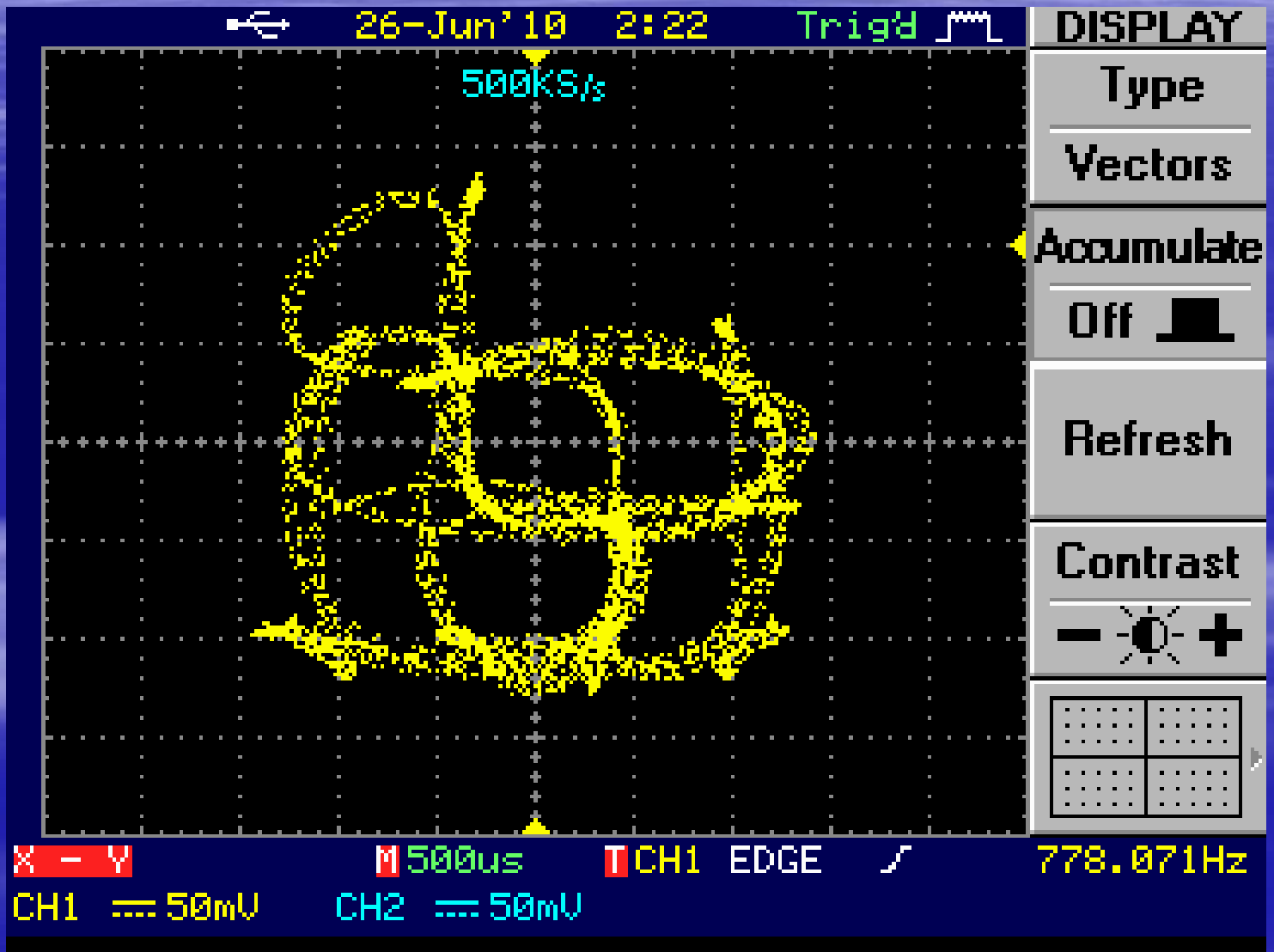
OQPSK transition diagram at receiver, rolloff = 0.85, SNR = 35 dB



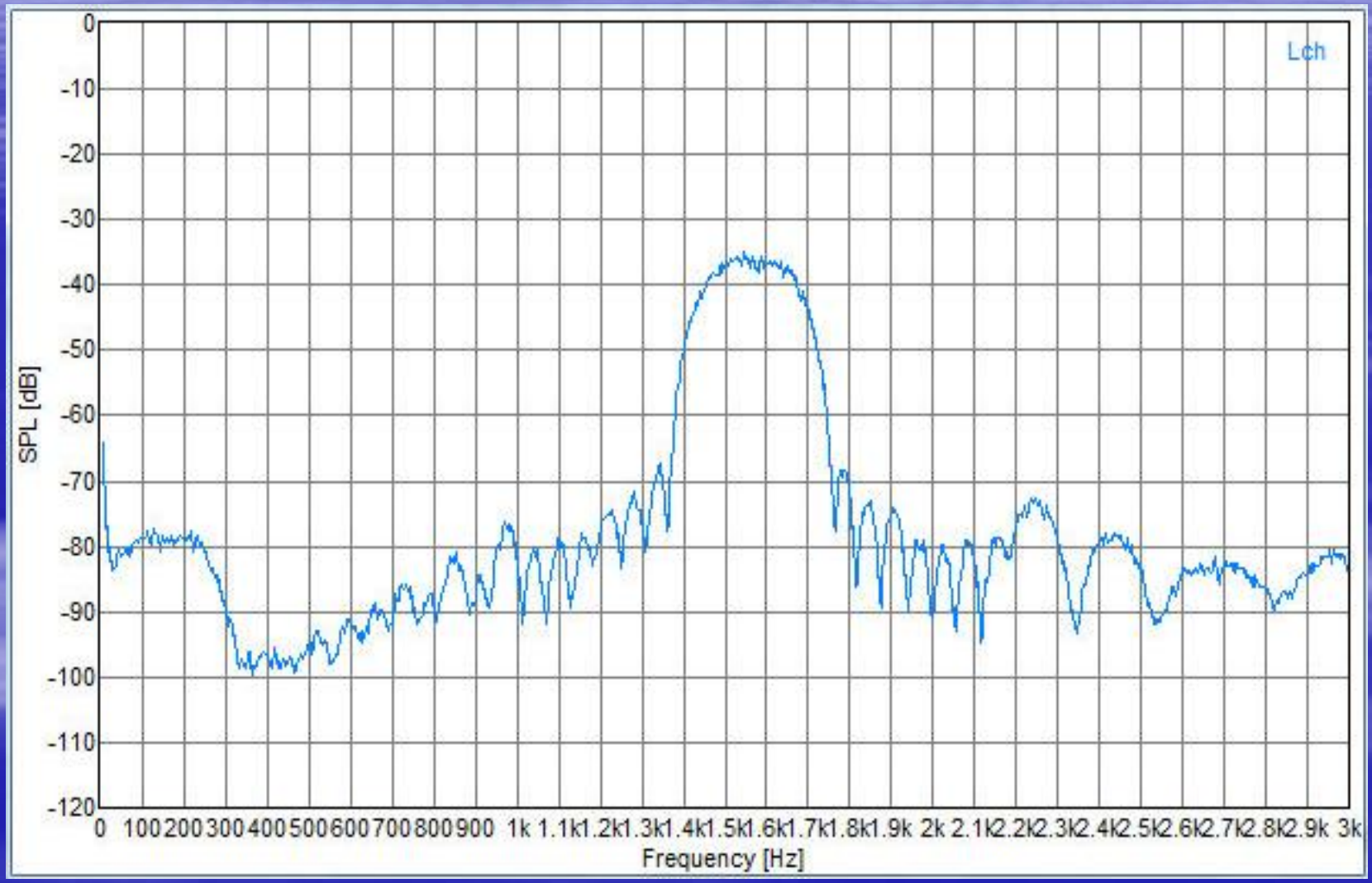
QPSK transition diagram at receiver, rolloff = 0.35, SNR = 35 dB



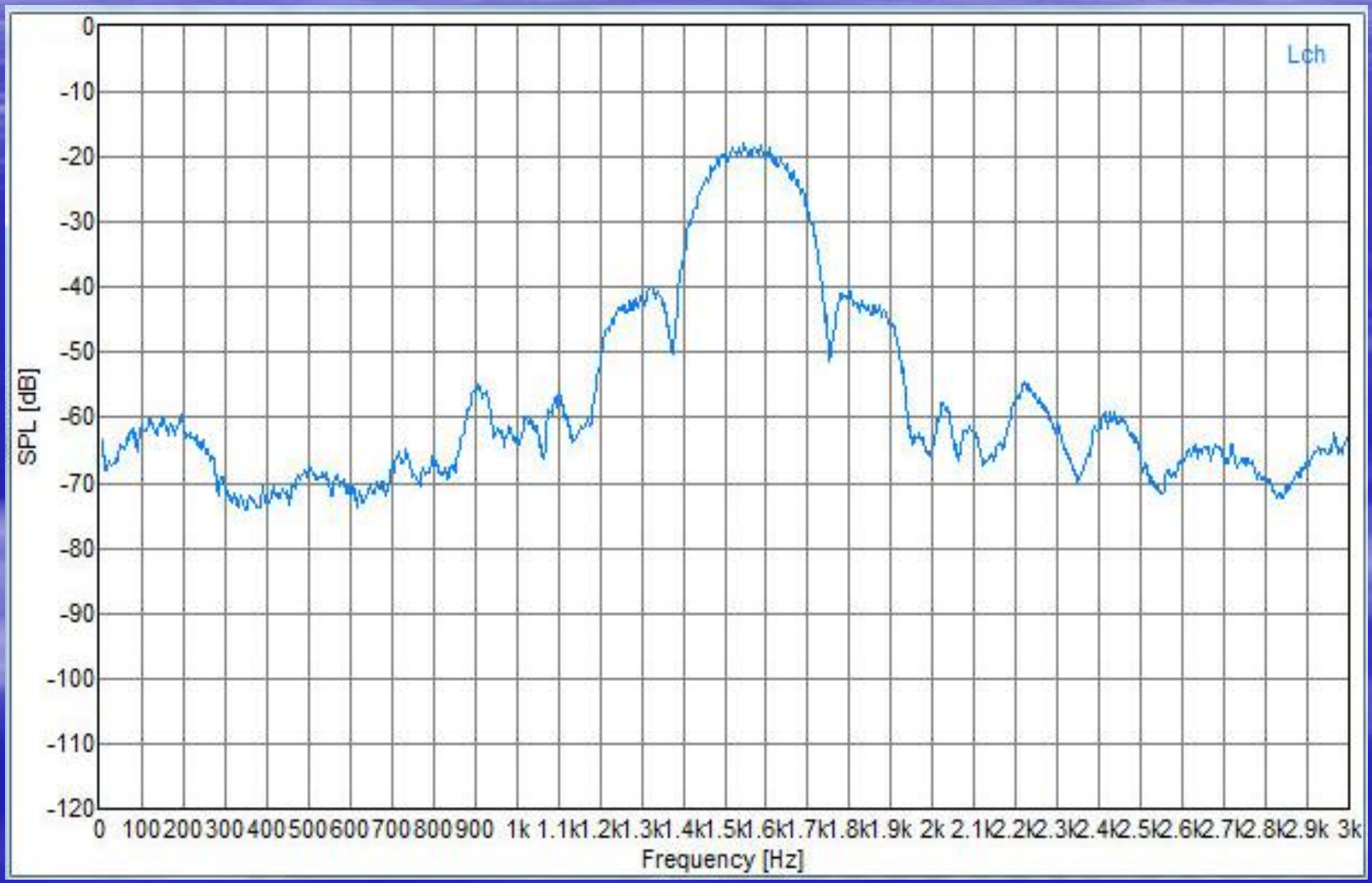
Partially formed transition diagram at the transmitter for Offset QAM-16 with a rolloff factor of 0.35



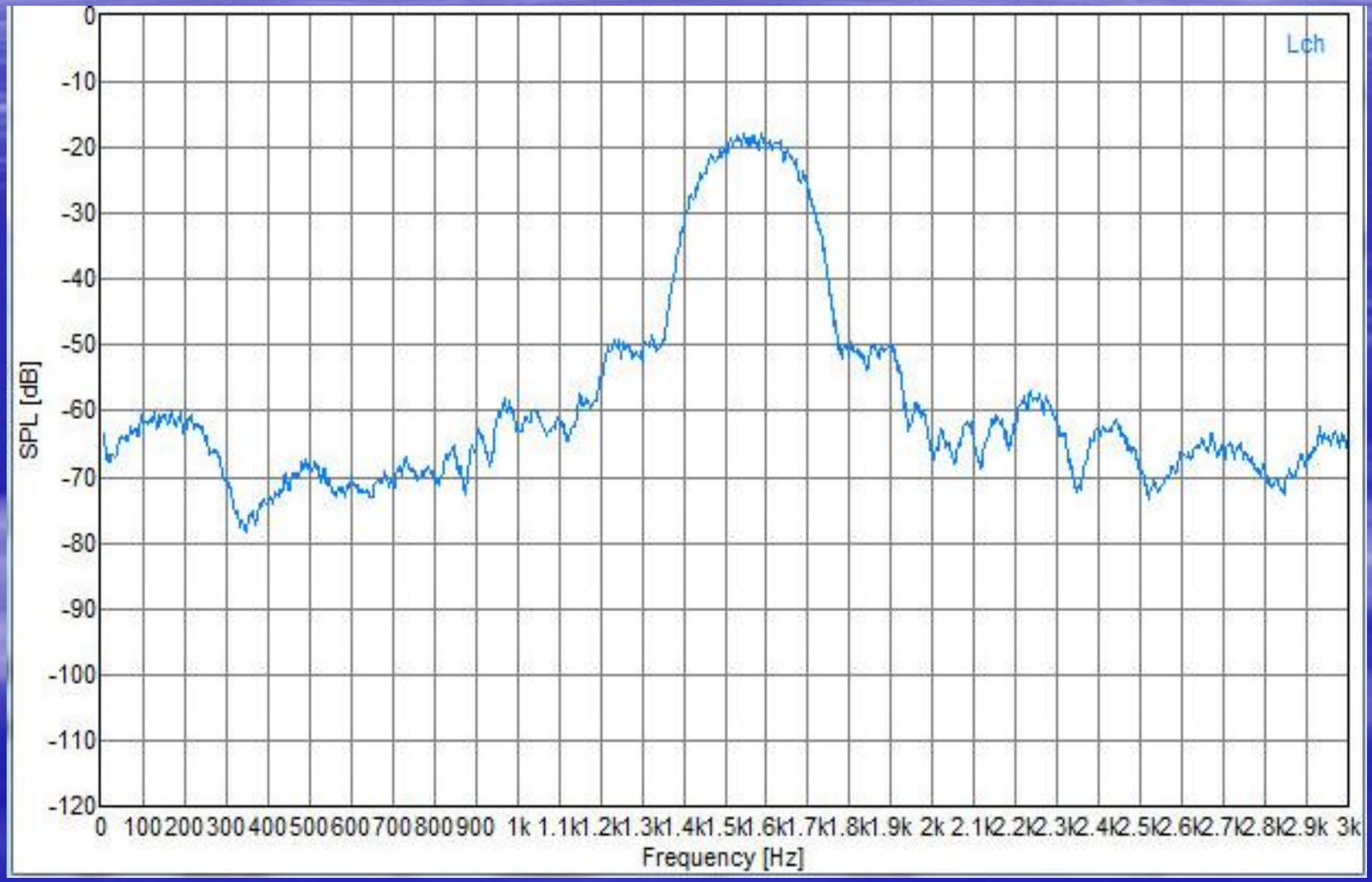
QPSK or OQPSK spectrum, rolloff = 0.85



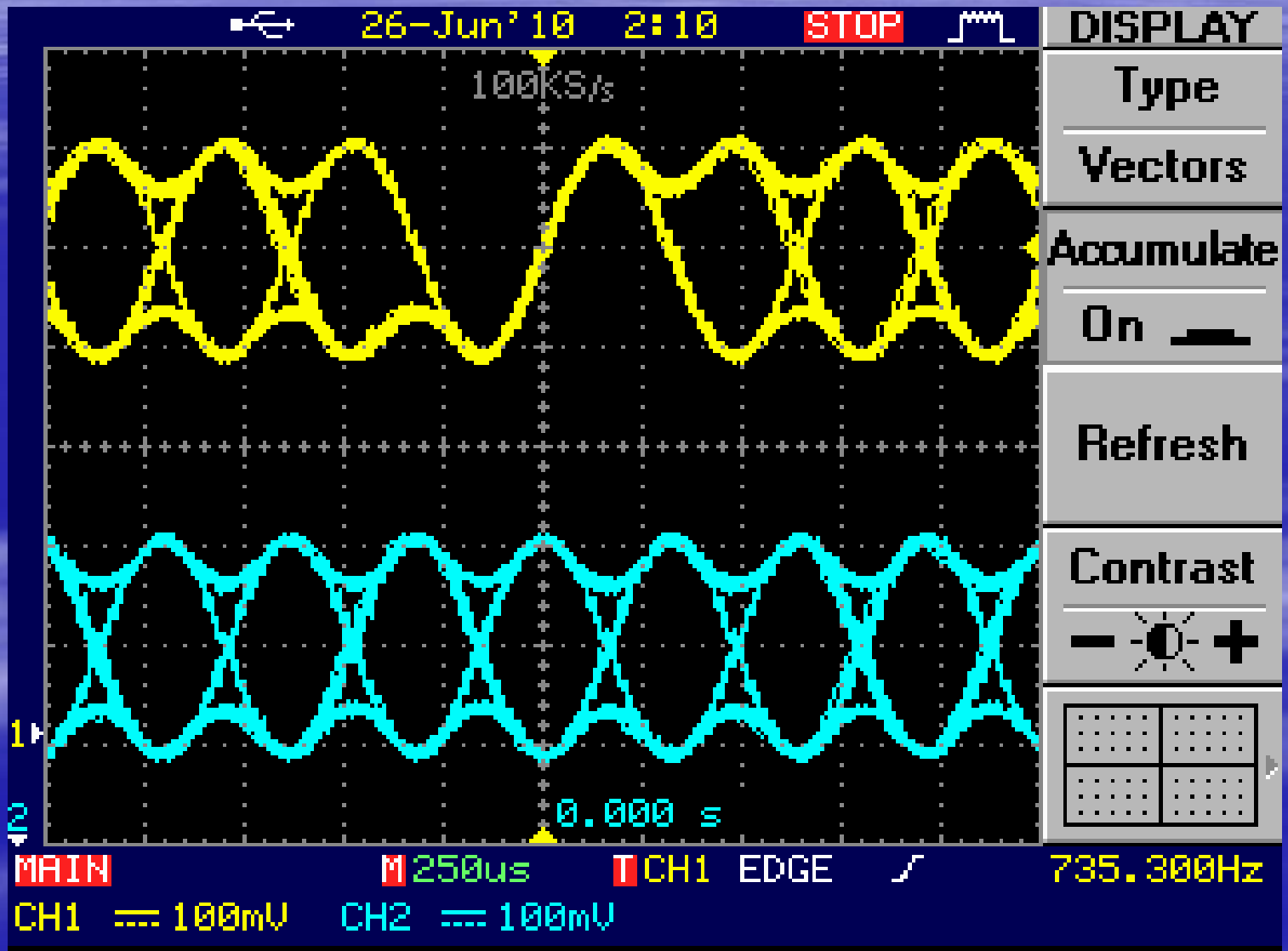
QPSK Spectrum, rolloff = 0.85, through saturated amplifier



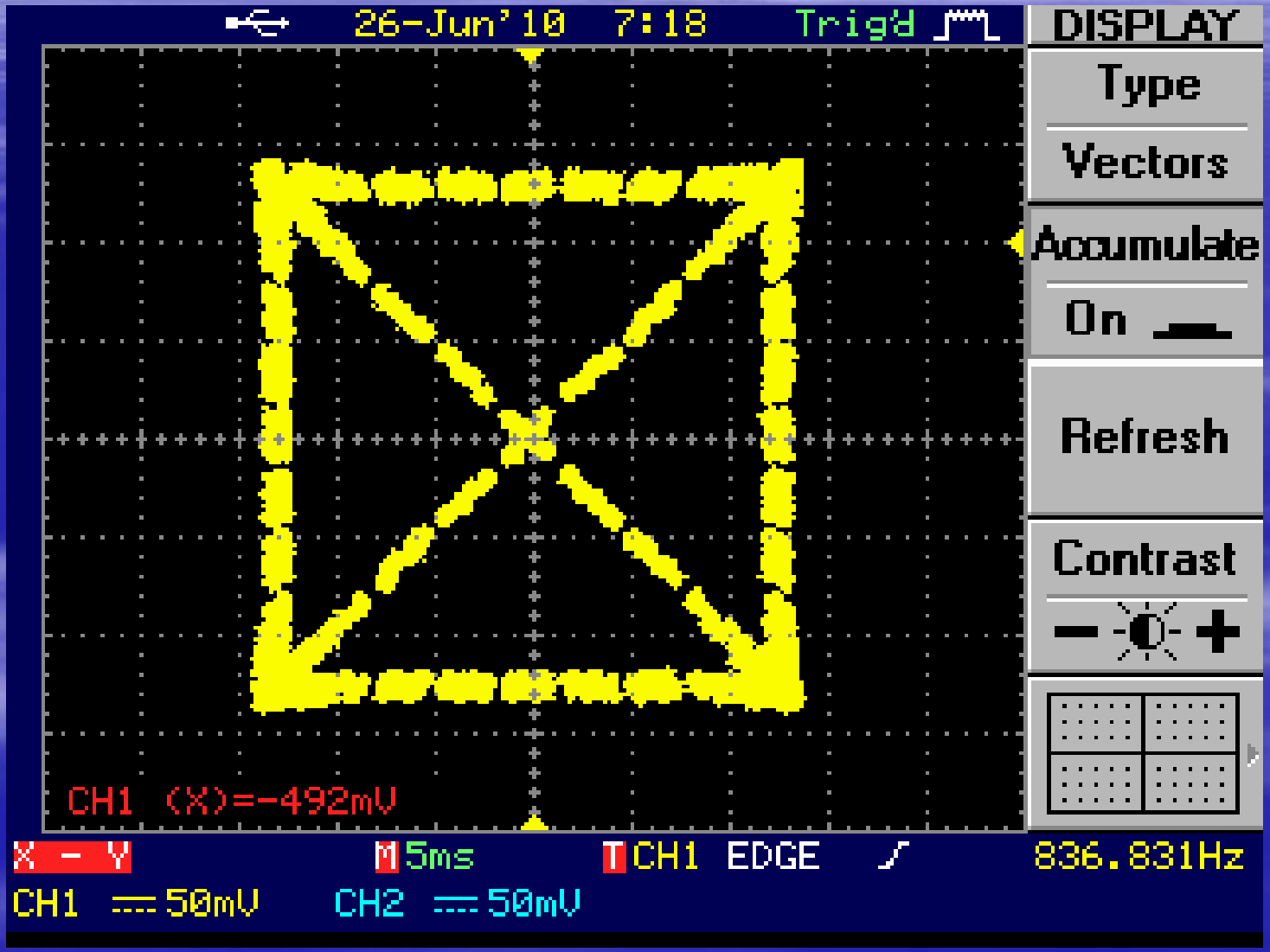
OQPSK Spectrum, rolloff = 0.85, through saturated amplifier



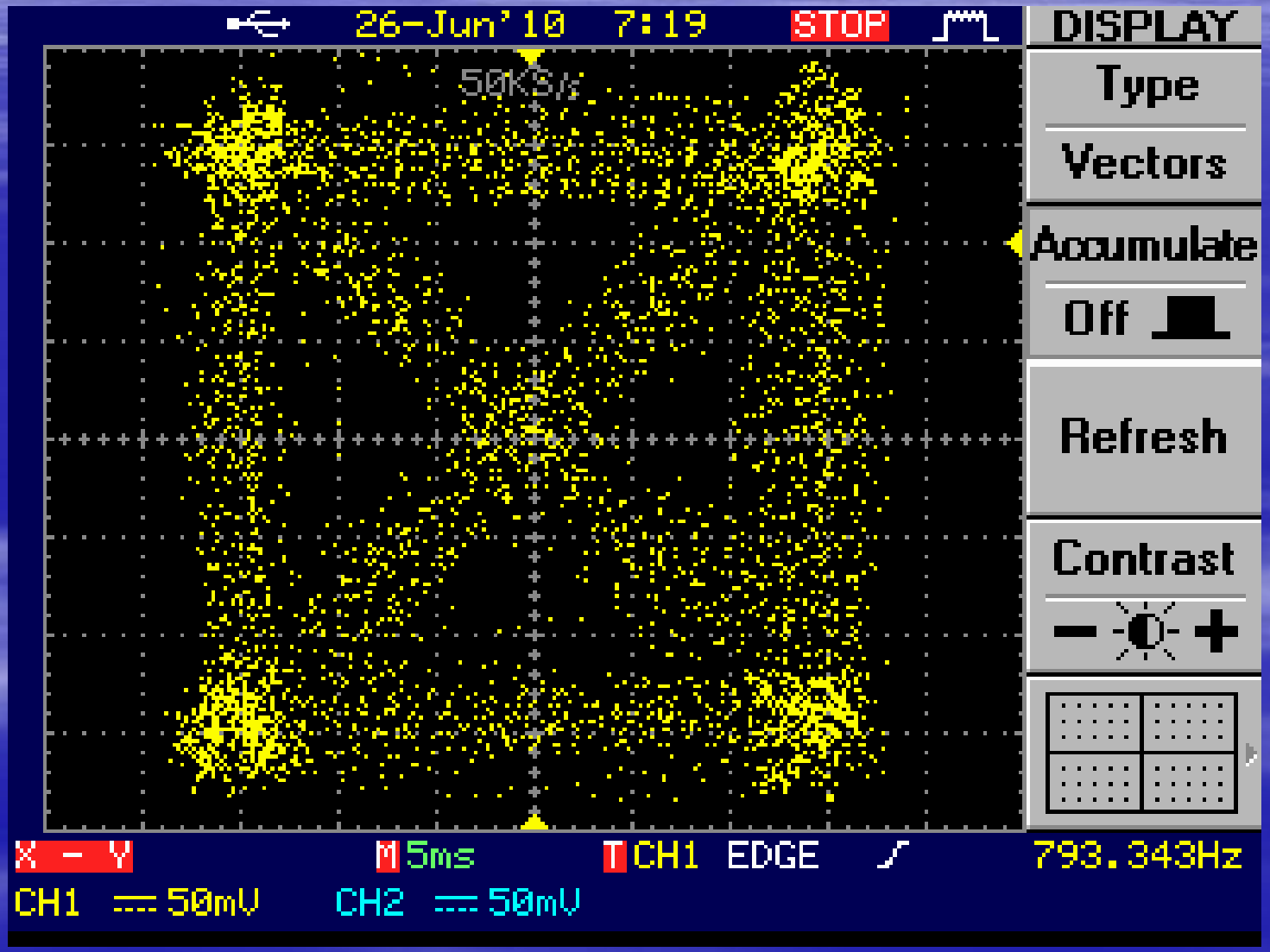
MSK eye diagram at the receiver for SNR=35 dB



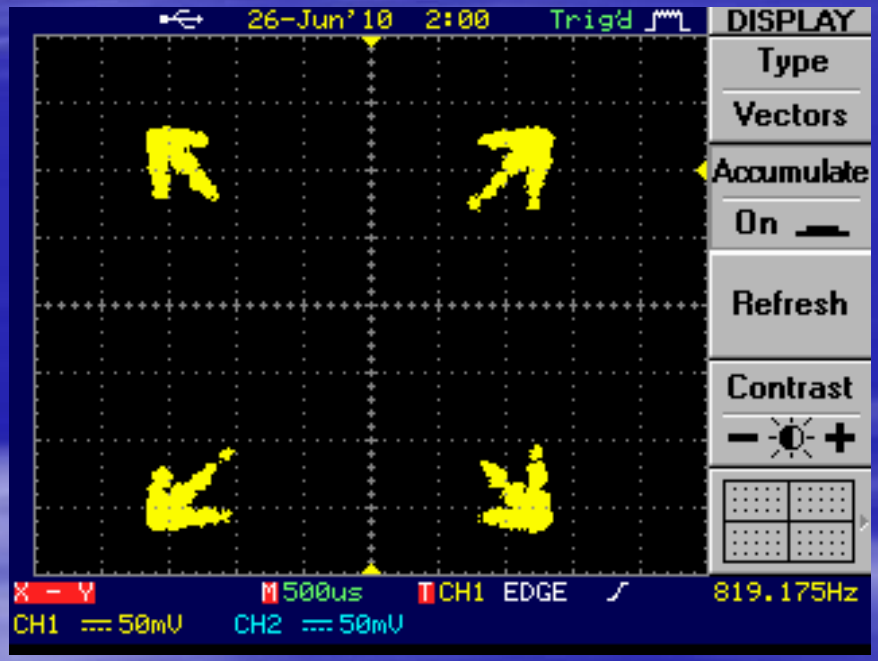
QPSK transition diagram at the receiver, SNR = 35 dB

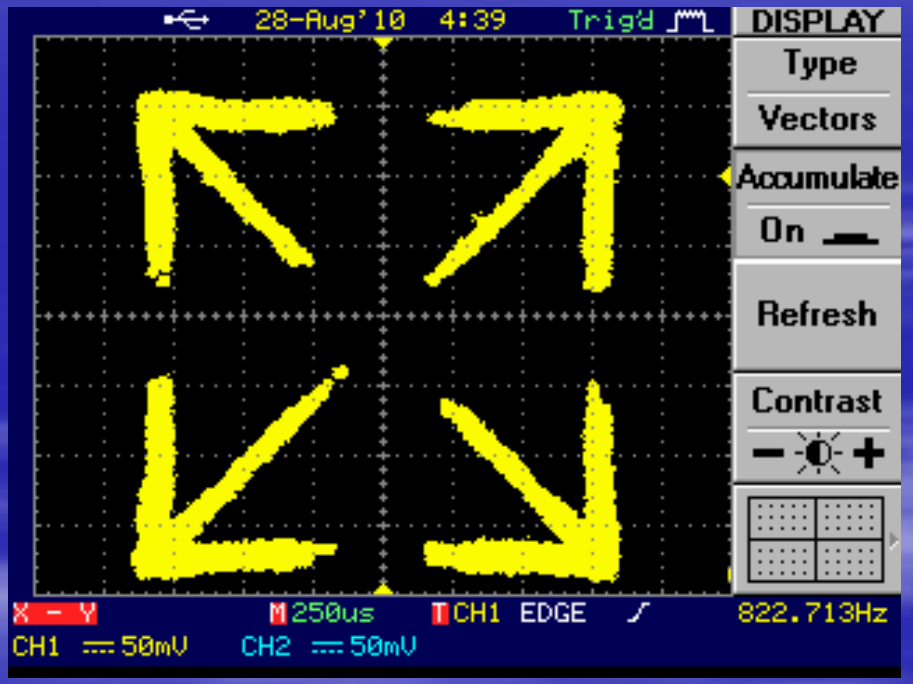


QPSK transition diagram at the receiver, SNR = 18 dB

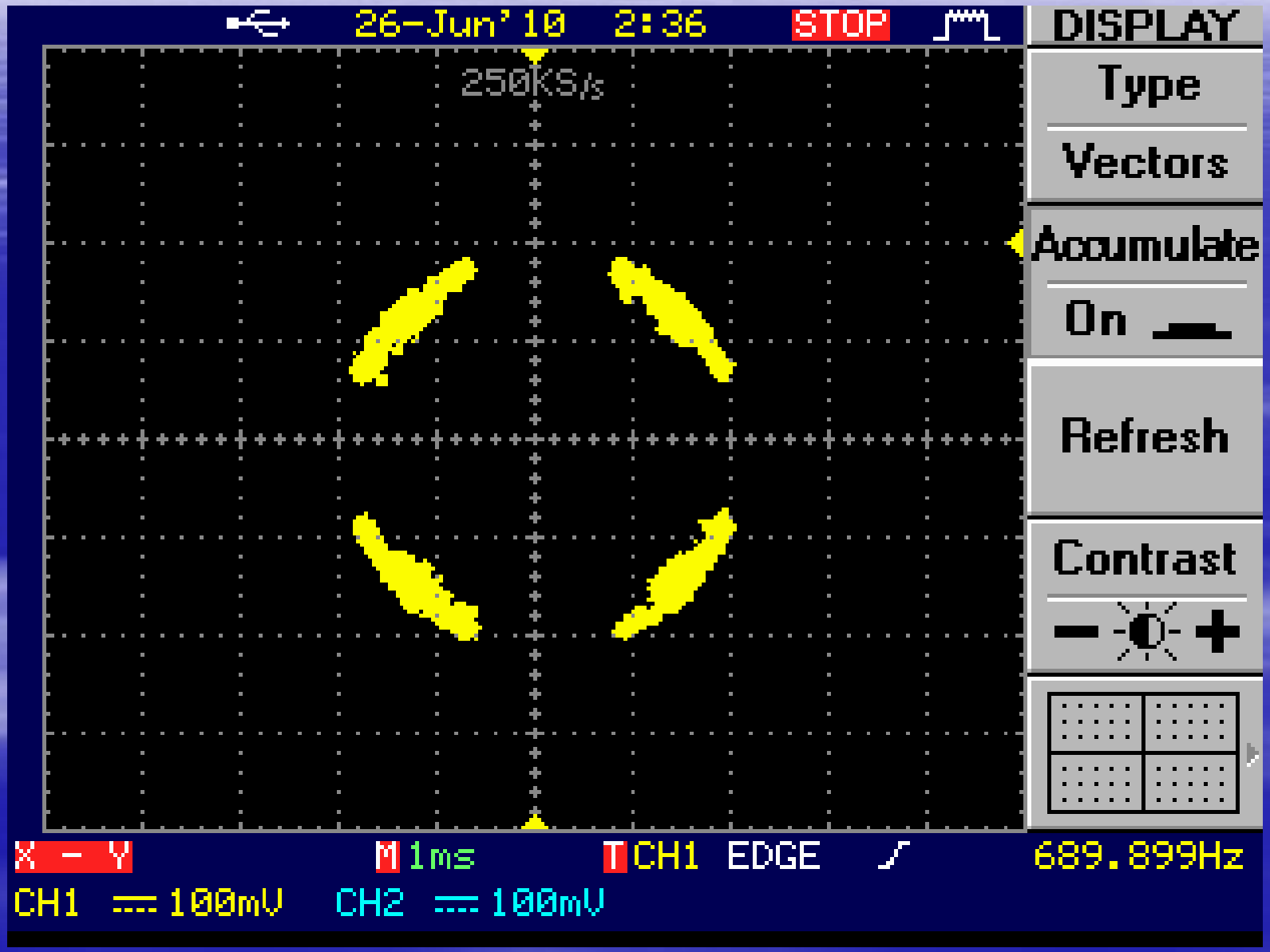


Effect of Timing Jitter on QPSK

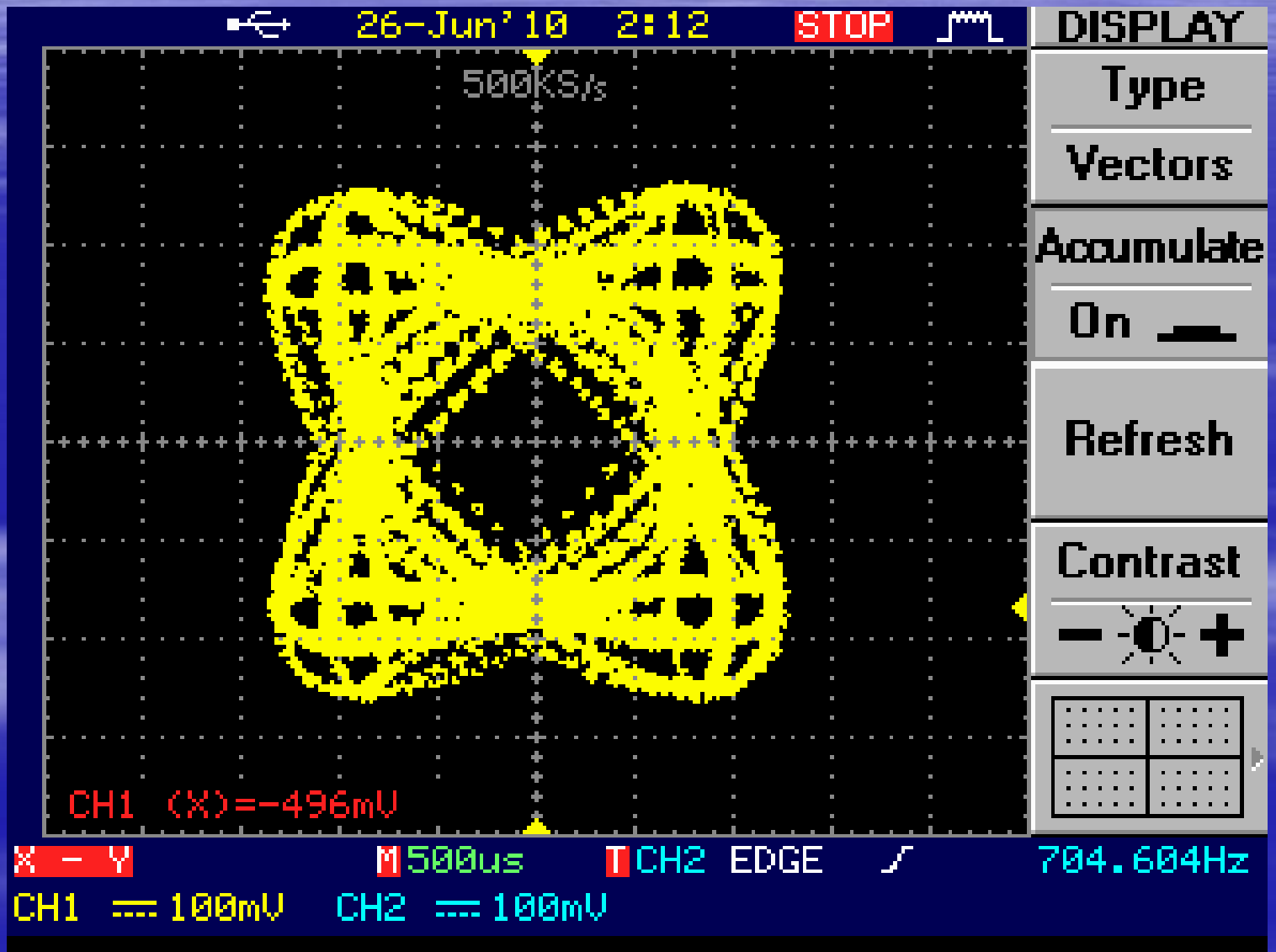




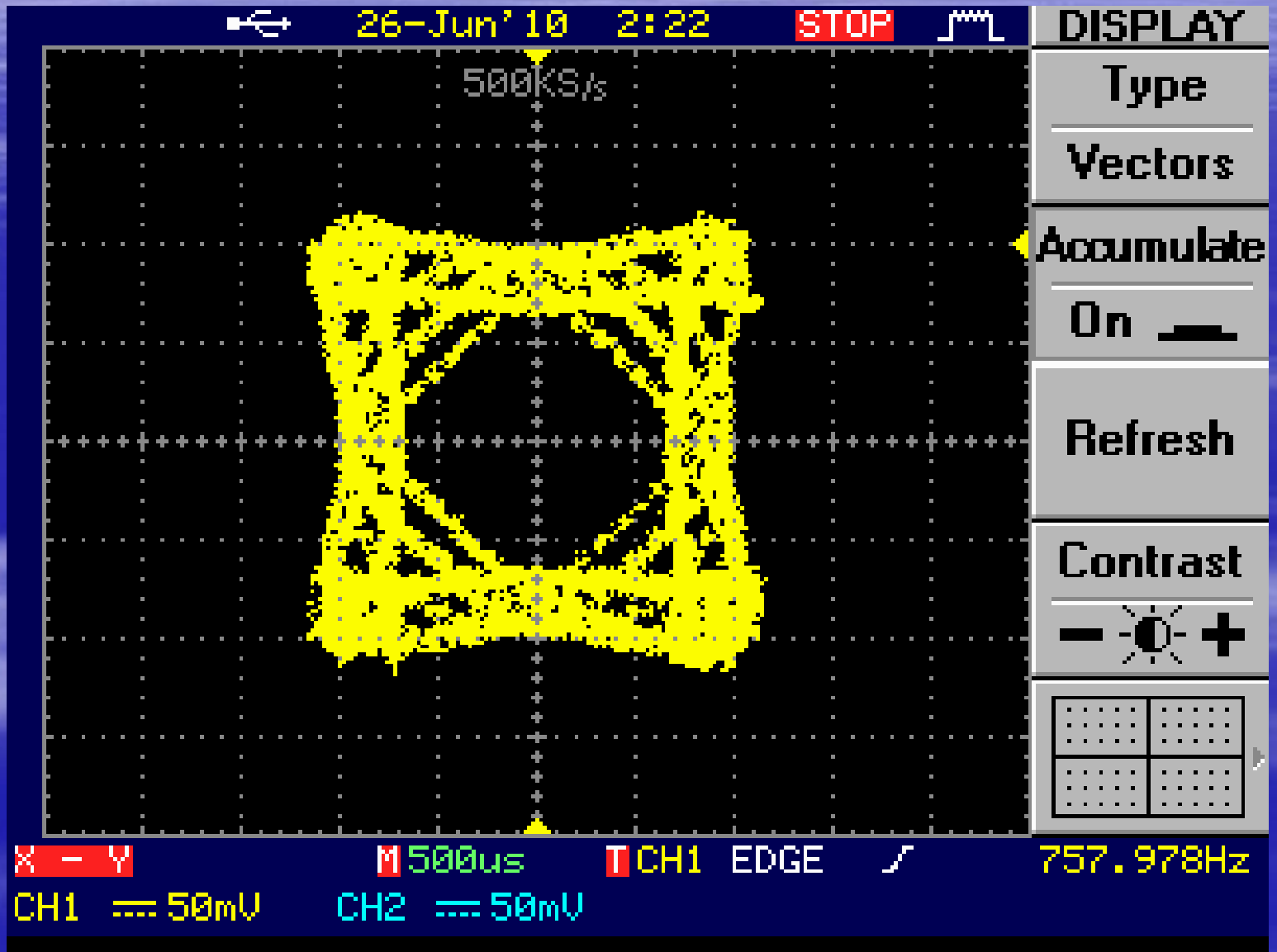
Effect of Carrier Jitter on QPSK



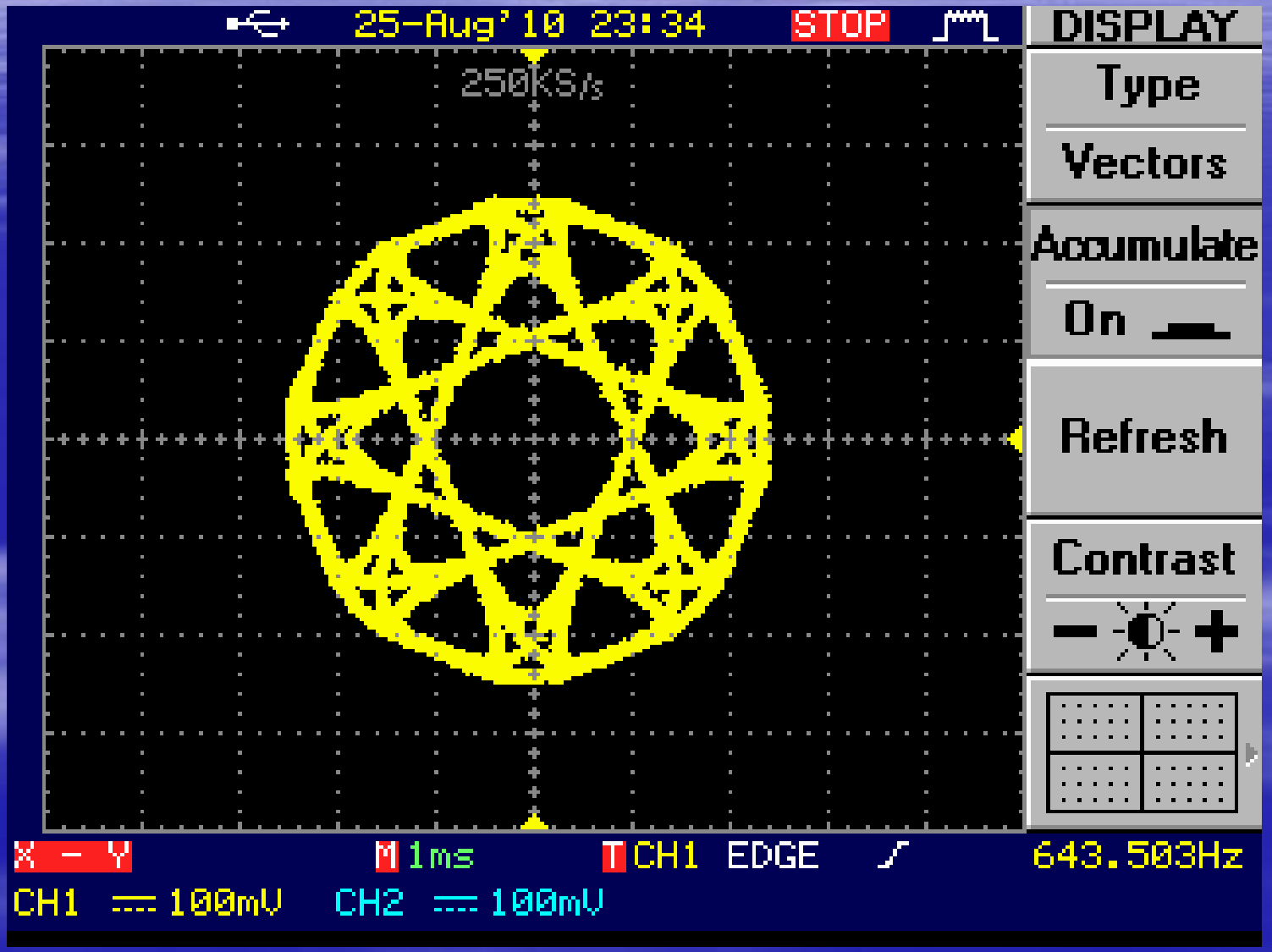
TX transition diagram, OQPSK with SRRC rolloff =0.35



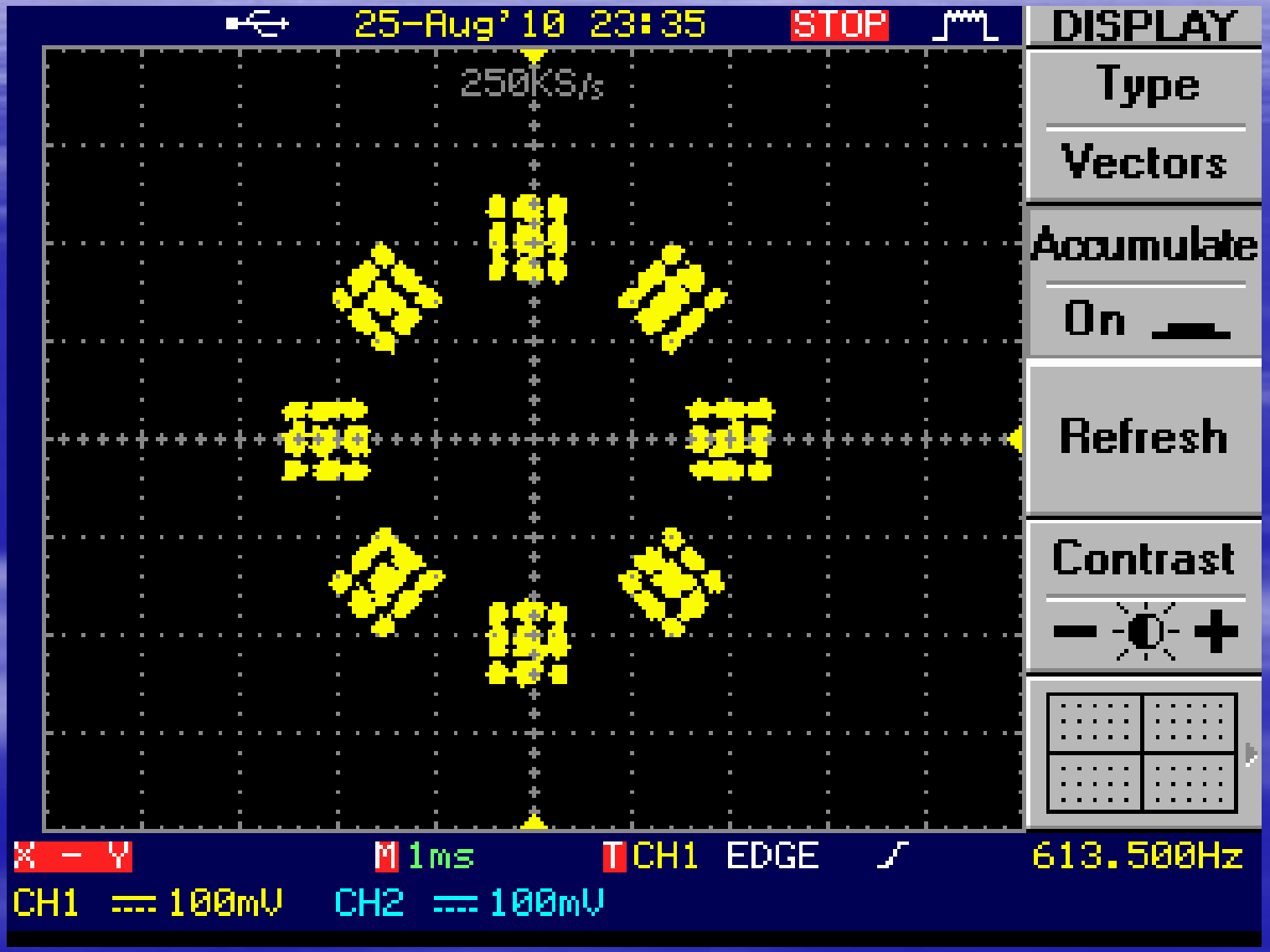
TX transition diagram, OQPSK with SRRC rolloff =0.85



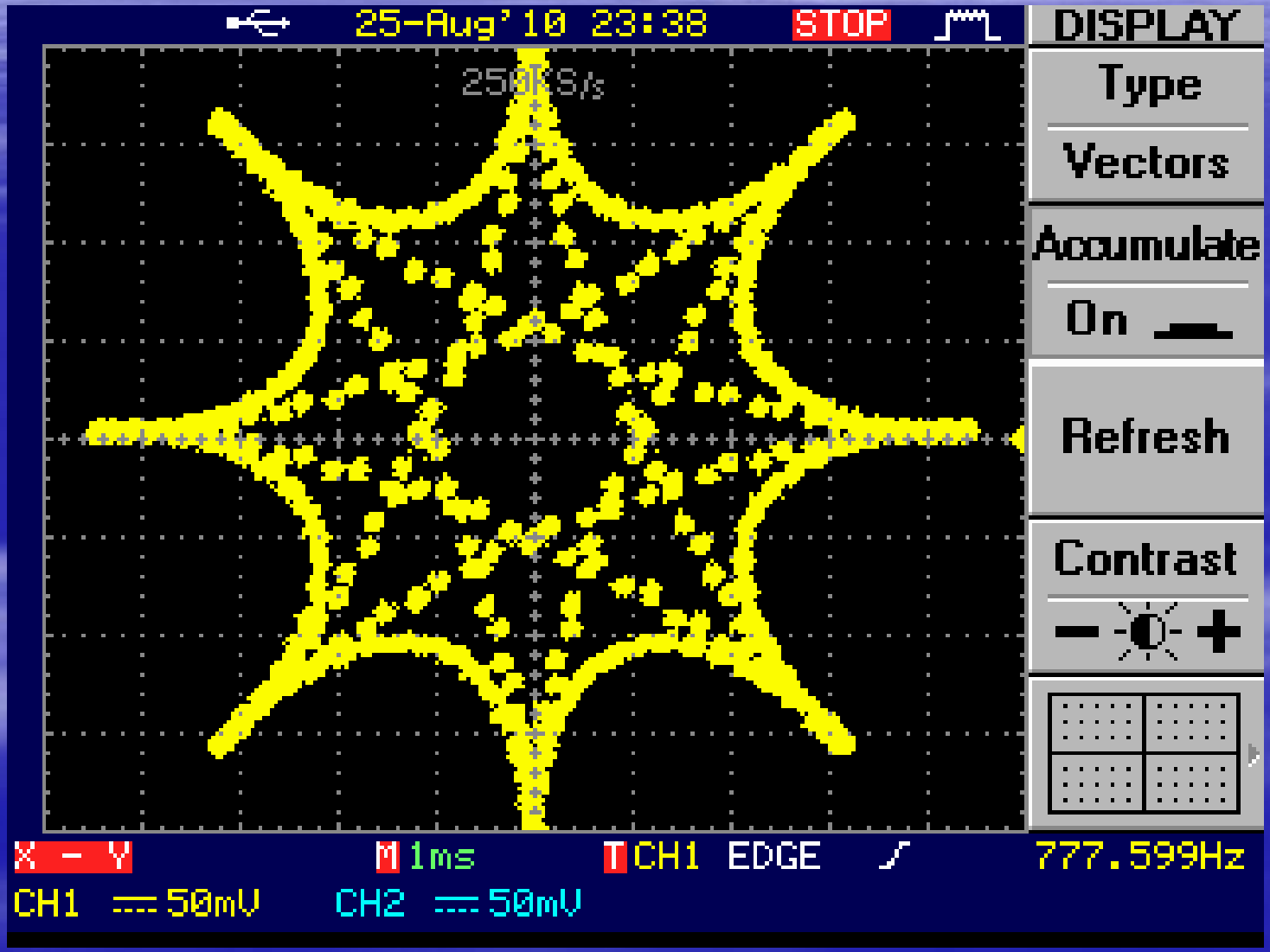
Transition diagram at the receiver of pi/4-QPSK with Gaussian pulse shaping, SNR = 35 dB.



