



