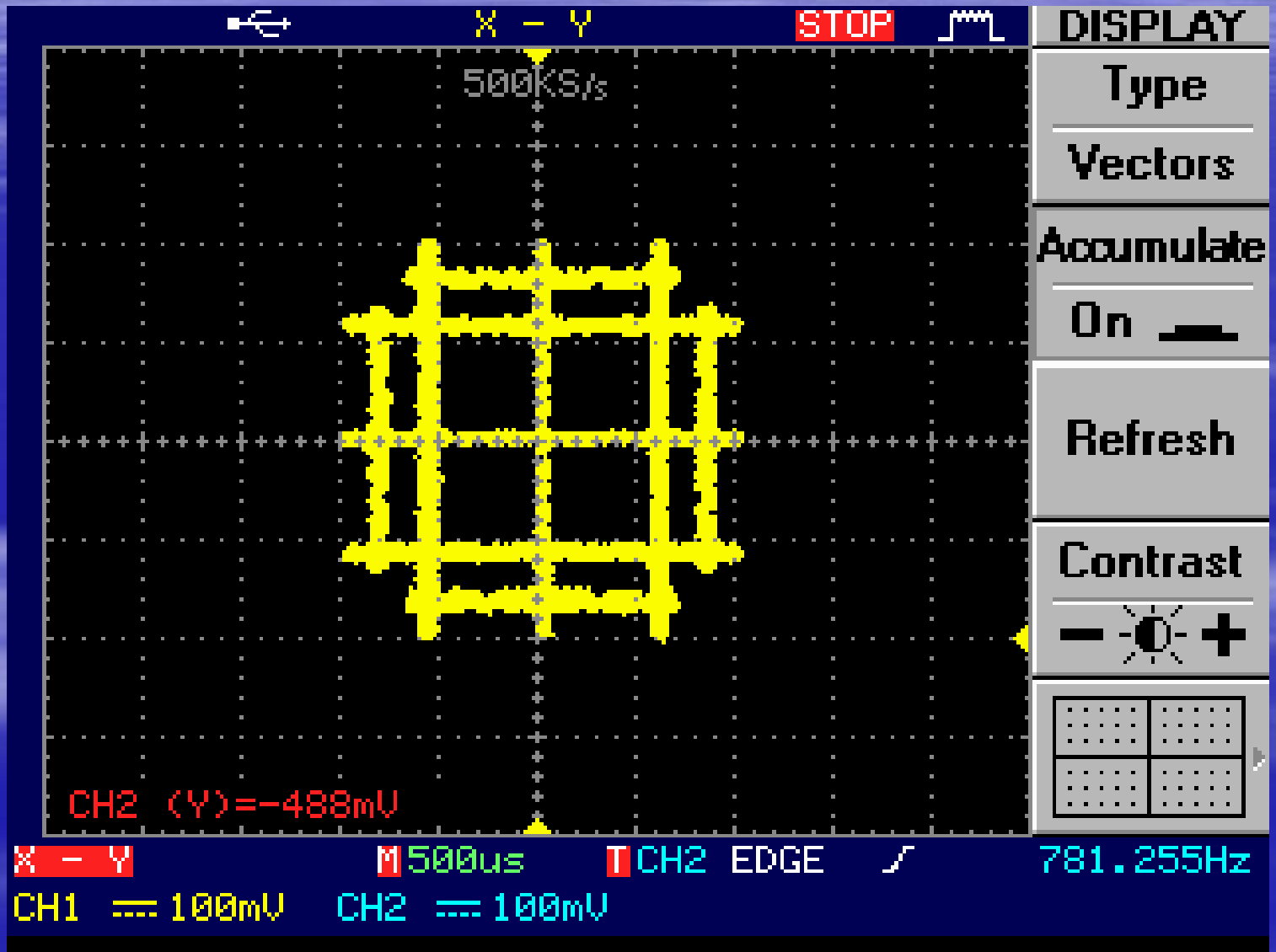
Constellation diagram at the receiver of pi/4-QPSK with Gaussian pulse shaping, SNR = 35 dB.



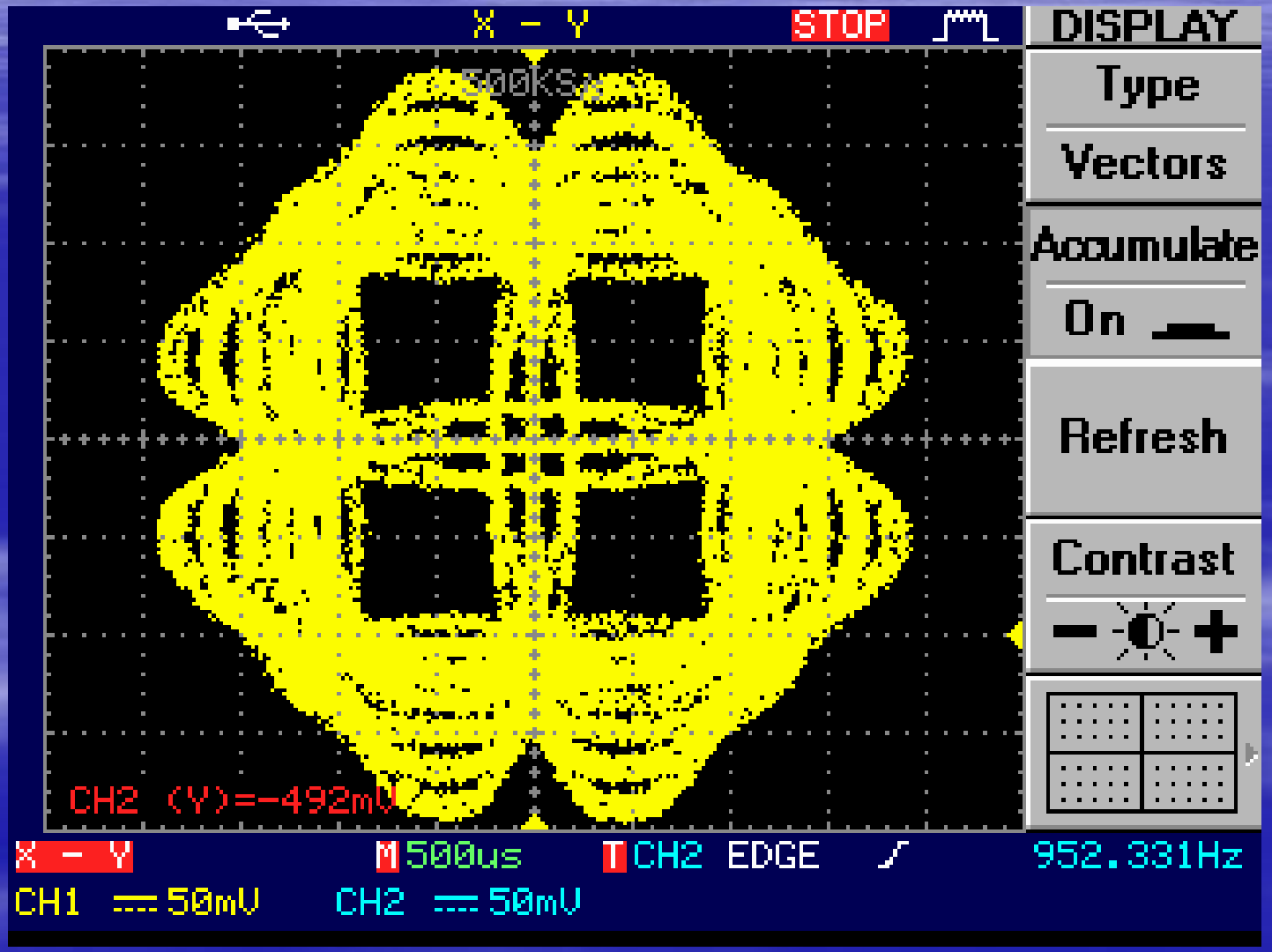
Transition diagram at the receiver of pi/4-QPSK with half-sinusoid pulse shape, SNR=35 dB.



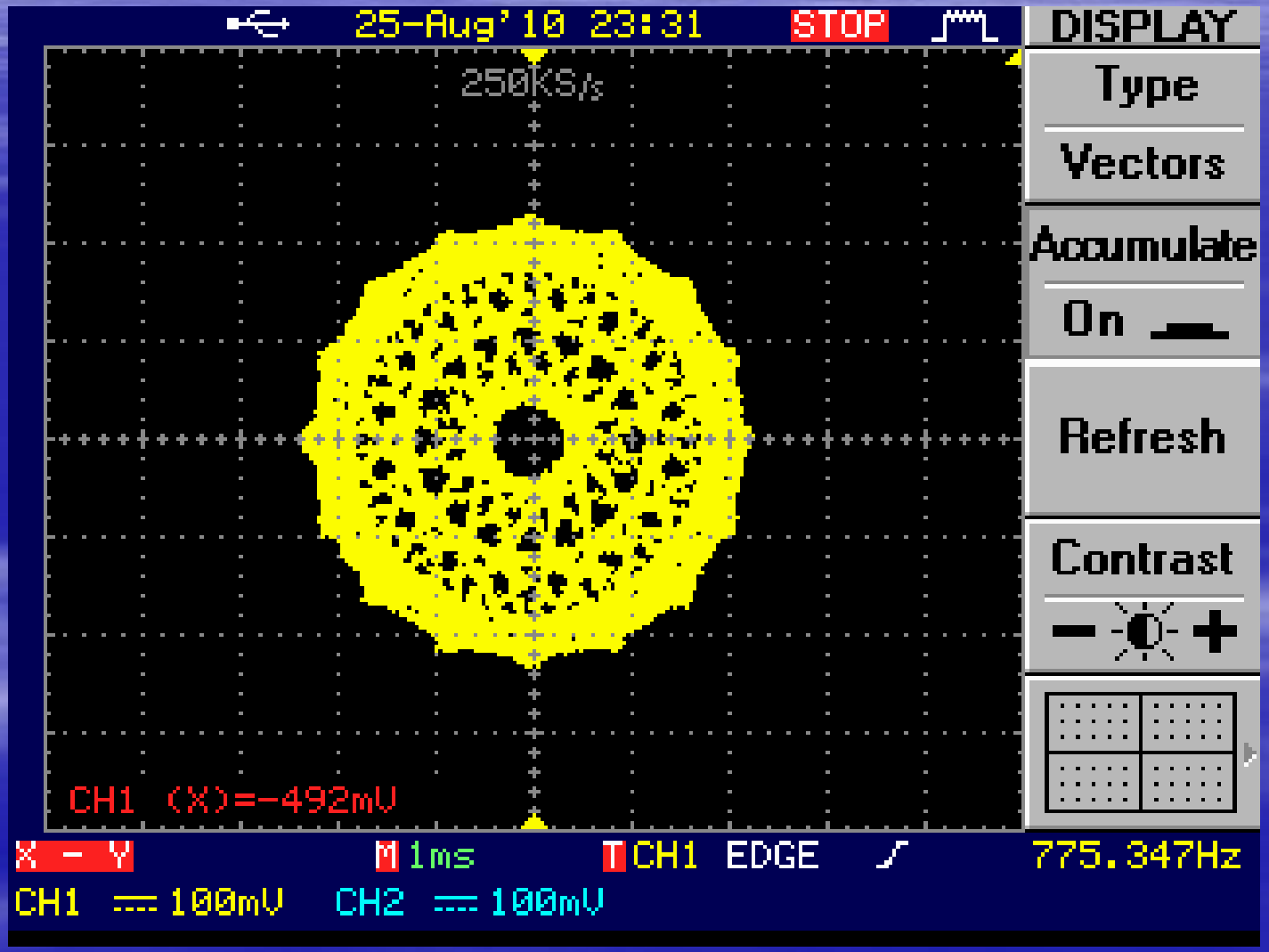
Transition diagram at the transmitter of Offset pi/4-QPSK with rectangular pulse shape.



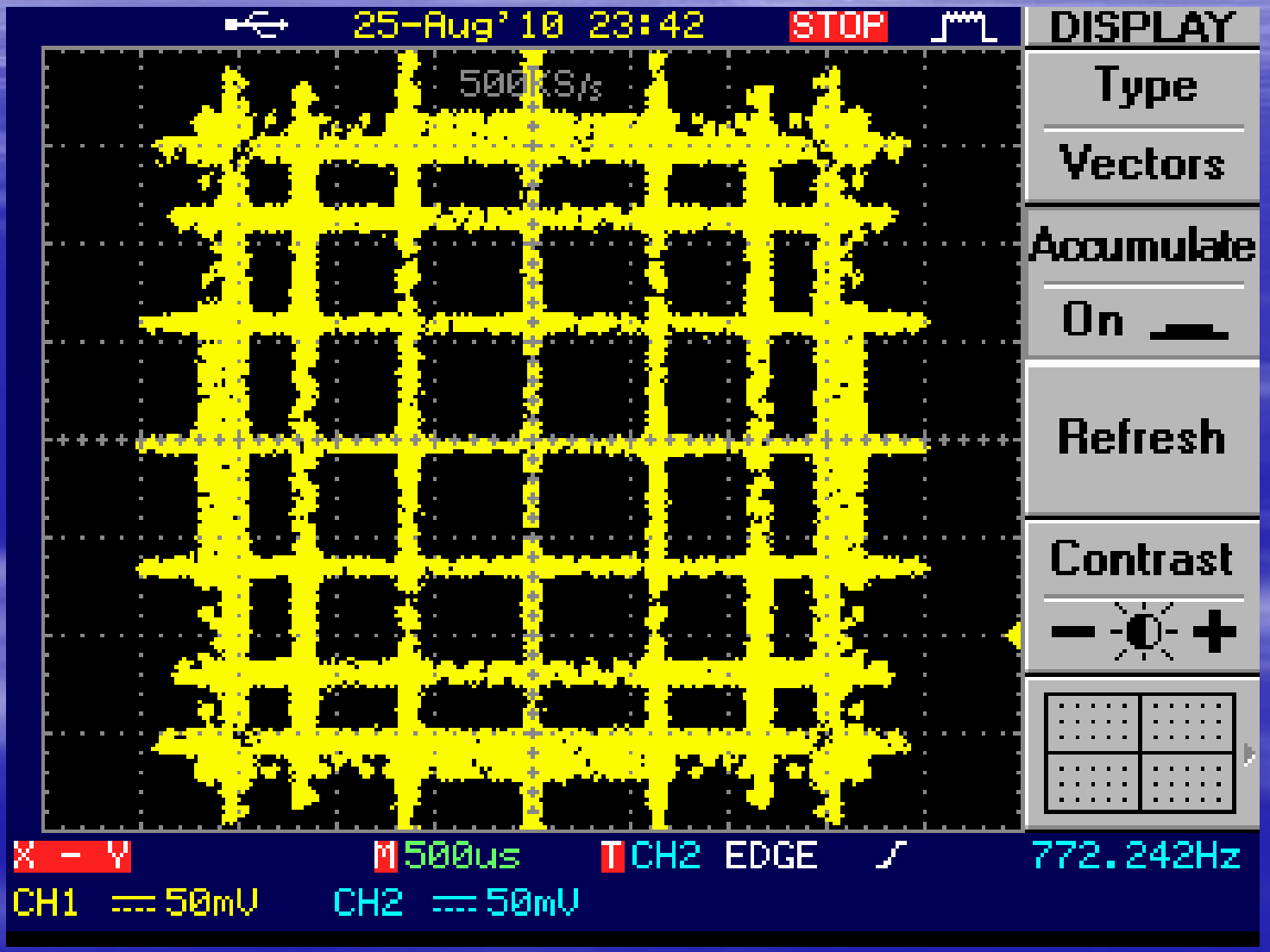
Transition diagram at the transmitter of Offset pi/4-QPSK with SRRC pulse shaping with rolloff factor of 0.35



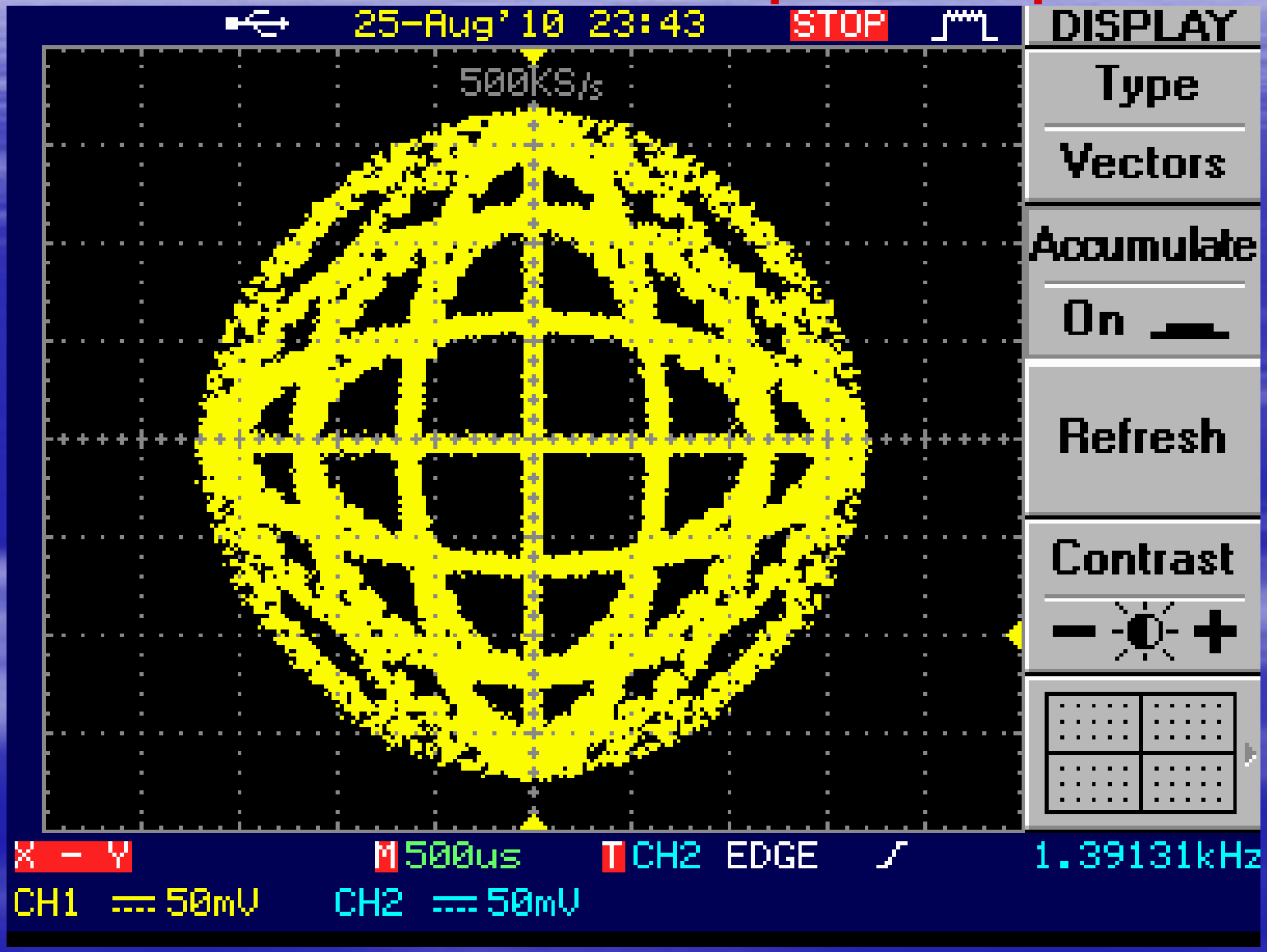
pi/8-8PSK transition diagram at the receiver, rectangular pulse shape, SNR = 35 dB



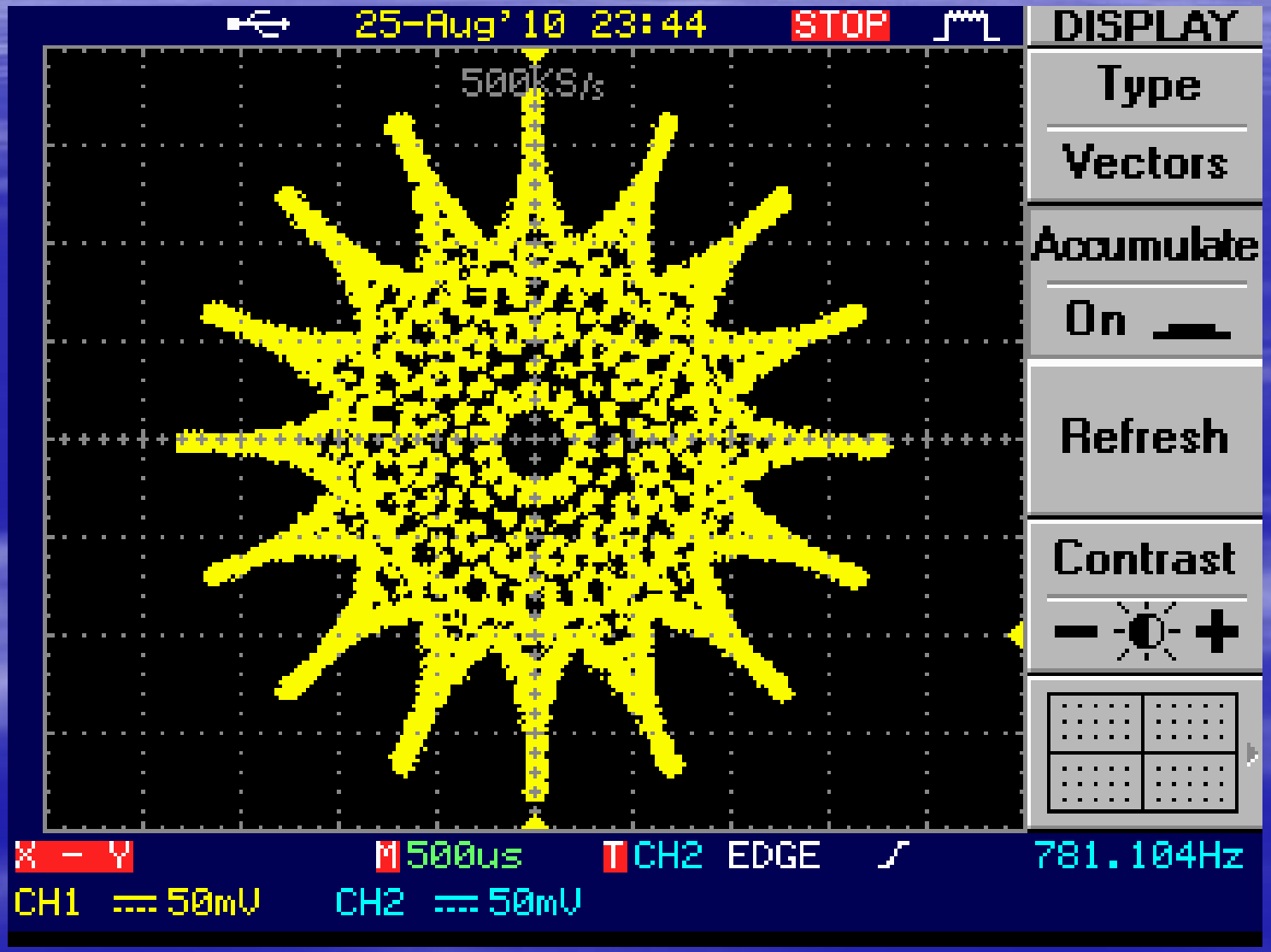
Transition diagram at the transmitter of Offset pi/8-8PSK with rectangular pulse shape



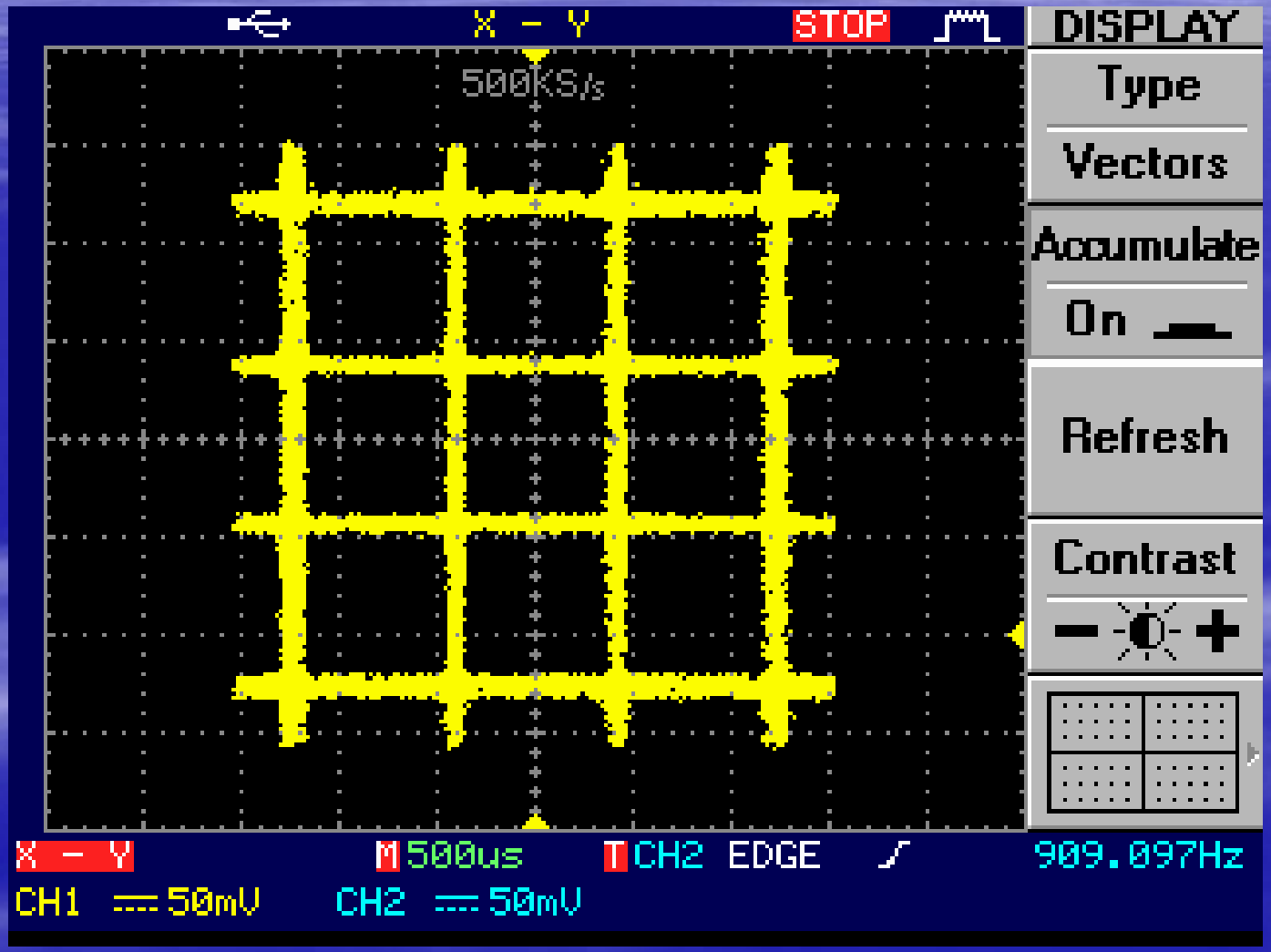
Transition diagram at the transmitter of Offset pi/8-8PSK with half-sinusoid pulse shape



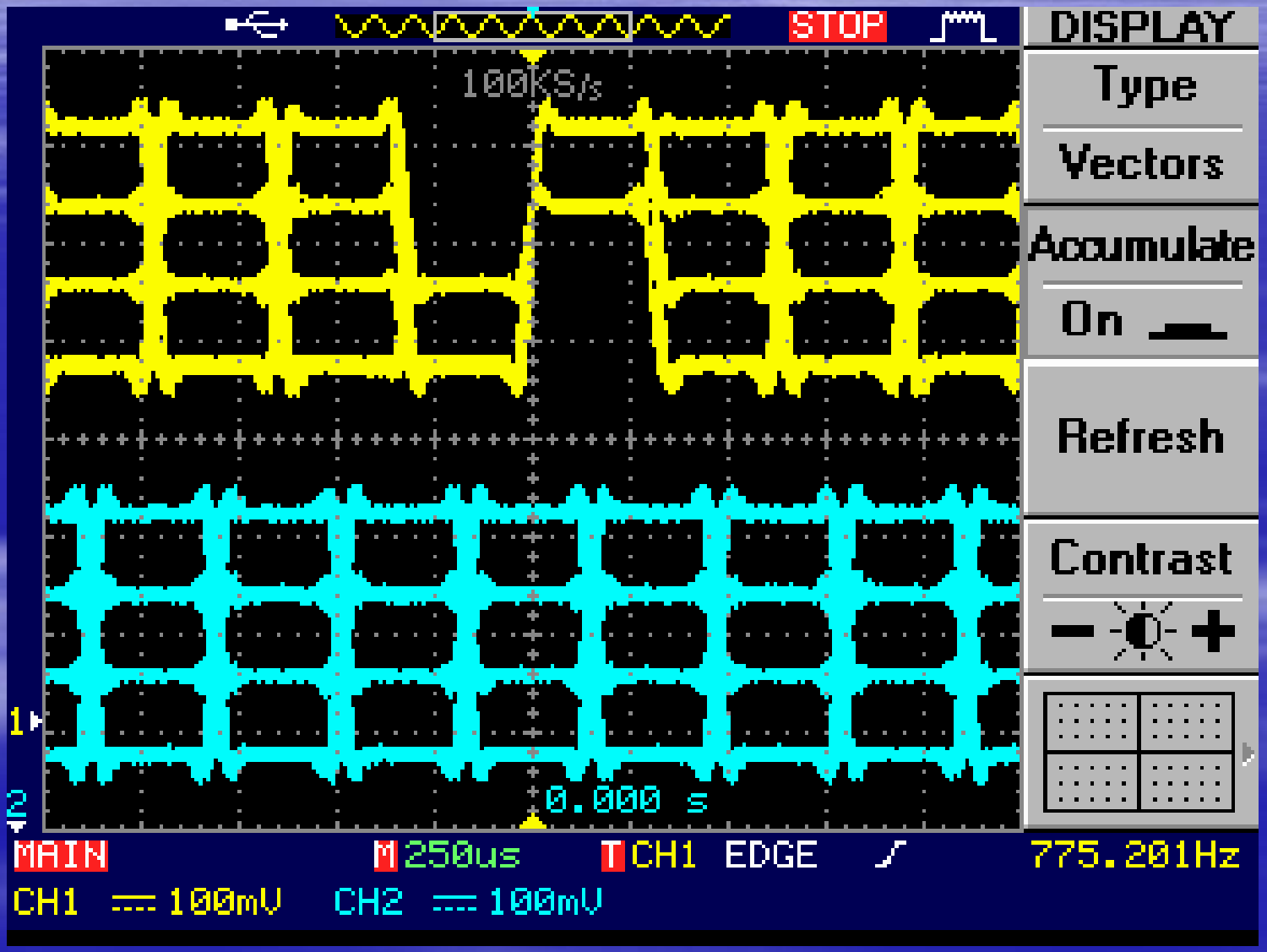
Transition diagram at the receiver of Offset pi/8-8PSK with half-sinusoid pulse shape, SNR=35 dB



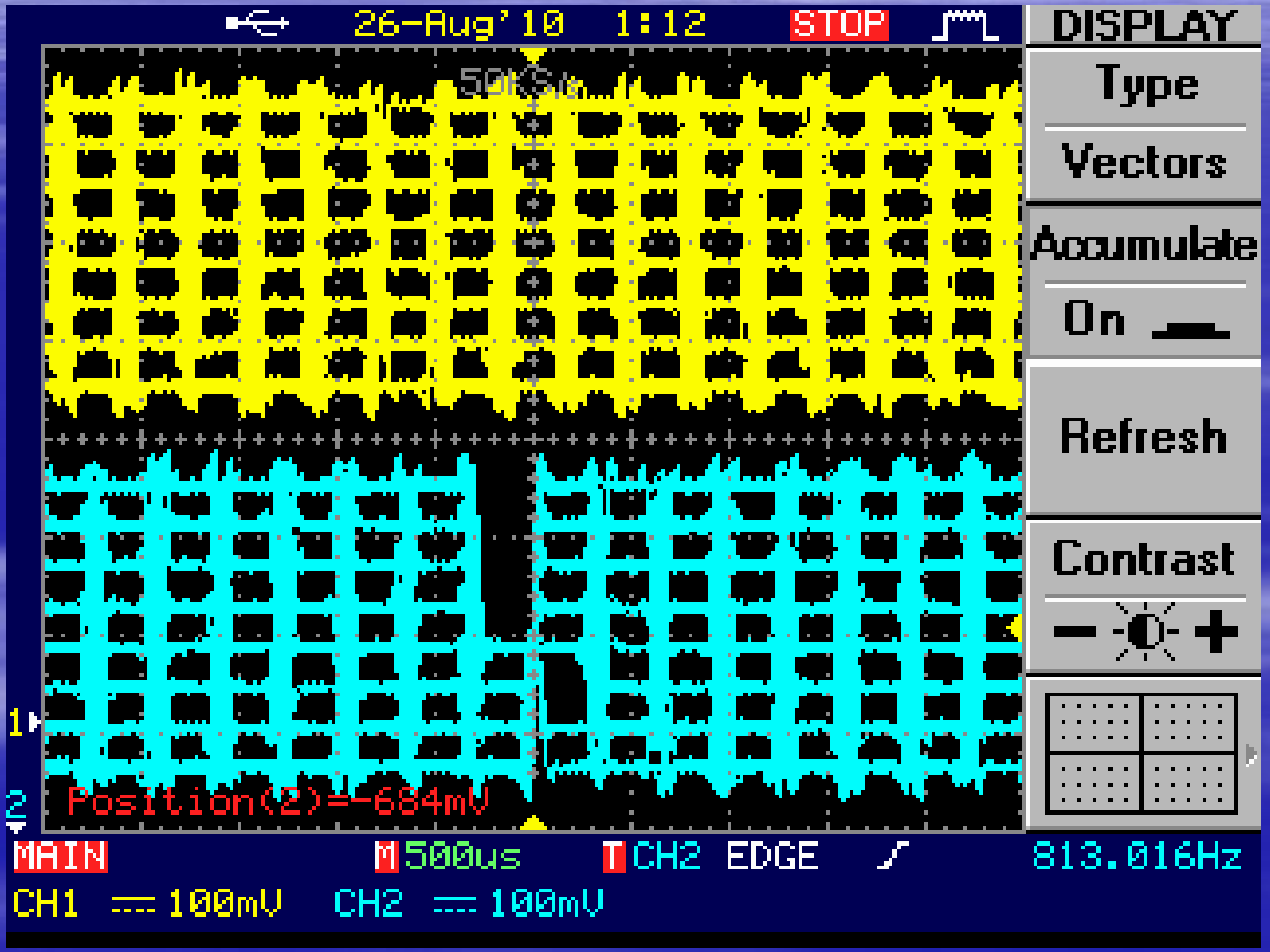
Offset QAM-16 transition diagram at the transmitter, rectangular pulse shape.



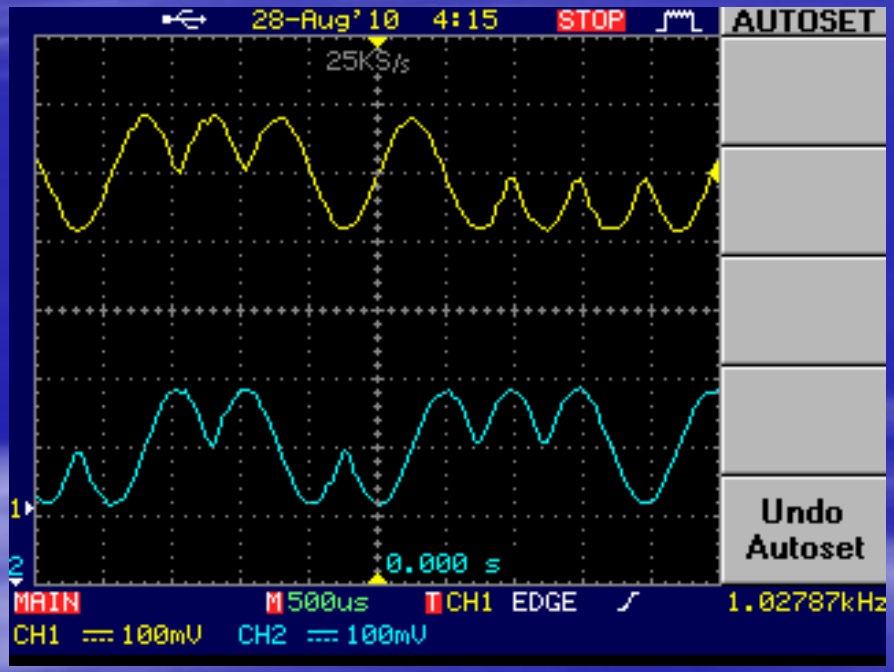
Offset QAM-16 eye diagram for I and Q channels at the transmitter, rectangular pulse shape

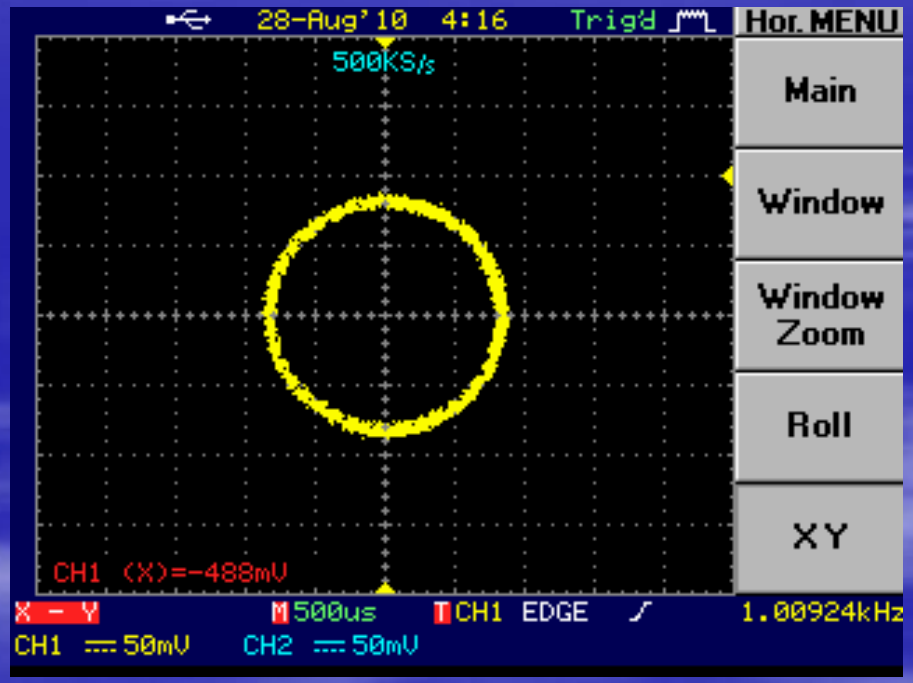


Offset QAM-64 eye diagrams for I and Q channels at the transmitter, rectangular pulse shape

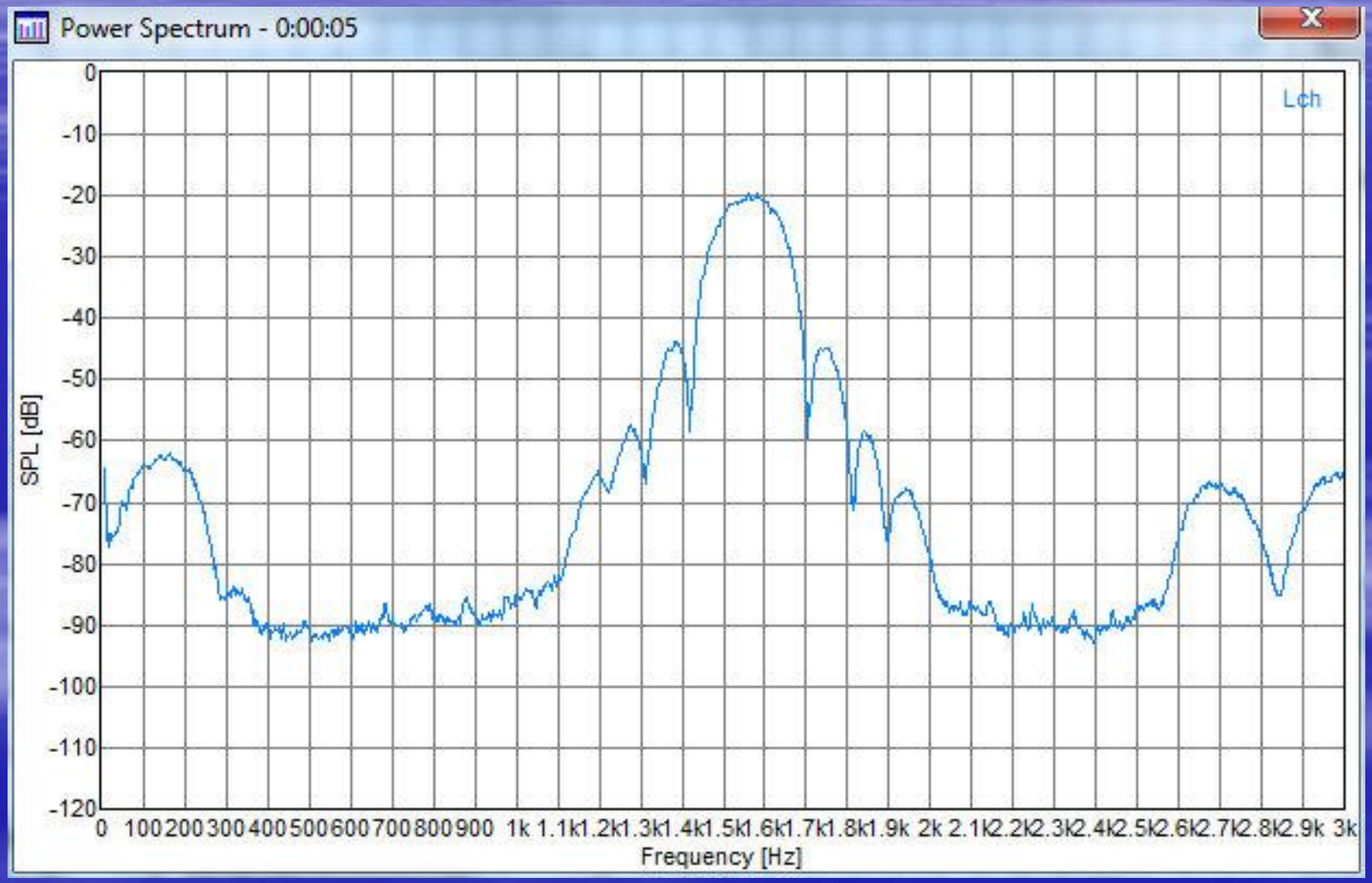


MSK I-Q Arms at TX





GMSK Spectrum, BT = 0.8



Conclusions

- We presented a laboratory that costs $550
- Based on a COTS unmodified FPGA board
- If the same card is used for other courses in digital logic, microprocessors, networking, etc., the incremental cost of the laboratory can approach $0
- Can be used with PC-based spectrum analyzers and oscilloscopes
- Ideal for developing countries
- Ideal for take-home labs for students in developed and developing countries
- Robust enough to allow serious academic research
- Lots and lots of fun!

Thank you!!!!

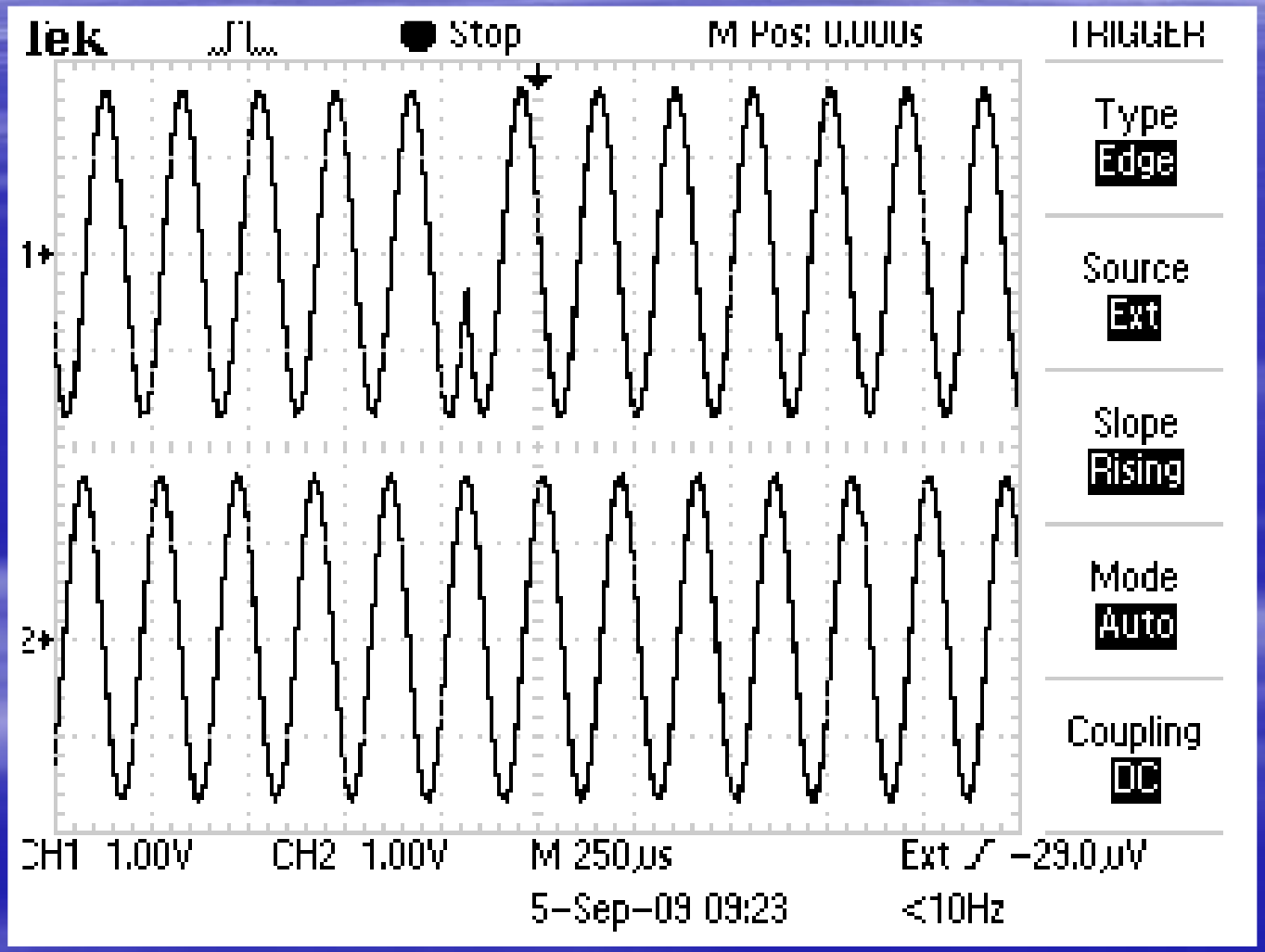
Questions? Comments?

yairlinn@gmail.com
http://yairlinn.googlepages.com

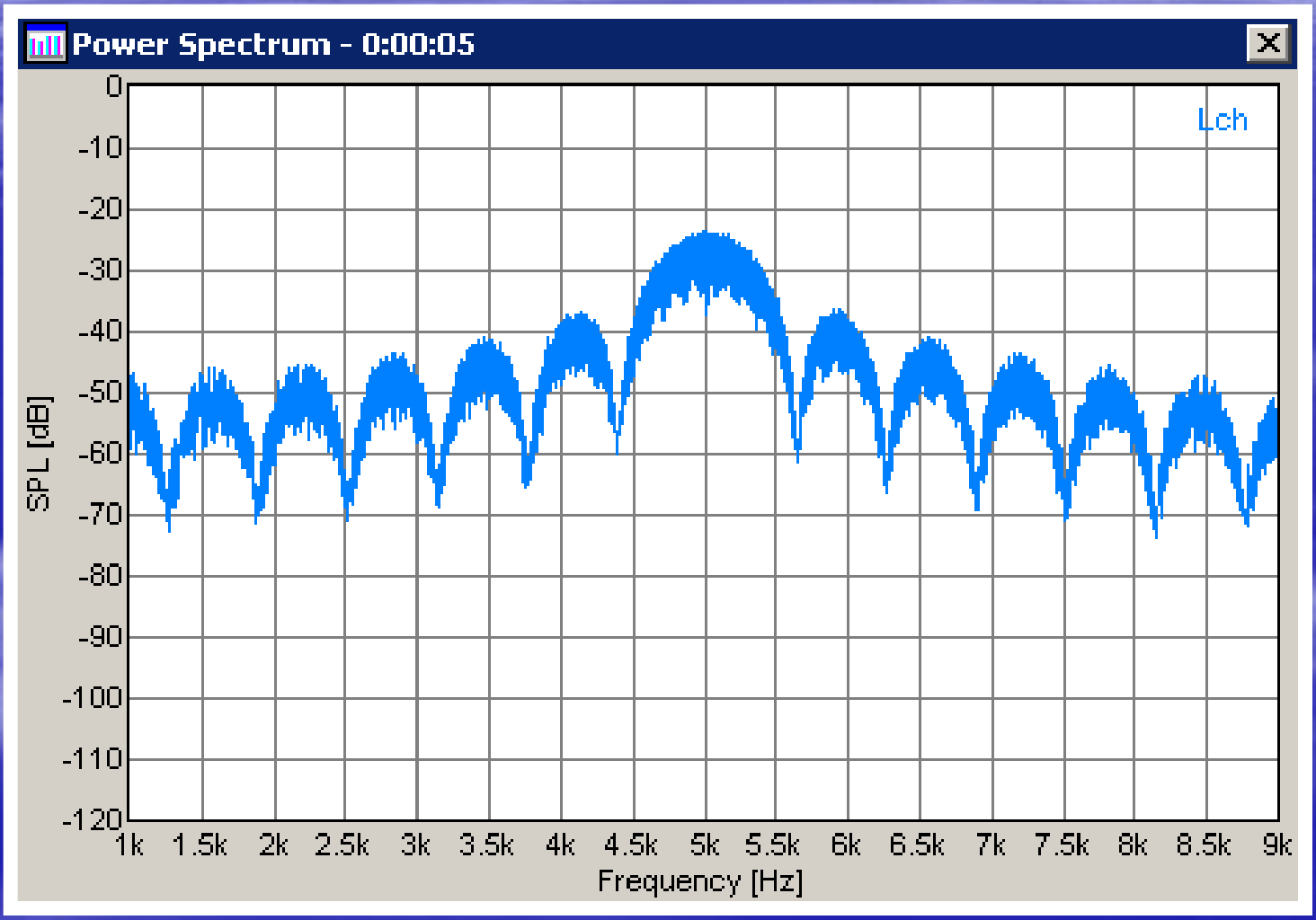
Screenshots from SDR’09 Lab which can also be generated by SDR’10 Lab

BPSK!!!!

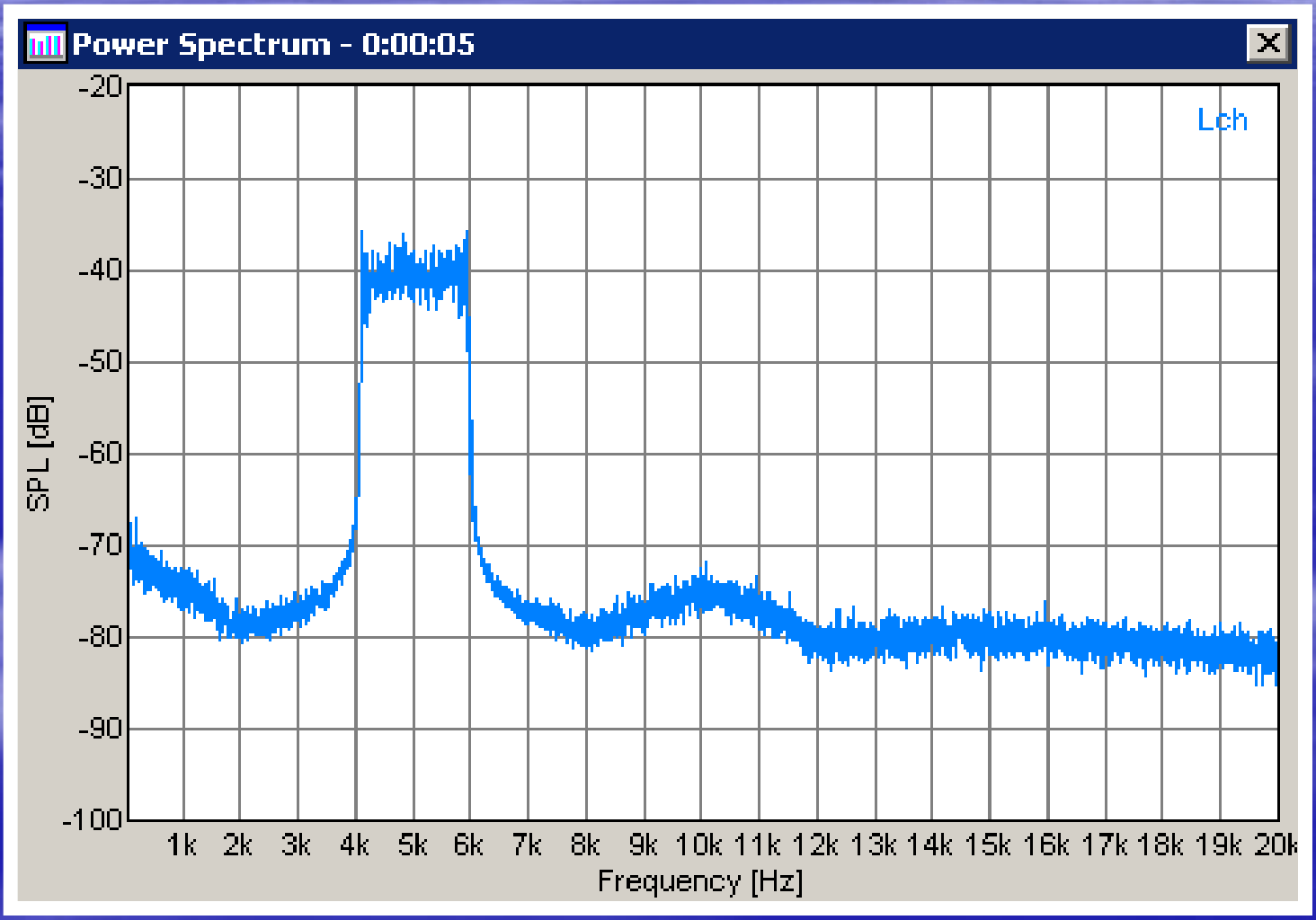
BPSK: Transmitted carrier vs. Local Oscillator



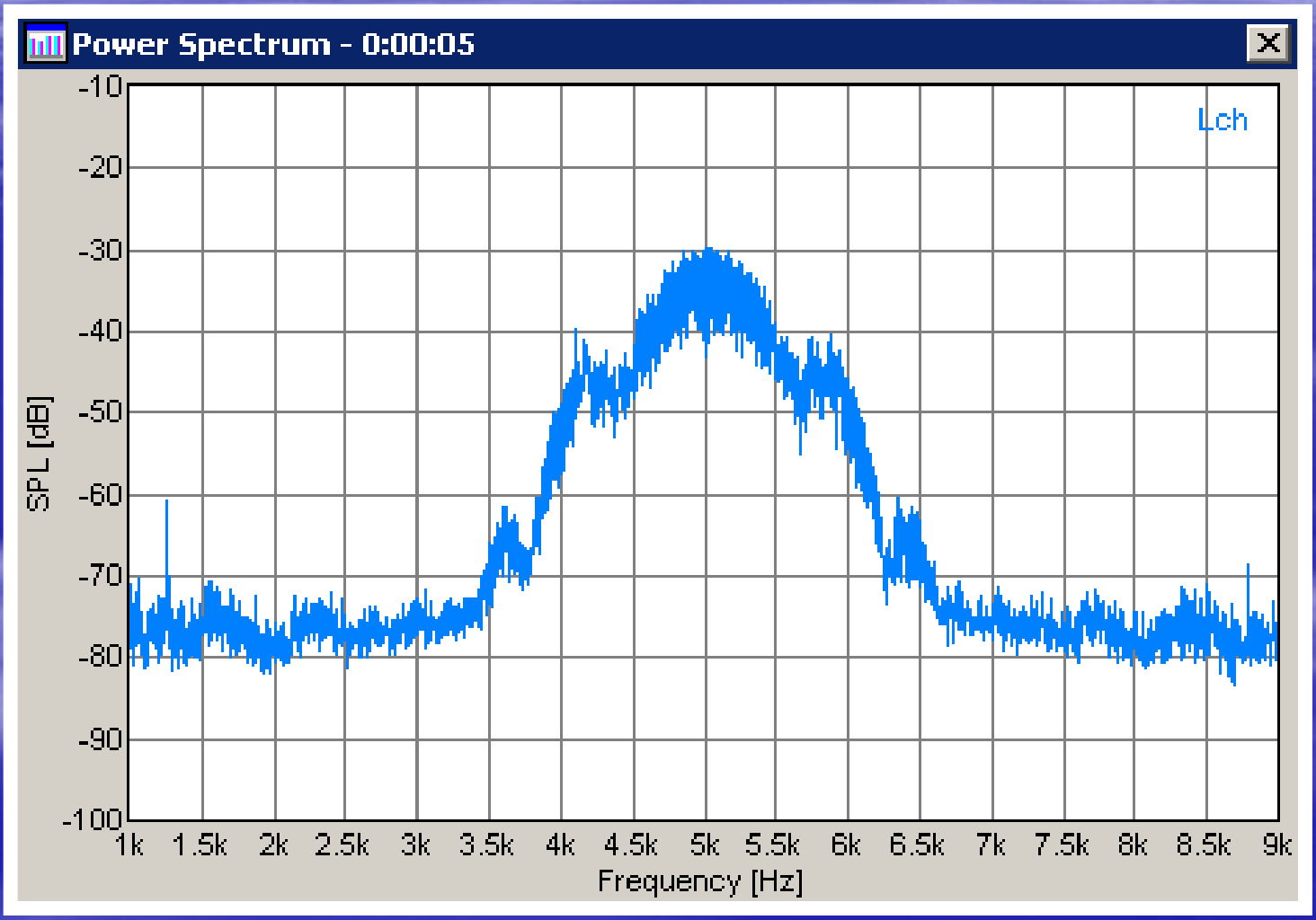
BPSK, Spectrum of Transmitted Signal before TX filter



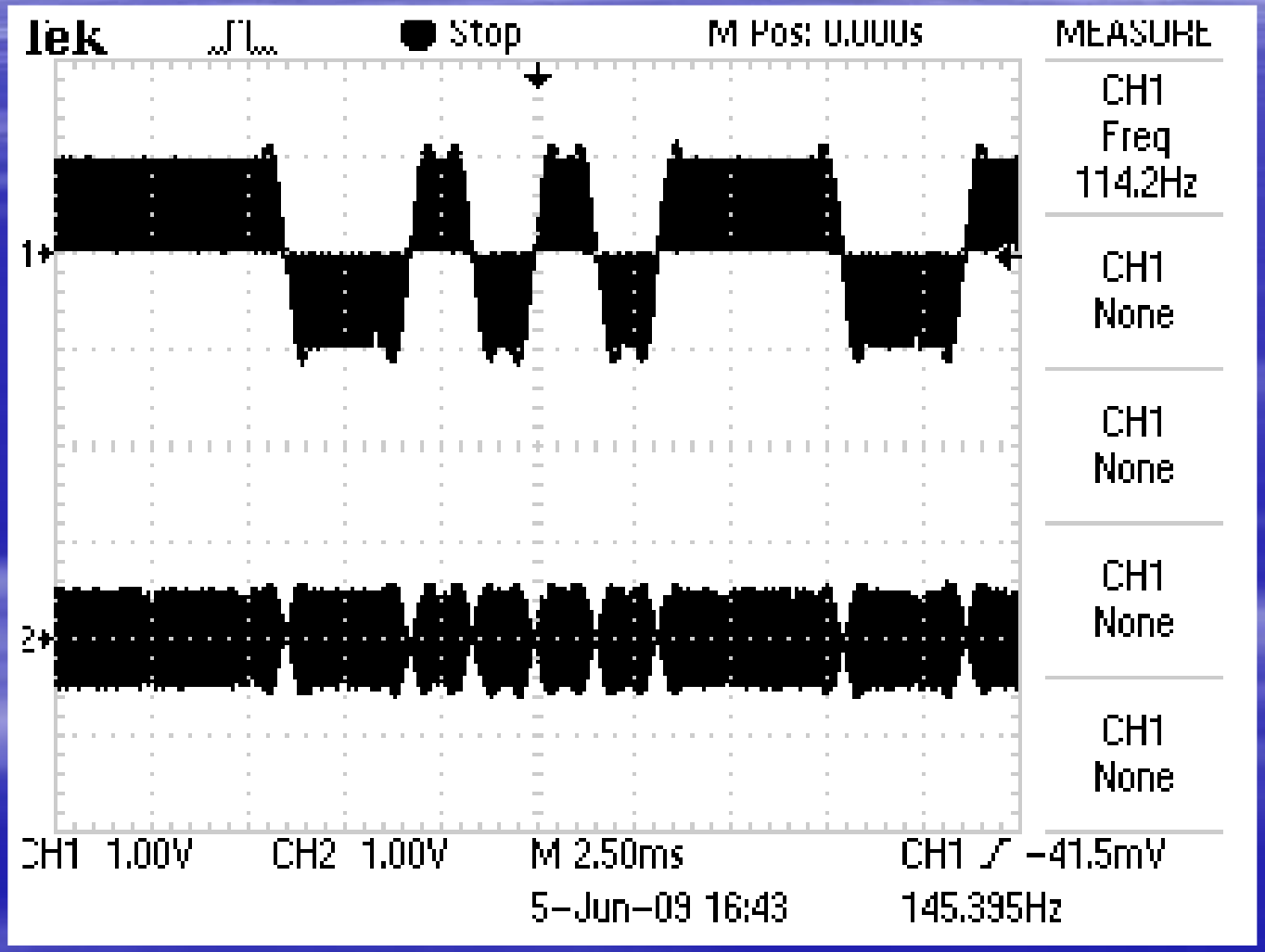
Noise Spectrum around 5 KHz, new Gaussian noise generation method



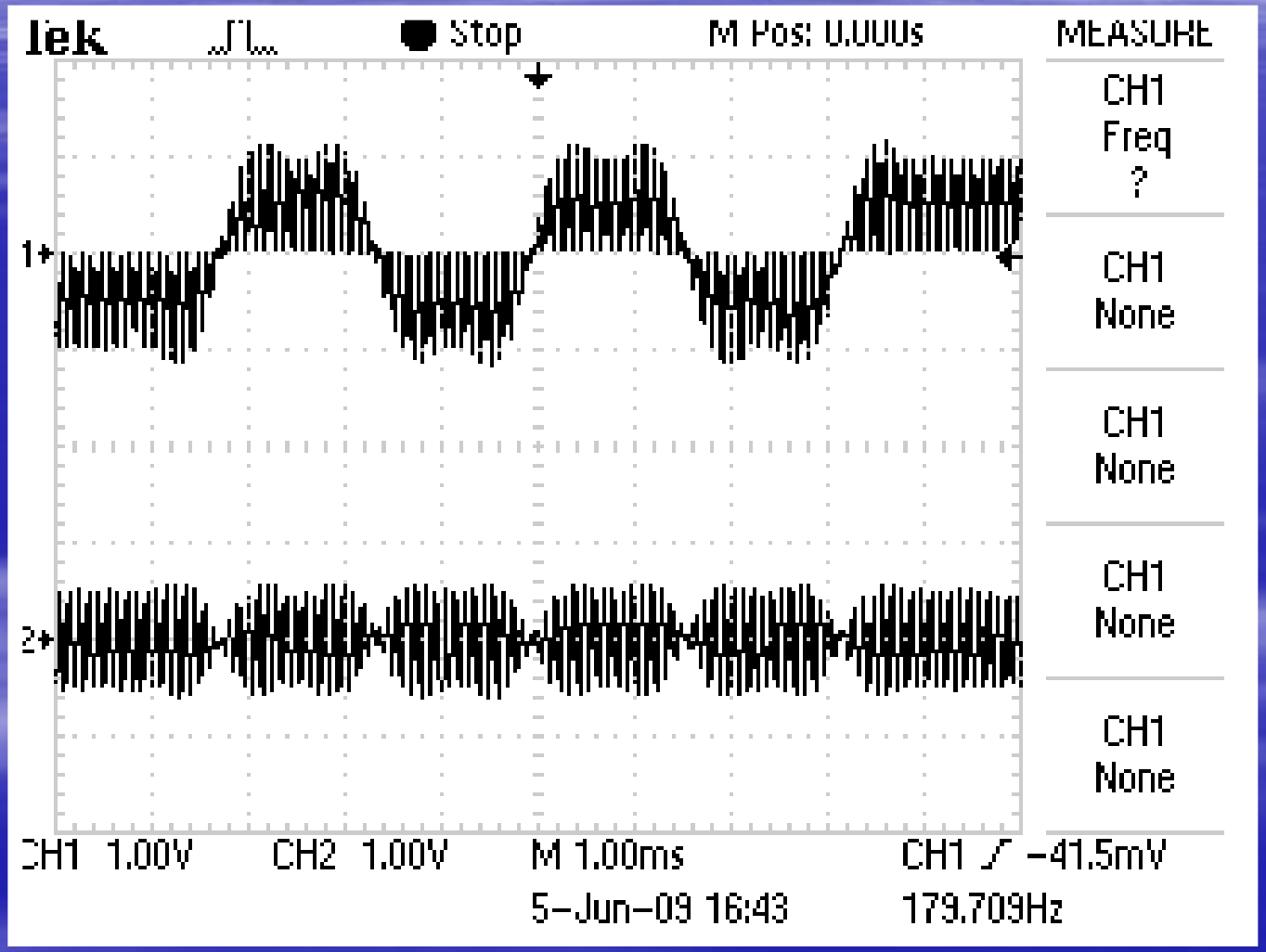
BPSK receiver signal after RX filter, SNR = 12 dB



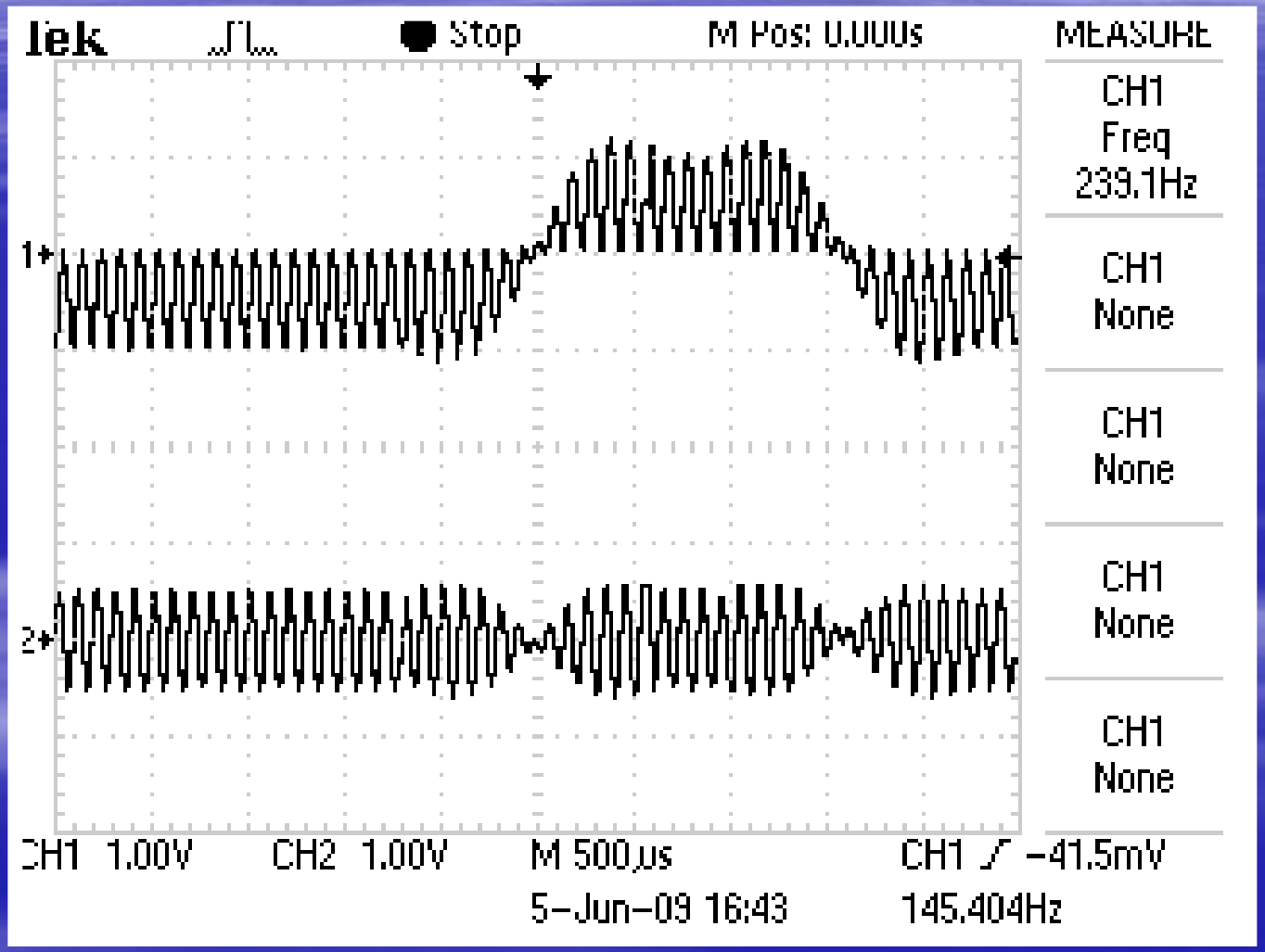
BPSK: post-IQ demodulator, no noise



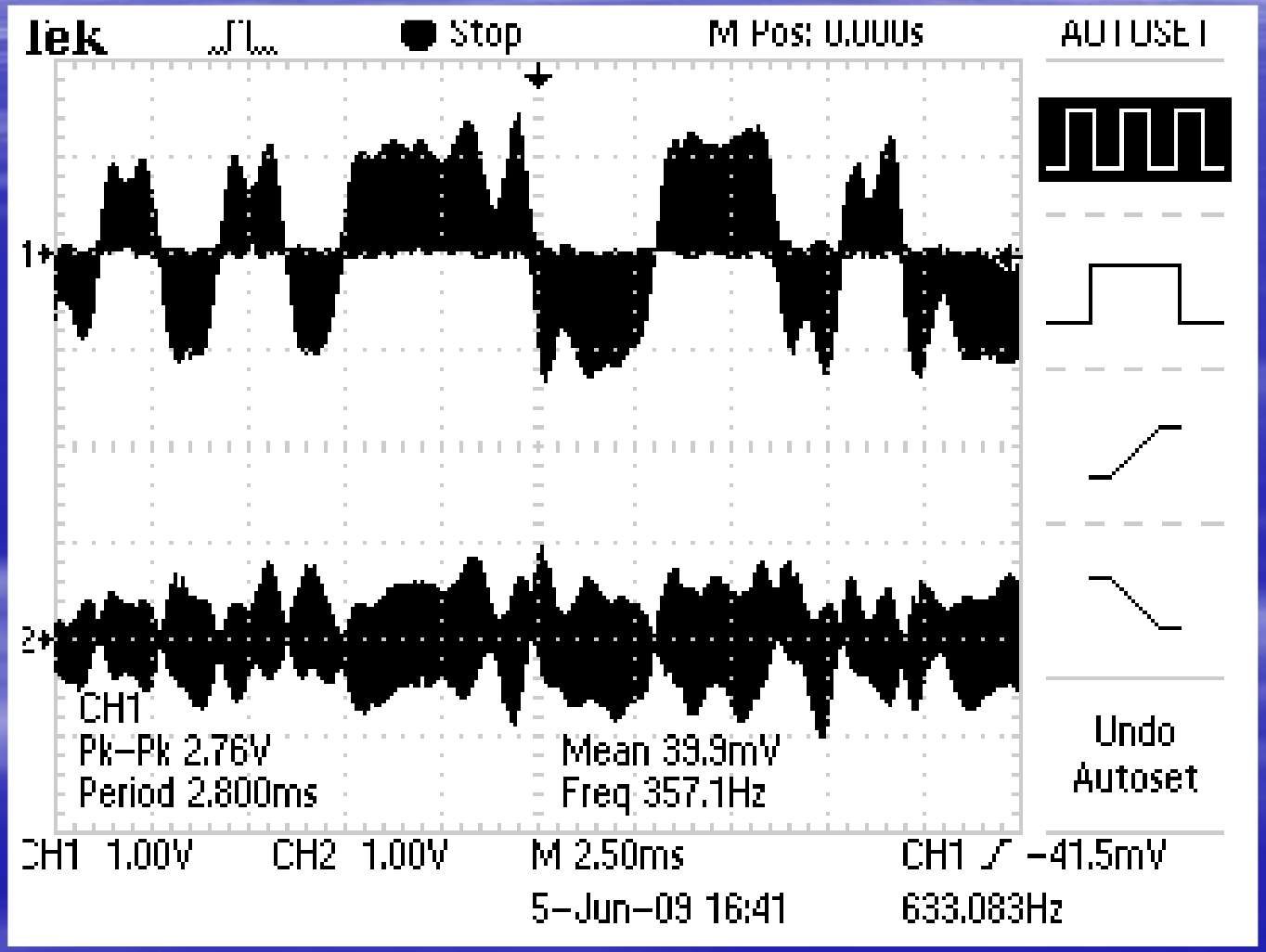
BPSK: post-IQ demodulator, no noise, zoom



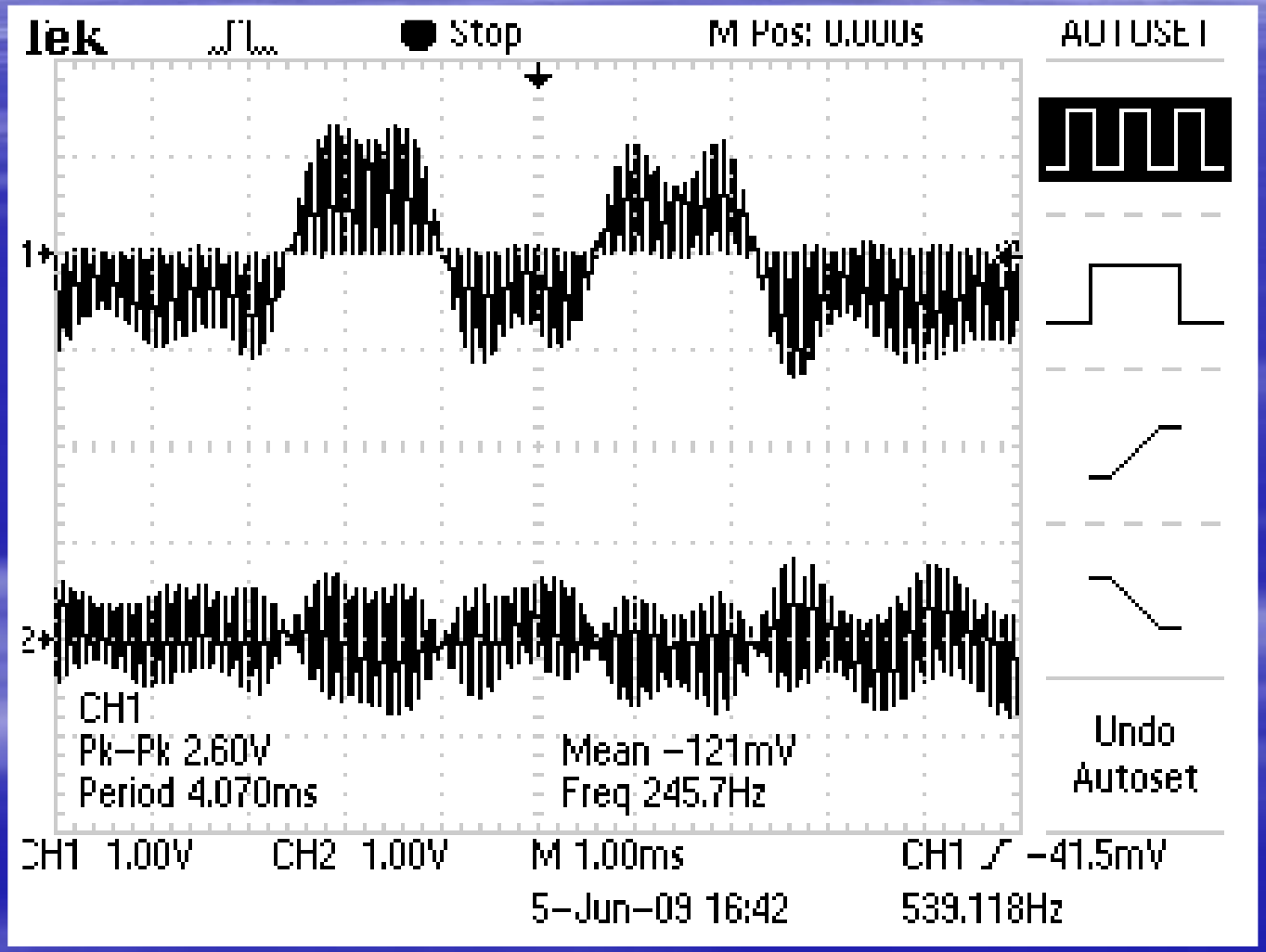
BPSK: post-IQ demodulator, no noise, more zoom



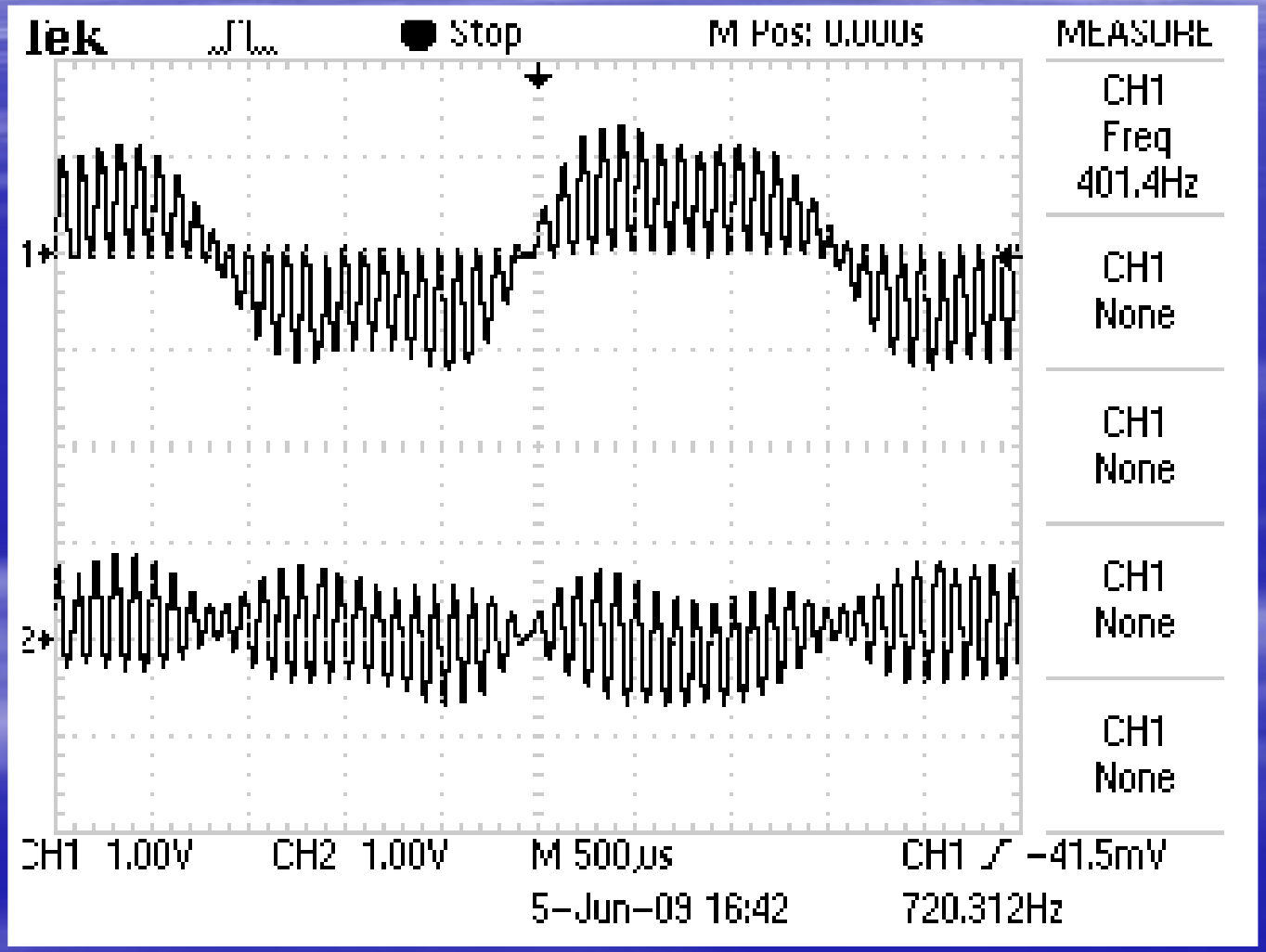
BPSK: post-IQ demodulator, SNR=12dB



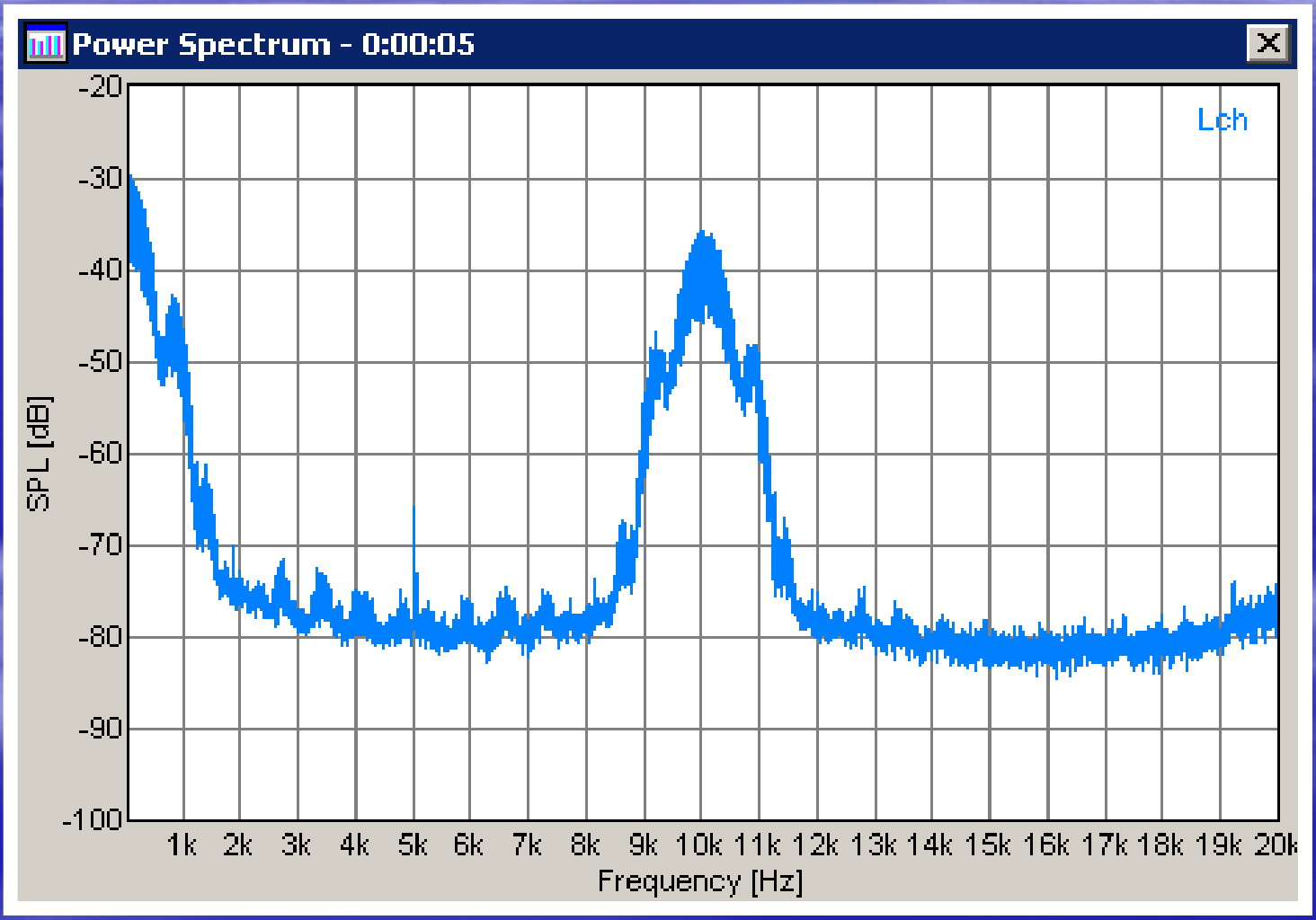
BPSK: post-IQ demodulator, SNR=12dB, zoom



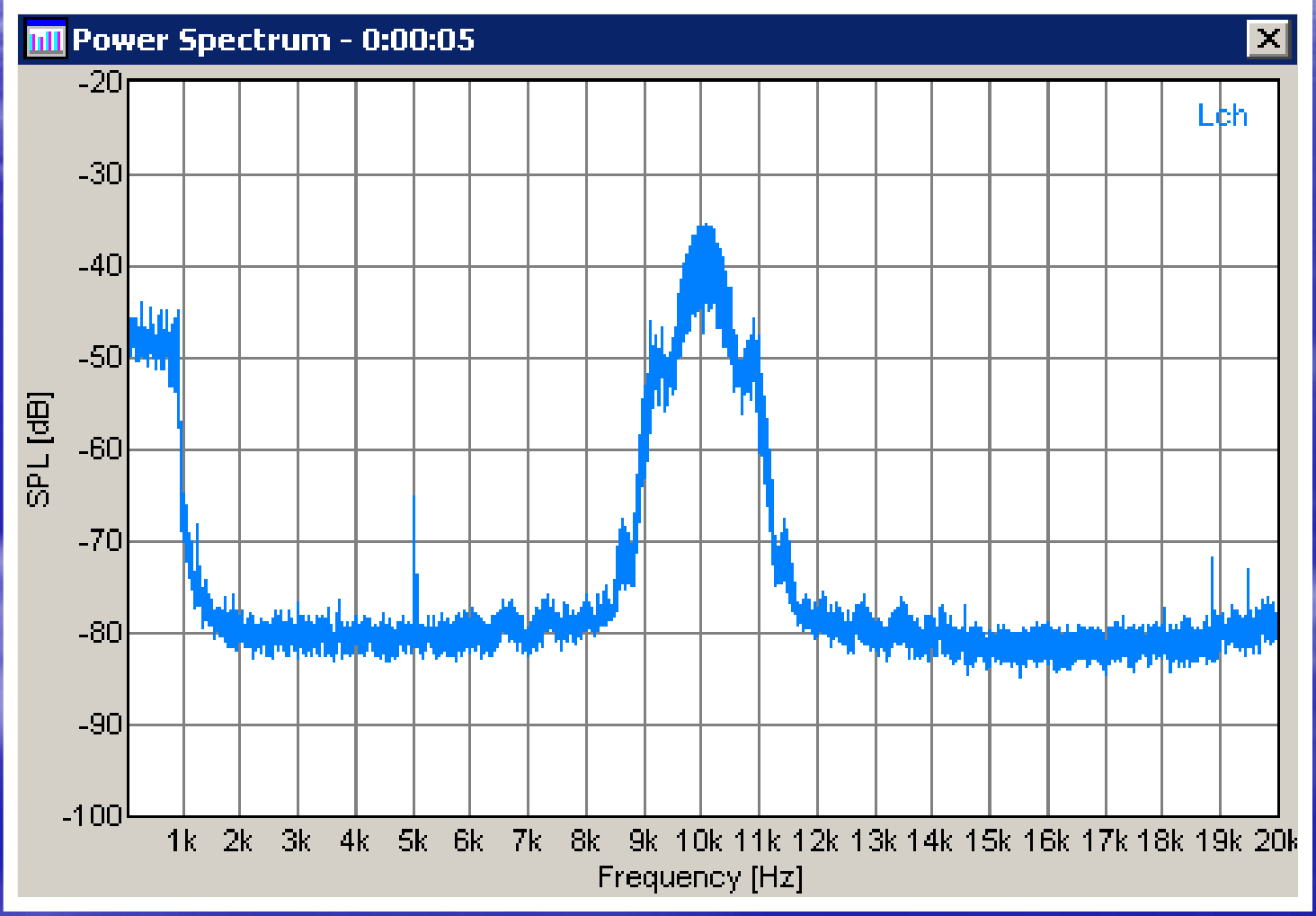
BPSK: post-IQ demodulator, SNR=12dB, more zoom



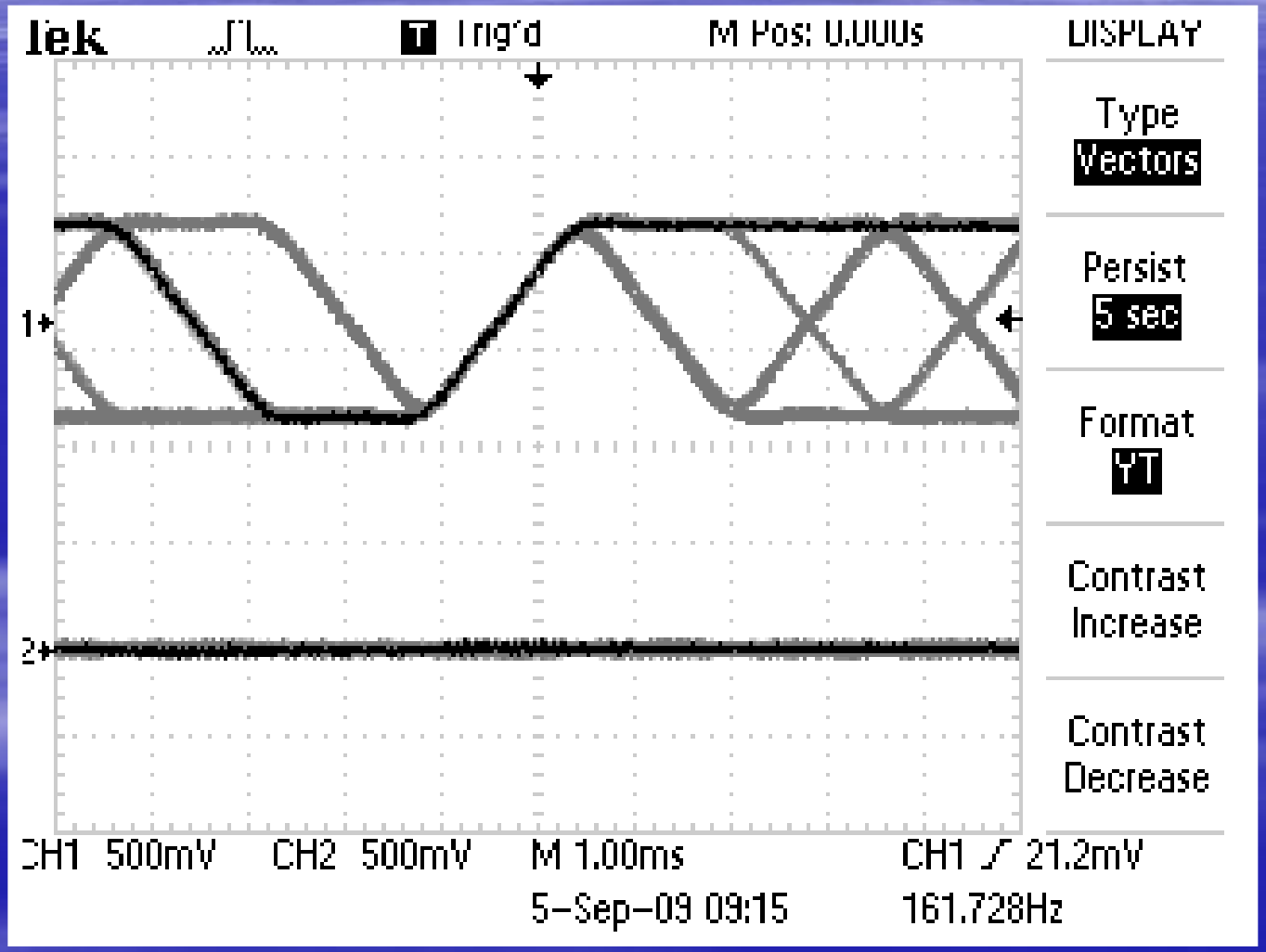
BPSK, I channel after I-Q Demodulator



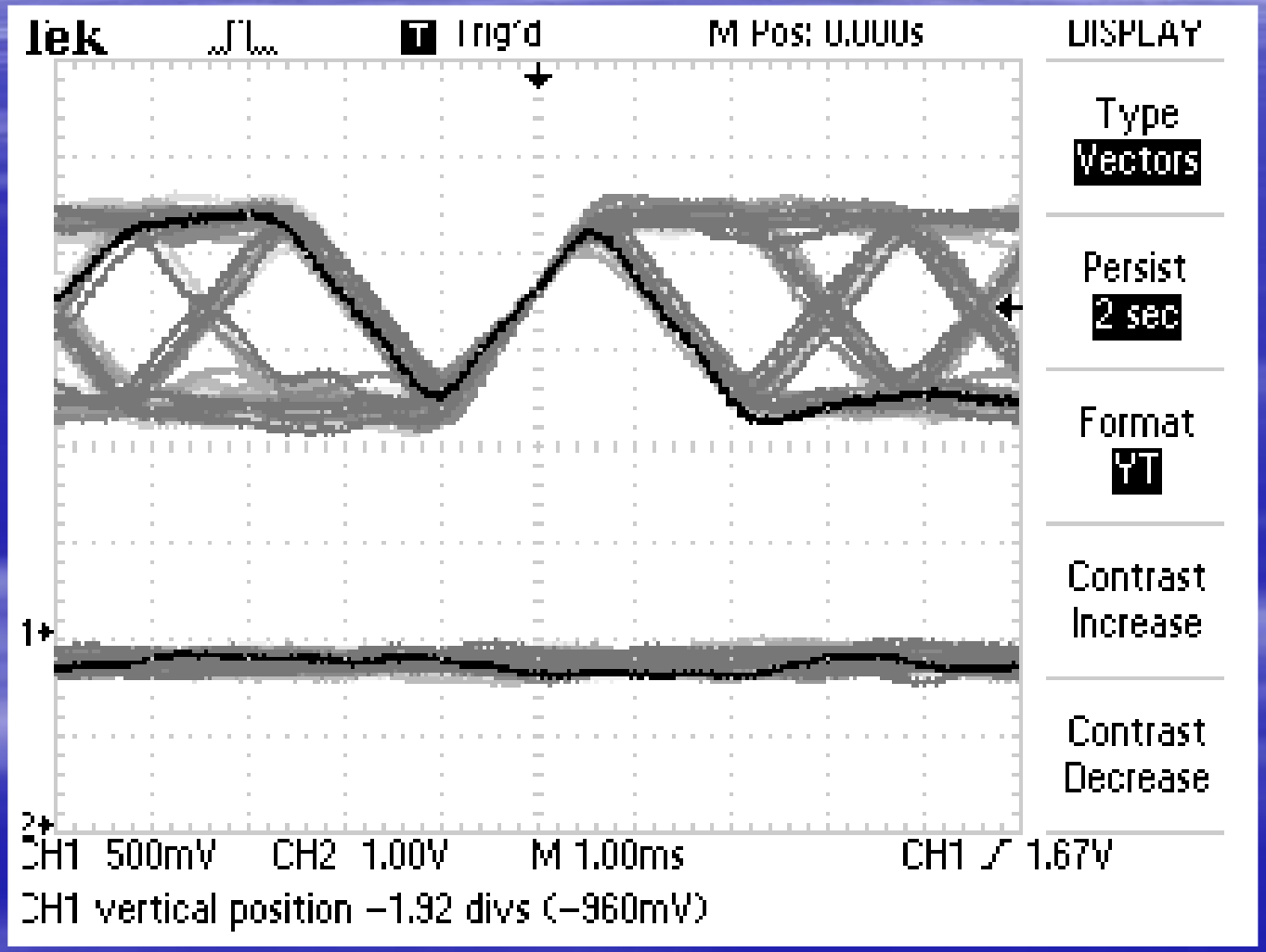
BPSK, Q channel after I-Q Demodulator



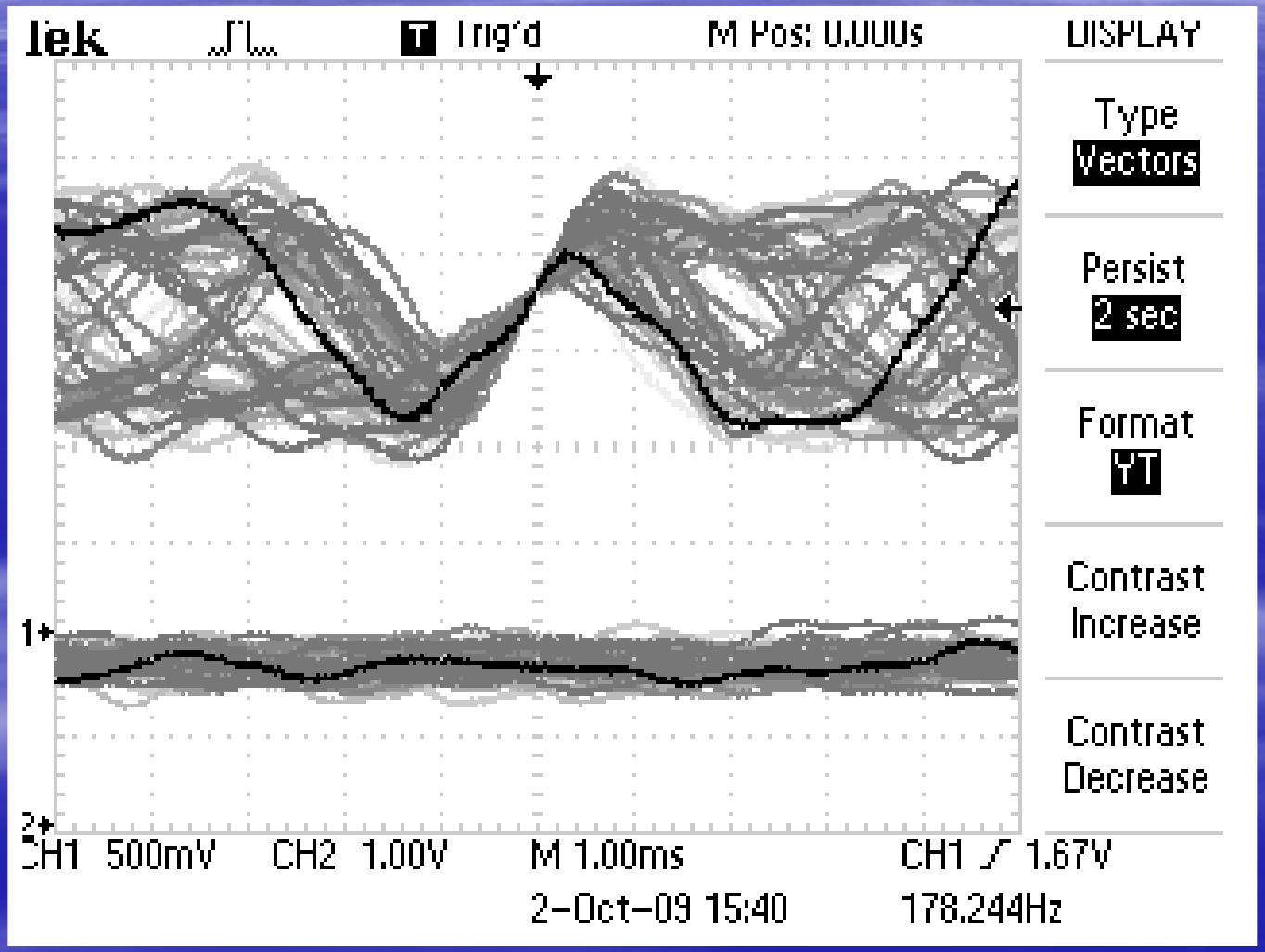
BPSK – In receiver after matched filter – no noise



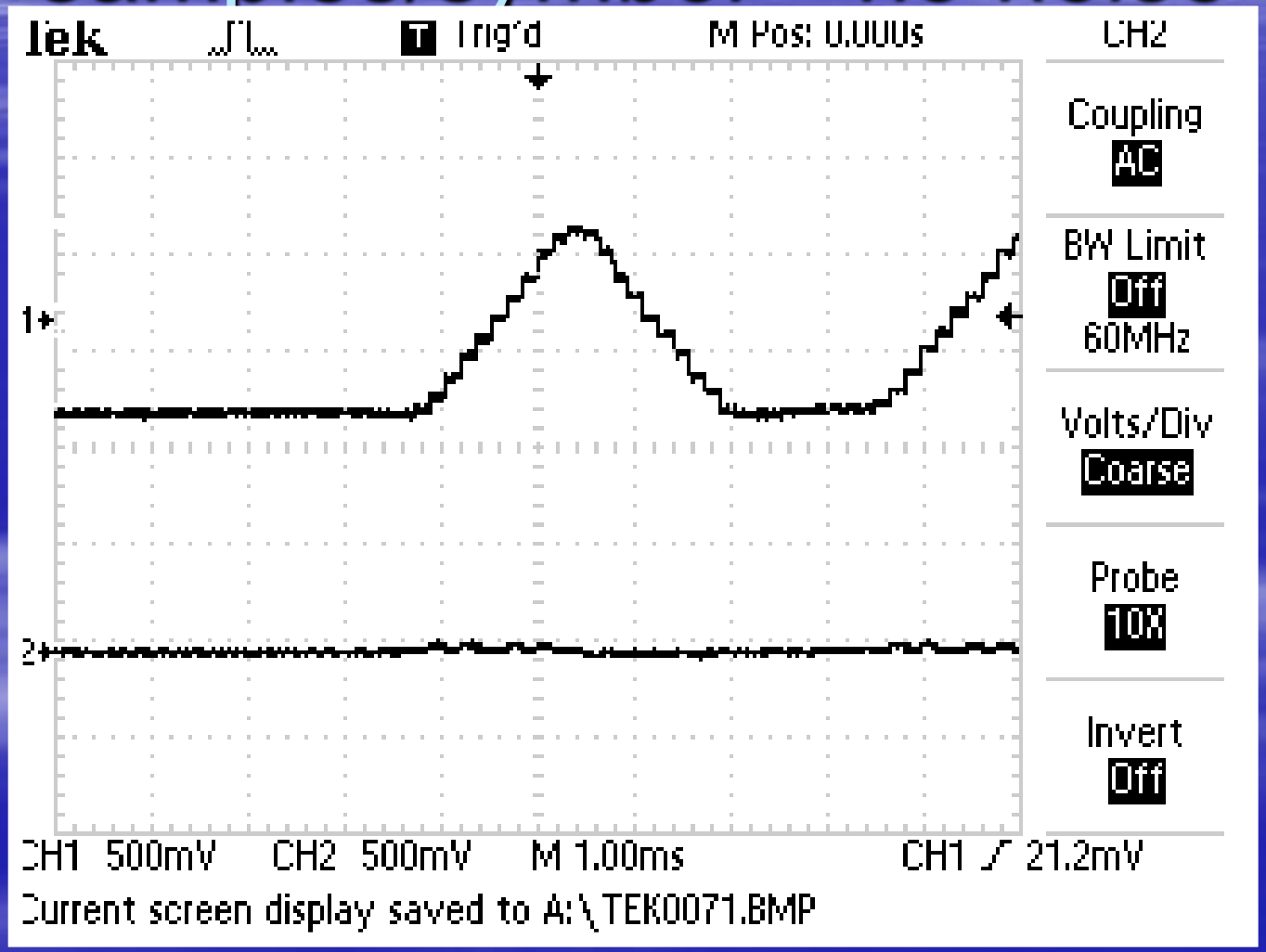
BPSK eye diagram – high SNR



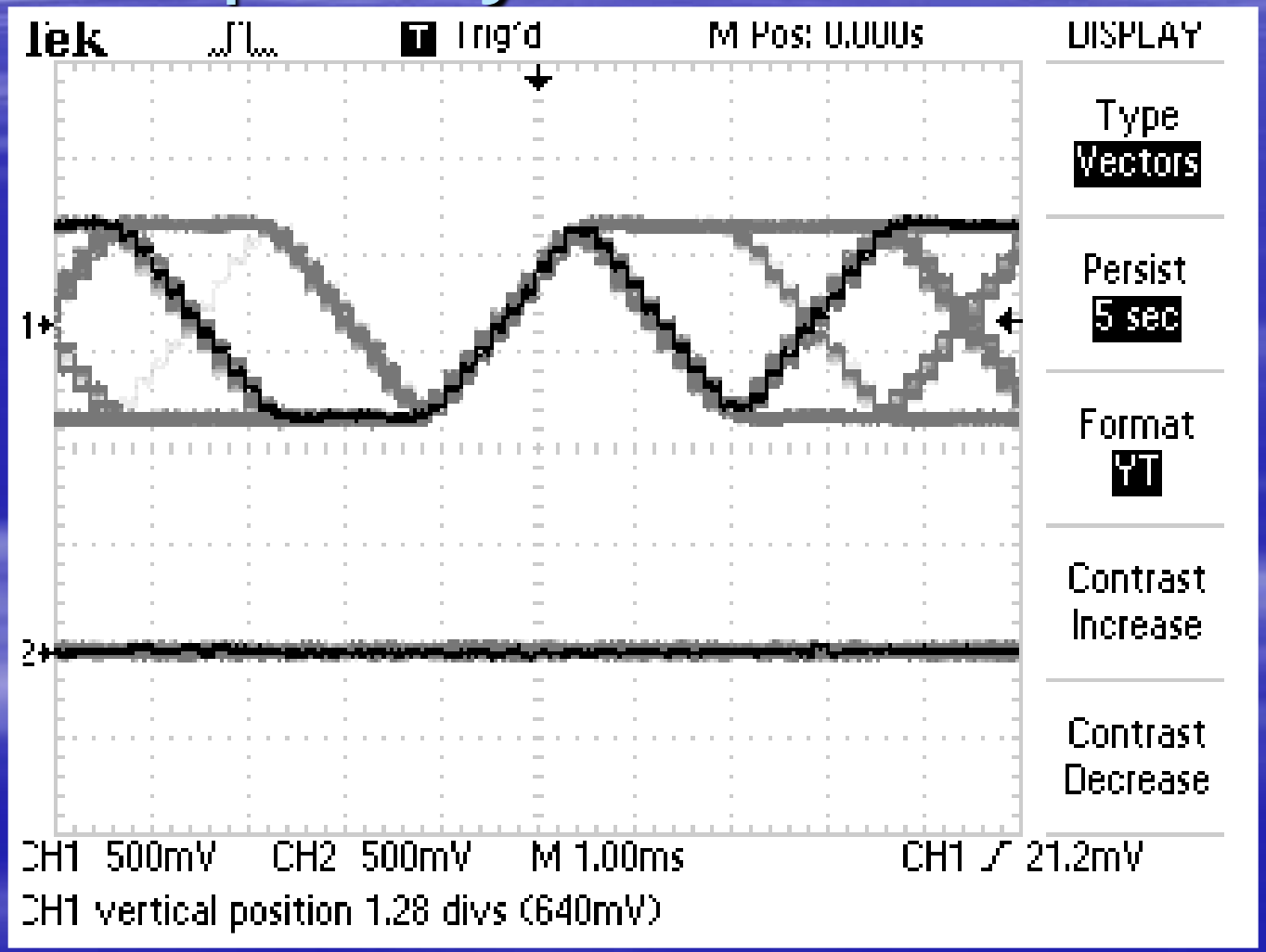
BPSK eye diagram – low SNR



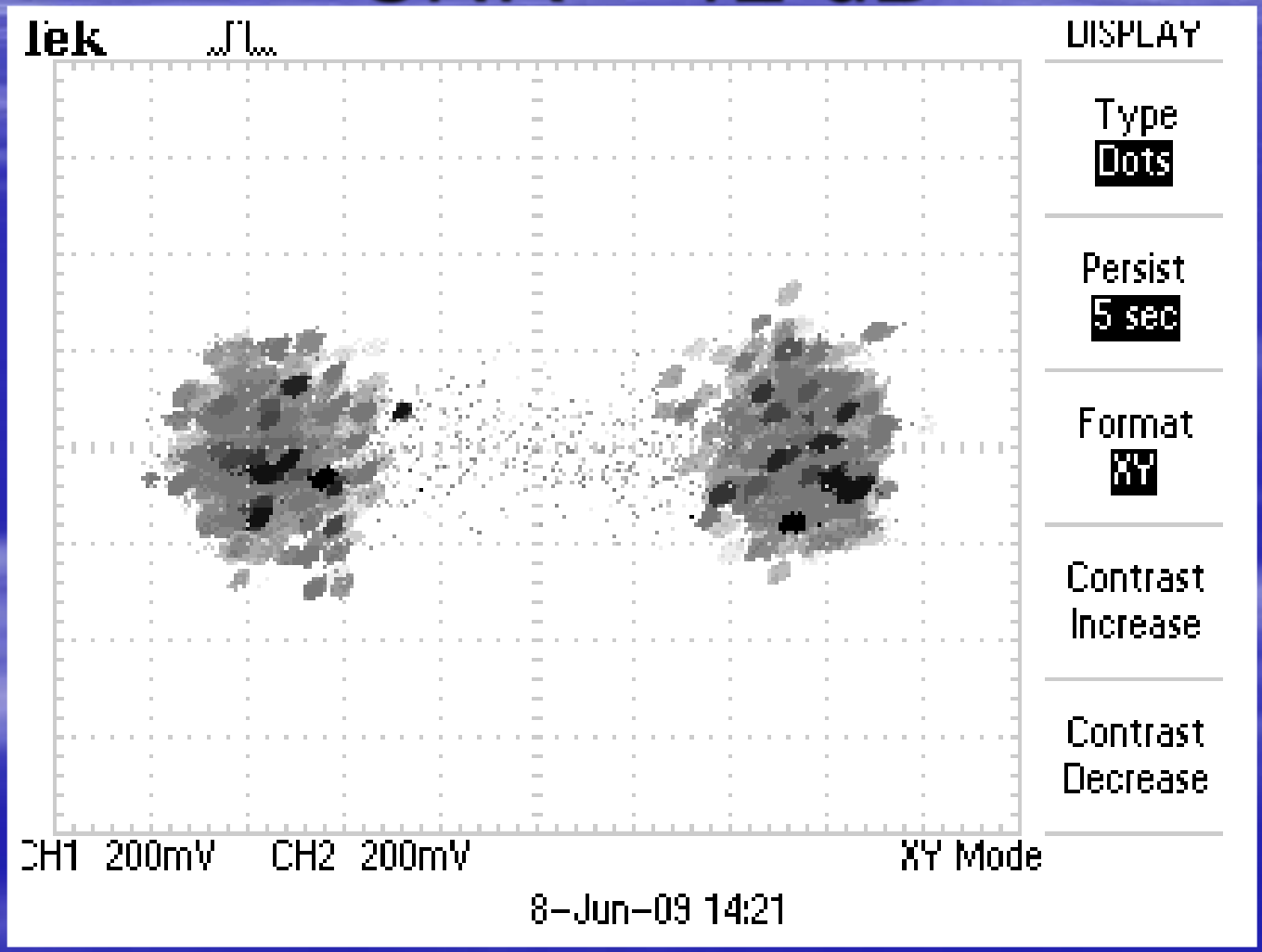
BPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



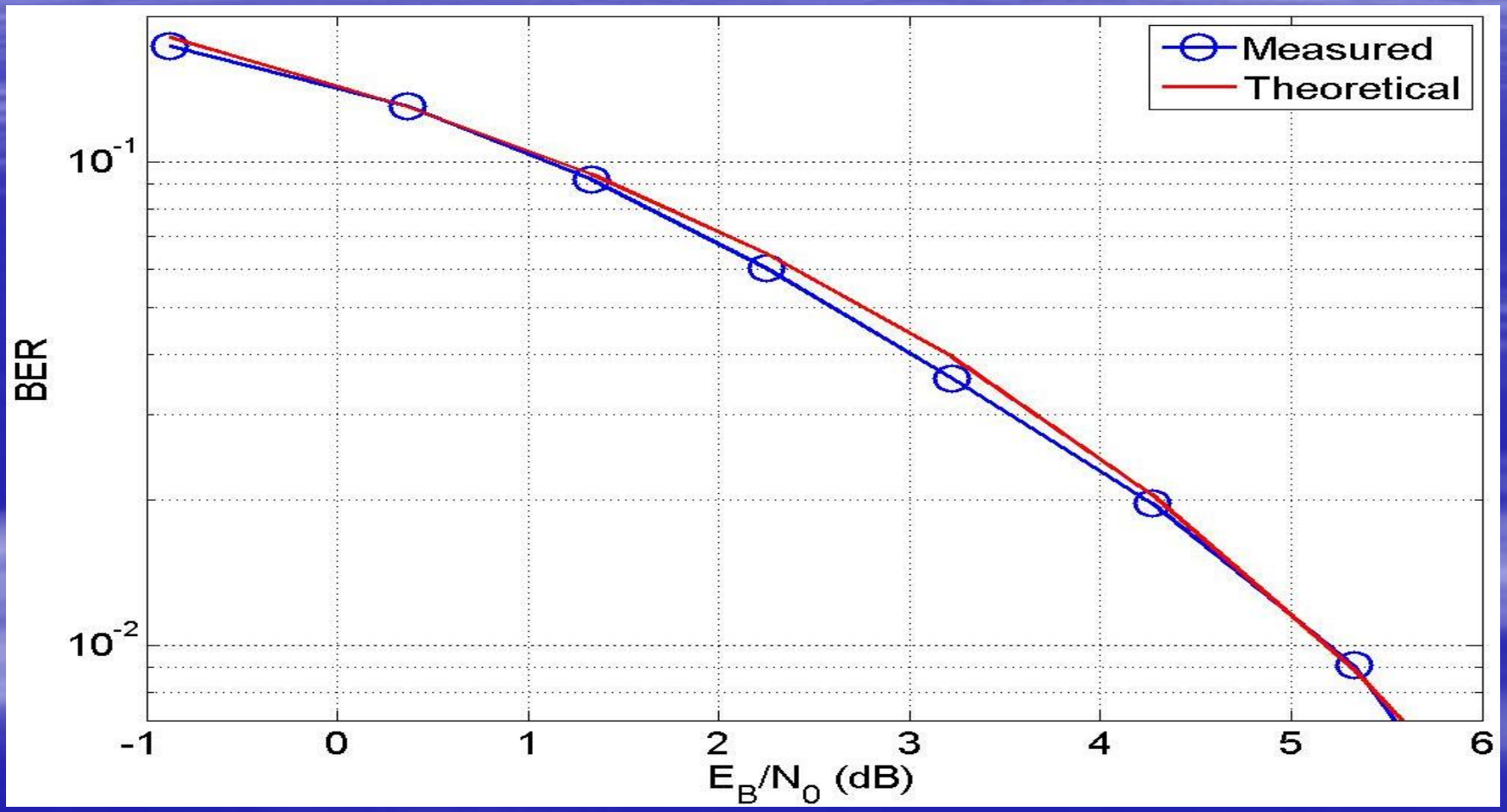
BPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



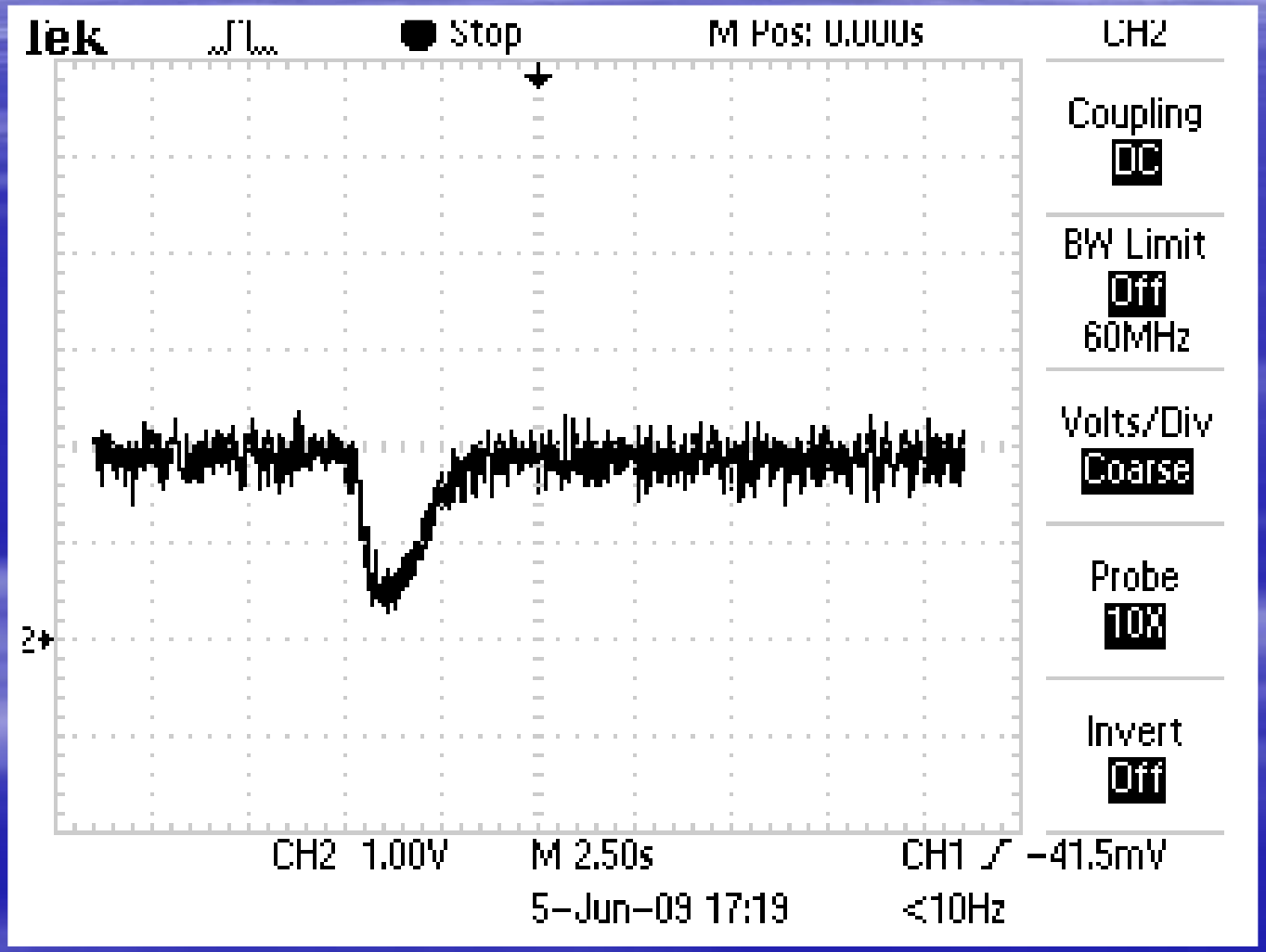
BPSK- after demodulation and sampling at 1 sample/symbol, SNR = 12 dB



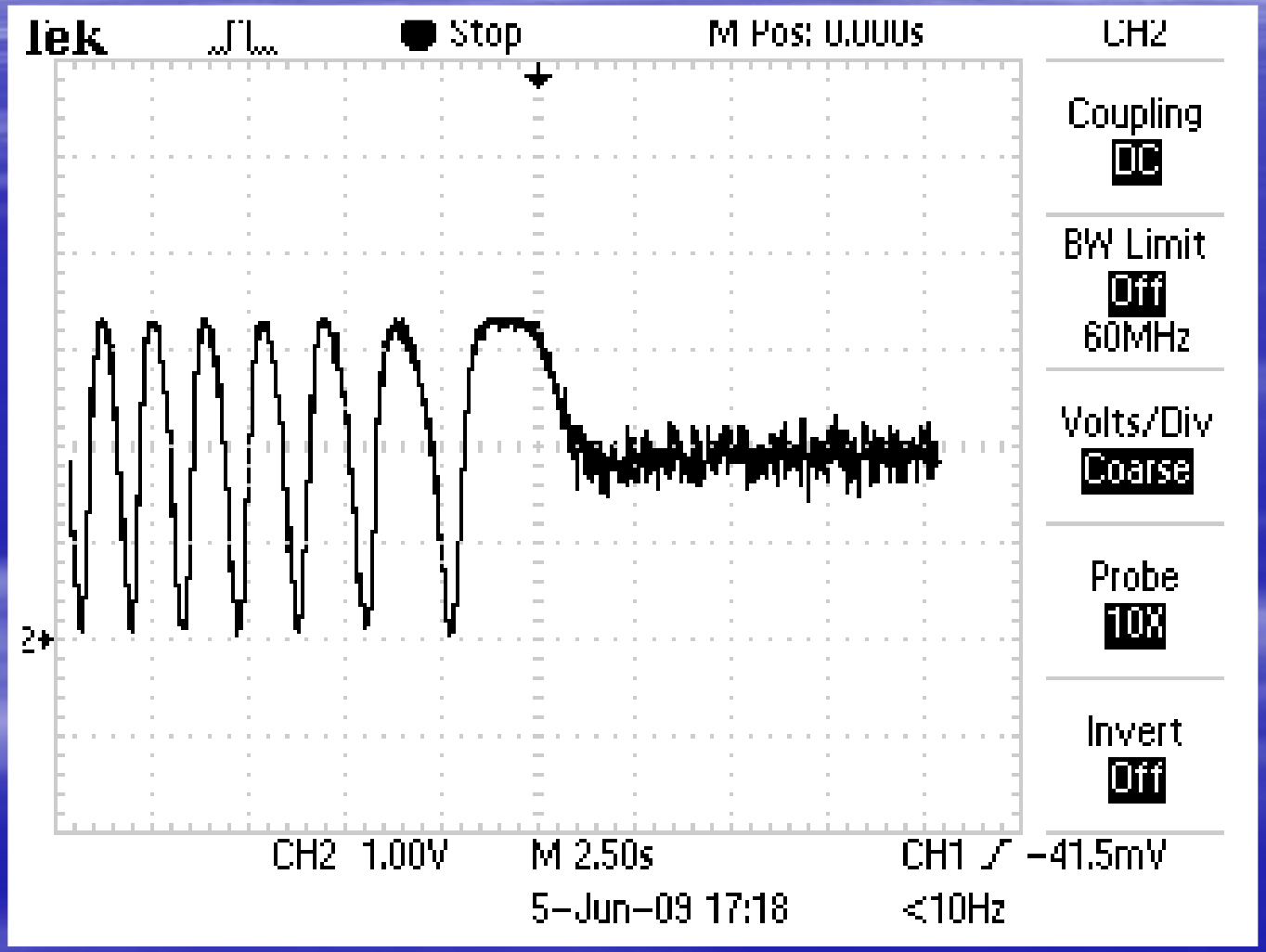
BER mesurements using LAB: DEBPSK



BPSK, carrier PLL phase detector output, response to a small frequency step

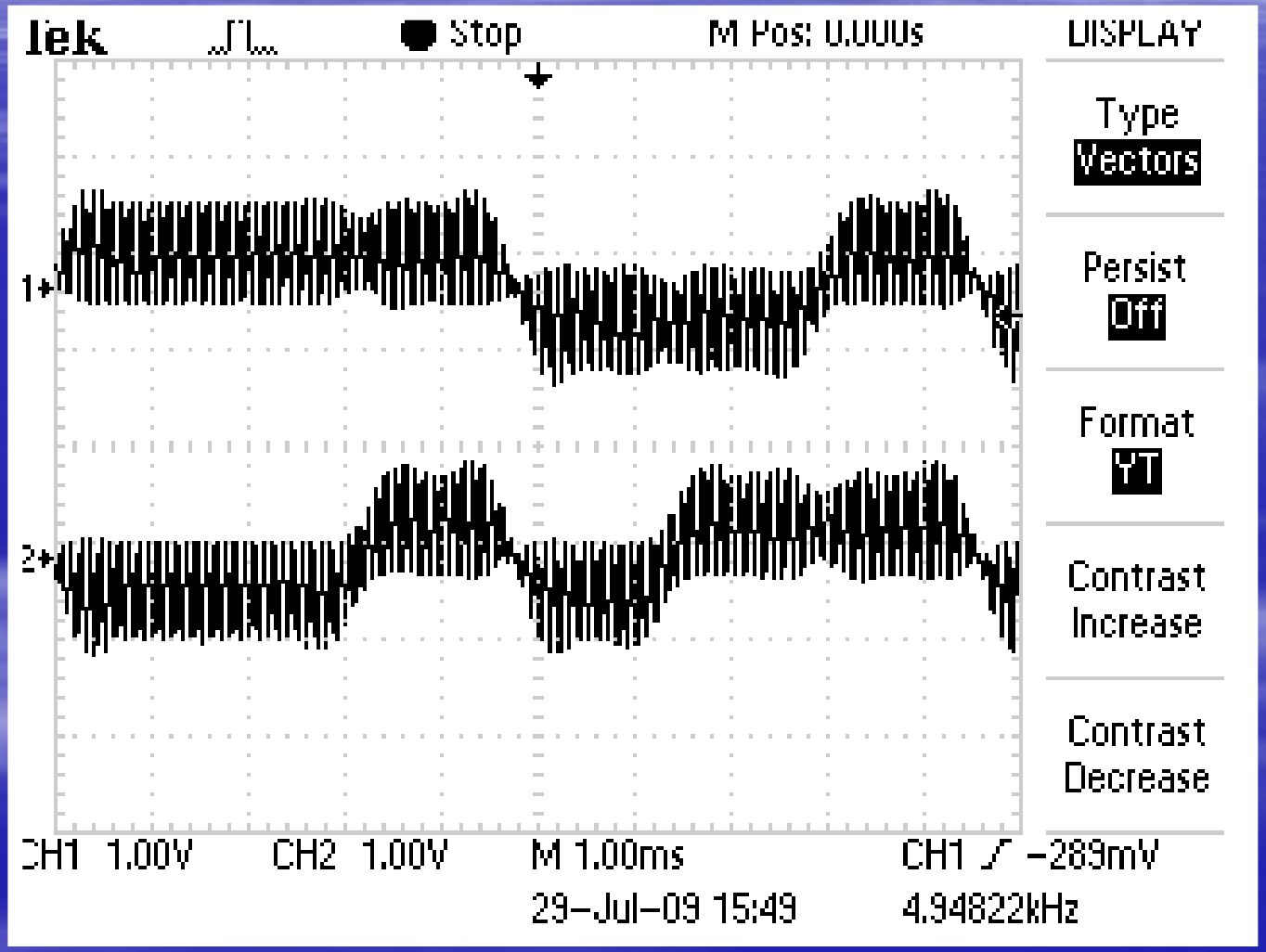


BPSK, carrier PLL phase detector output, pull-in process

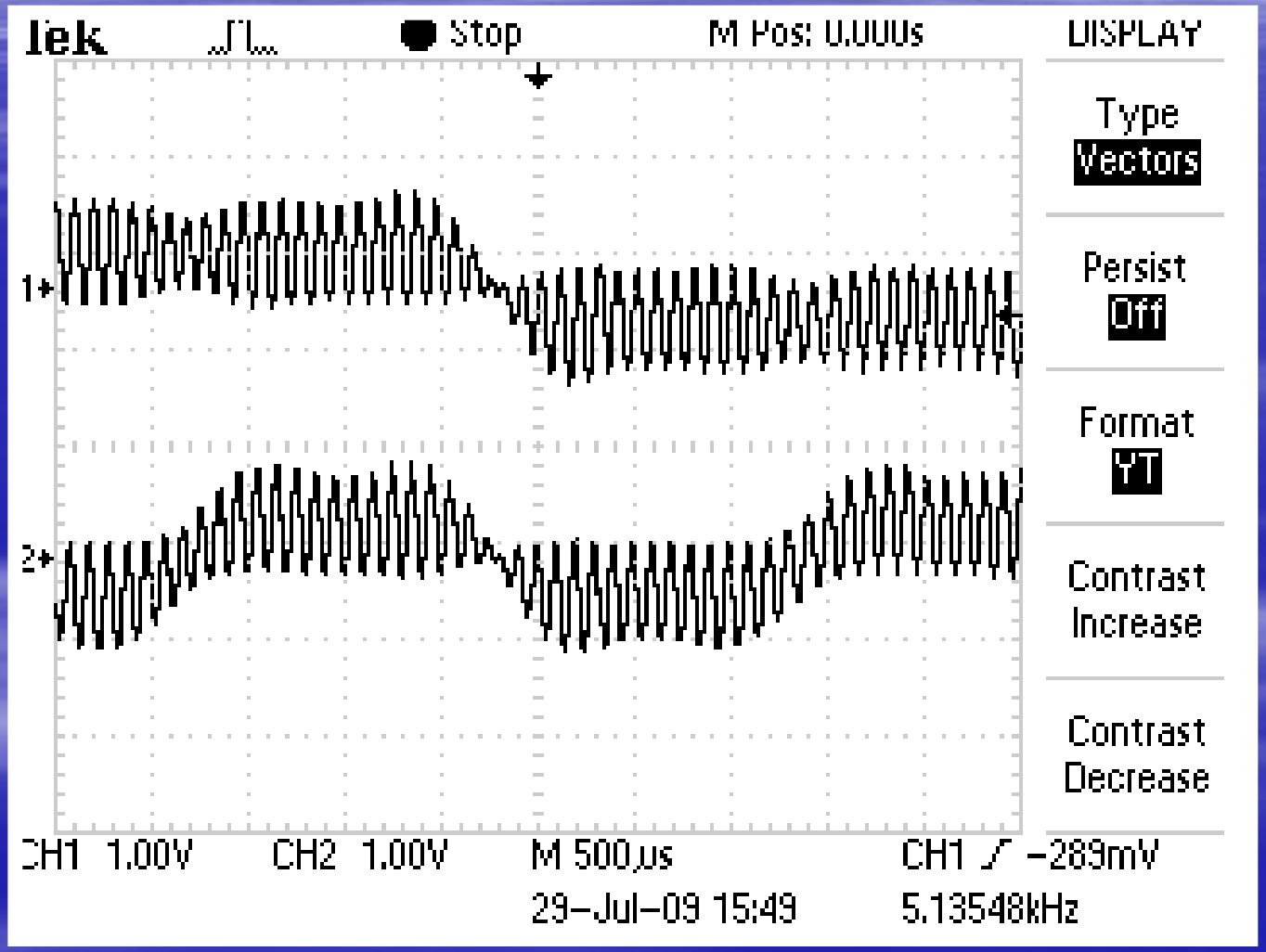


QPSK!!!!

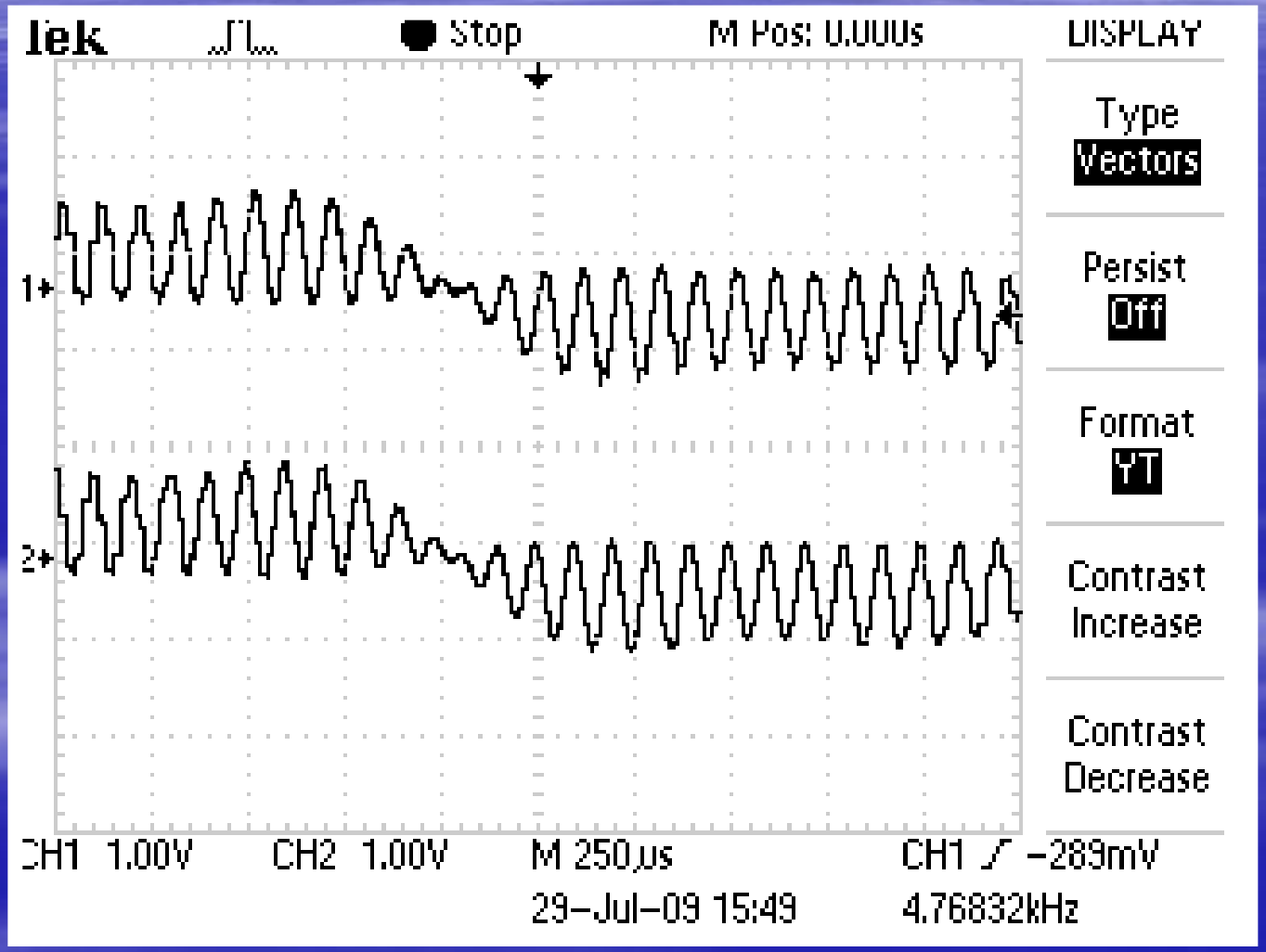
QPSK: post-IQ demodulator, SNR = 12dB



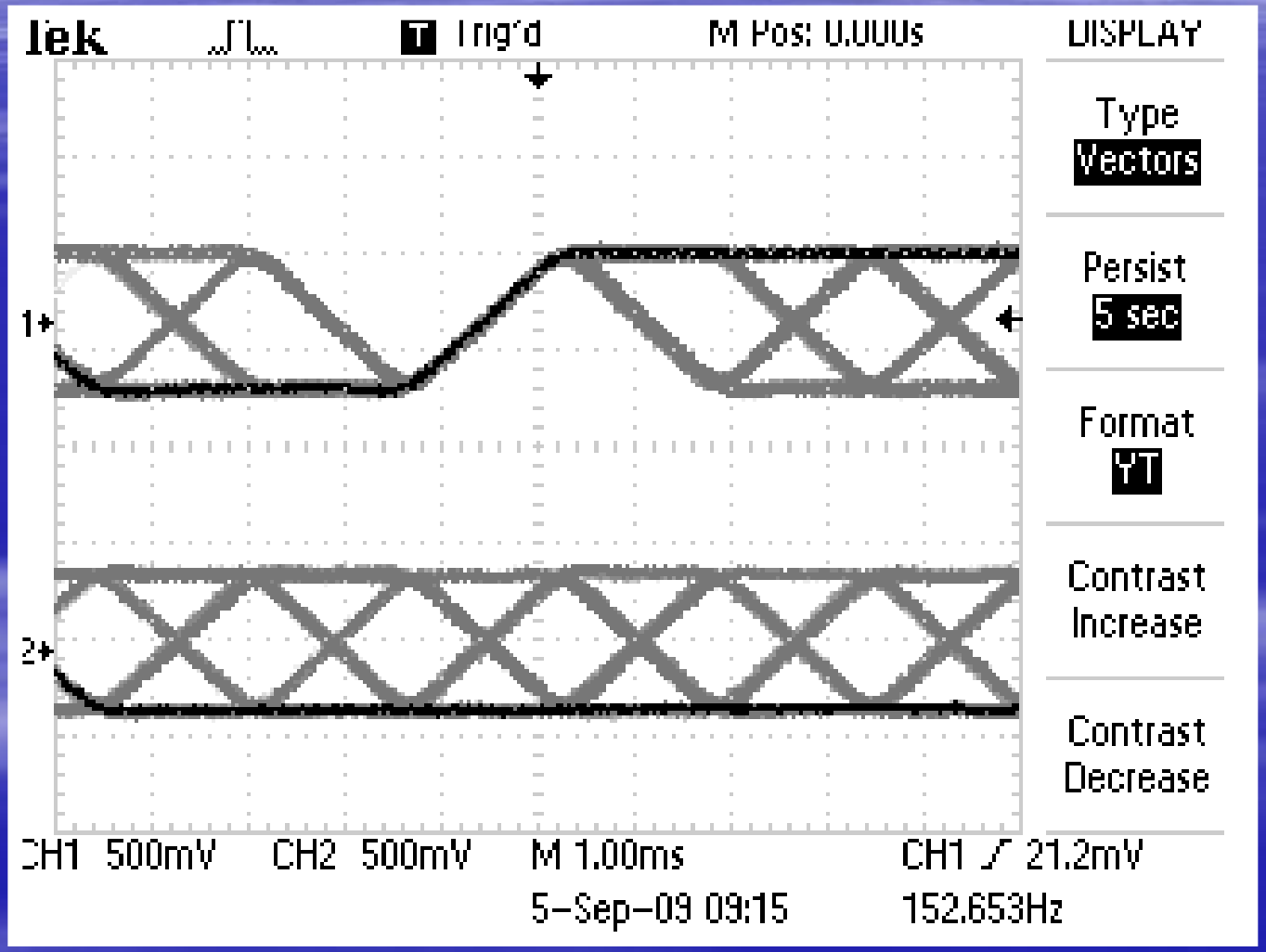
QPSK: post-IQ demodulator, SNR = 12dB, Zoom In



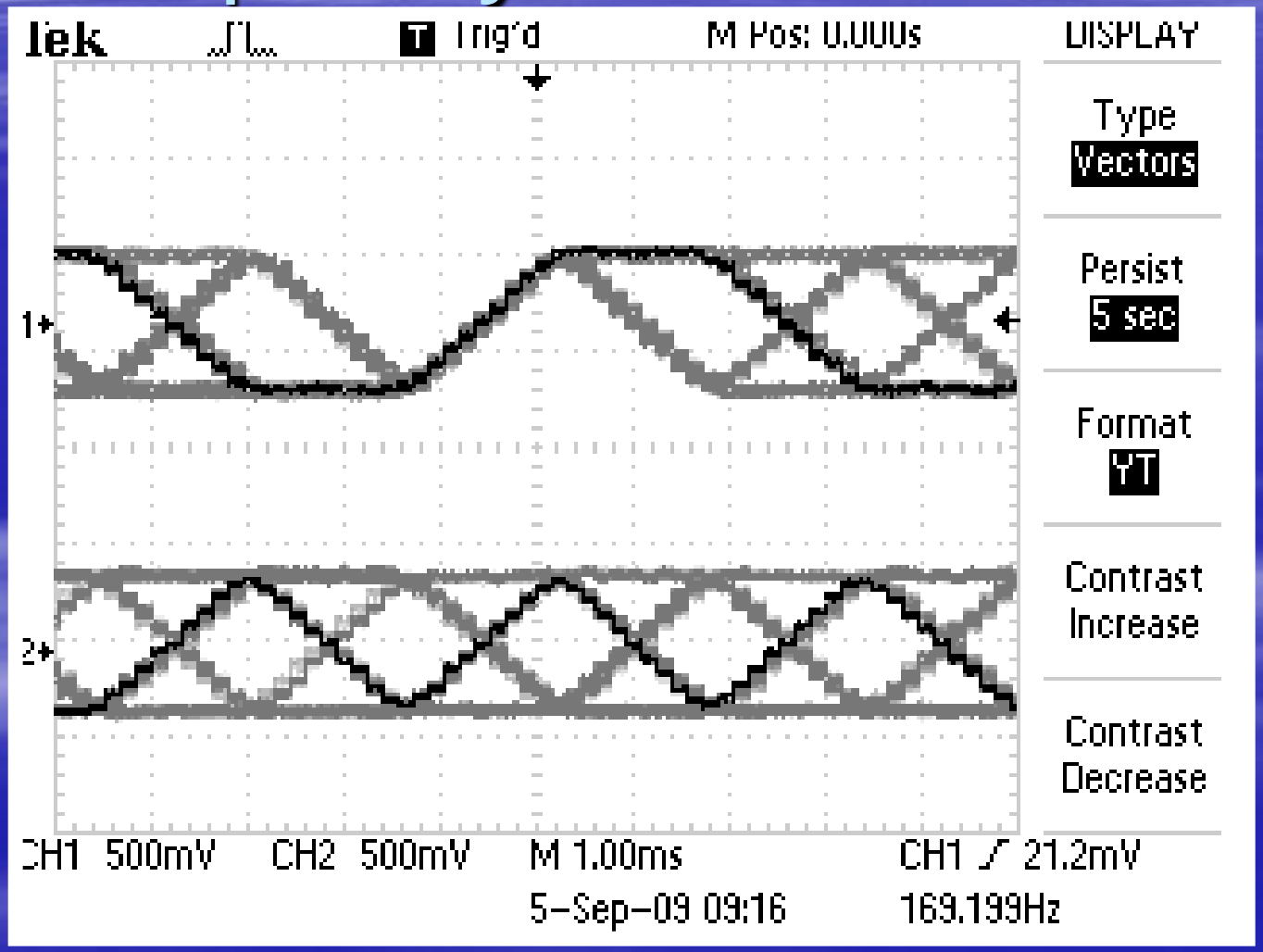
QPSK: post-IQ demodulator, SNR = 12dB, More zoom



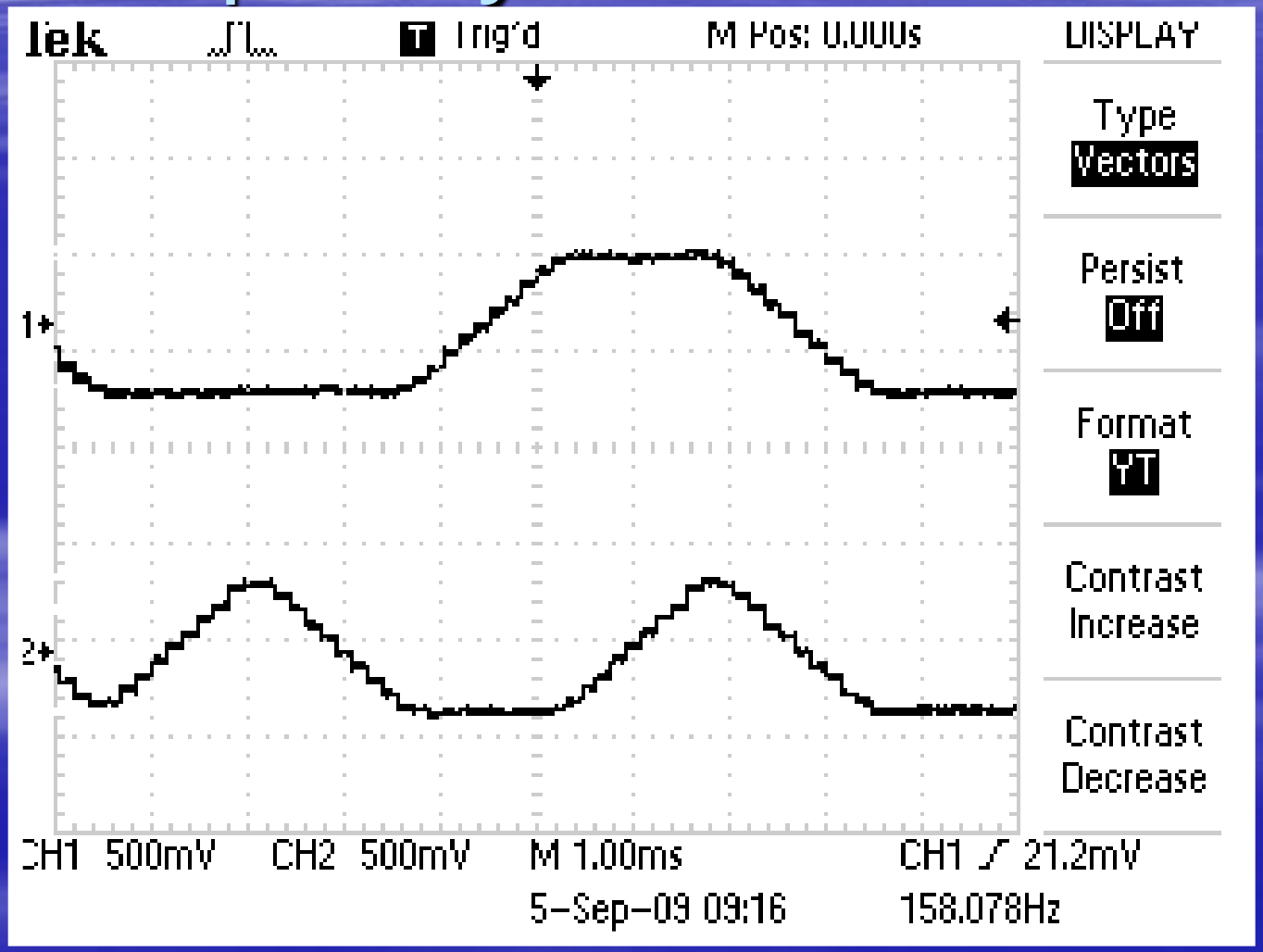
QPSK – In receiver after matched filter – no noise



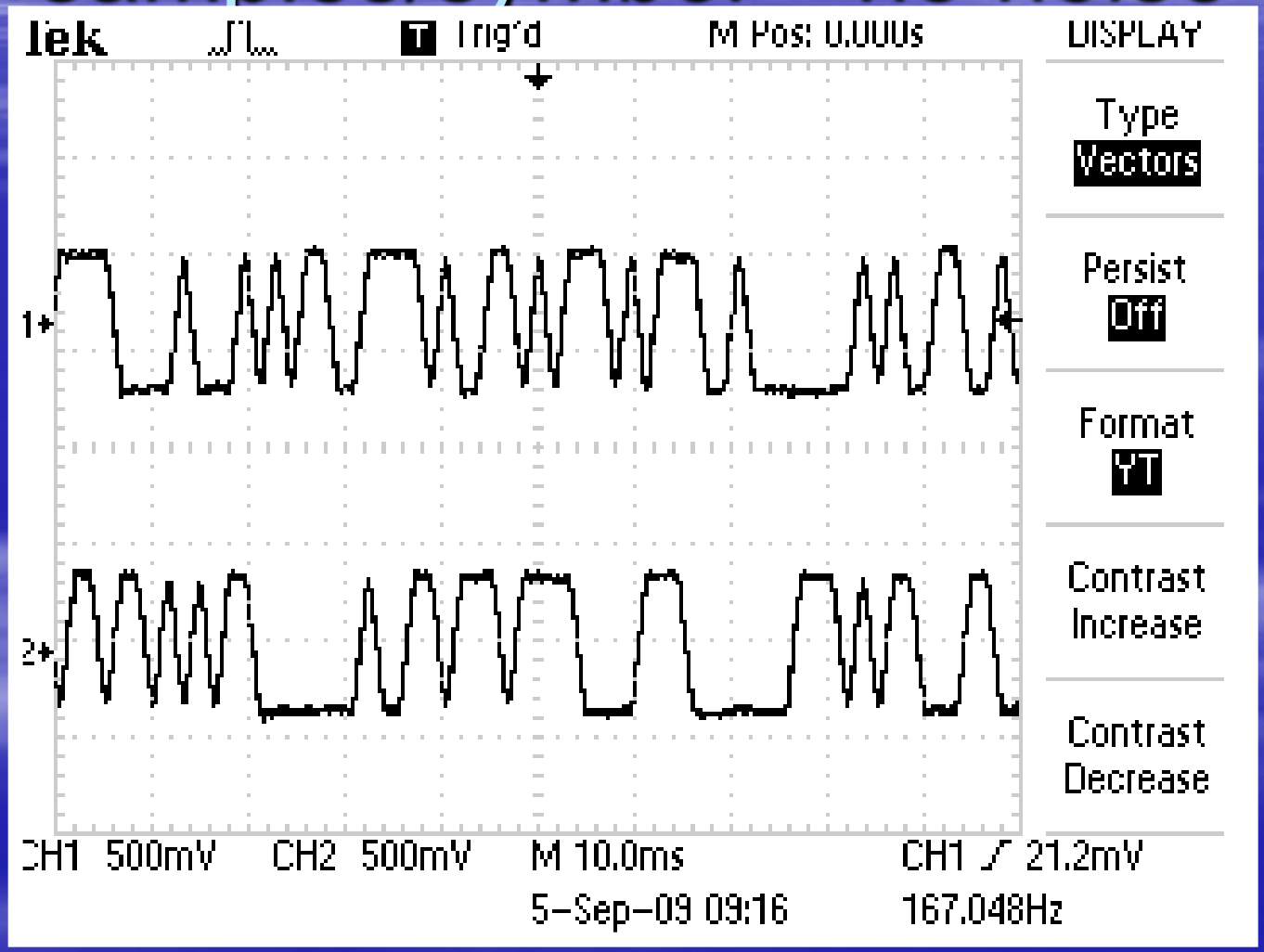
QPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



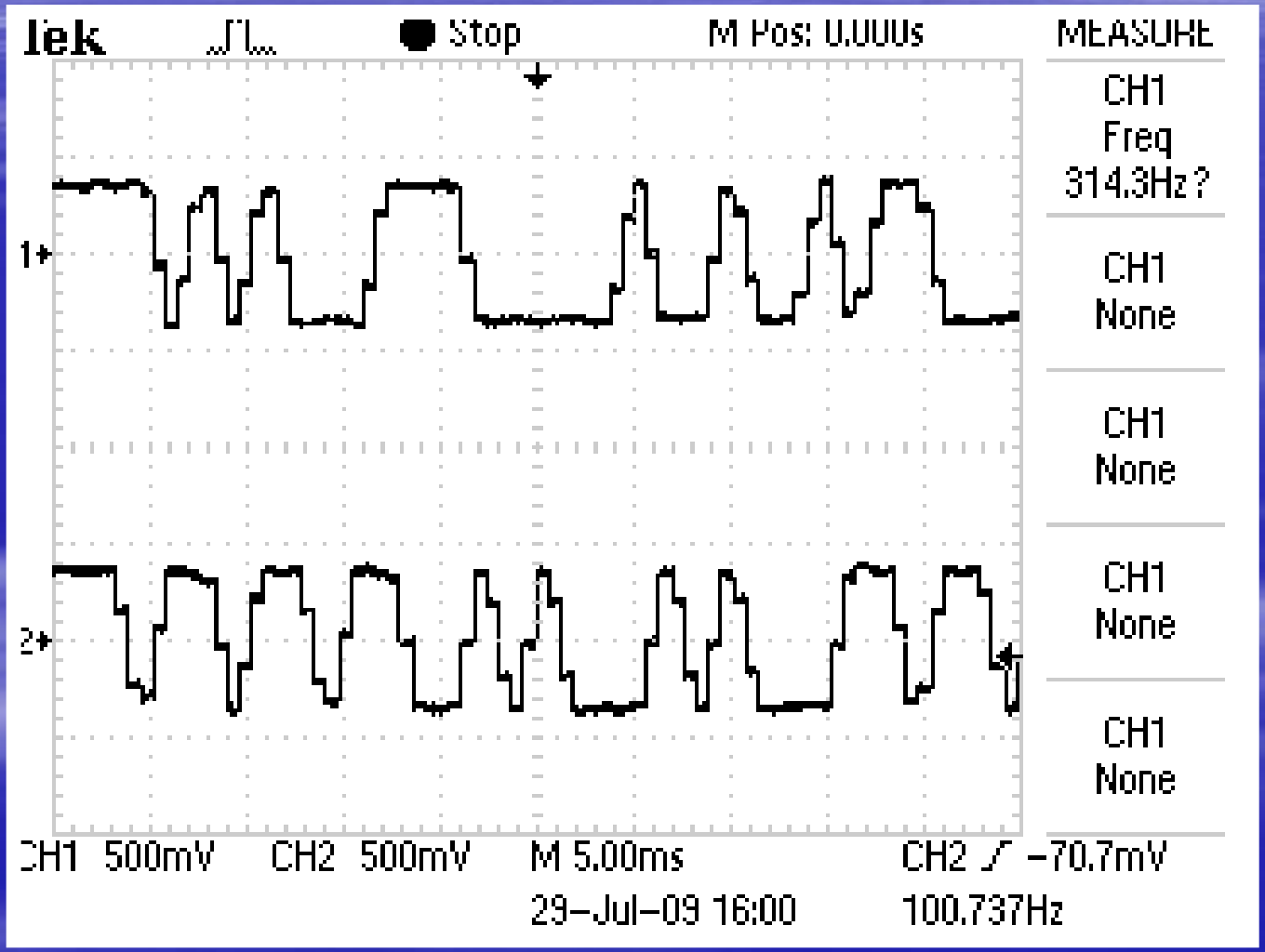
QPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



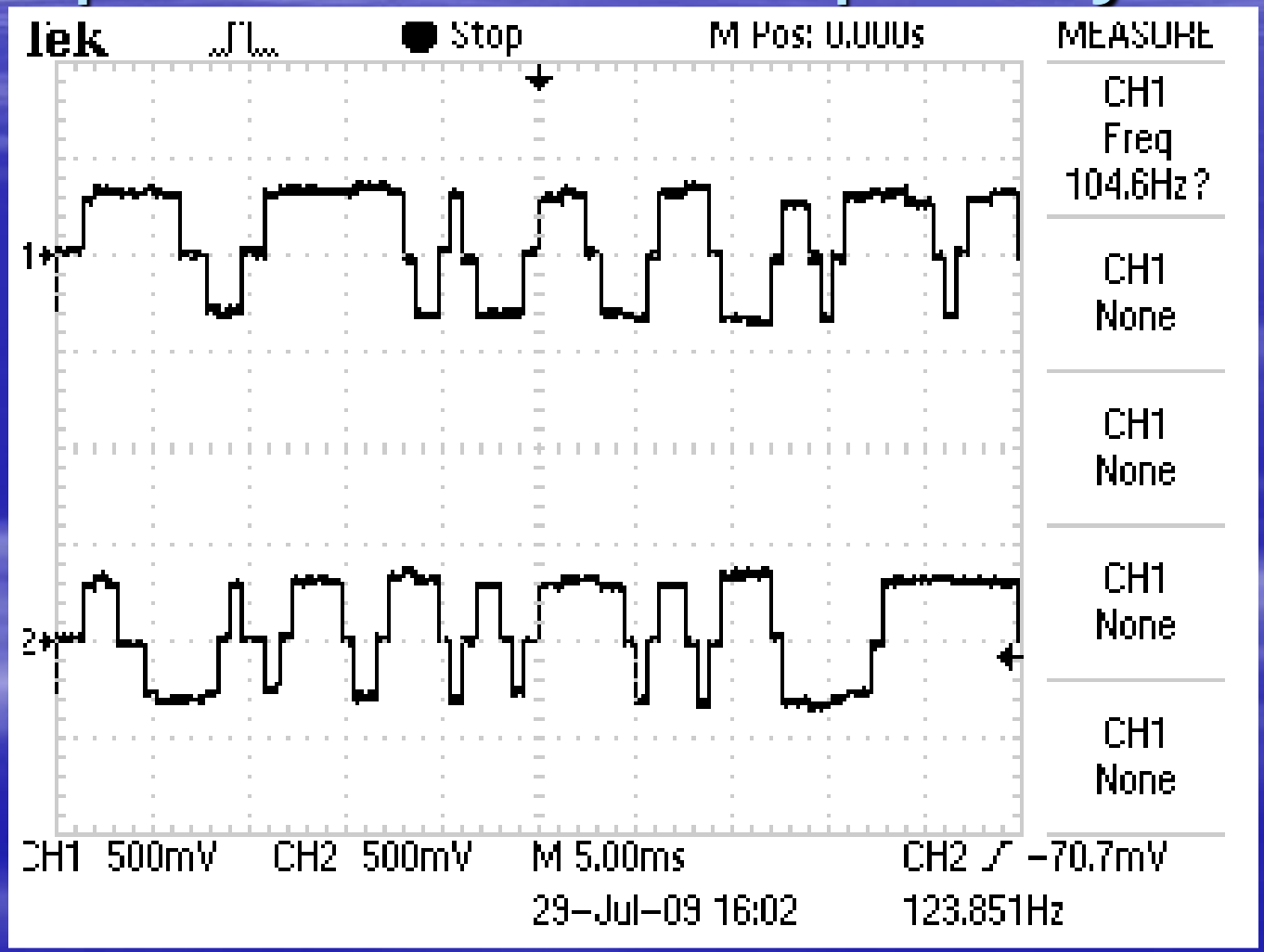
QPSK – In receiver after matched filter – After downsampling to 5 samples/symbol – no noise



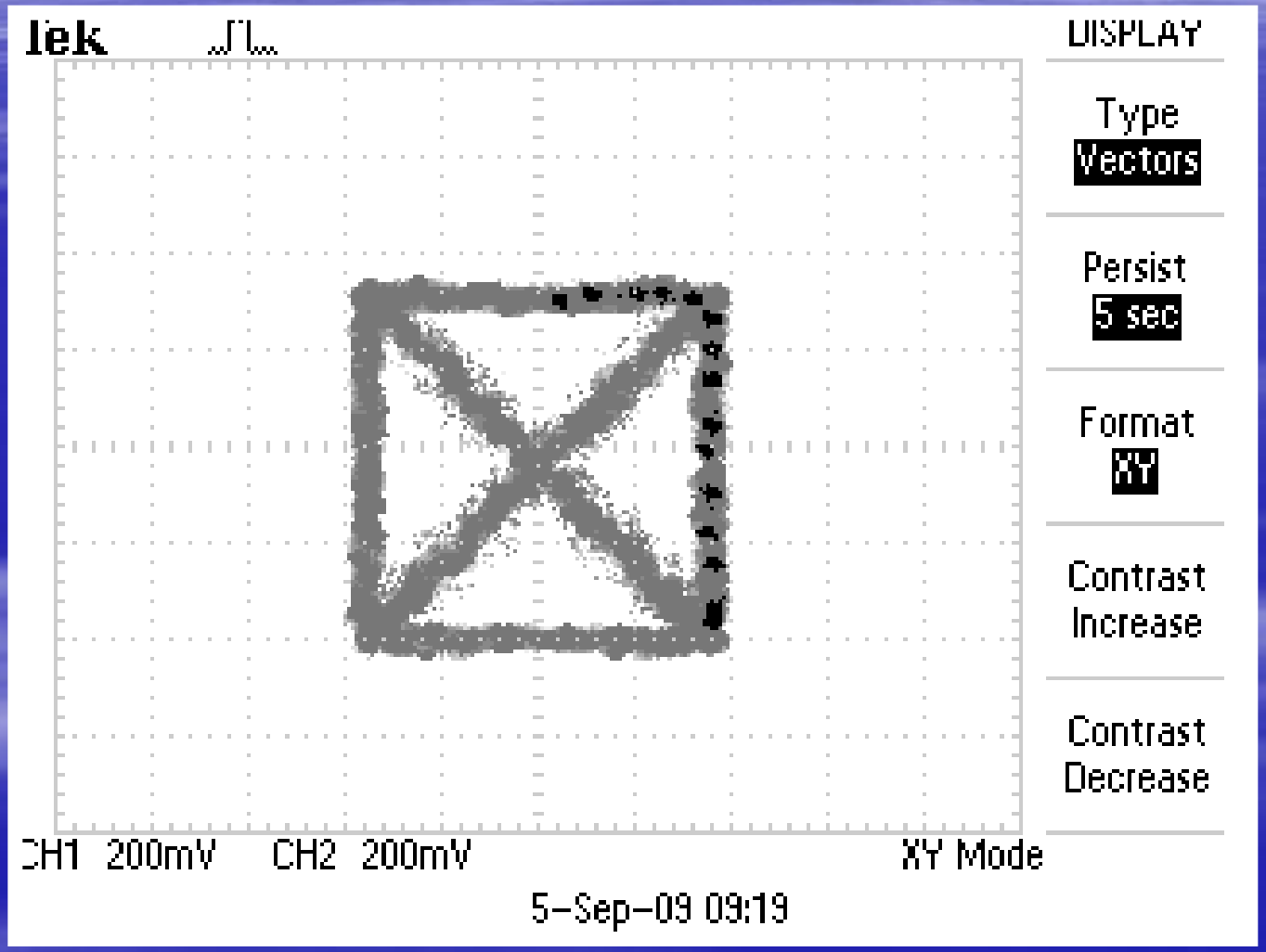
QPSK: after matched filter, carrier synchronized, 2.5 samples/symbol



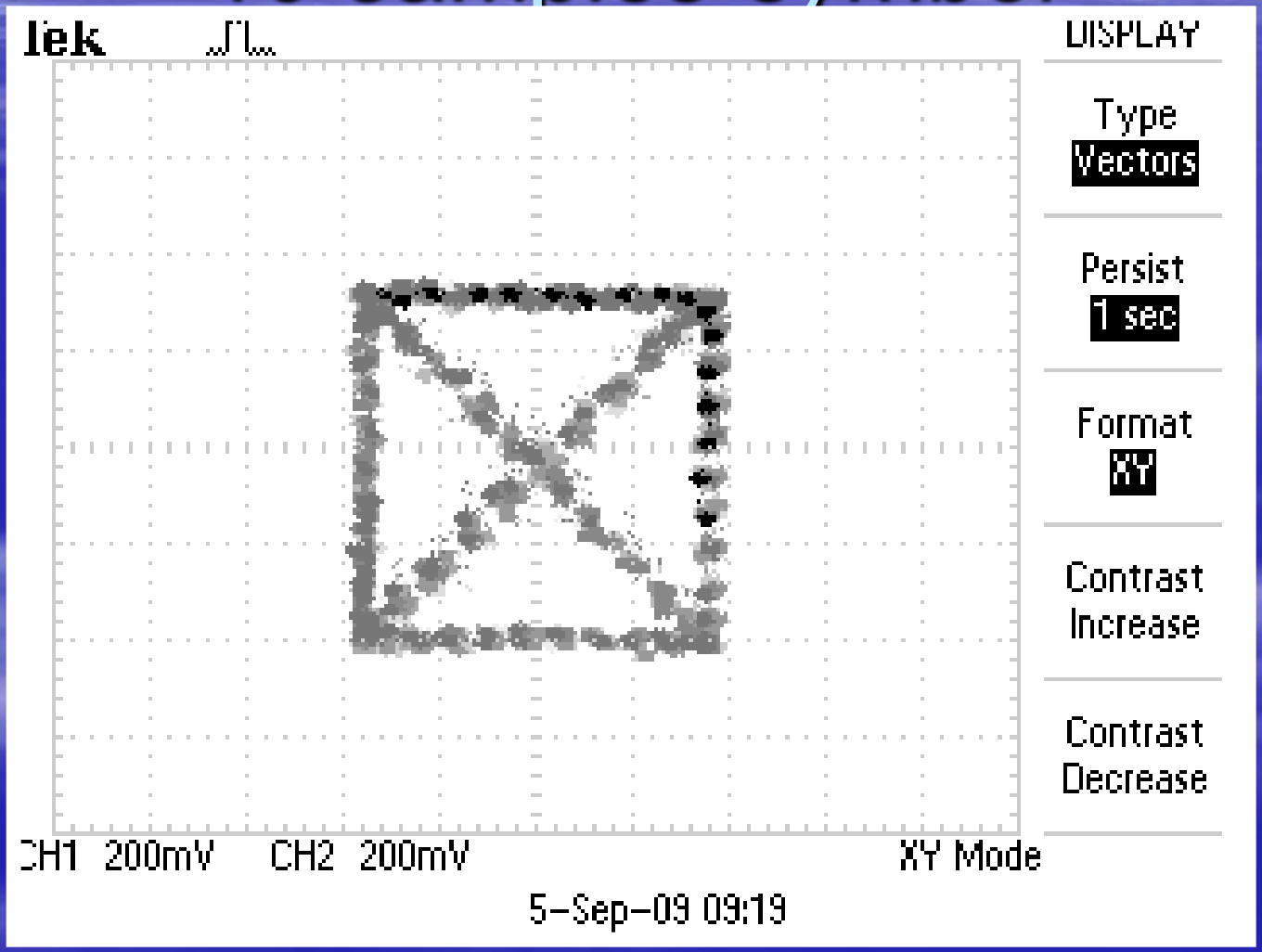
QPSK – I and Q at receiver, after synchronization and resampling interpolation to 2-samples/symbol



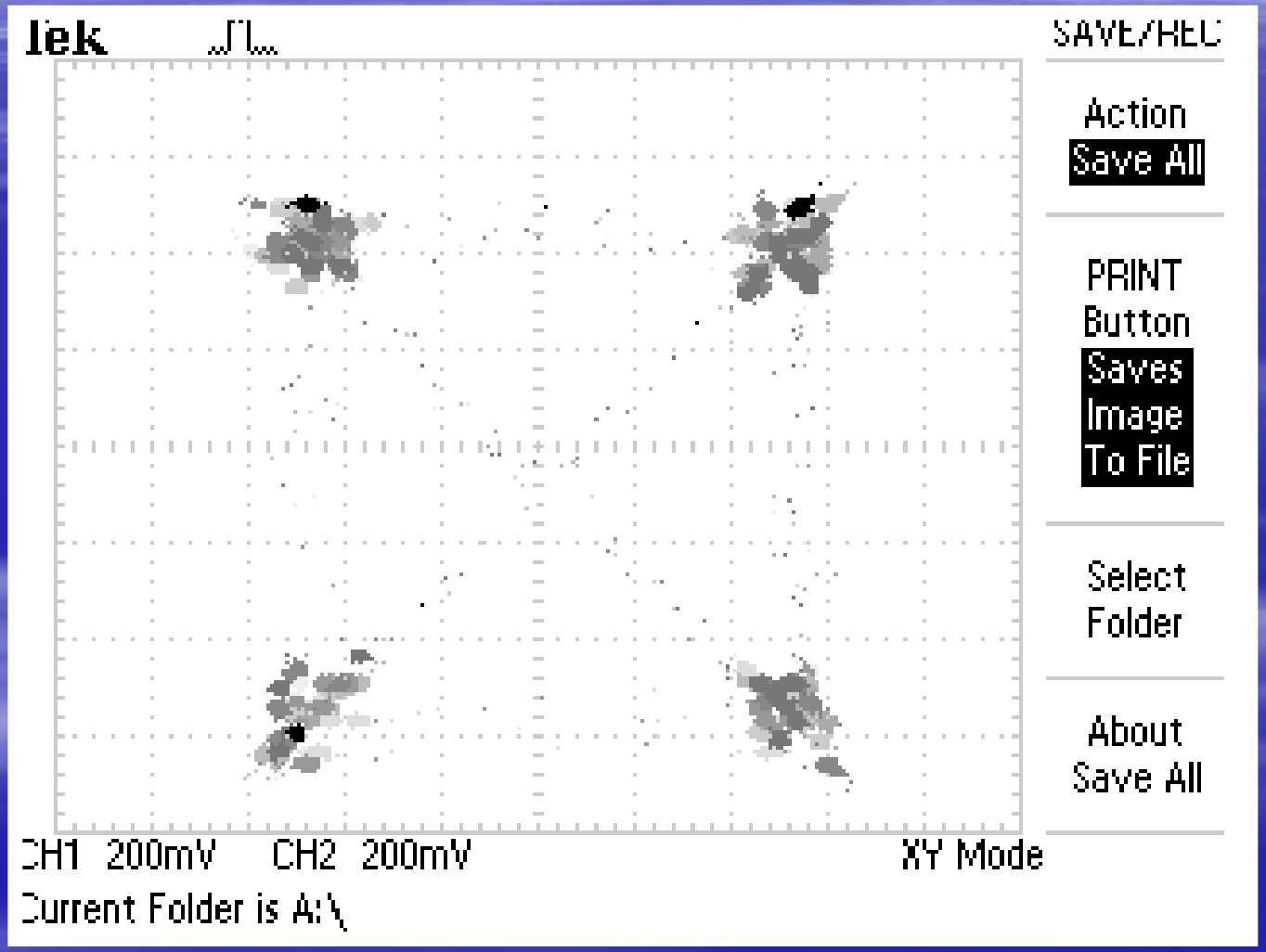
QPSK, X-Y graph of I vs. Q after matched filter



QPSK, X-Y graph of I vs. Q after matched filter and downsampling to 10 samples-symbol

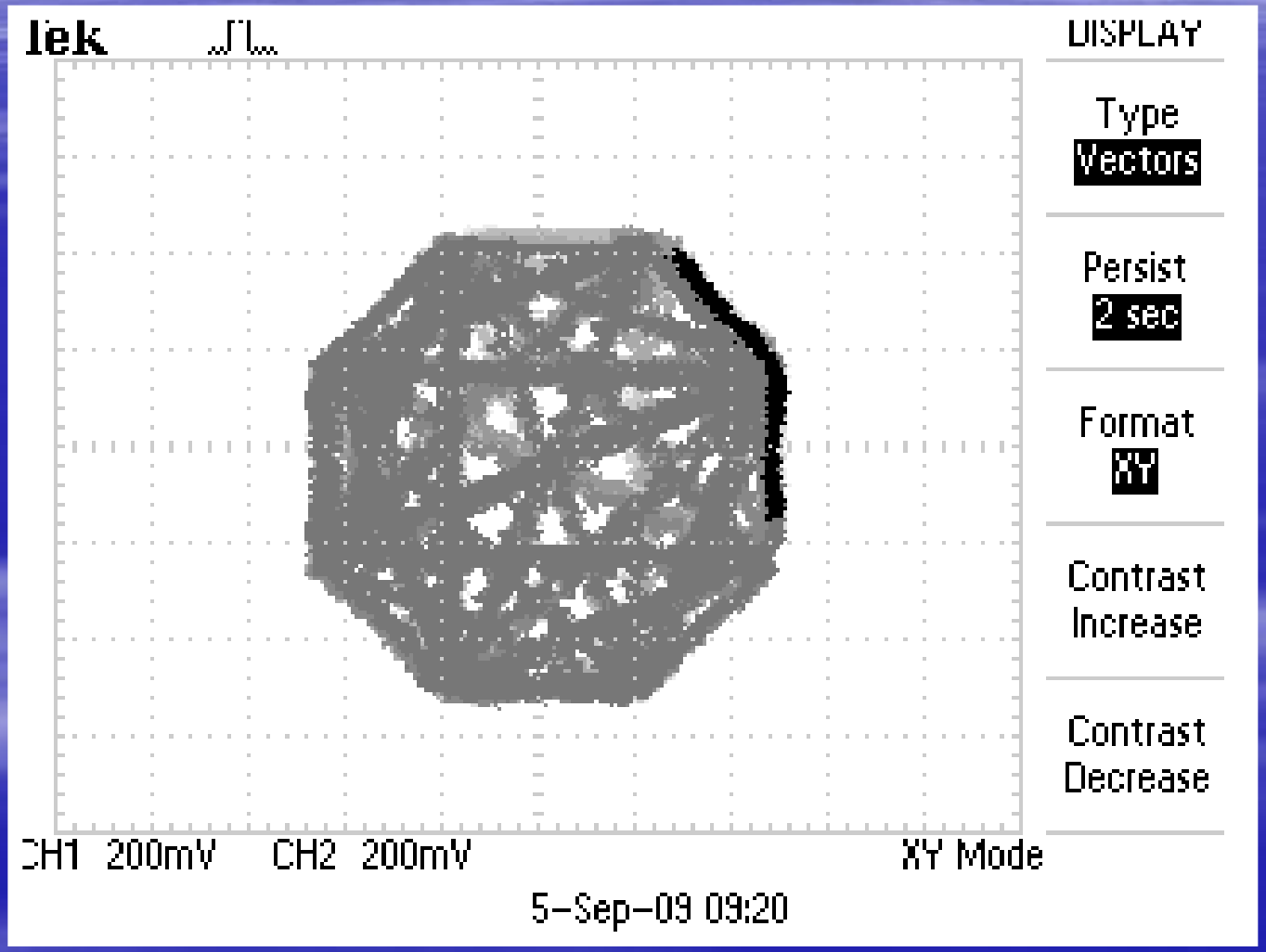


QPSK – at output of receiver, SNR = 12 dB, 1 sample/symbol

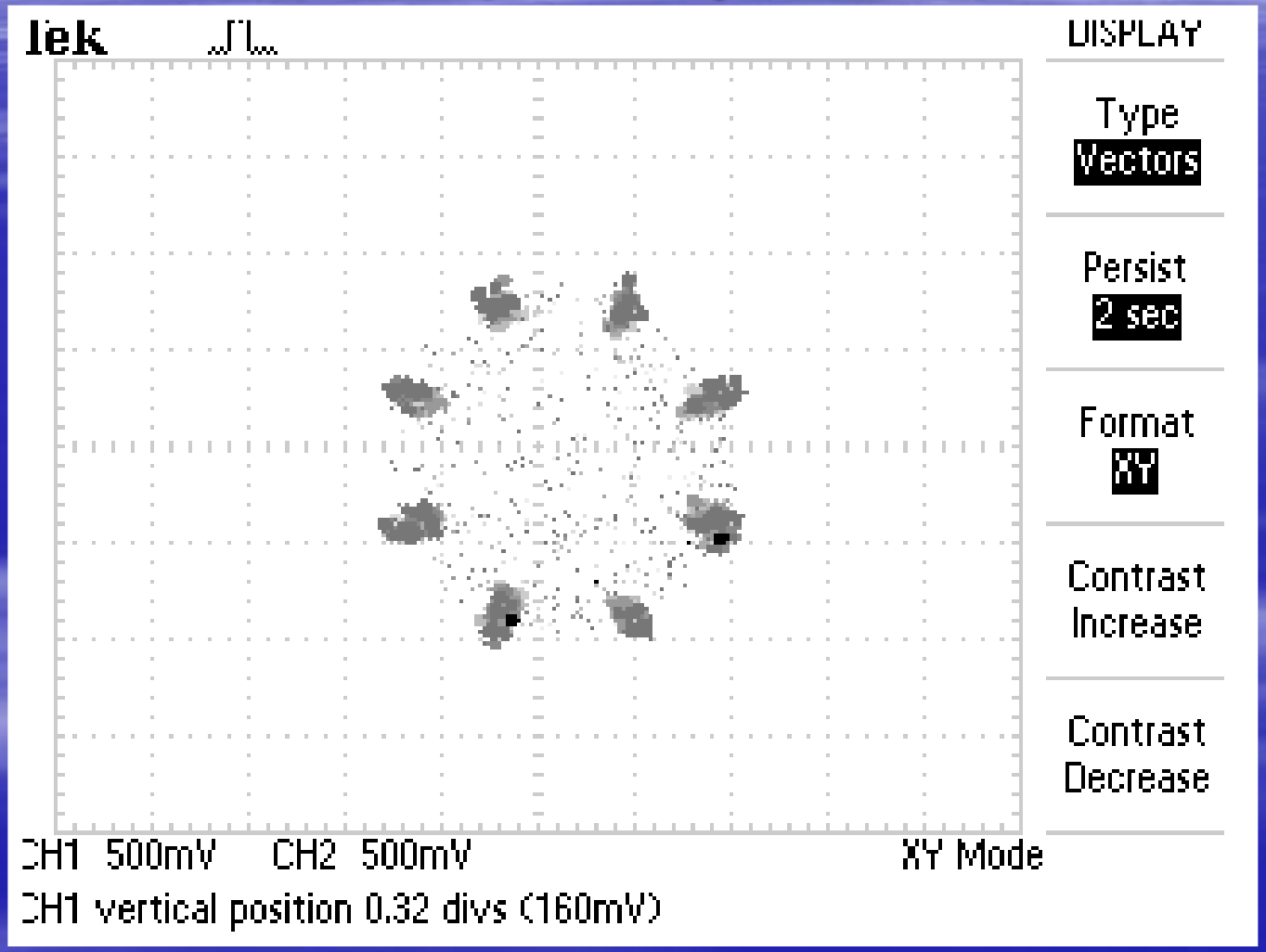


8-PSK

8-PSK, X-Y graph of I vs. Q after matched filter

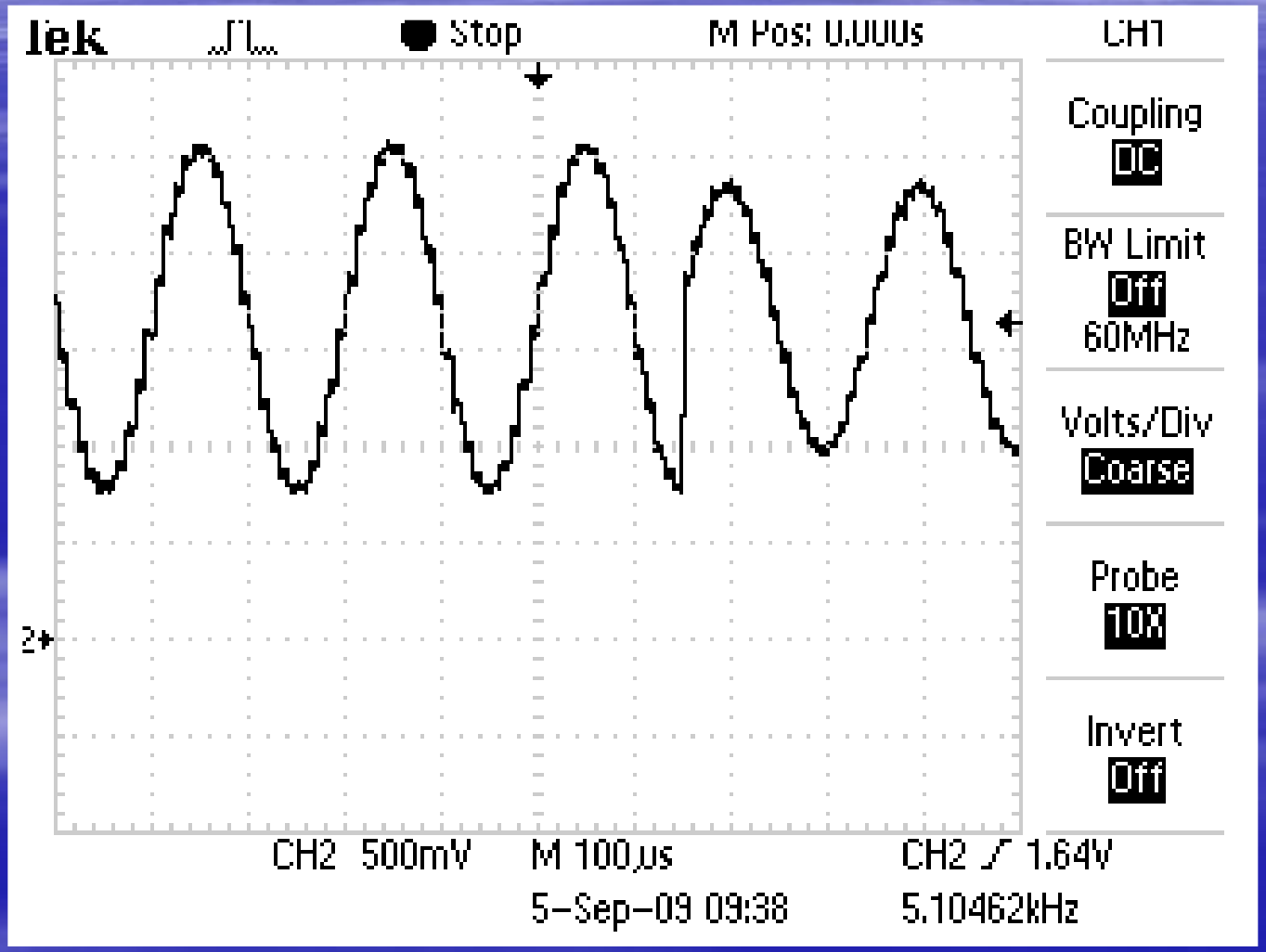


8-PSK after demodulation, 1 sample/symbol

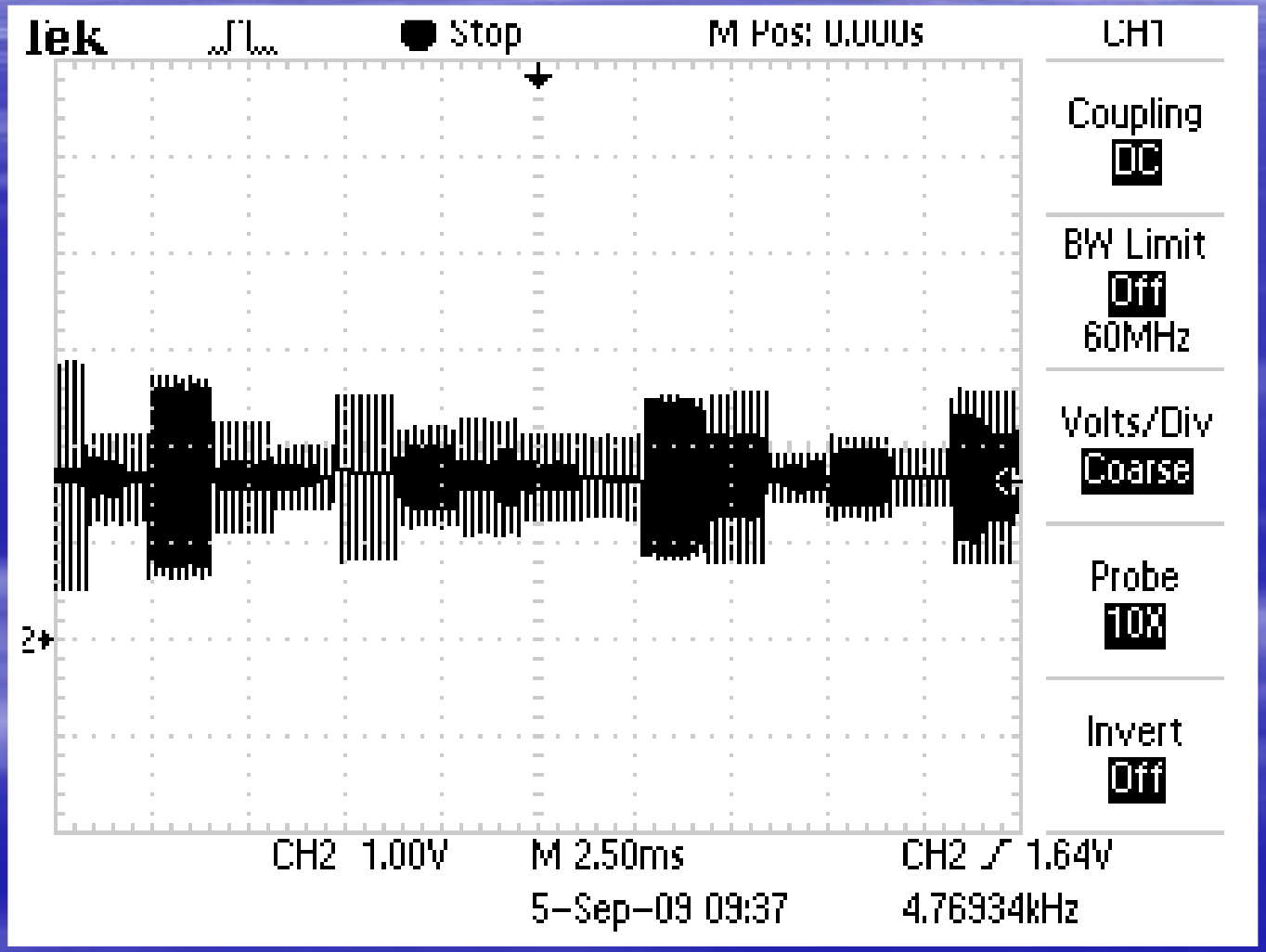


QAM

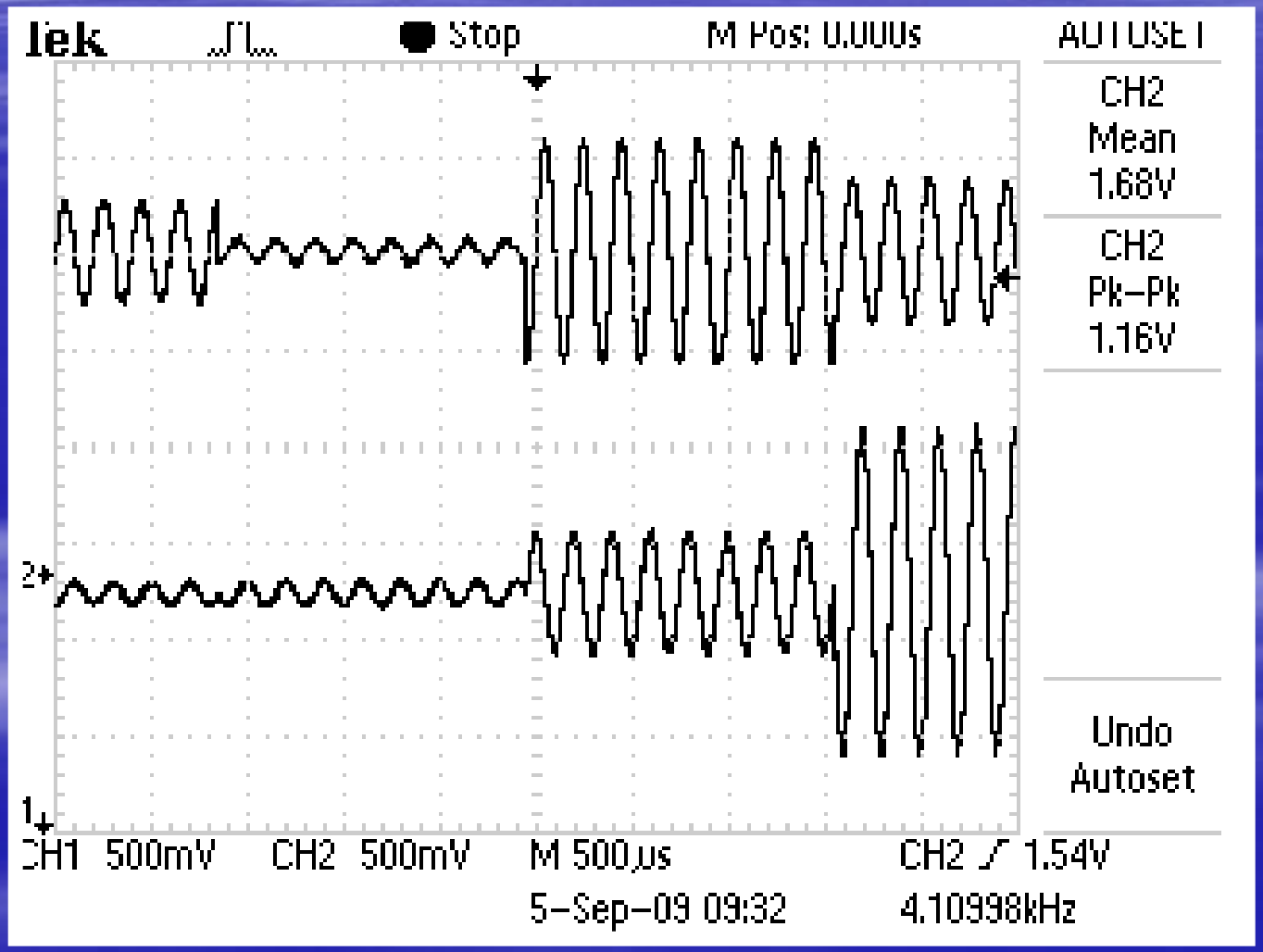
Transition in transmitted wave – 16-QAM modulation



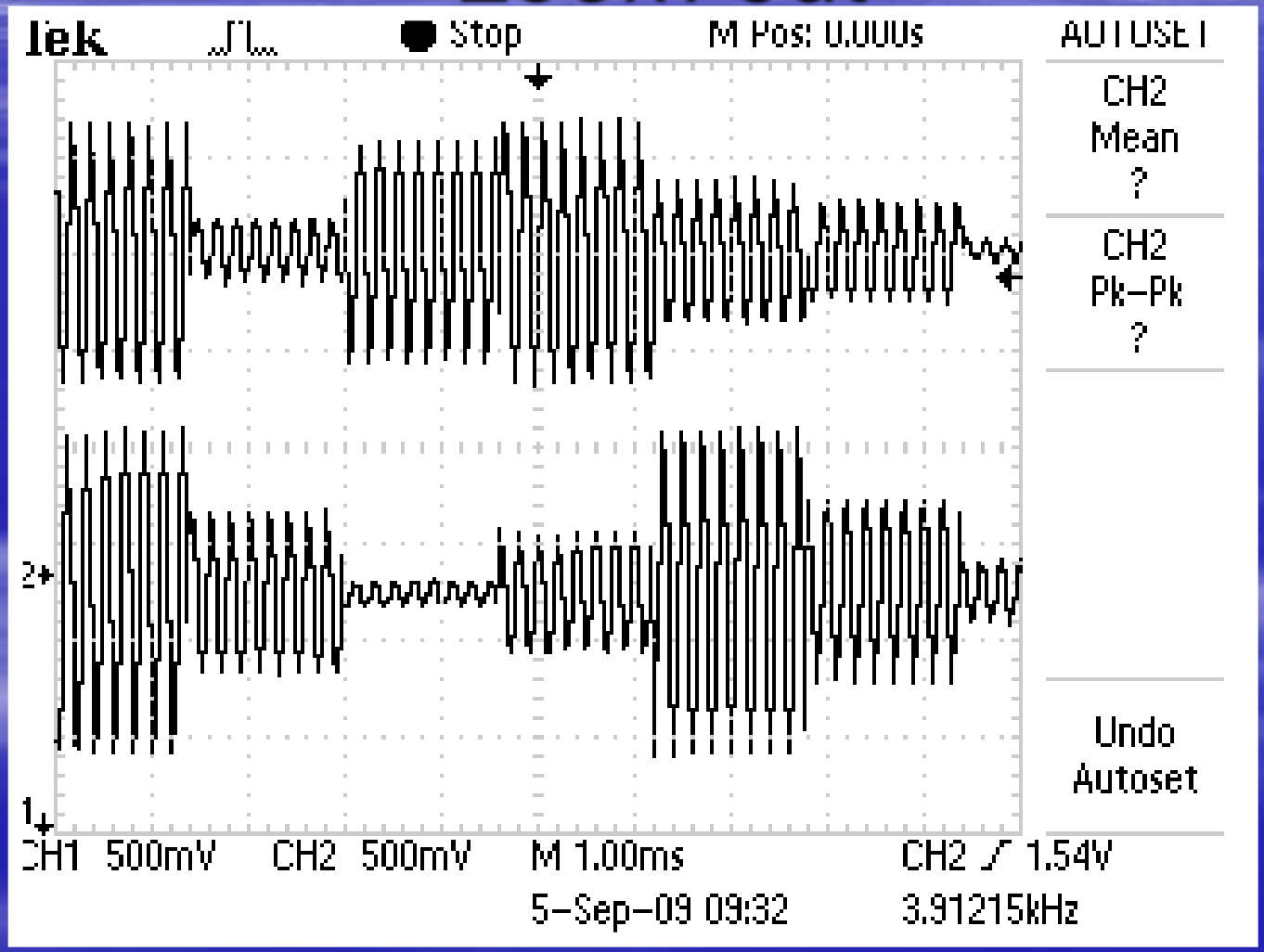
16-QAM Transmitted wave -



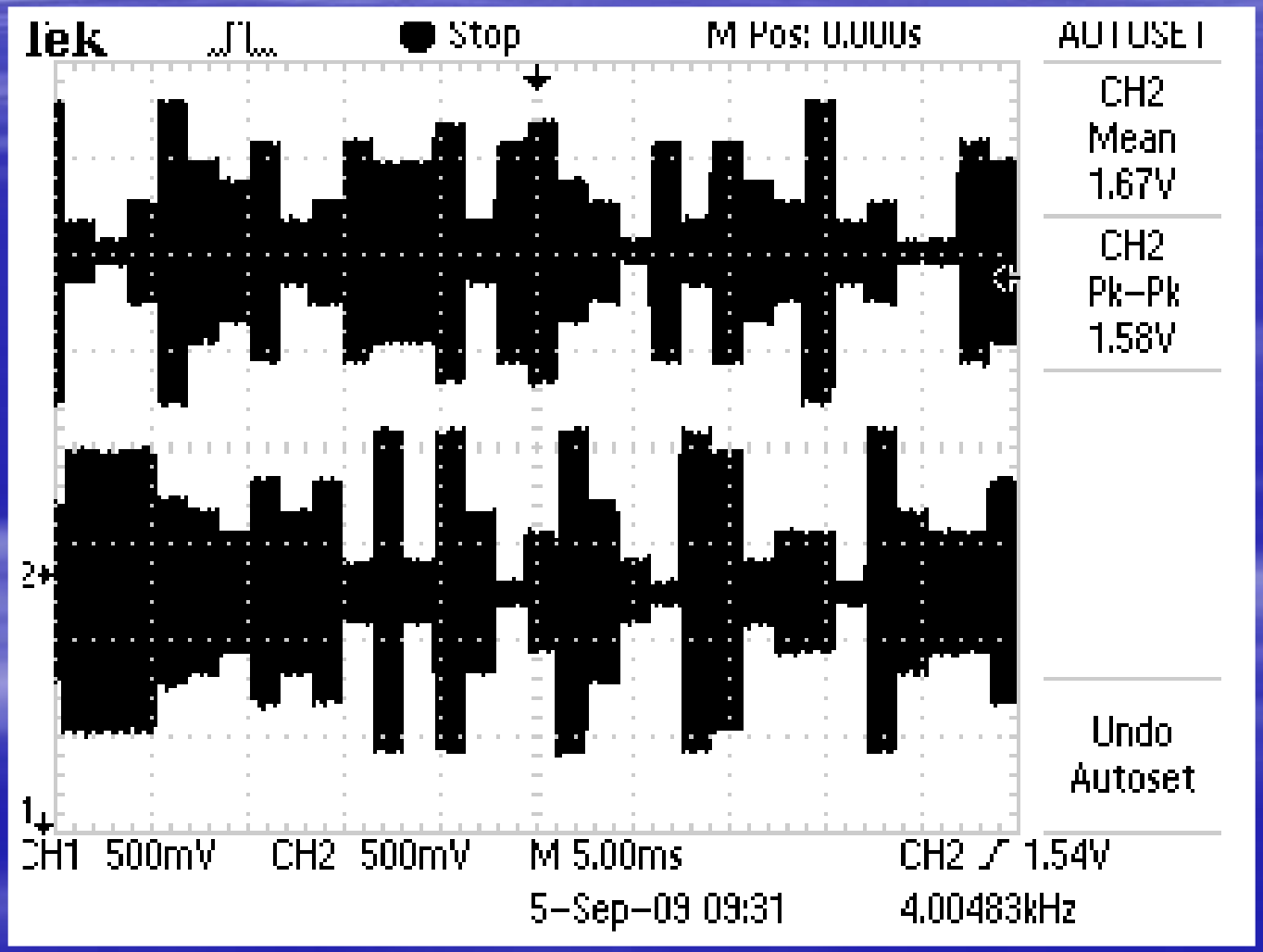
64-QAM I and Q arms before addition in transmitter



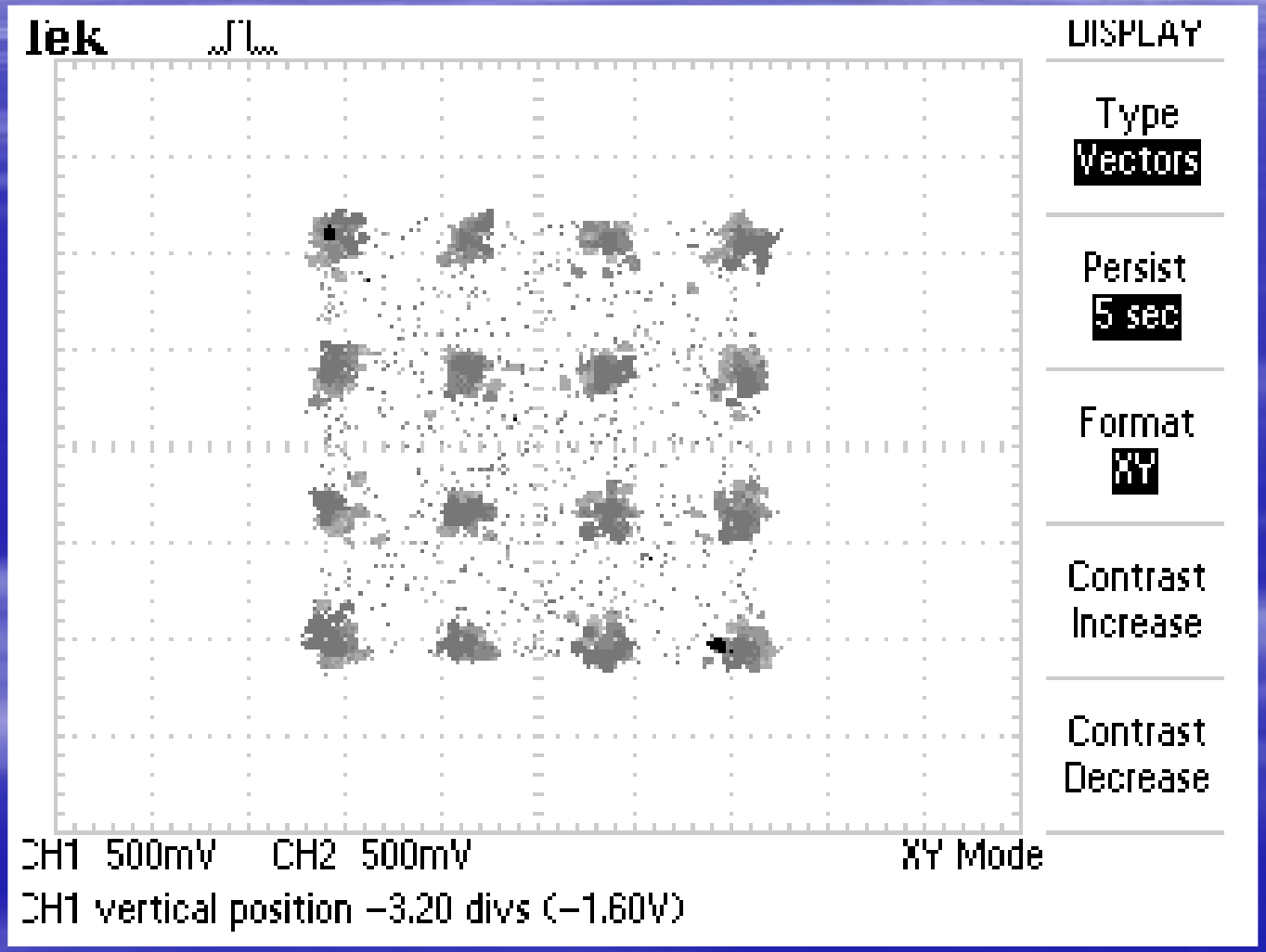
64-QAM I and Q arms before addition in transmitter - zoom out



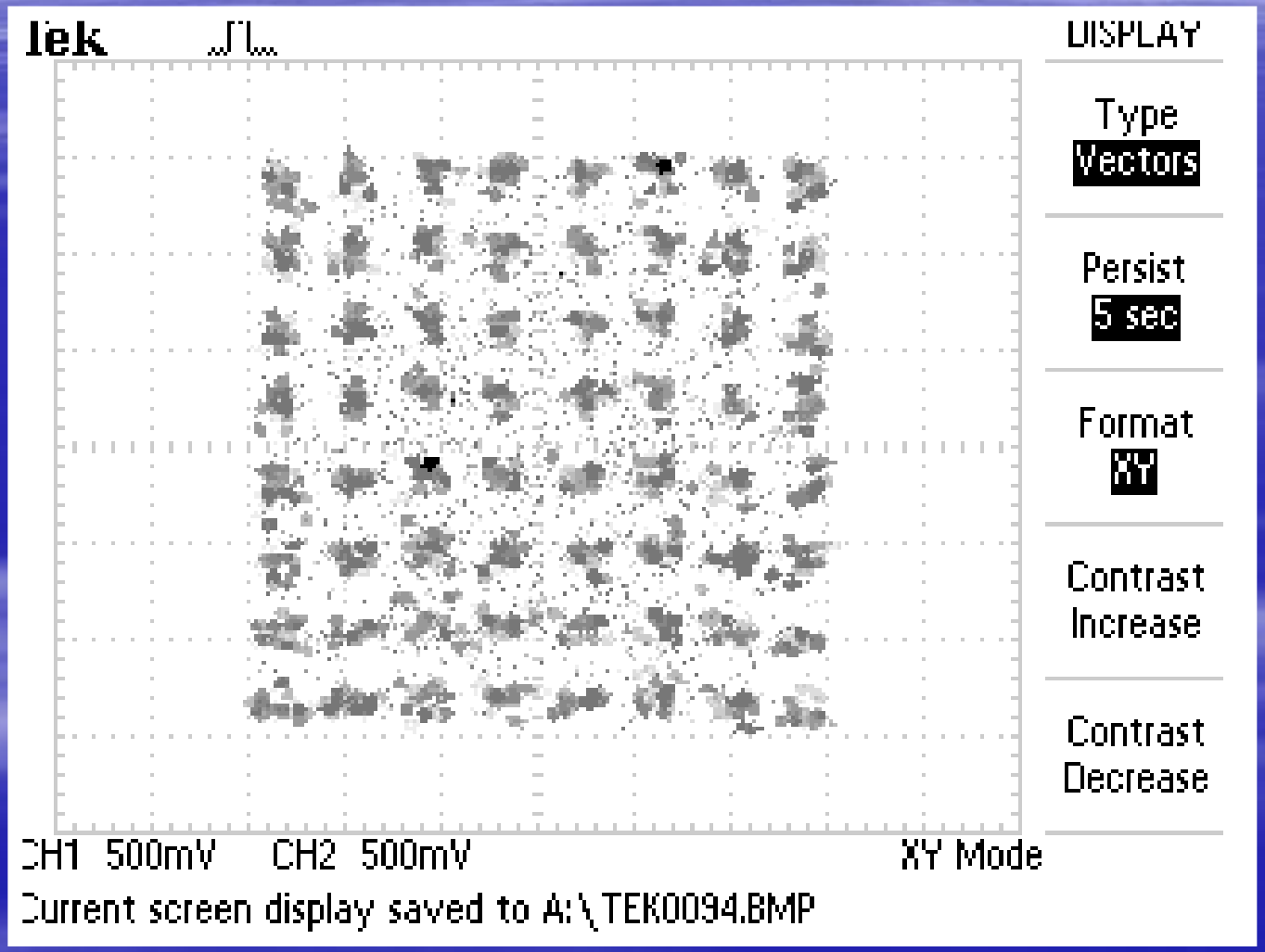
256-QAM I and Q arms before addition in transmitter - zoom out



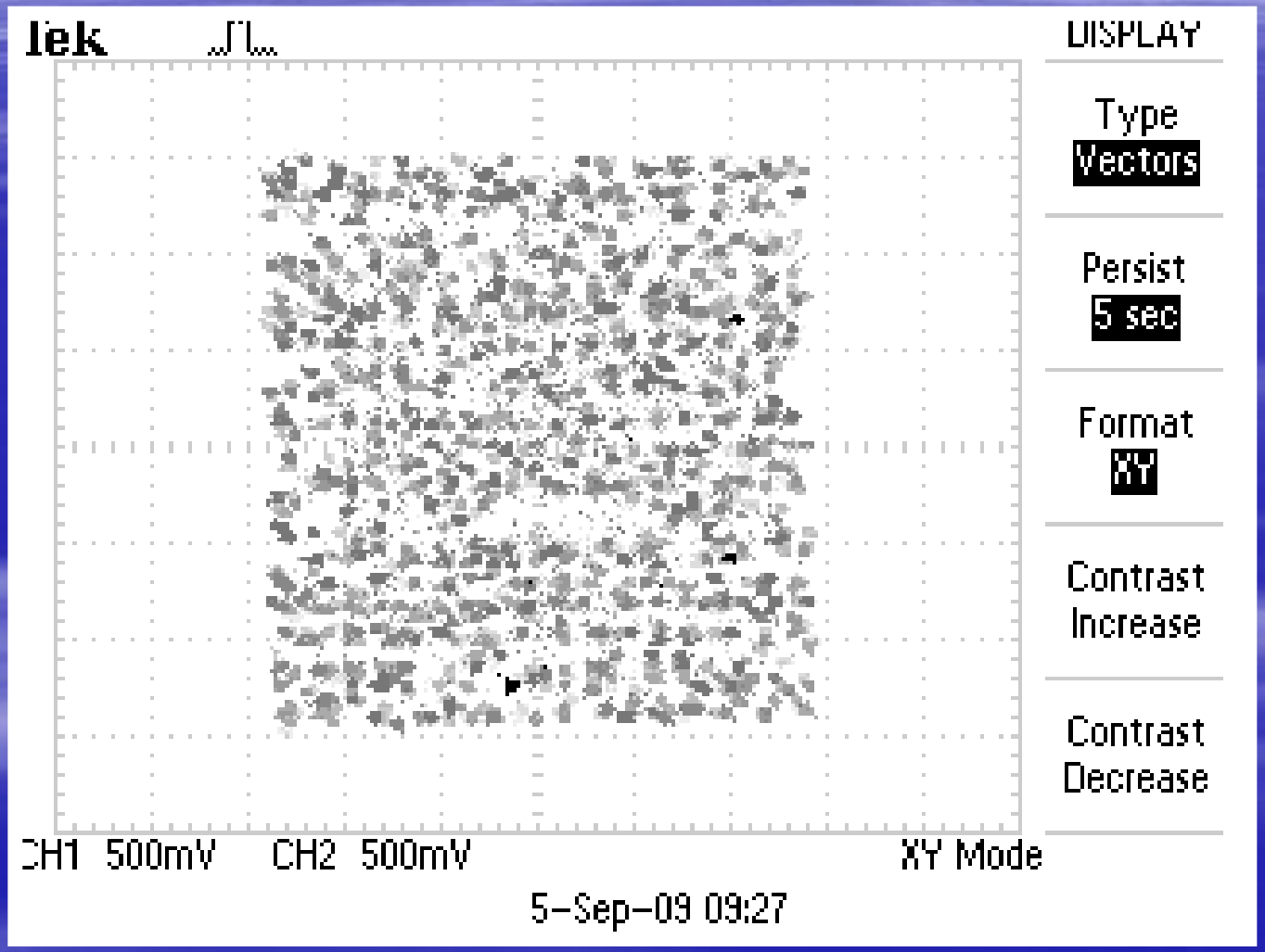
16-QAM received constellation



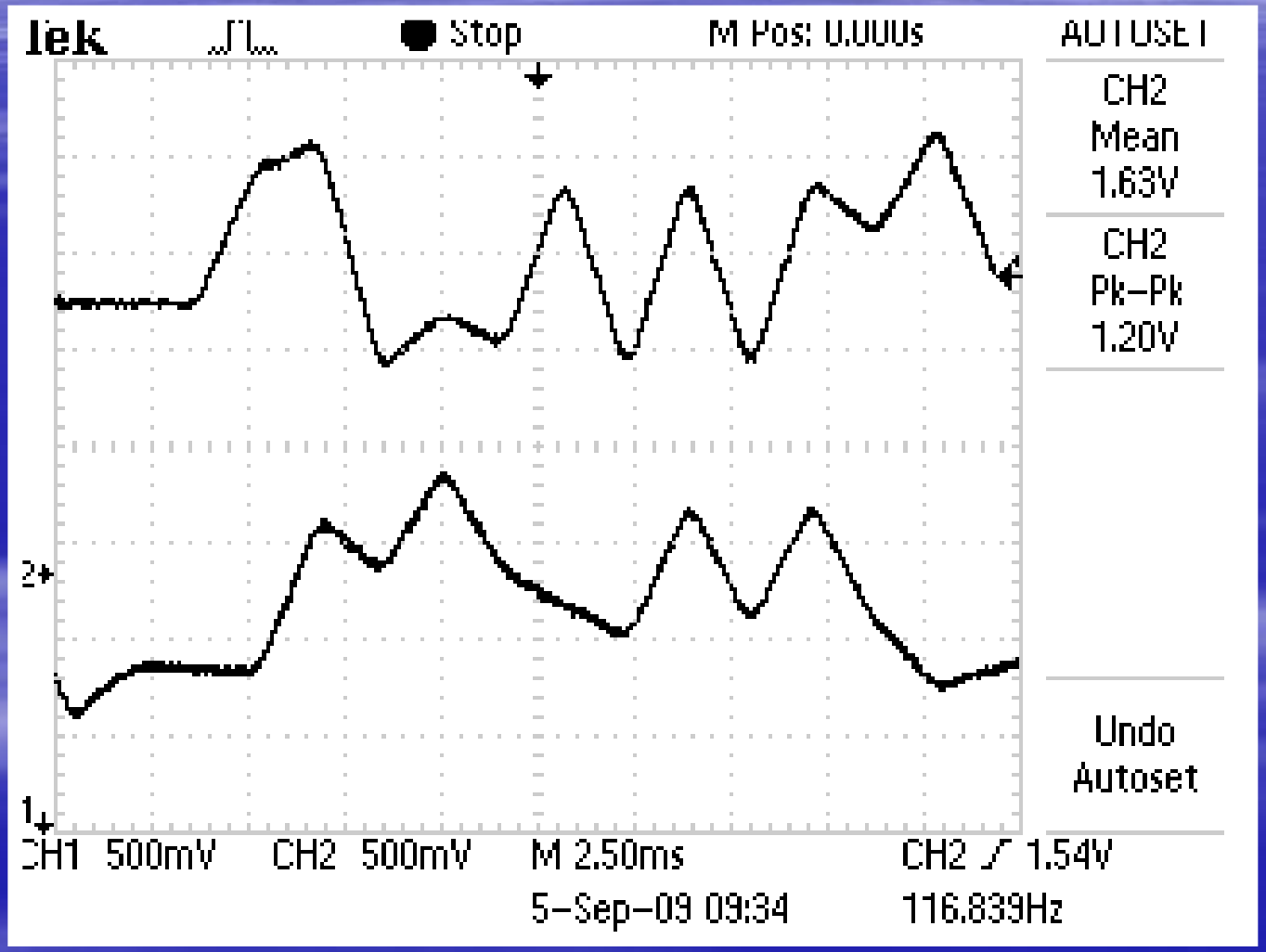
64-QAM received constellation



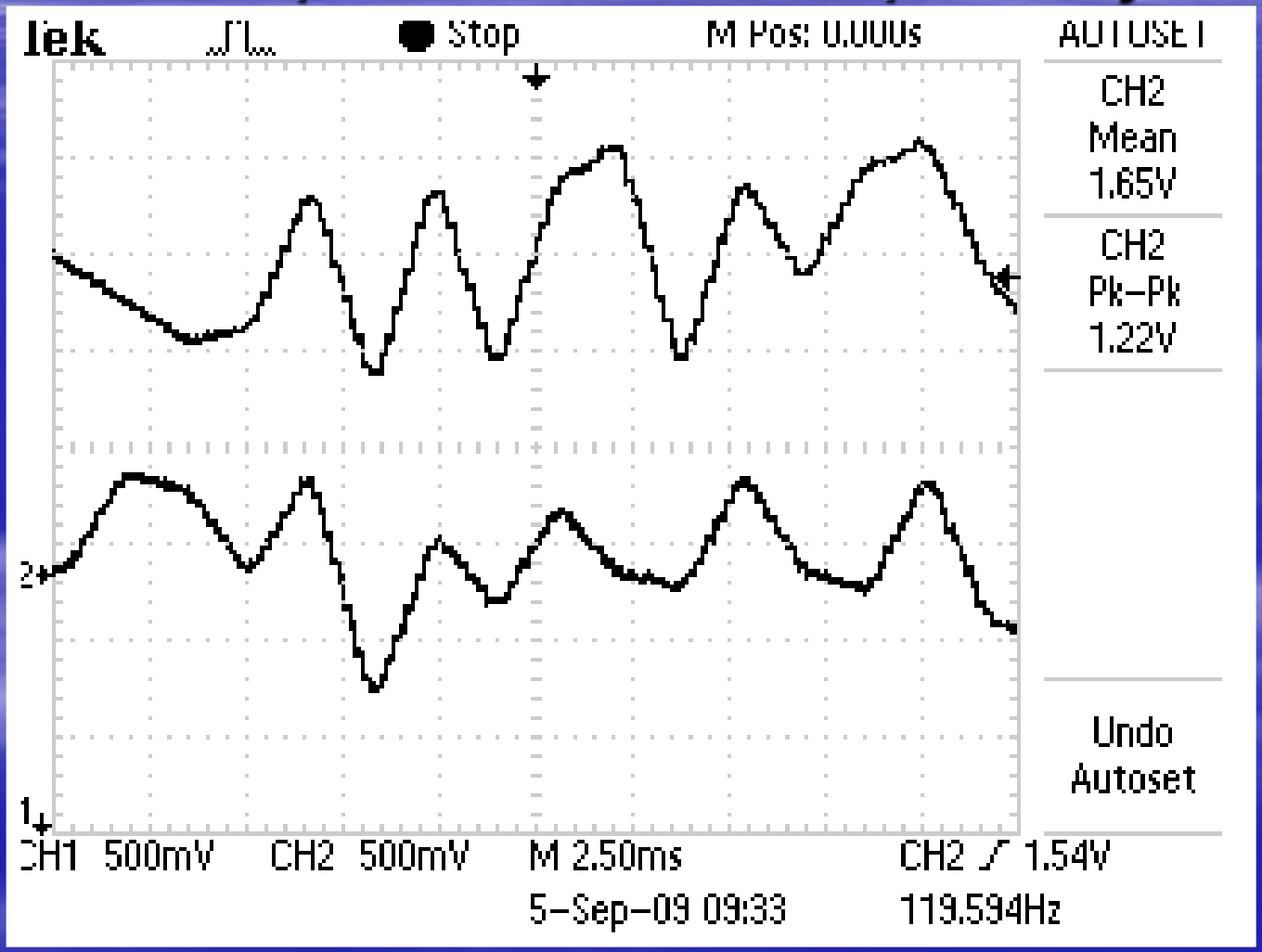
256 QAM received constellation – with slight carrier phase error



Demodulated post-matched-filter 256-QAM I and Q, no noise

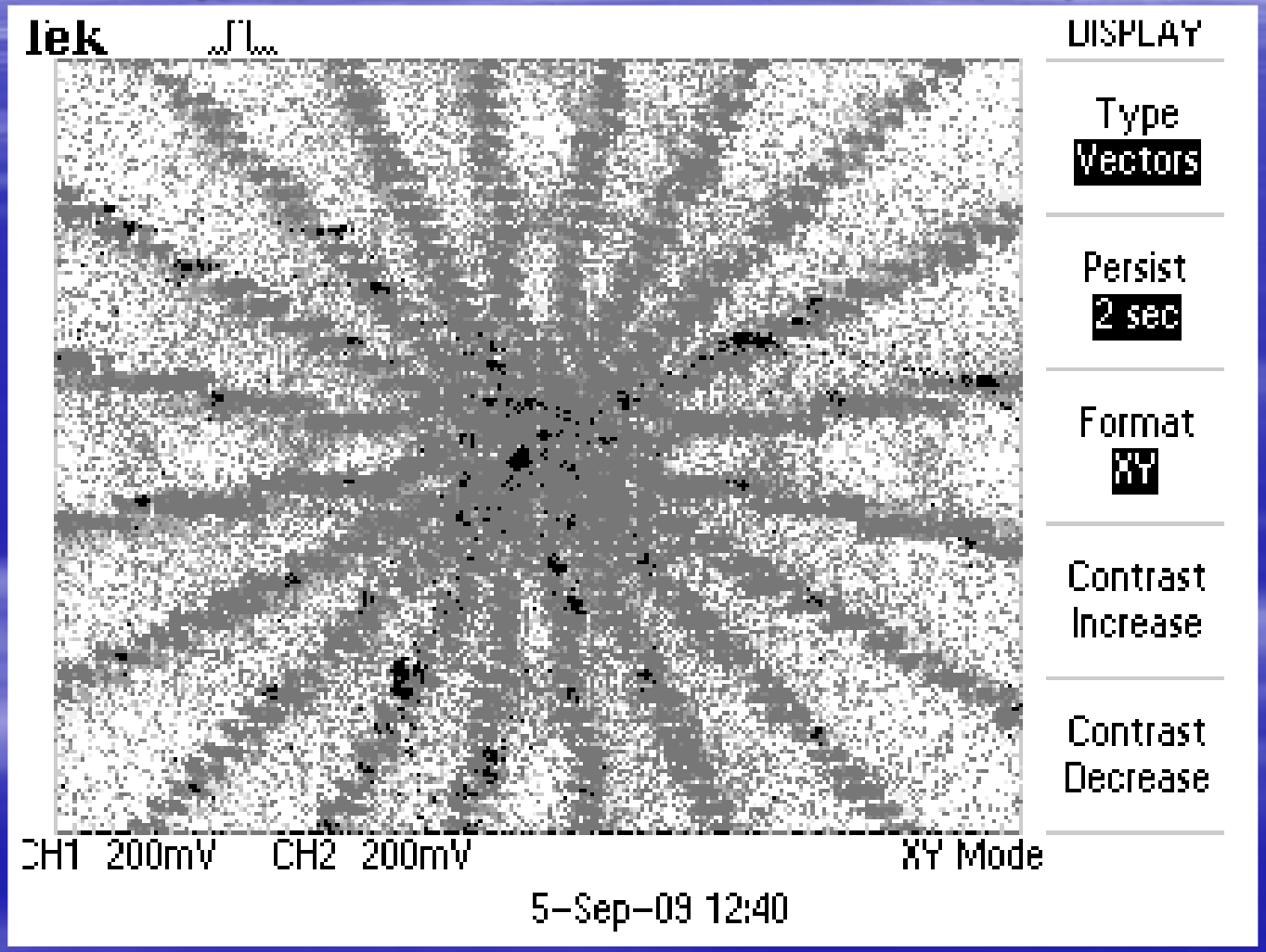


Demodulated post-matched-filter 256-QAM I and Q, no noise downsampled to 10-samples/symbol

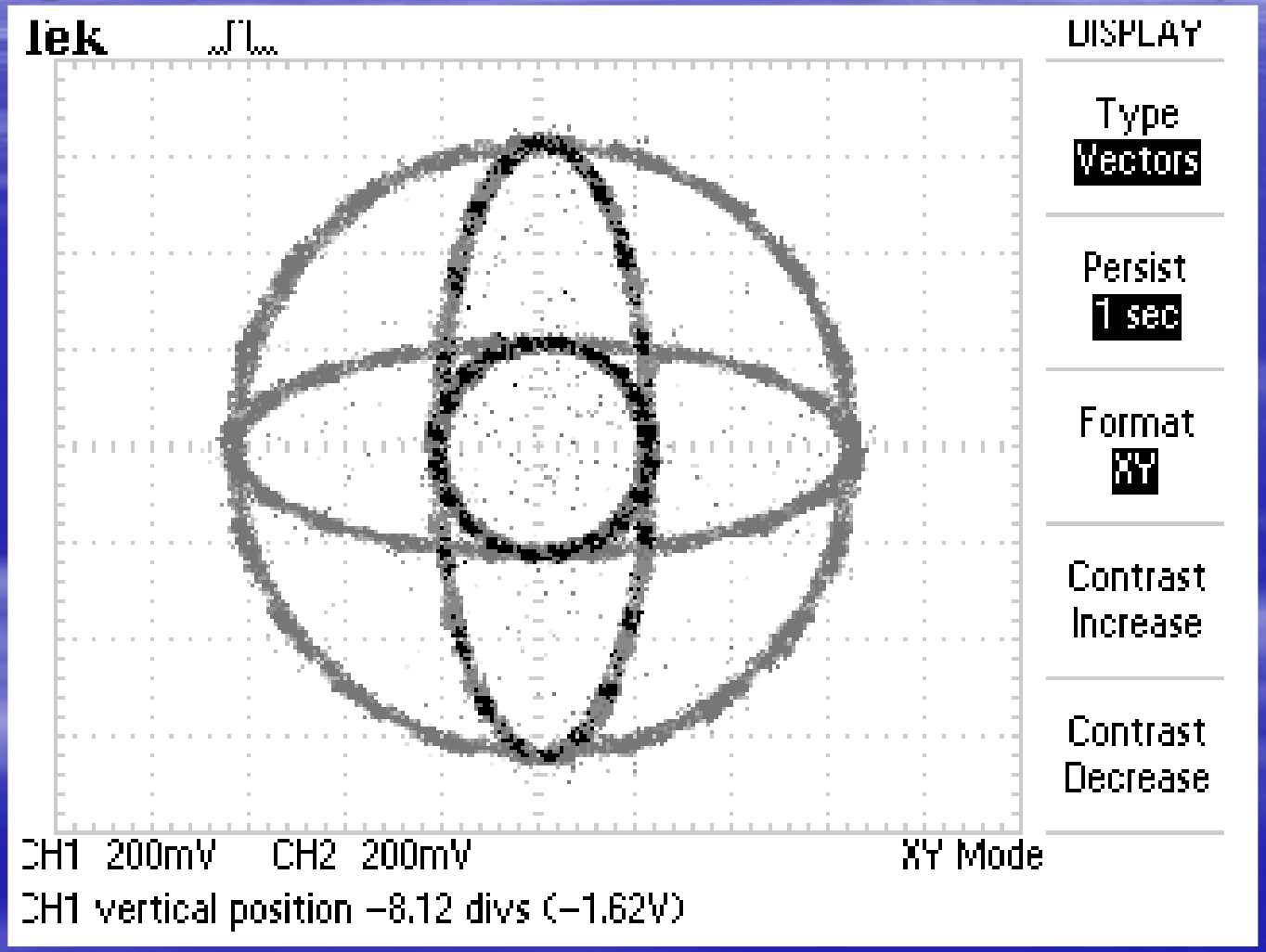


Various nice pictures….

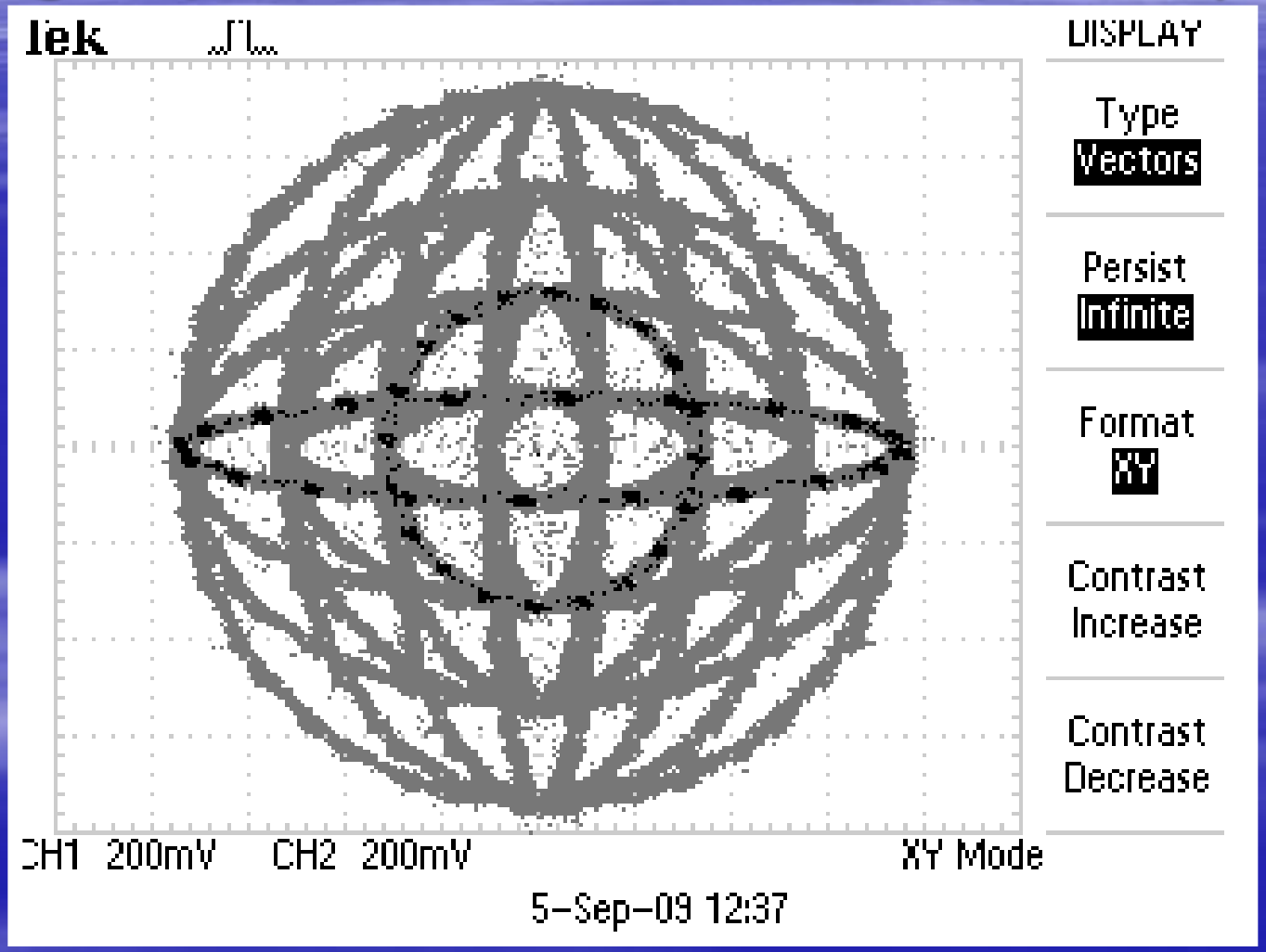
I-Q graph of post I-Q Demod (pre-matched filter)



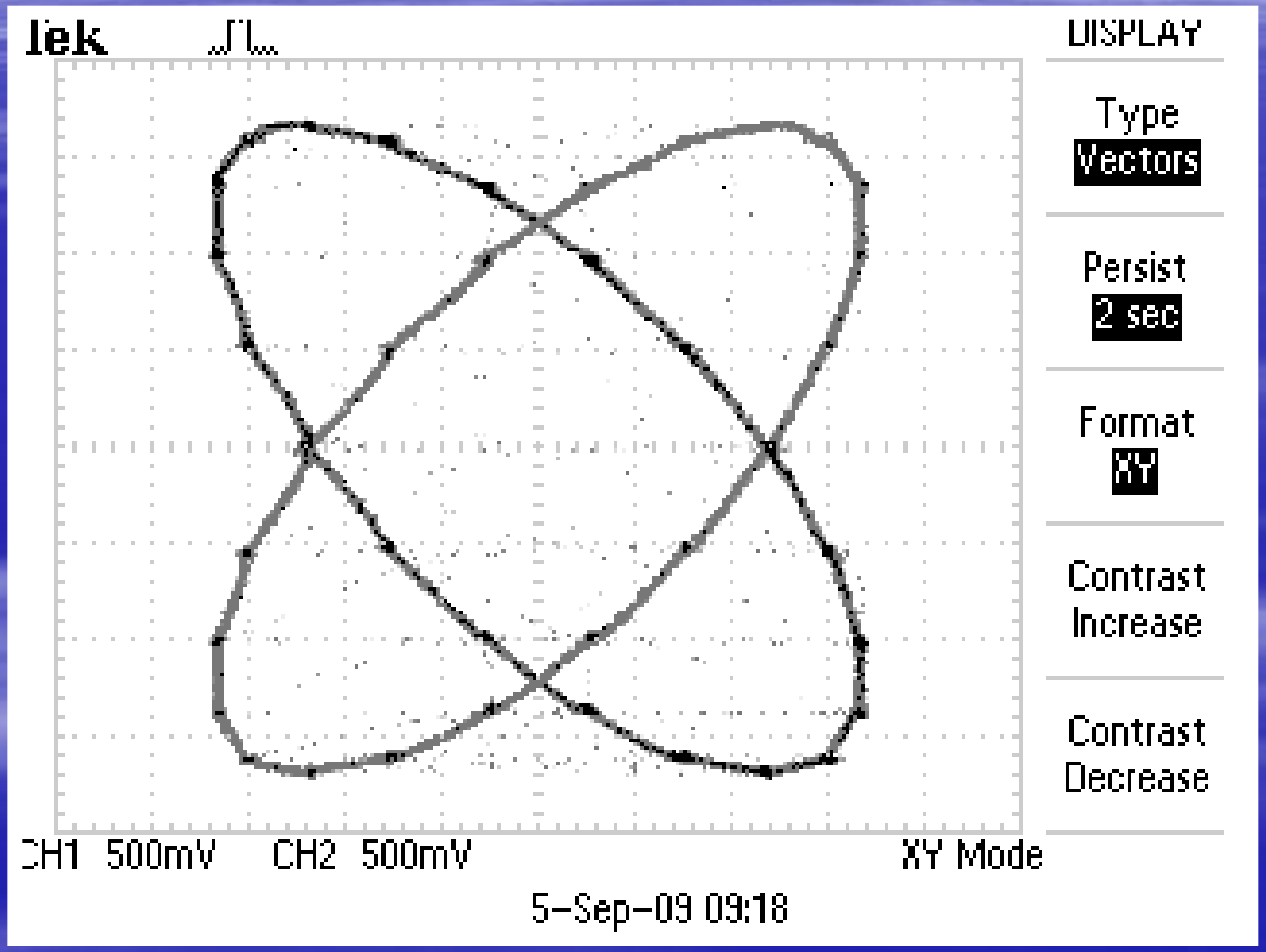
16-QAM Transmission (X-Y graph of I vs. Q TX arms)



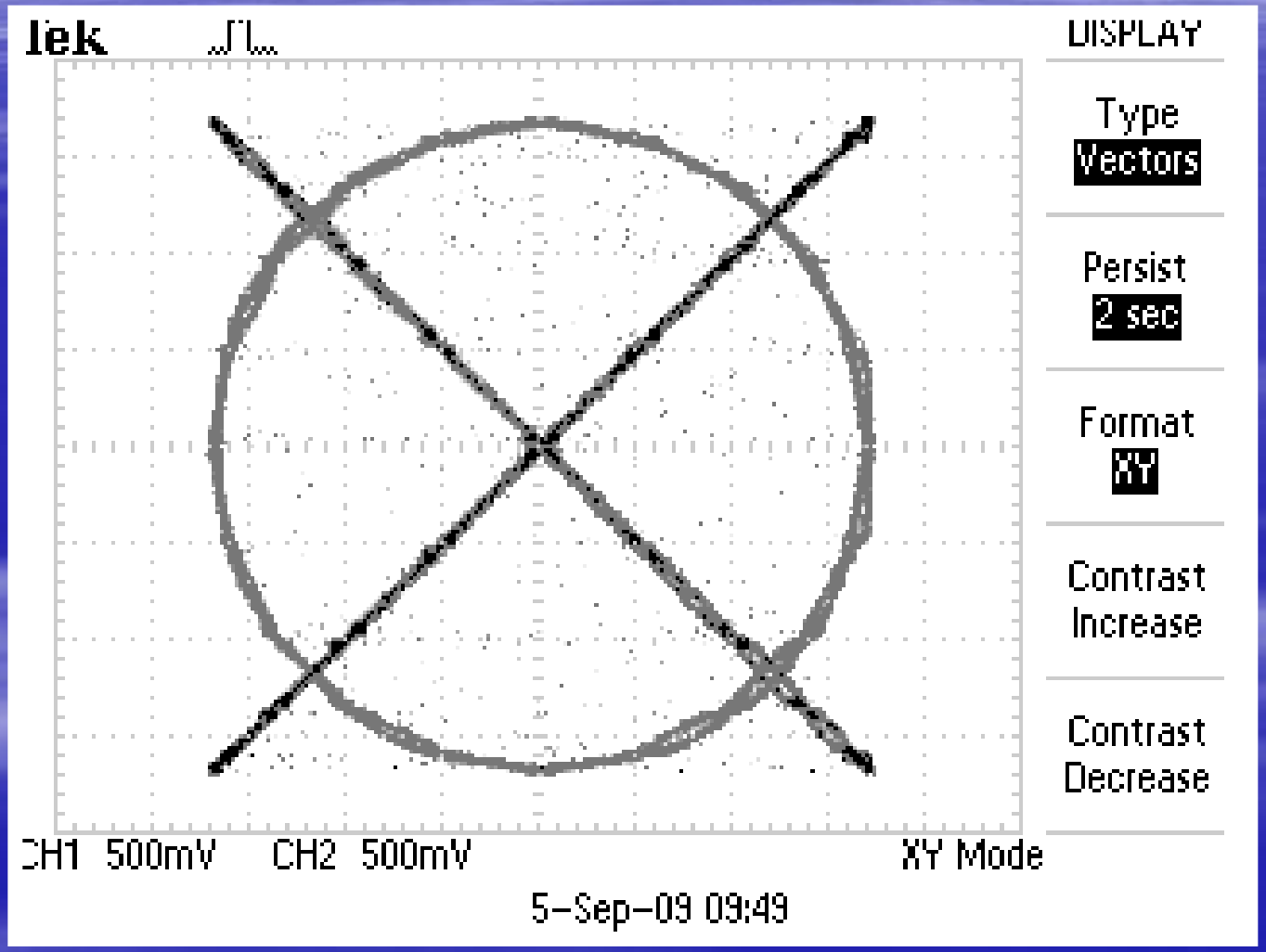
64-QAM Transmission (X-Y graph of I vs. Q TX arms)



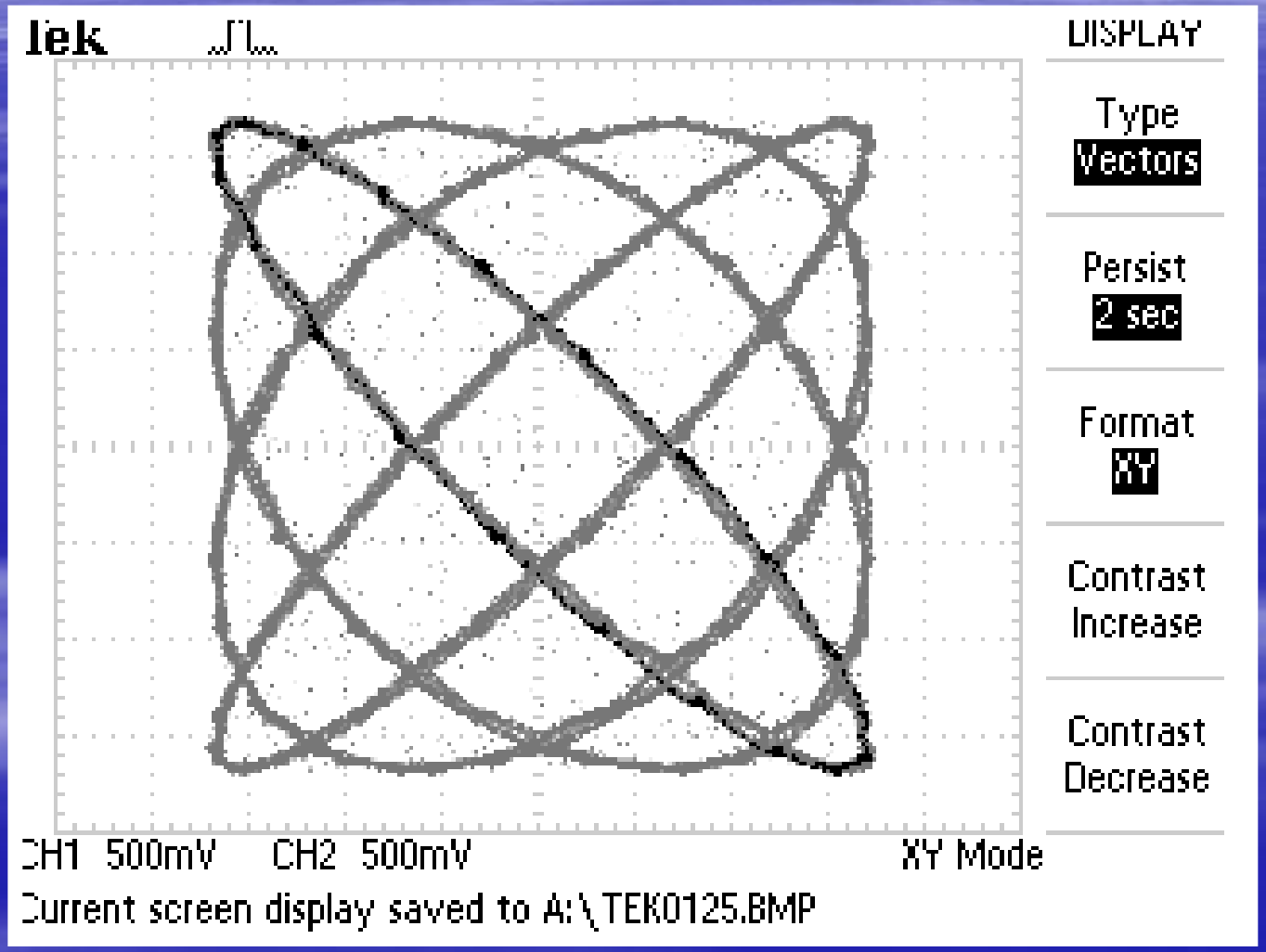
BPSK: Synchronized Local carrier vs. Transmitted Signal



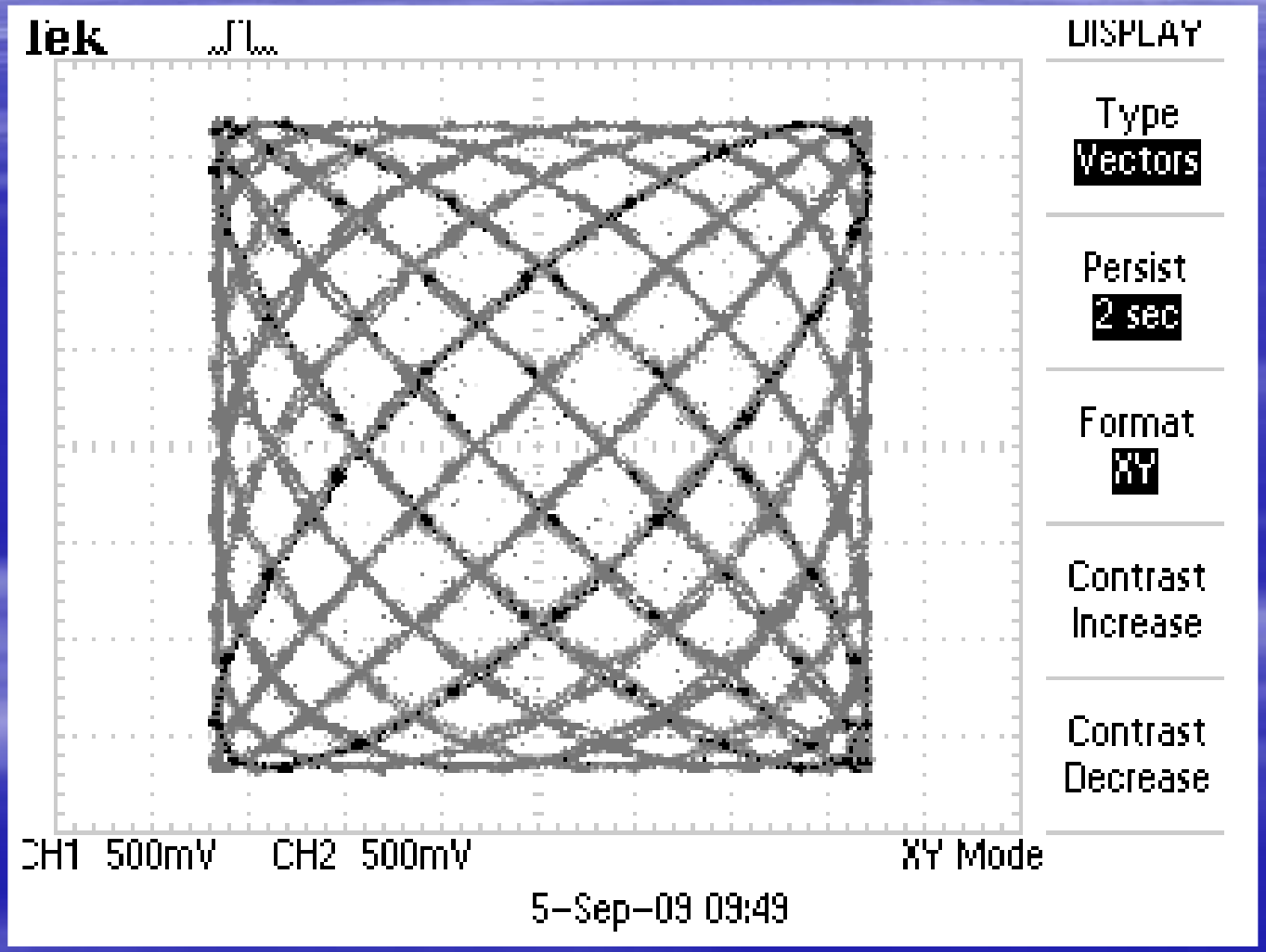
QPSK: Synchronized Local carrier vs. Transmitted Signal



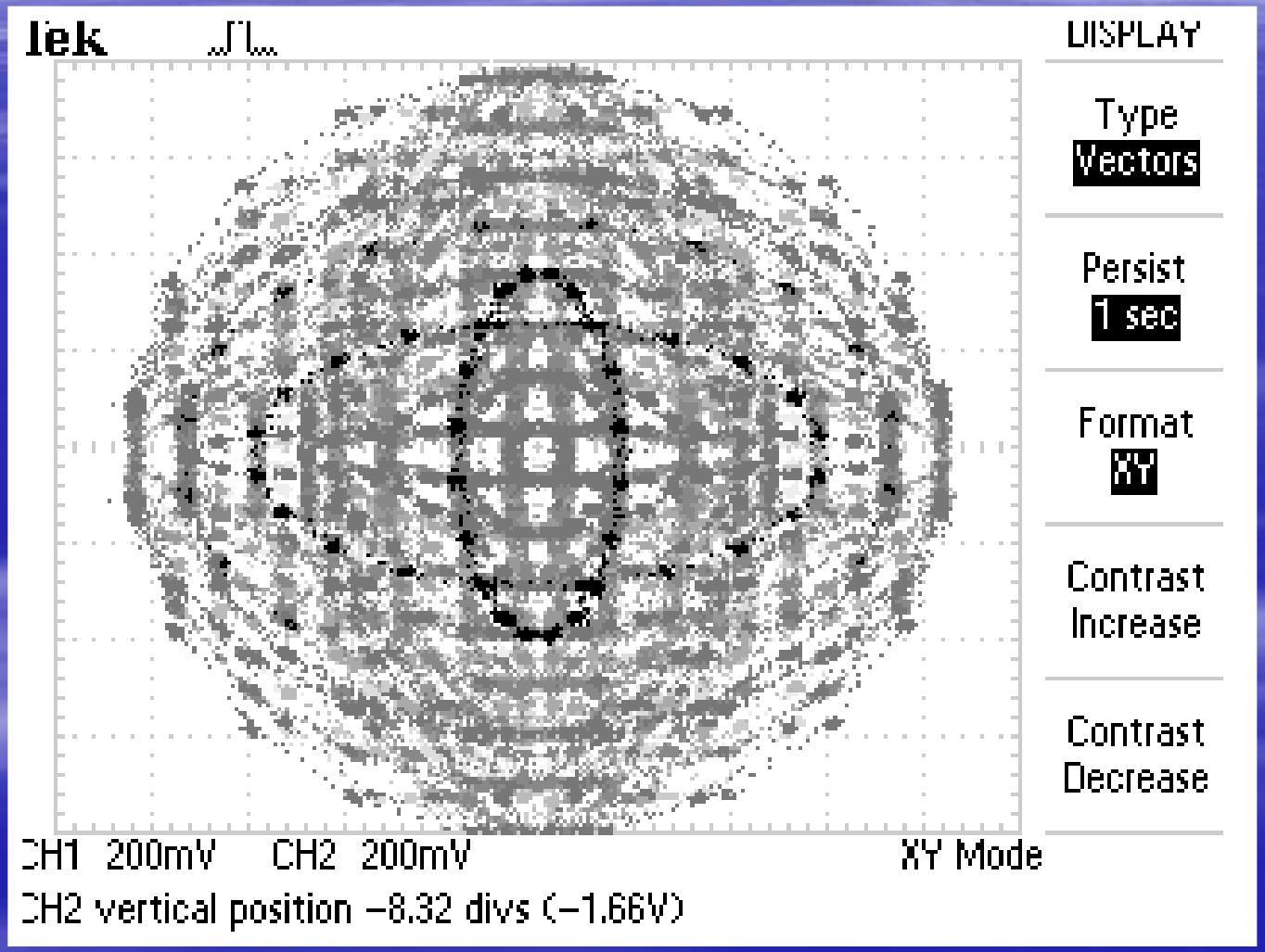
8-PSK: Synchronized Local carrier vs. Transmitted Signal



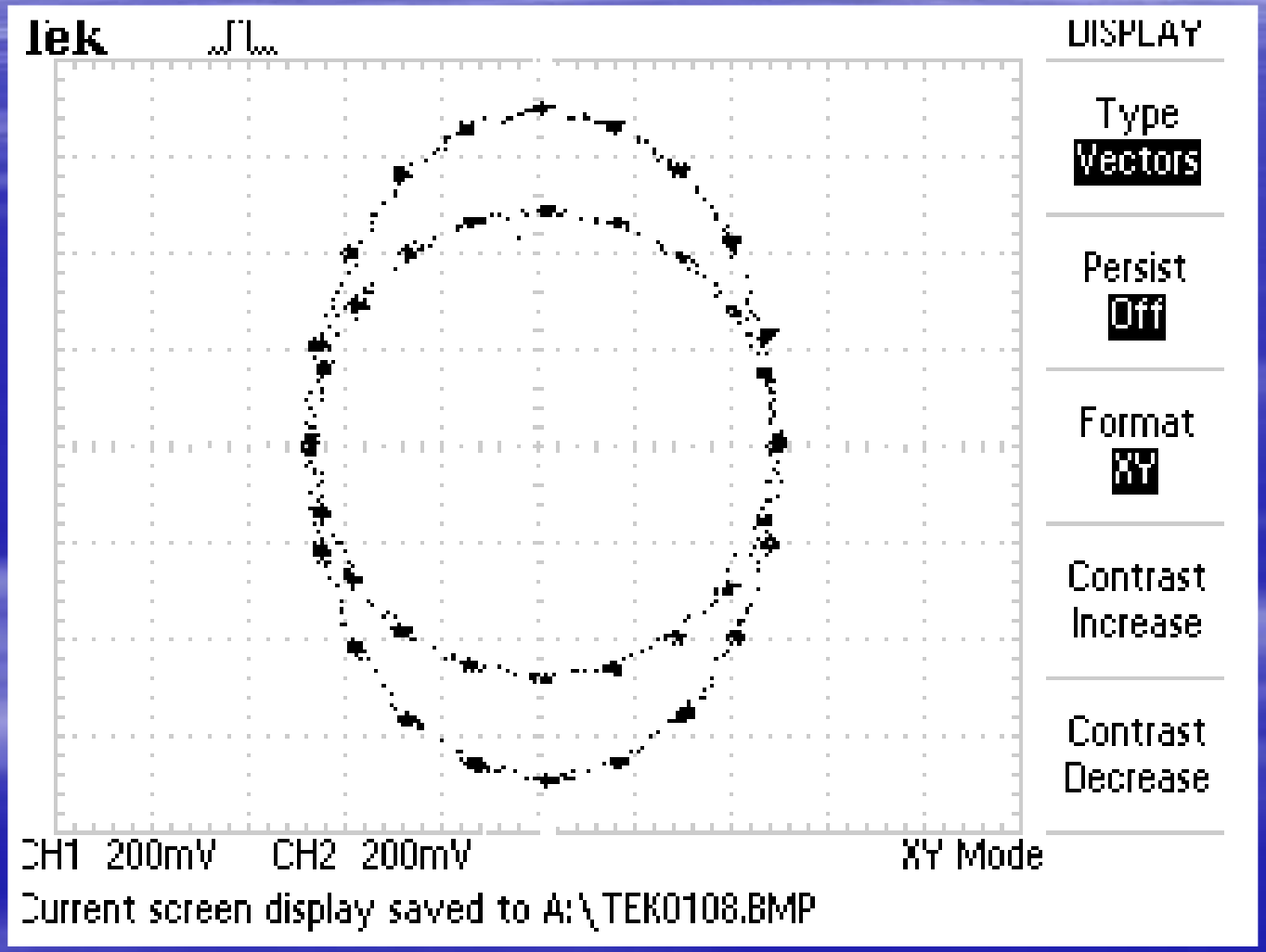
16-PSK: Synchronized Local carrier vs. Transmitted Signal



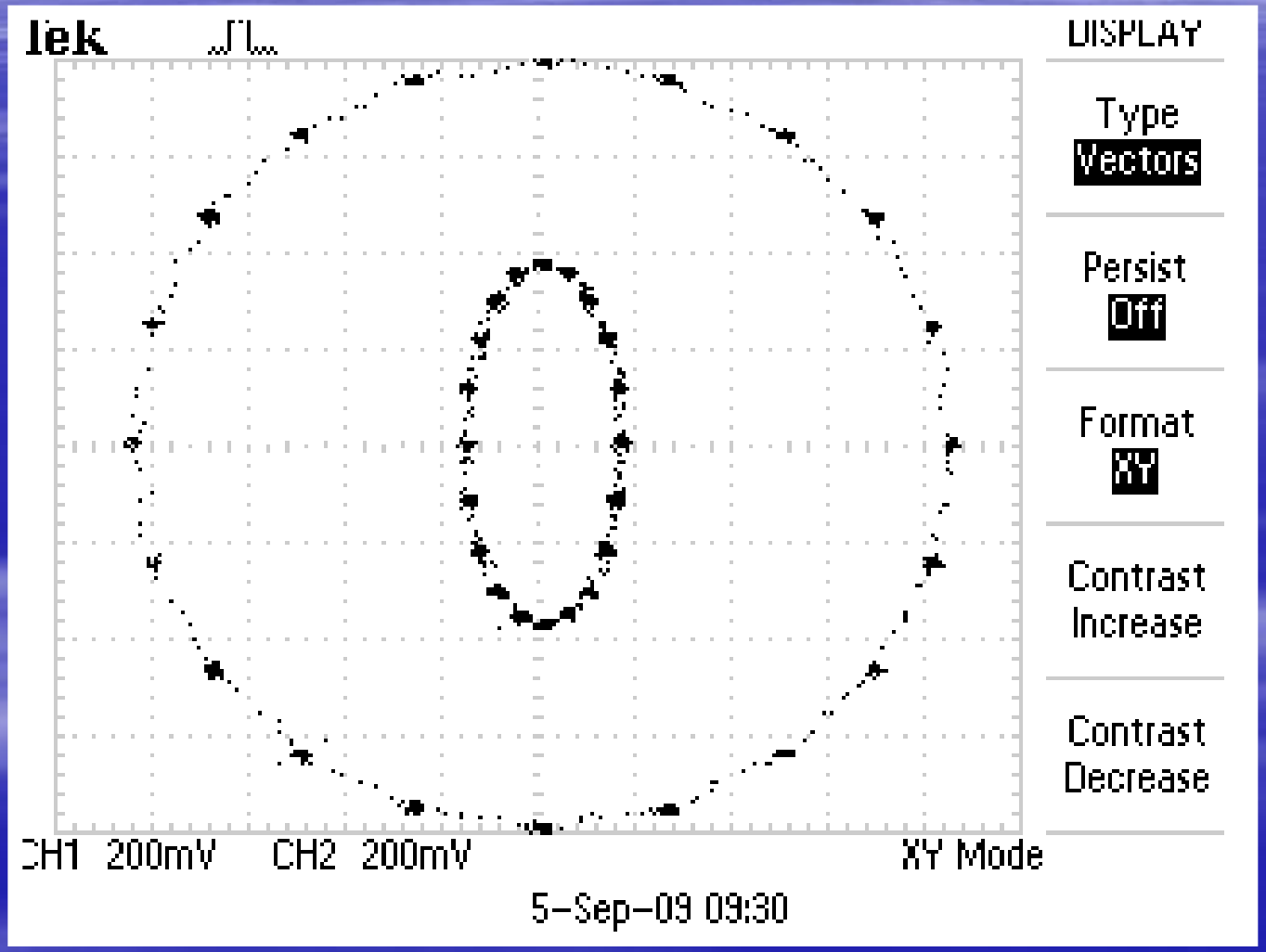
What's this?


DISPLAY
Type
Vectors
Persist
1 sec
Format
XY
Contrast
Increase
Contrast
Decrease
CH1 200mV
CH2 200mV
XY Mode
CH2 vertical position −8.32 divs (−1.66V)

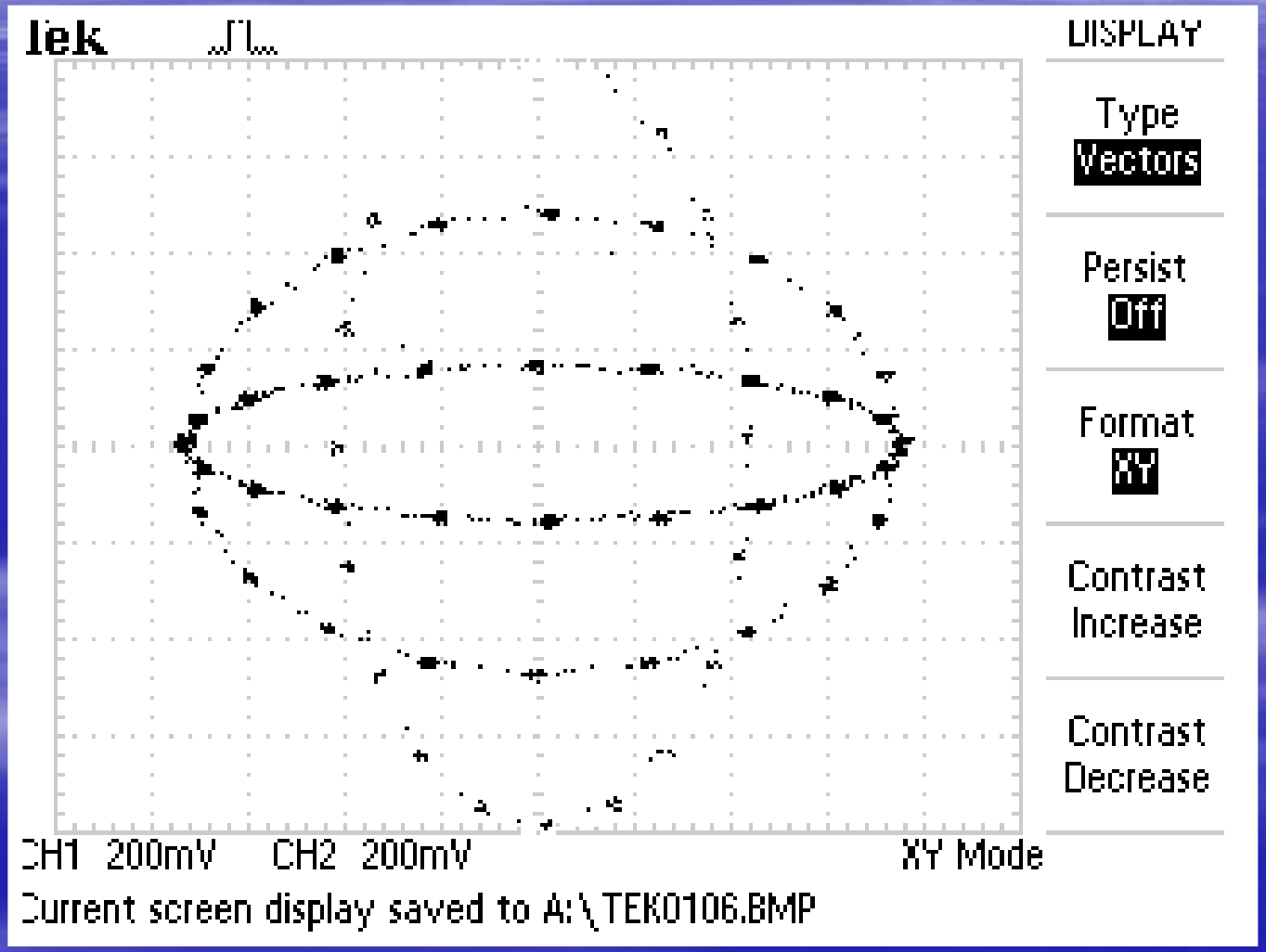
256-QAM X-Y graph of I and Q arms in Transmitter



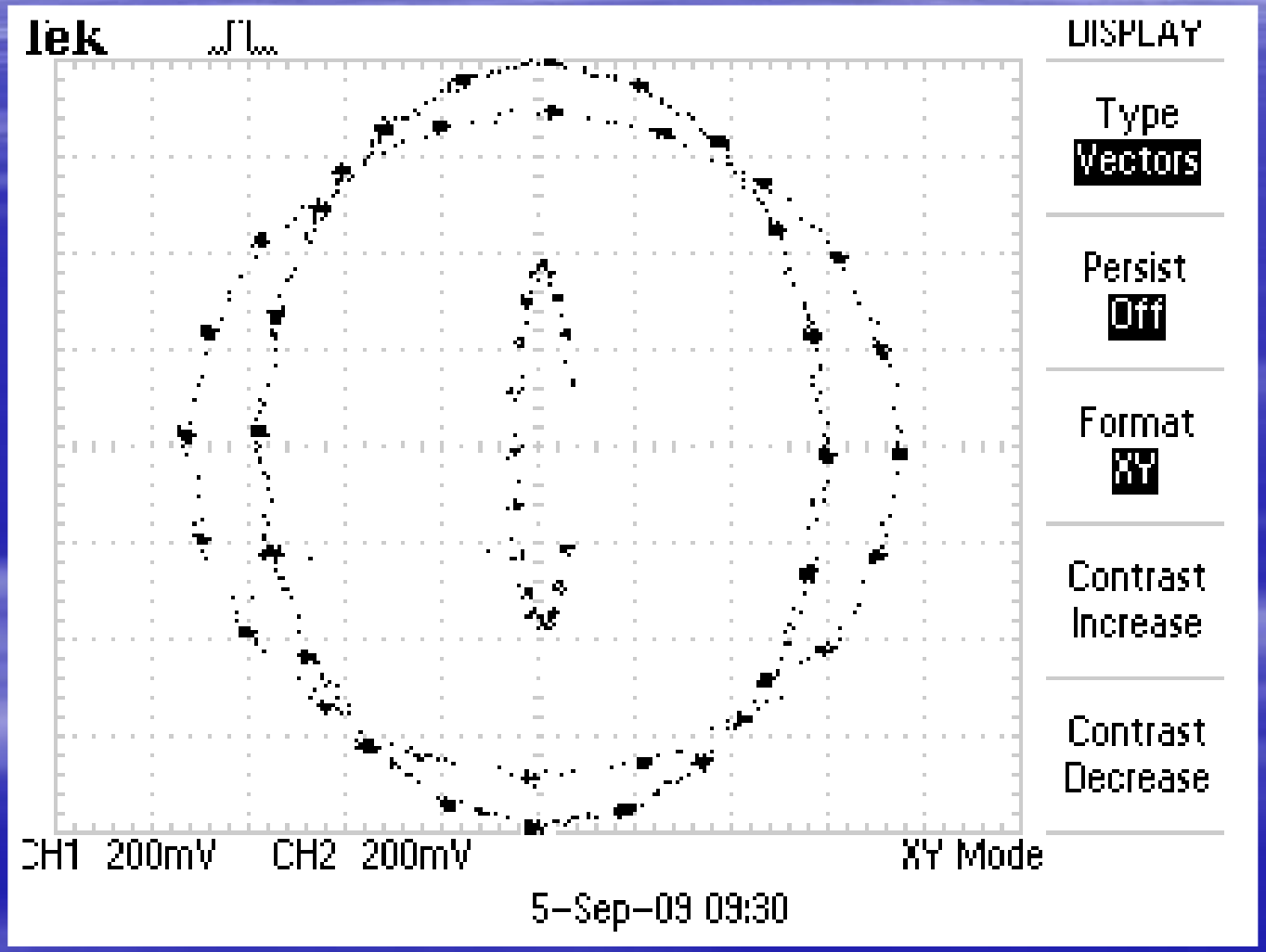
256-QAM X-Y graph of I and Q arms in Transmitter



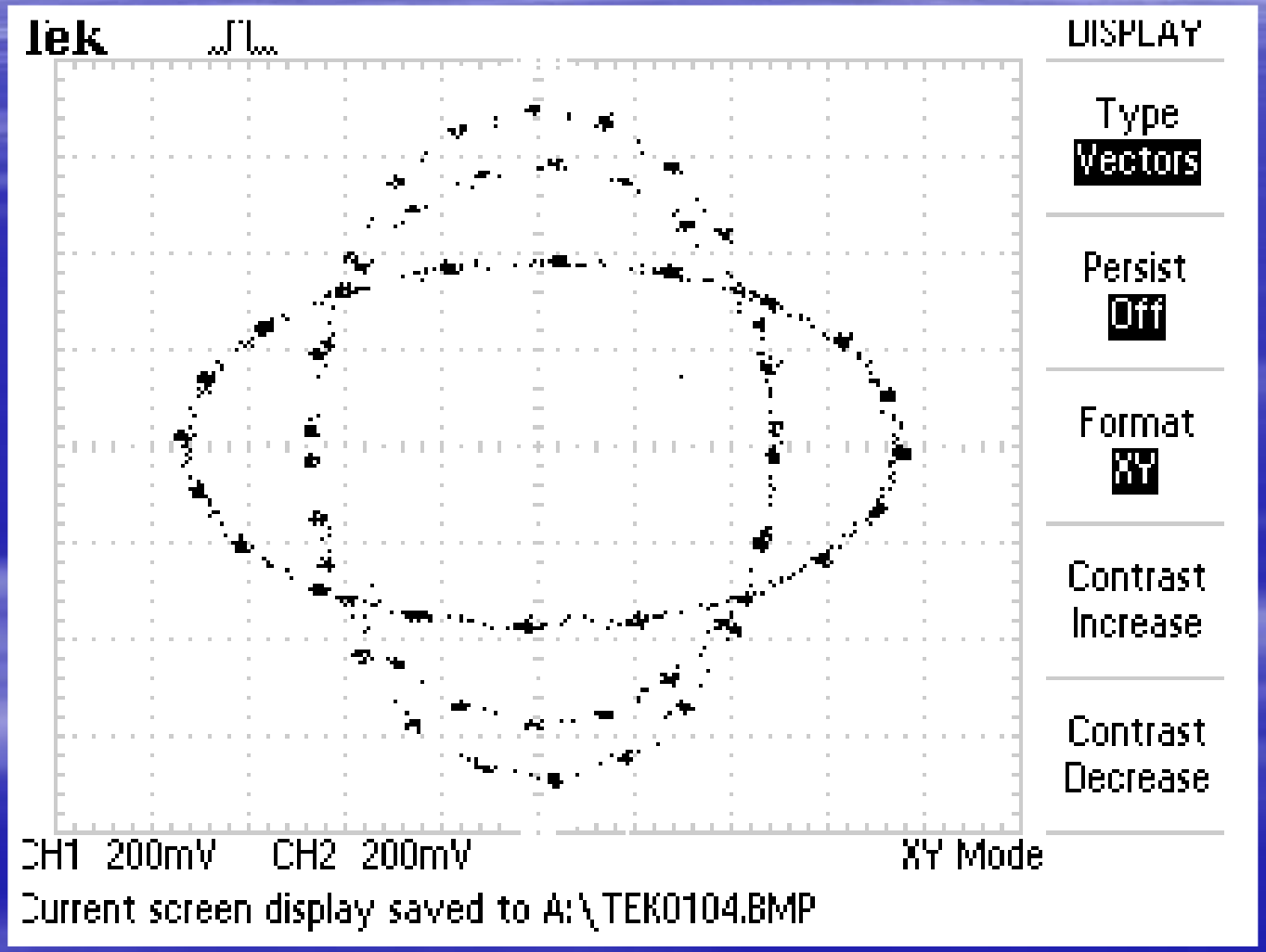
256-QAM X-Y graph of I and Q arms in Transmitter



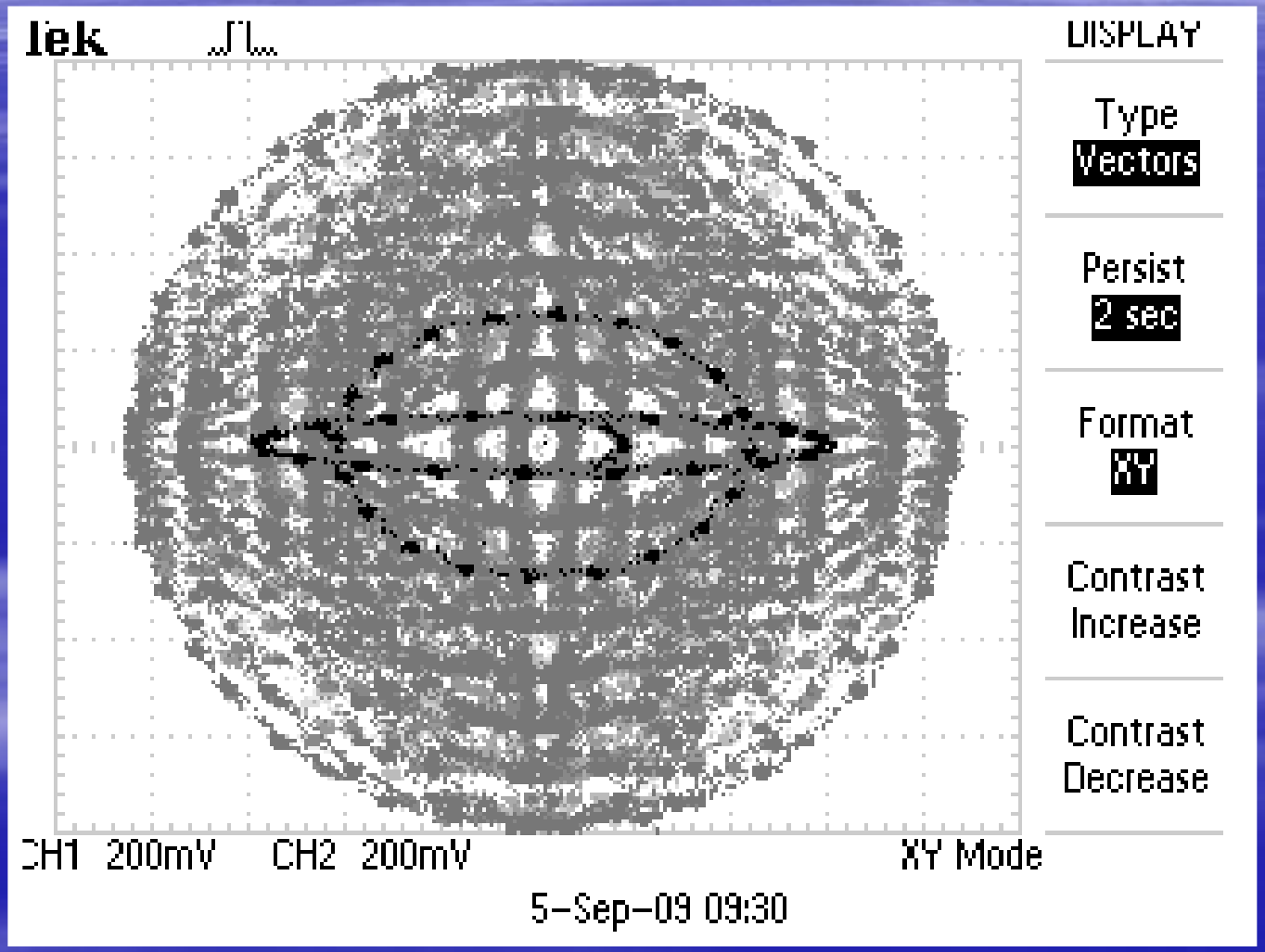
256-QAM X-Y graph of I and Q arms in Transmitter



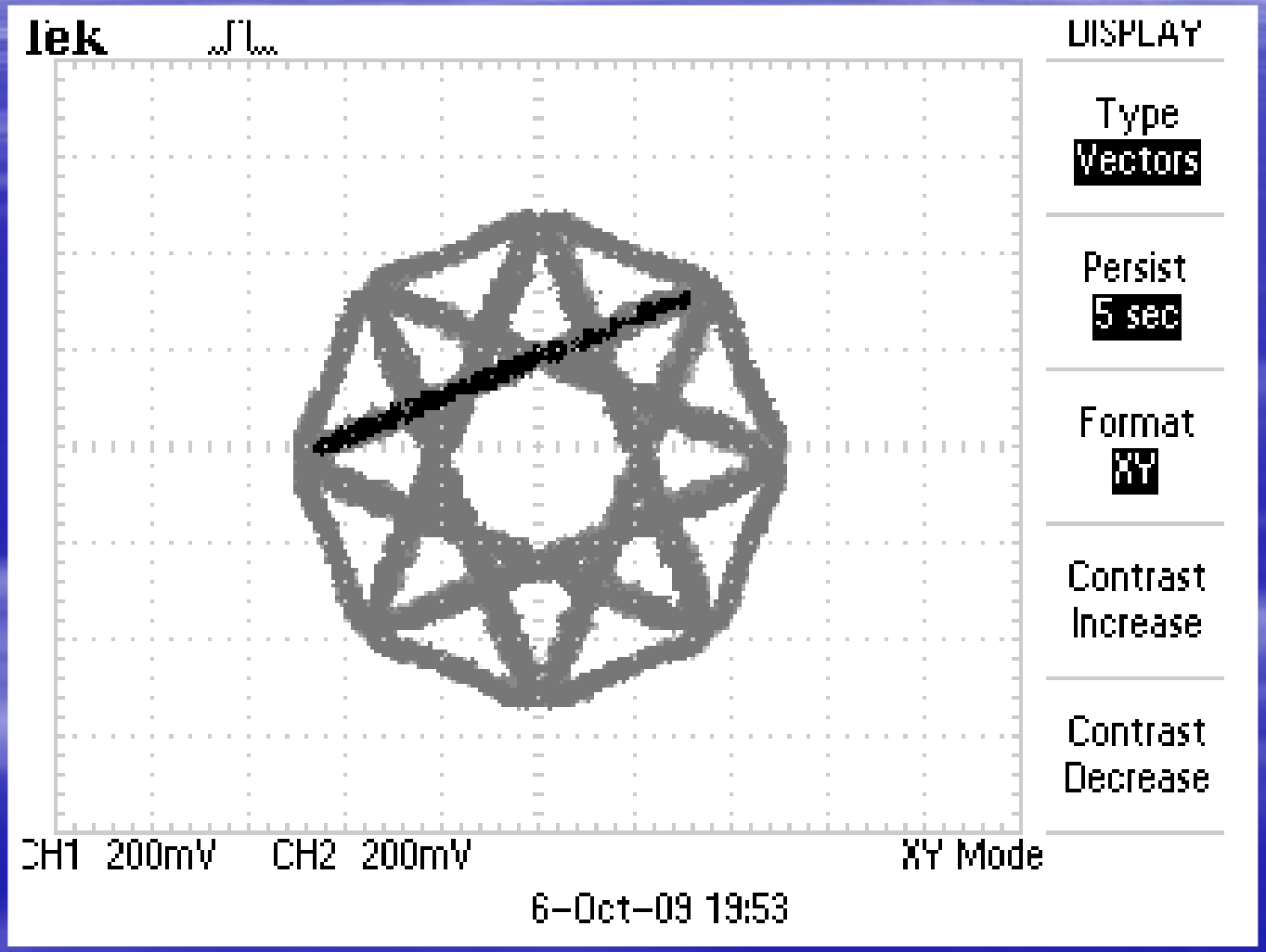
256-QAM X-Y graph of I and Q arms in Transmitter



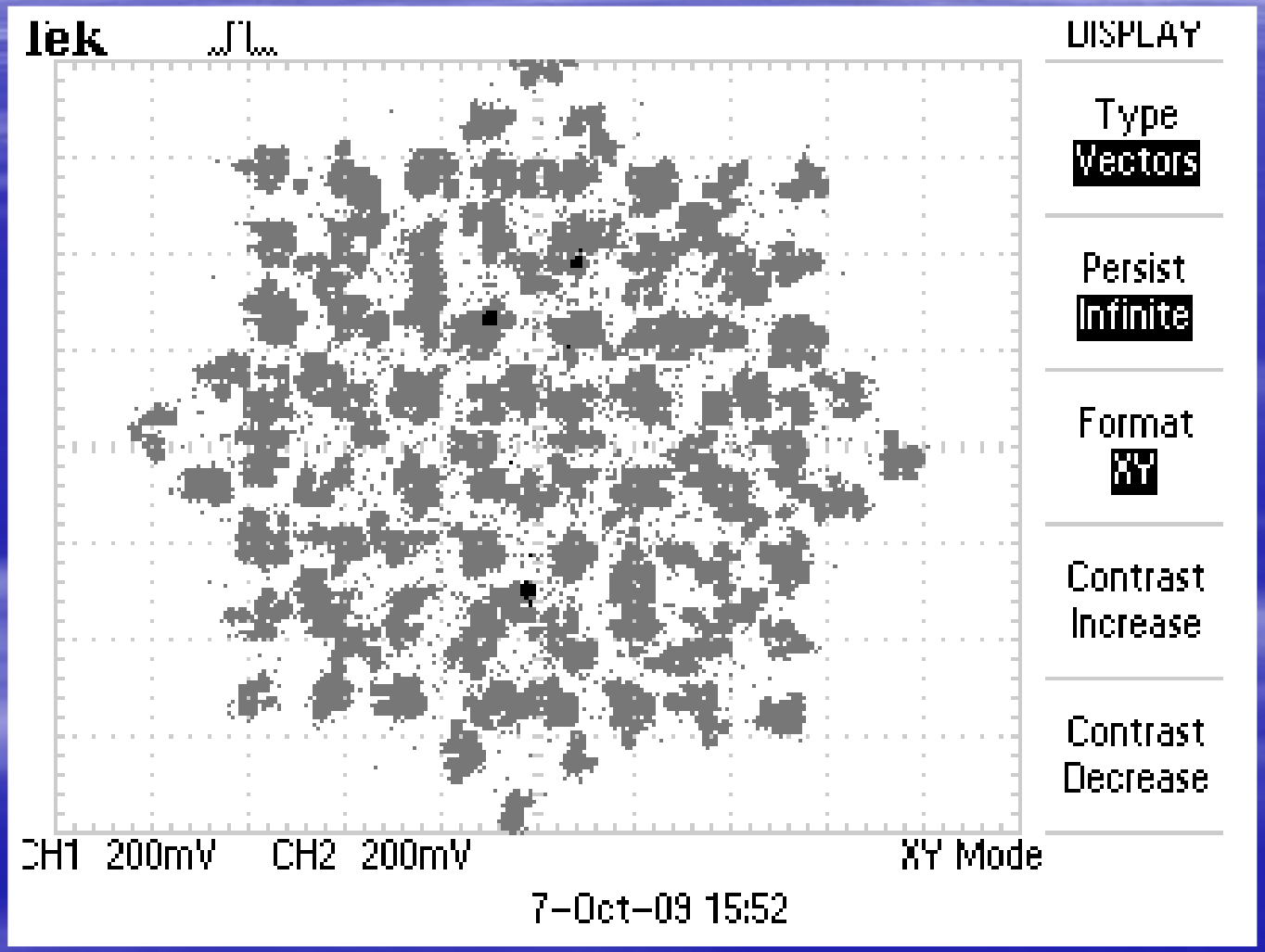
256-QAM X-Y graph of I and Q arms in Transmitter - Overlay



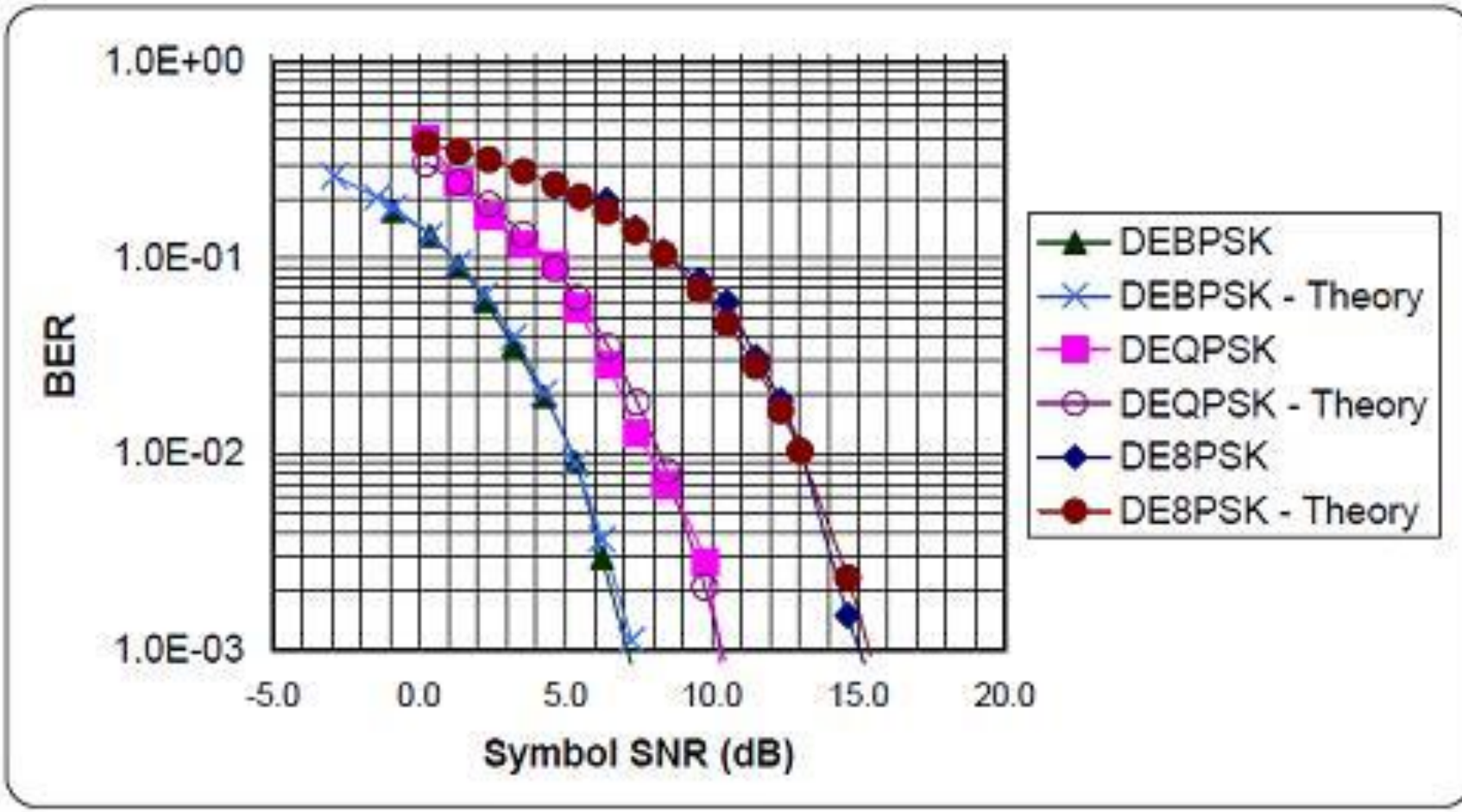
pi/4-QPSK reception



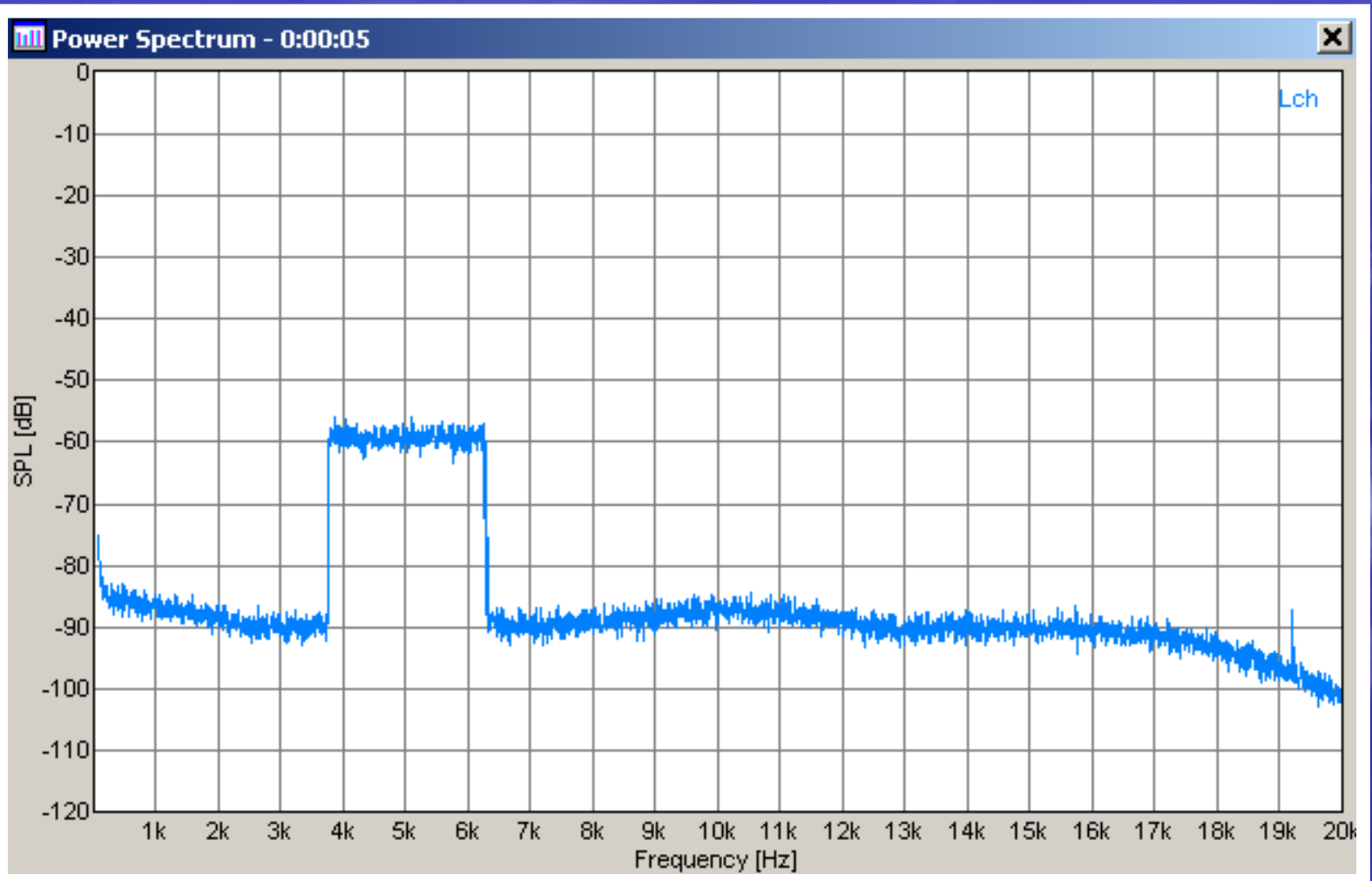
pi/4-QAM-64 reception



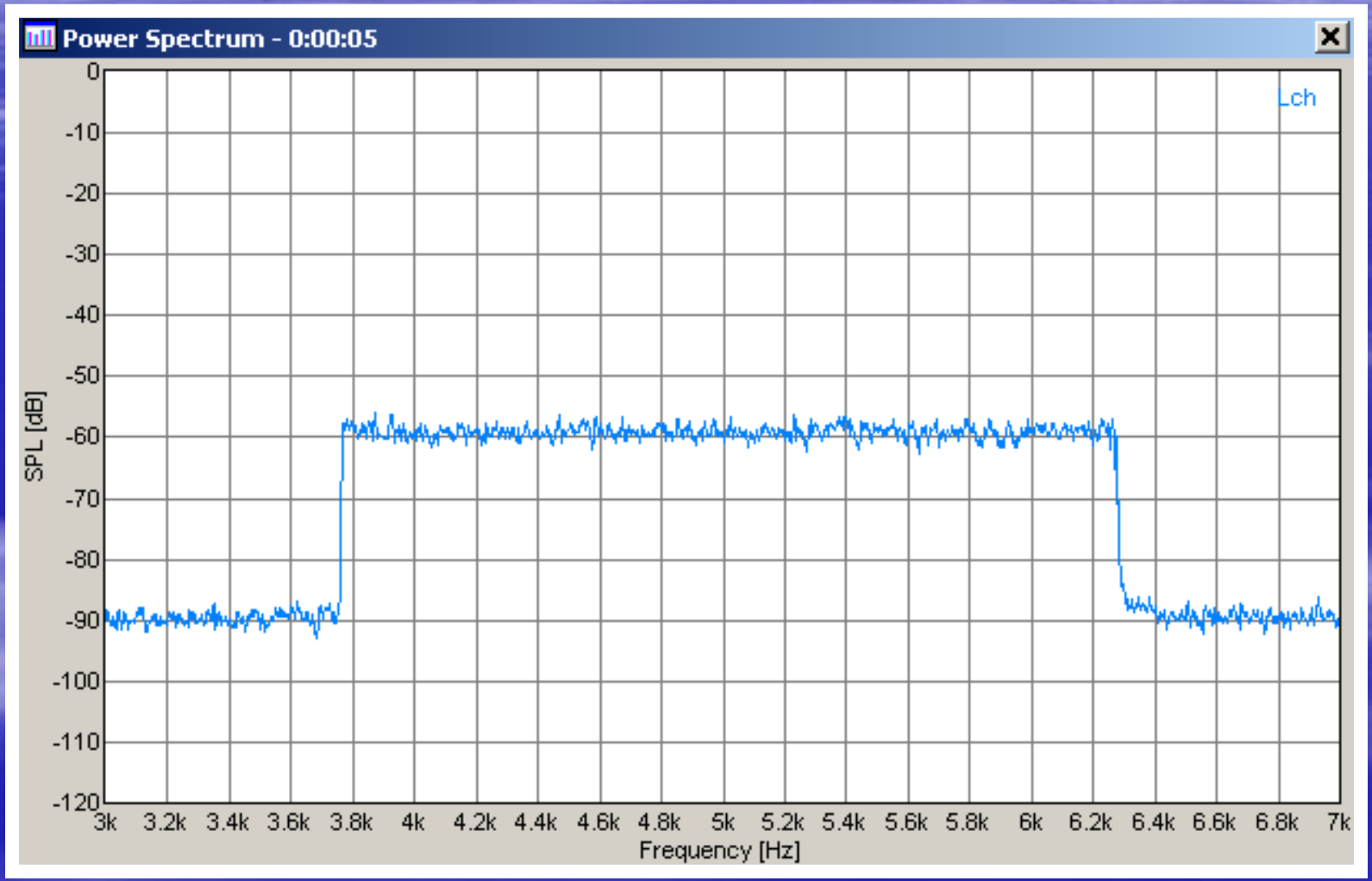
BER Measurements



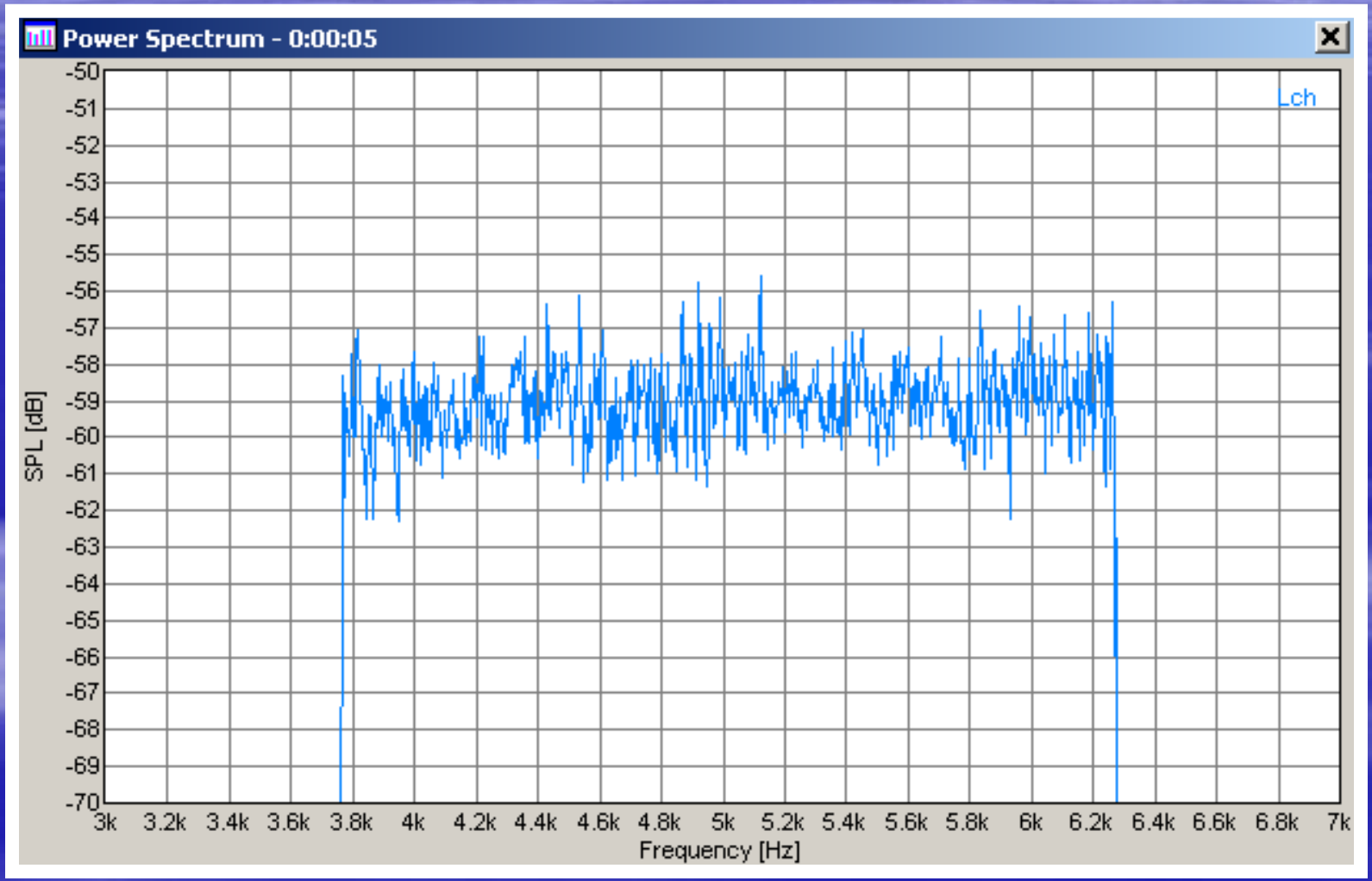
Bandpass Noise Generation For Channel Emulation



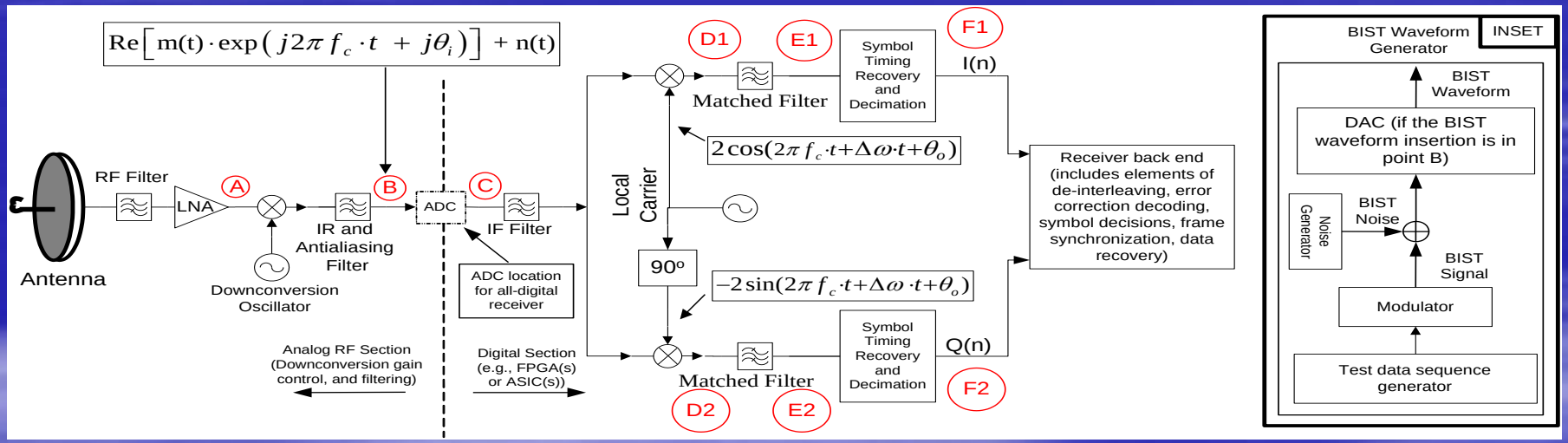
Bandpass Noise Generation (zoom in frequency)



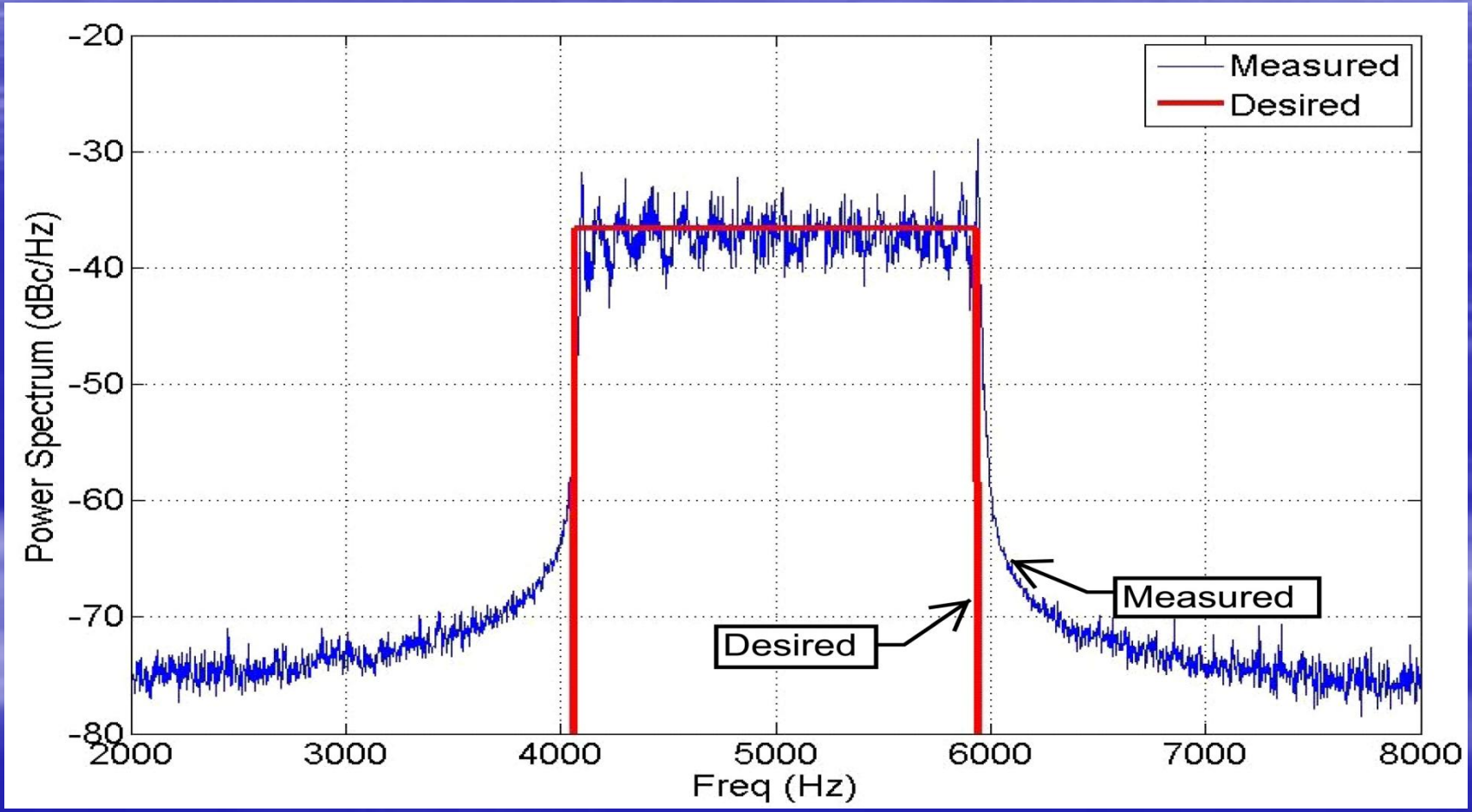
Bandpass Noise Generation (zoom in frequency and in amplitude)



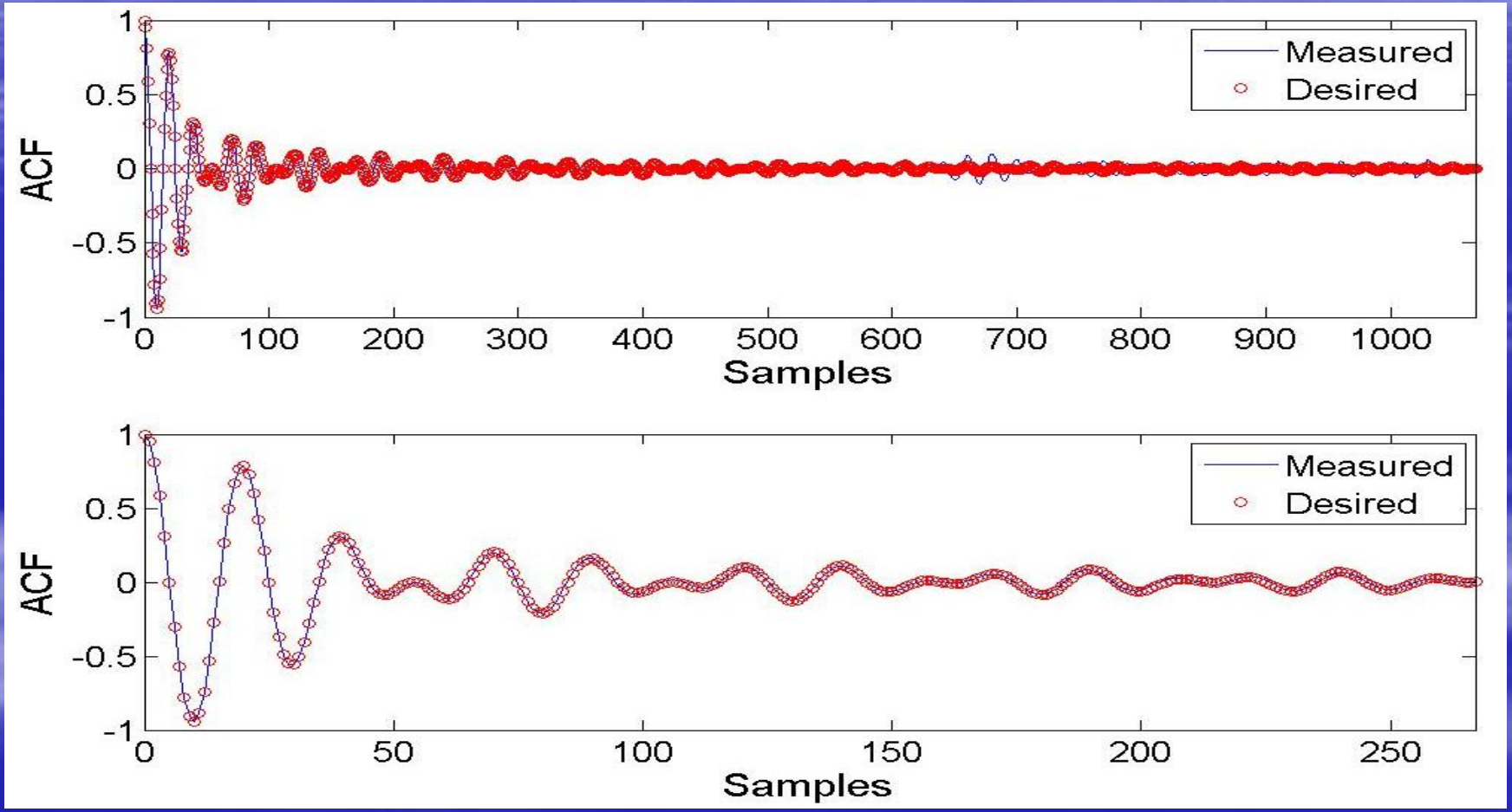
BIST – Where to insert the test signal



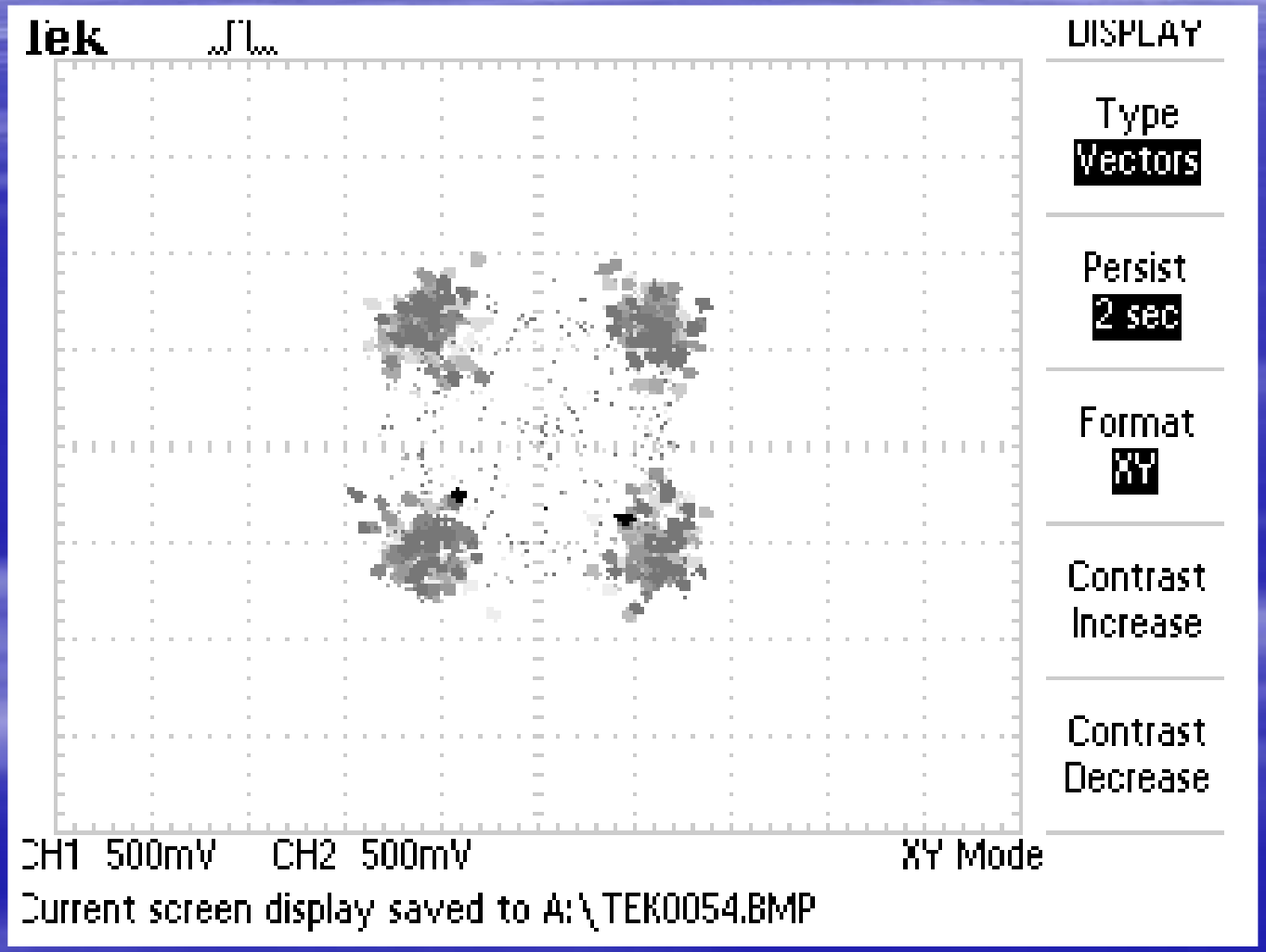
Noise Spectrum: Measured Vs. Desired, p=534



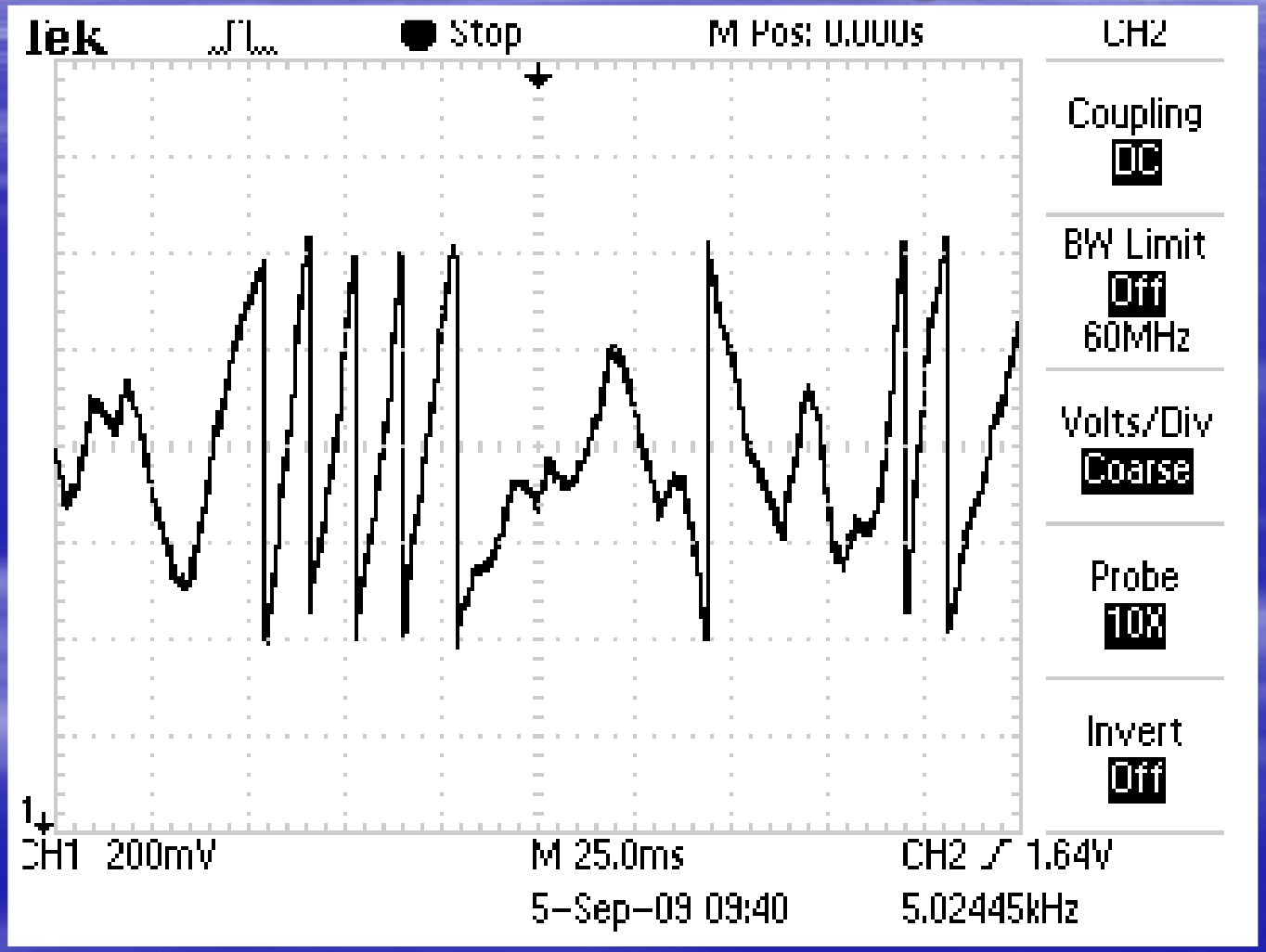
ACF function, measure vs. desired, p=534



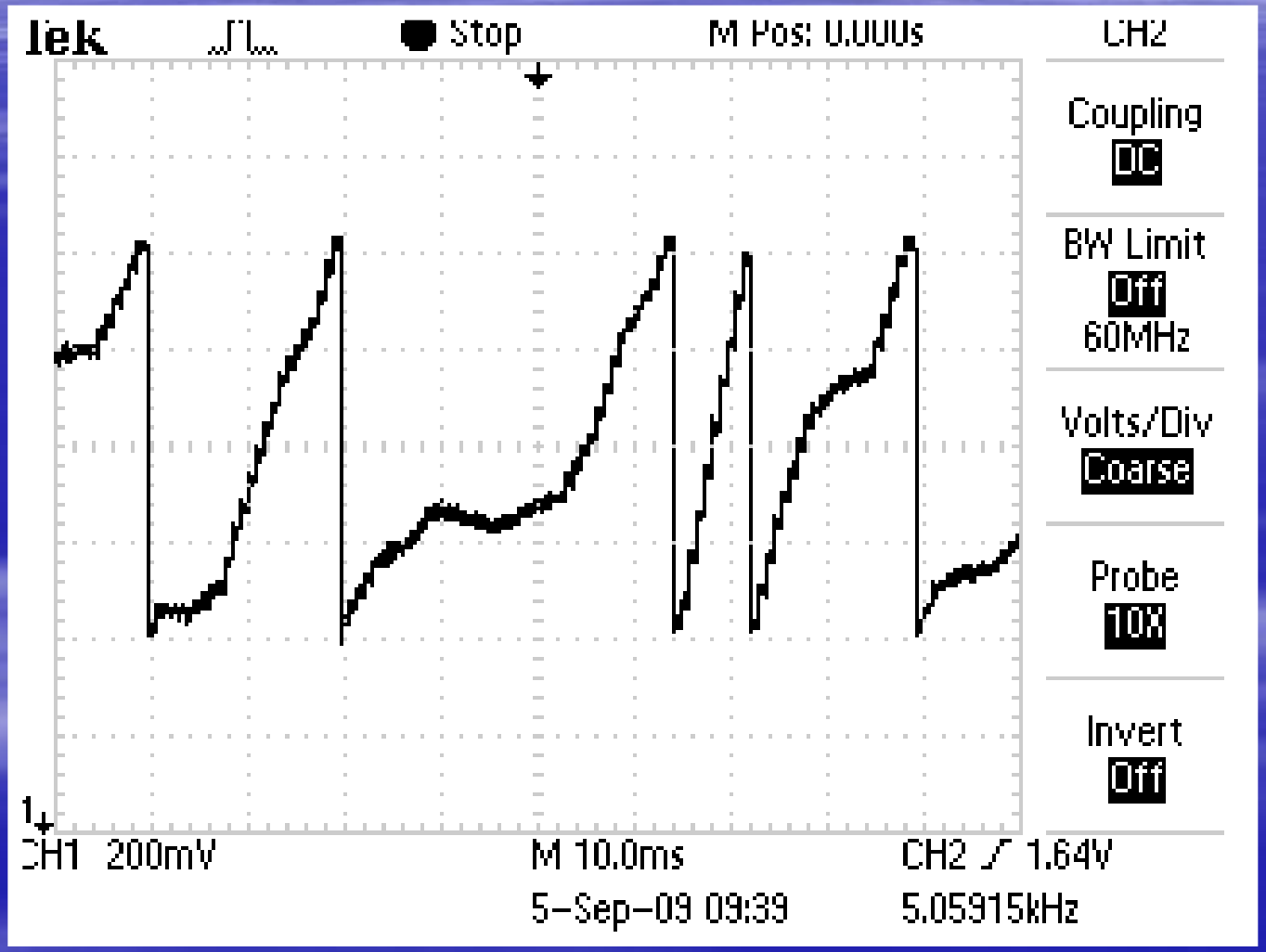
QPSK – at output of receiver, SNR = 12 dB, 1 sample/symbol



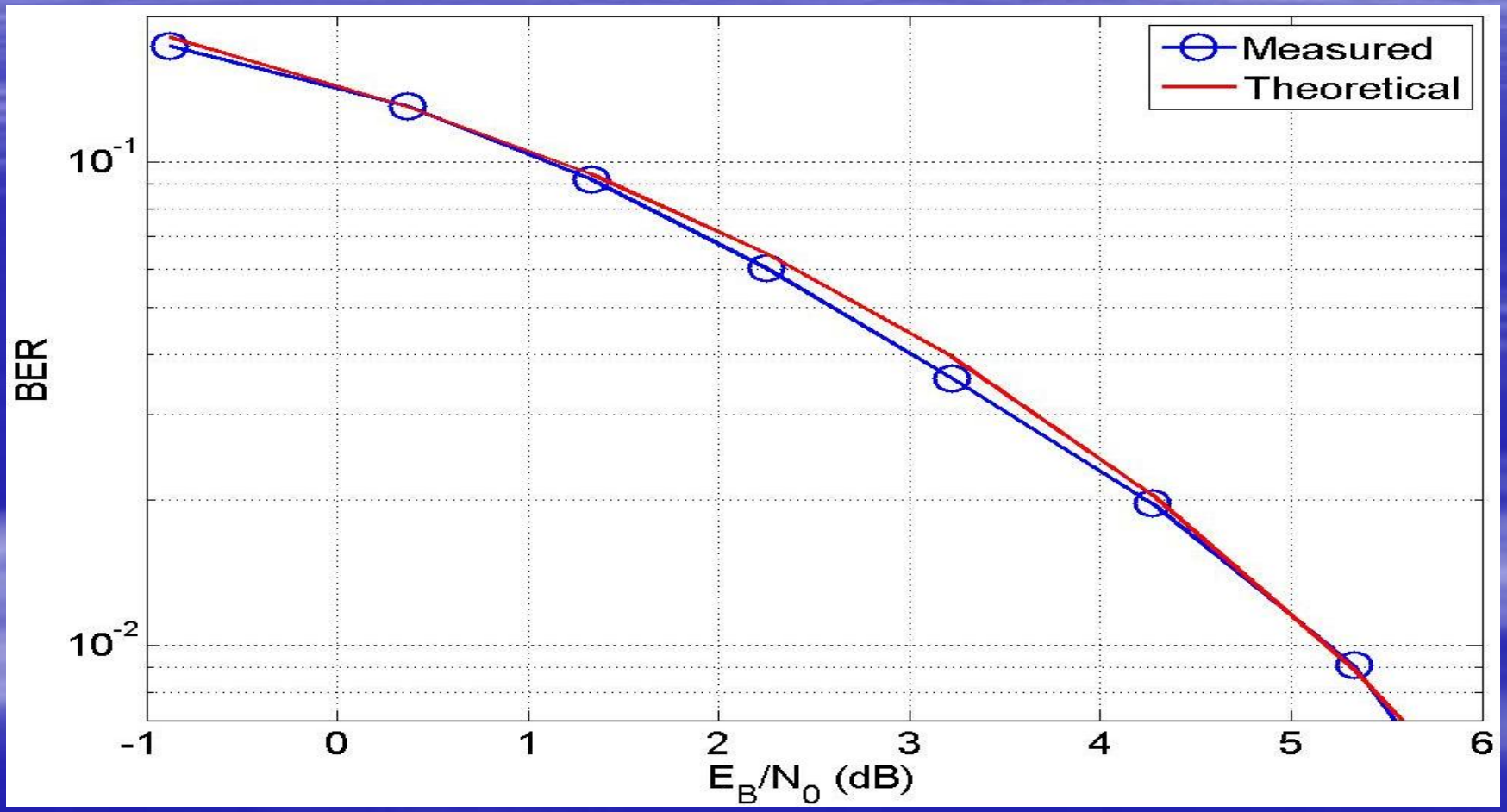
Interpolation mu vs. time for 10x oversampling



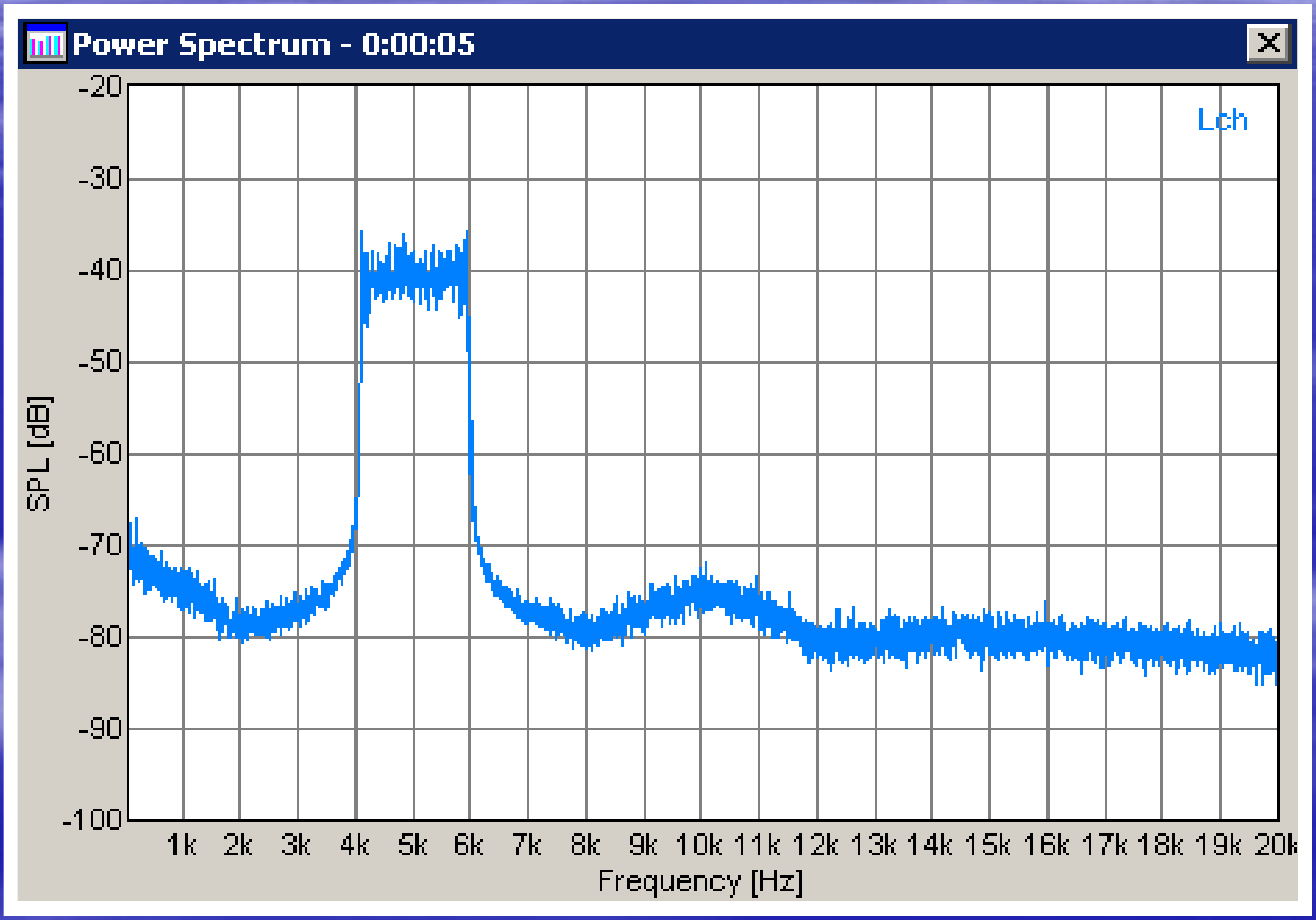
Interpolation mu vs. time for 10x oversampling - zoom



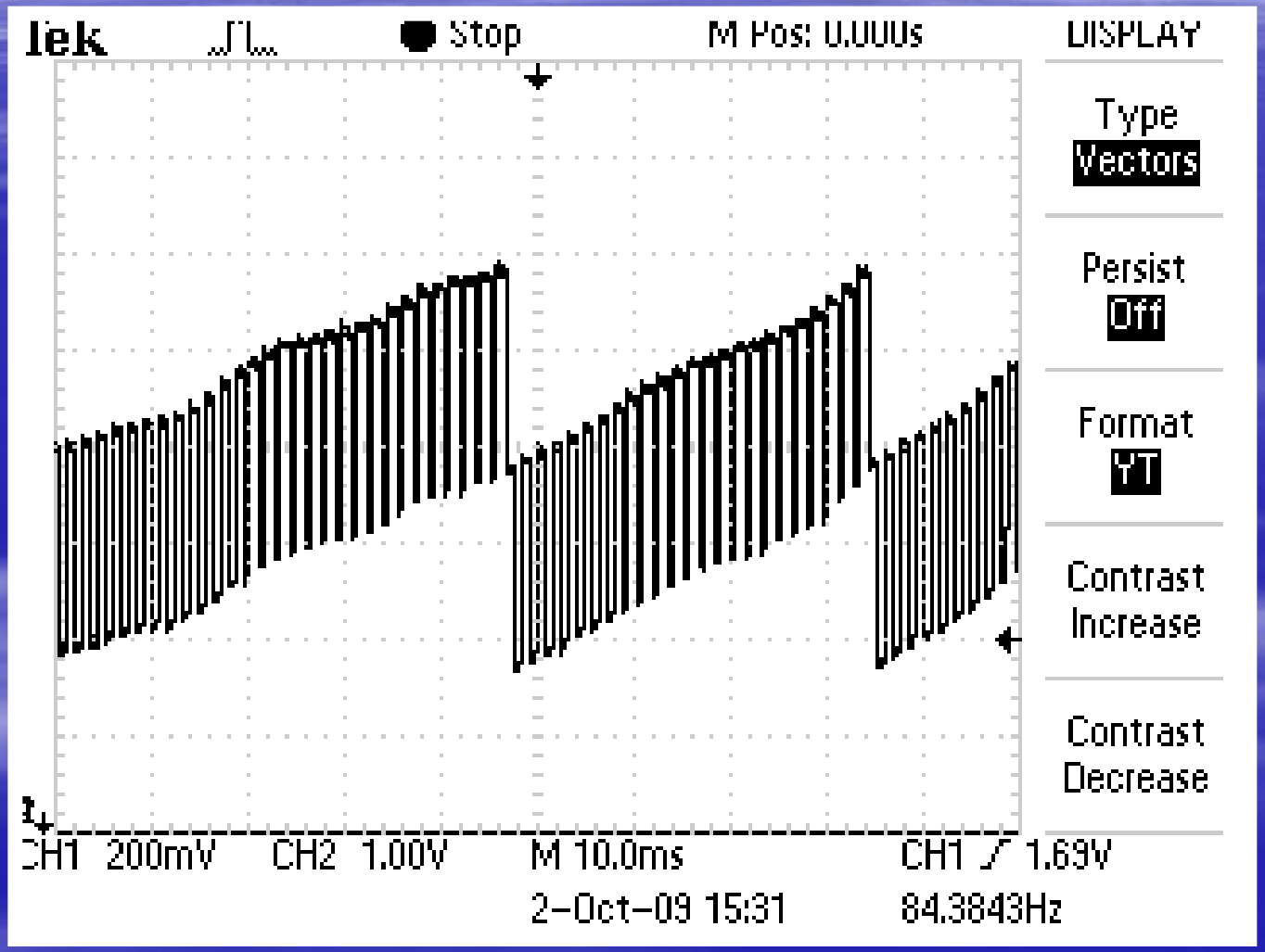
BER laboratory measurements for DEBPSK



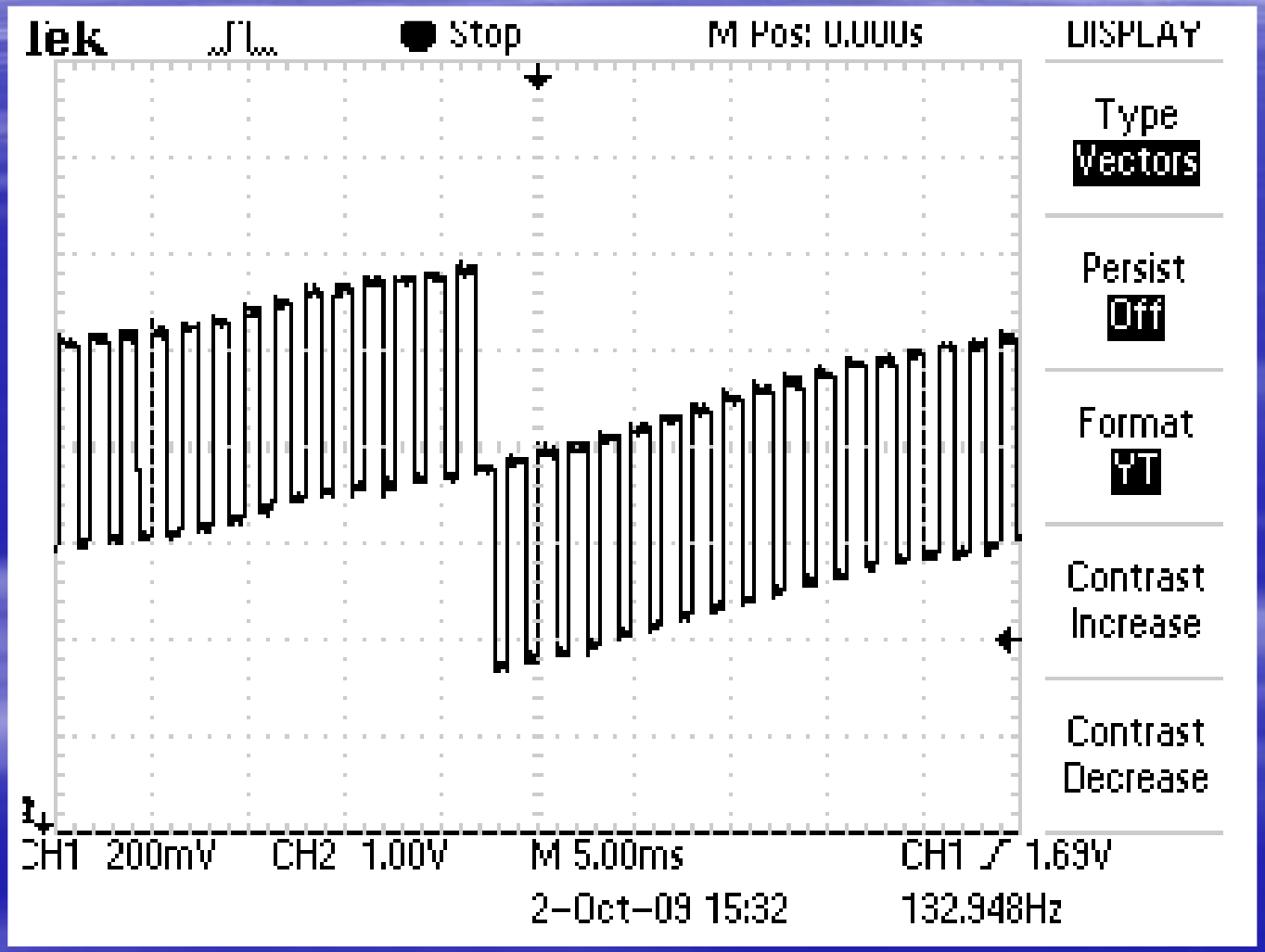
Noise Spectrum around 5 KHz, new Gaussian noise generation method



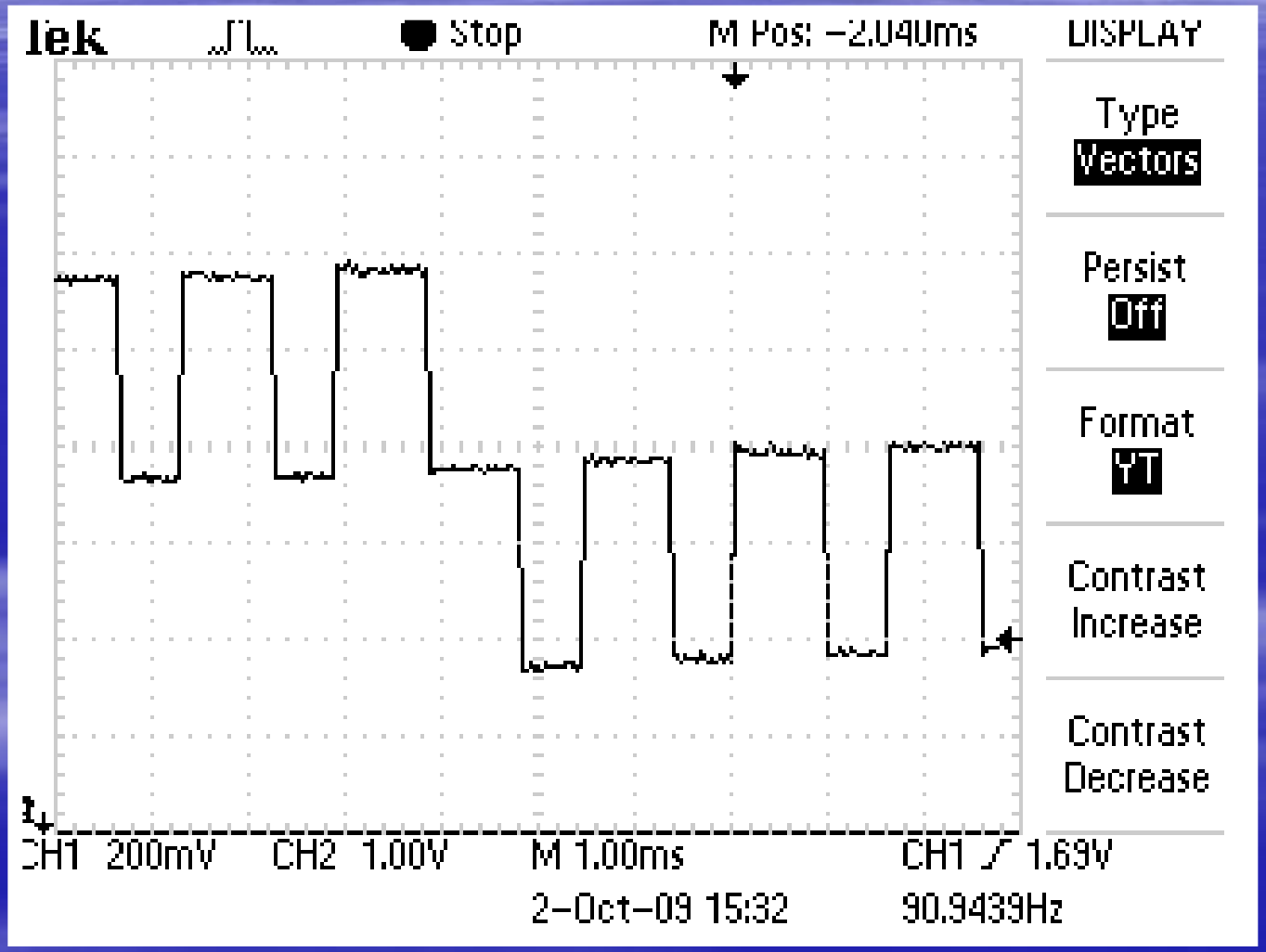
Interpolation mu variable behavior



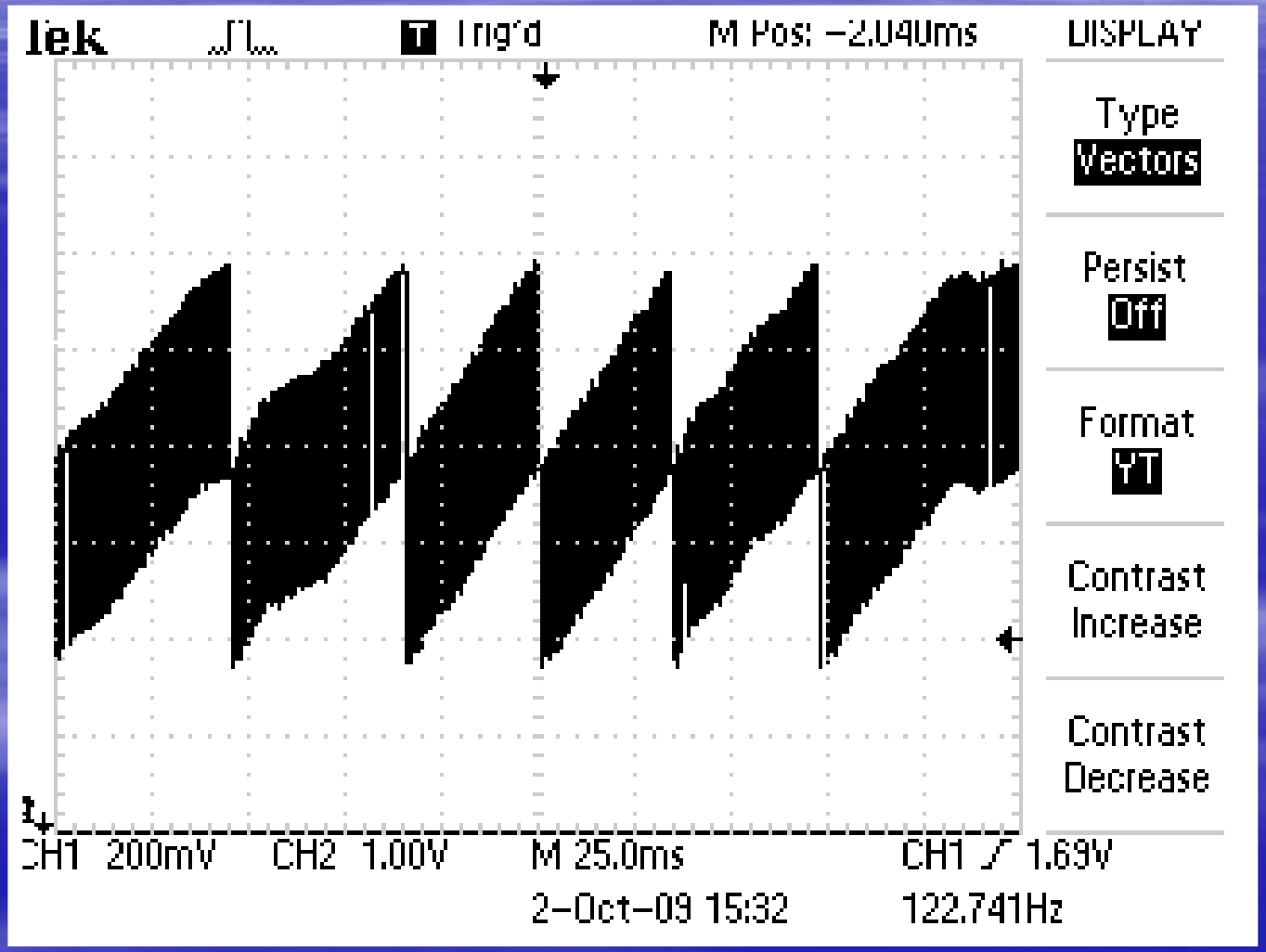
Interpolation mu variable behavior



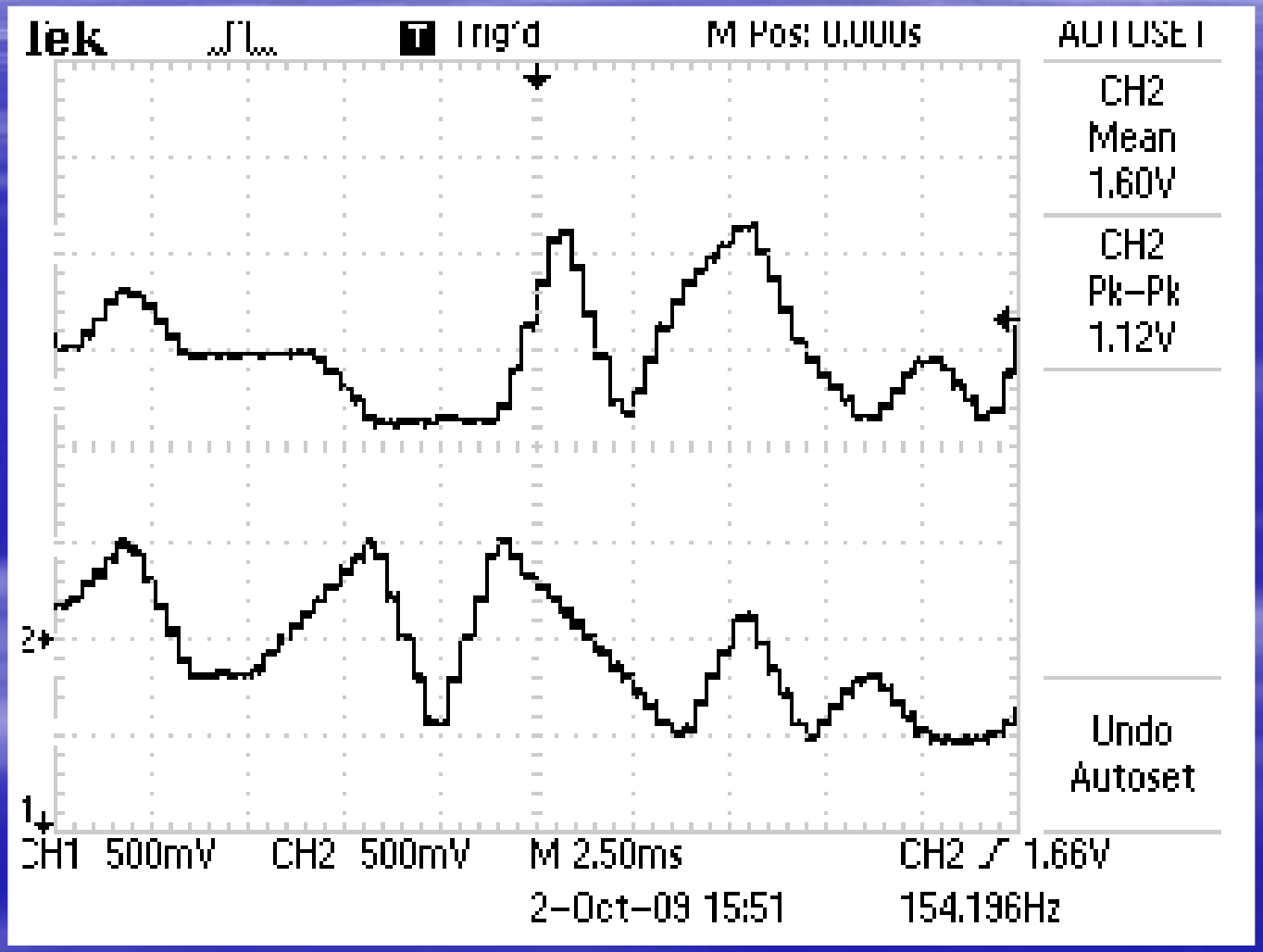
Interpolation mu variable behavior



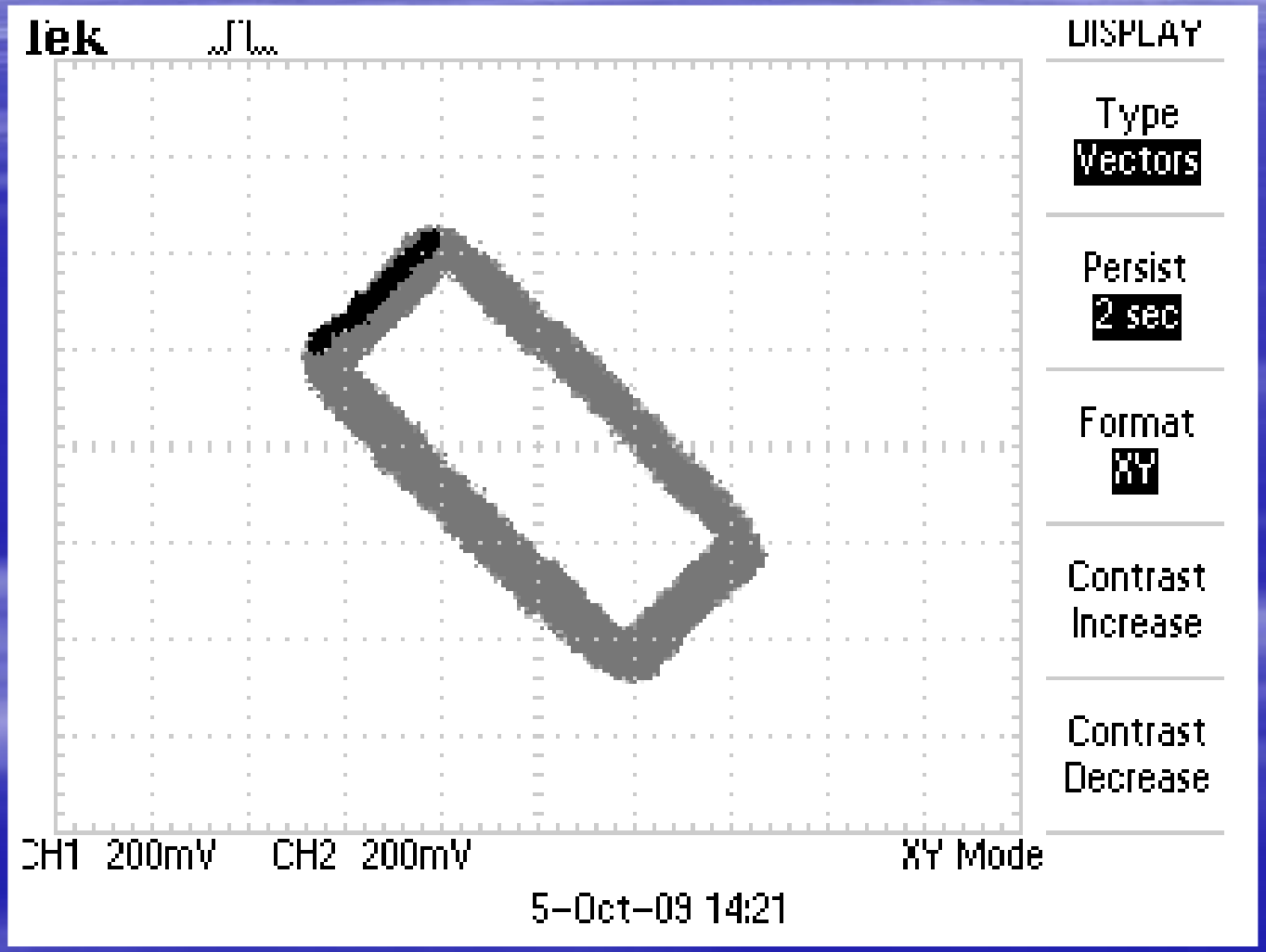
Interpolation mu variable behavior



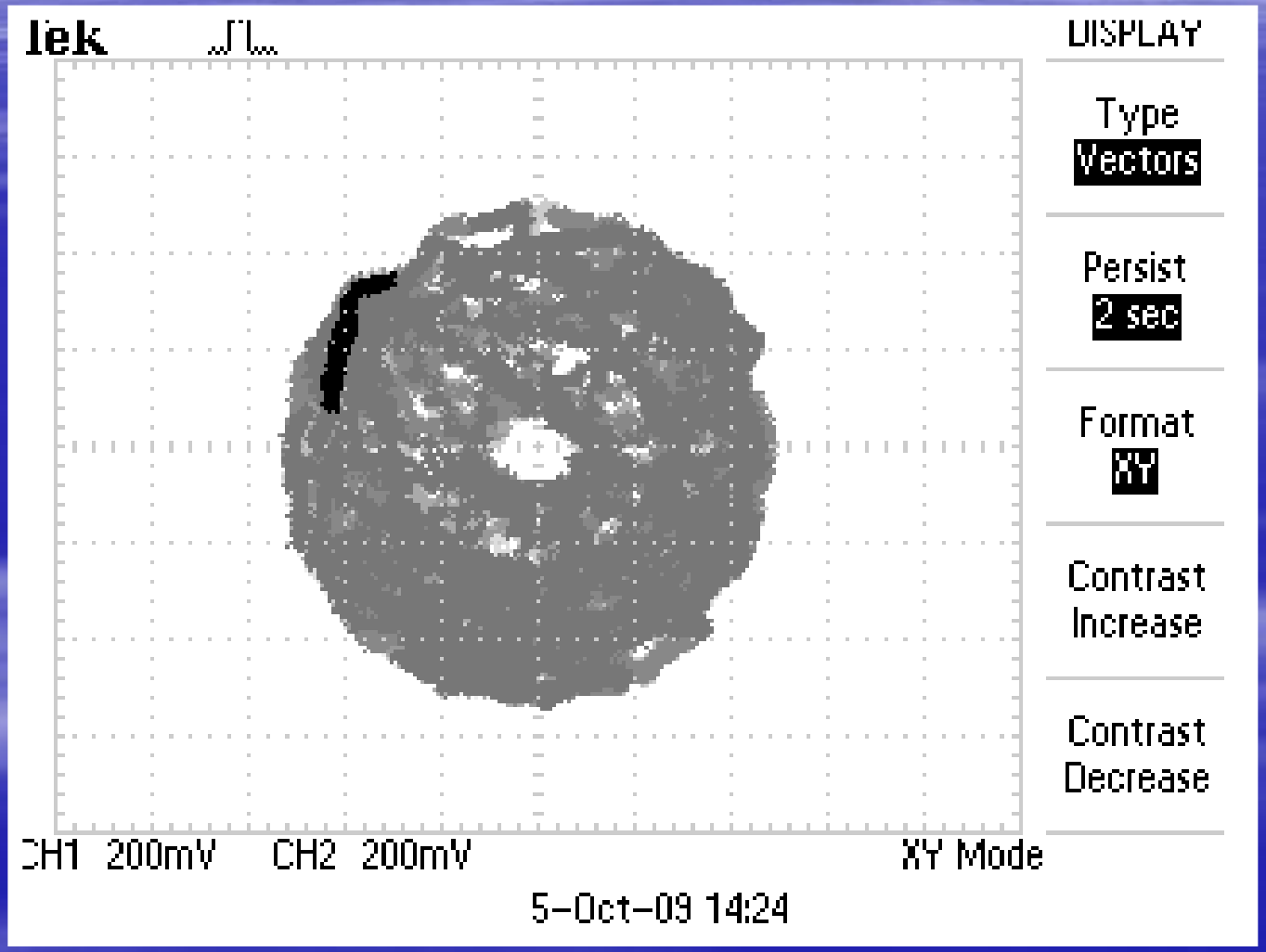
QAM-256 after matched filter and downsampling to 5 samples/symbol



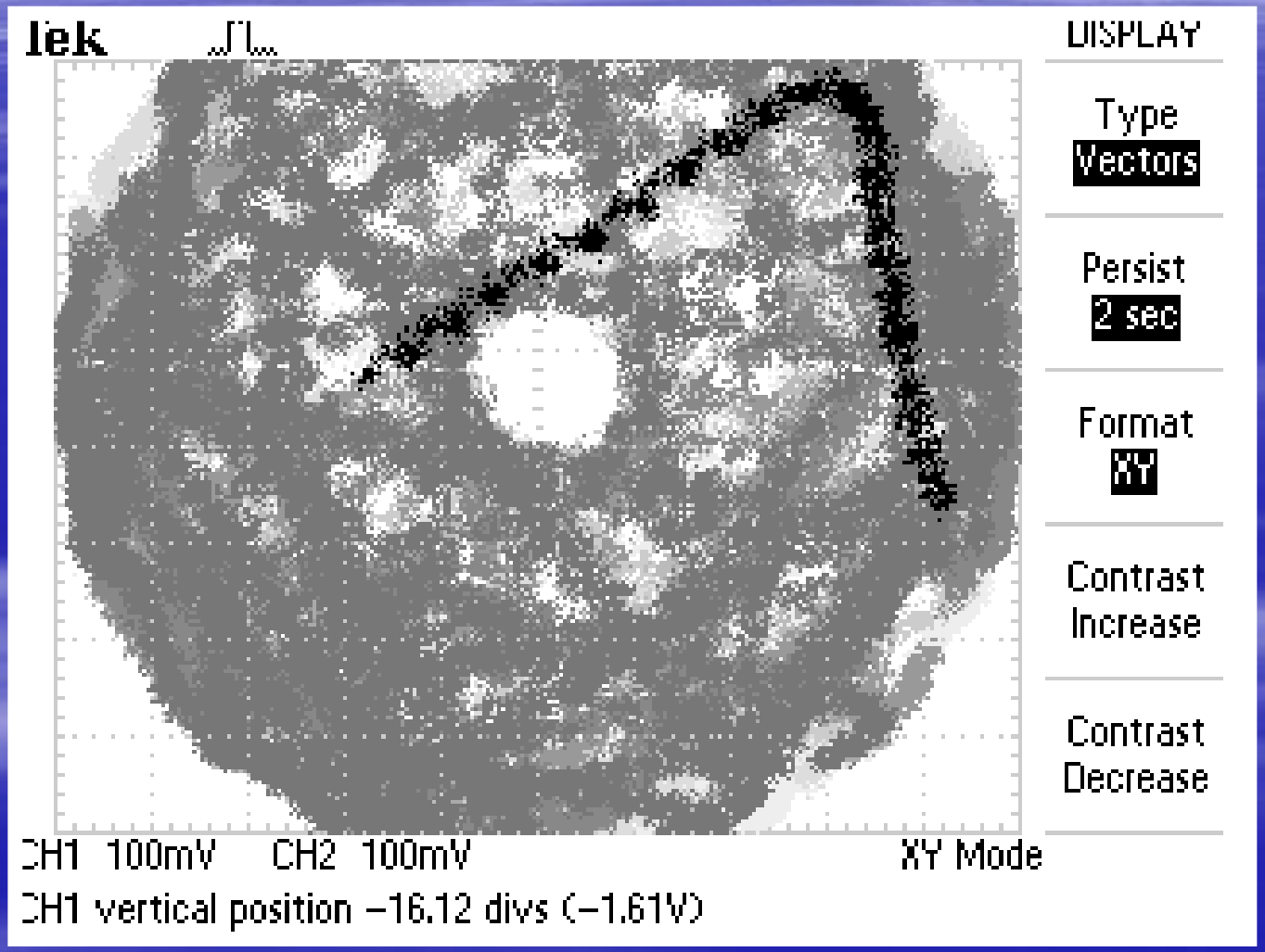
pi/4-BPSK reception



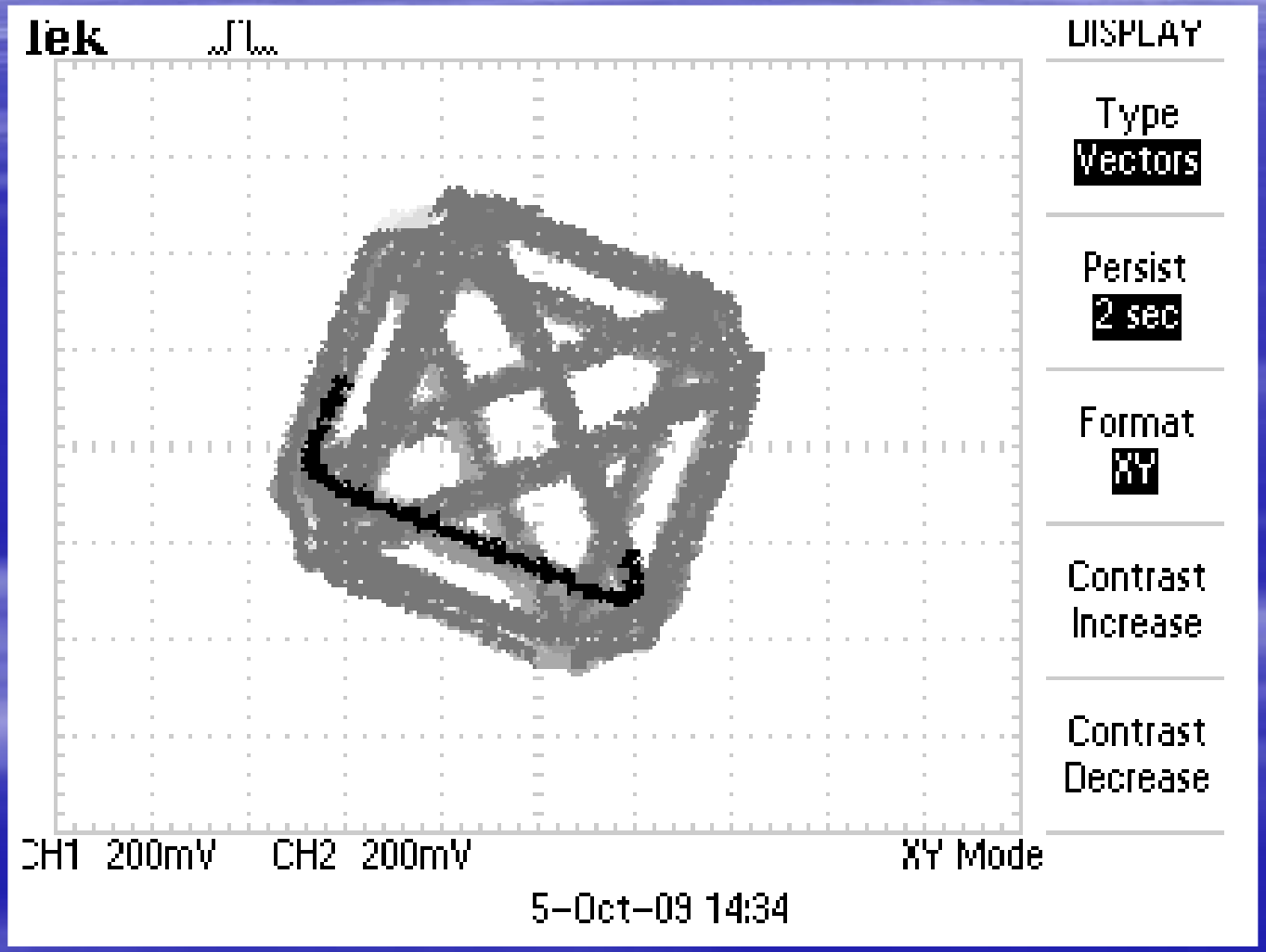
pi/8-8PSK reception



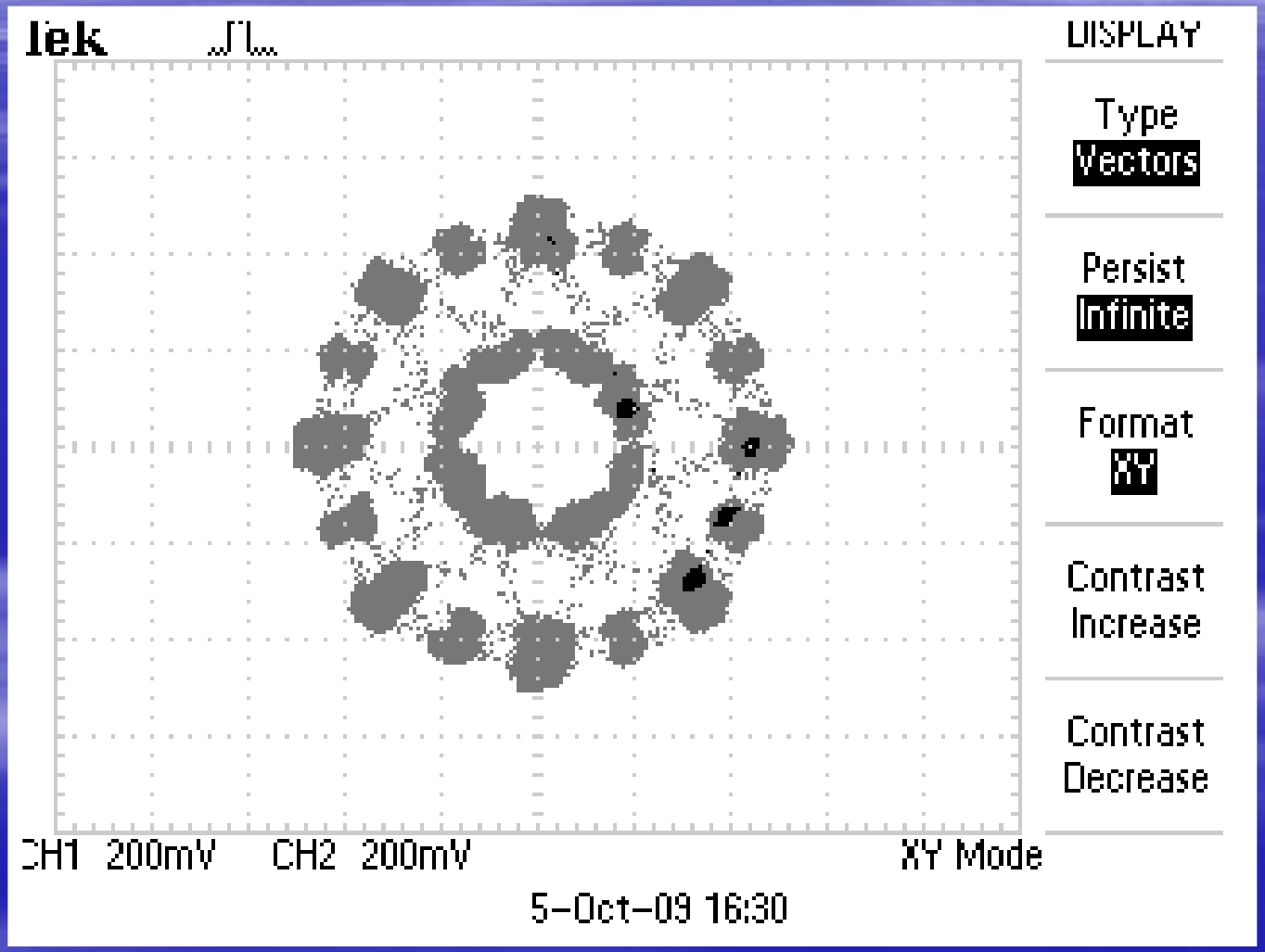
pi/8-8PSK reception



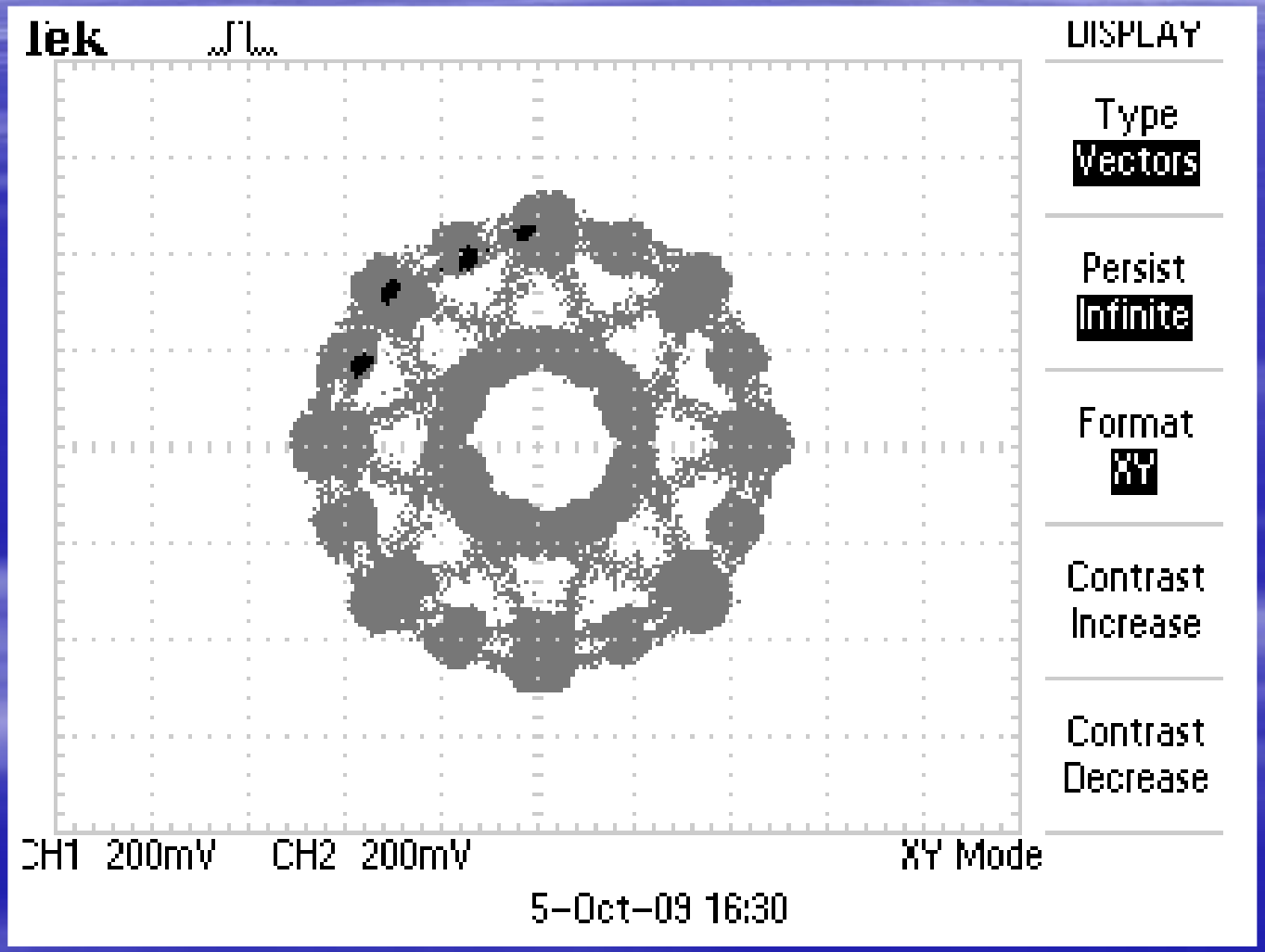
pi/8-QPSK reception



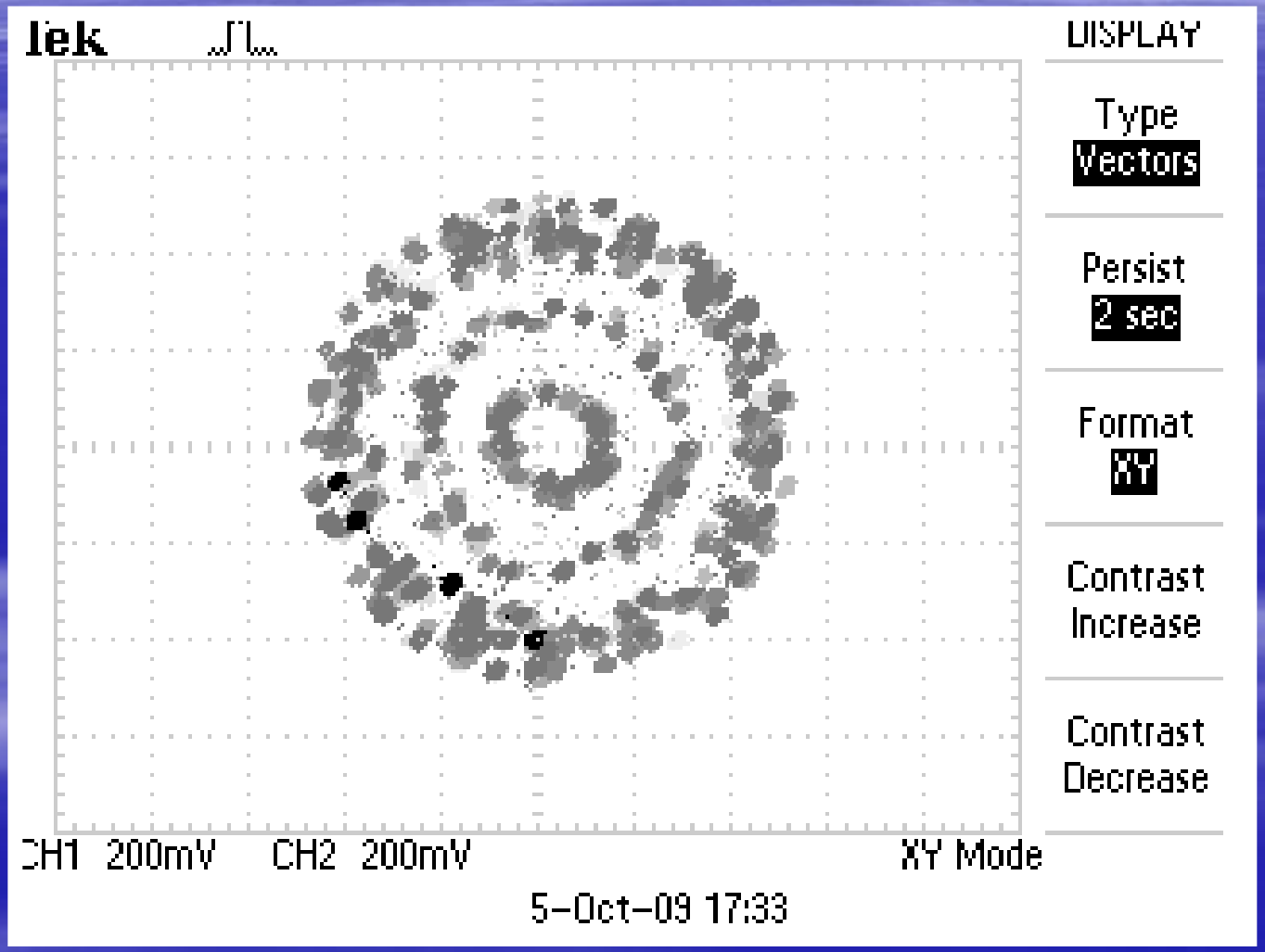
pi/8-8PSK after interpolator



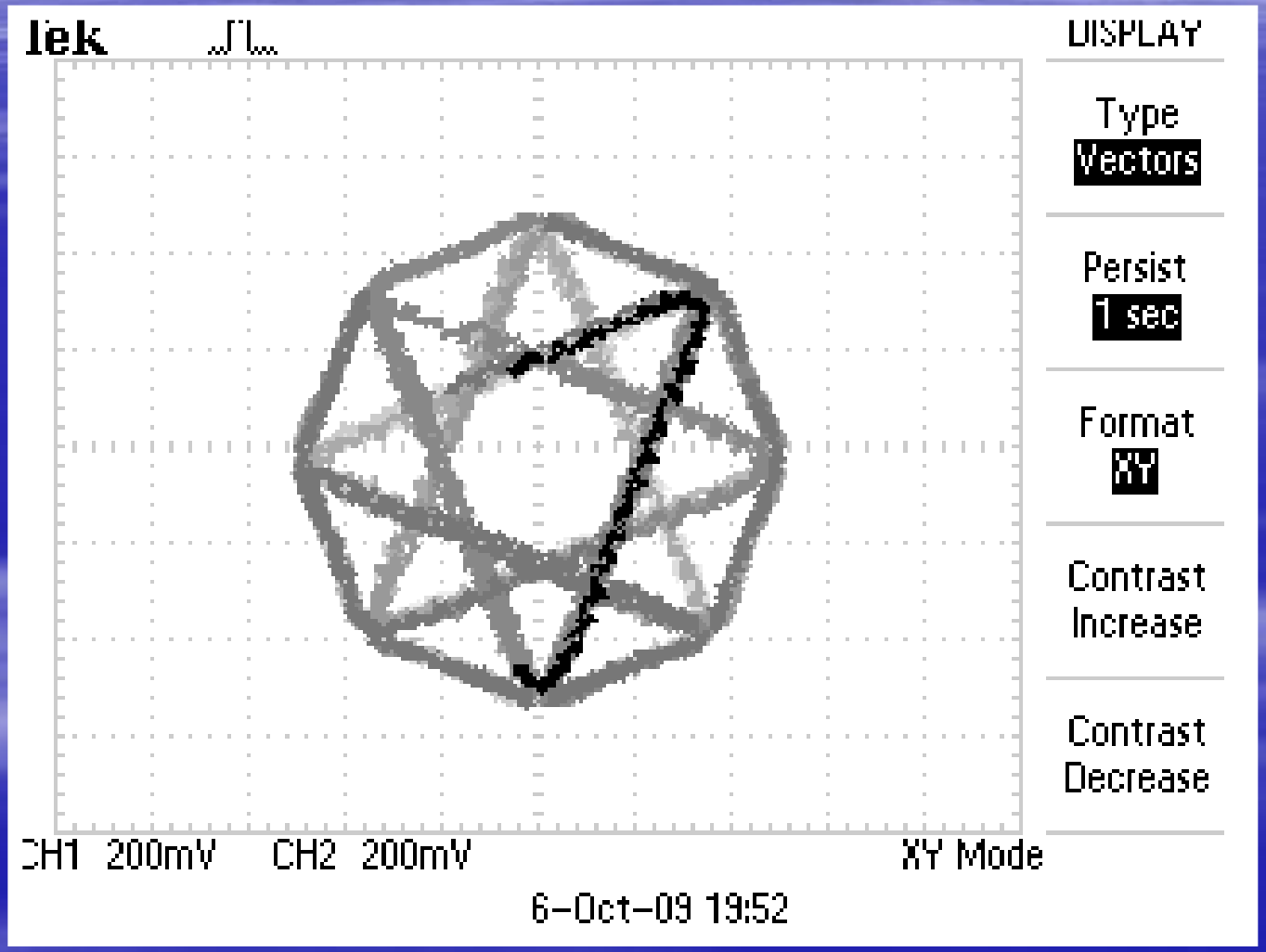
pi/8-8PSK after interpolator



pi/8-8PSK after interpolator



pi/4-QPSK reception



pi/4-QAM-64 reception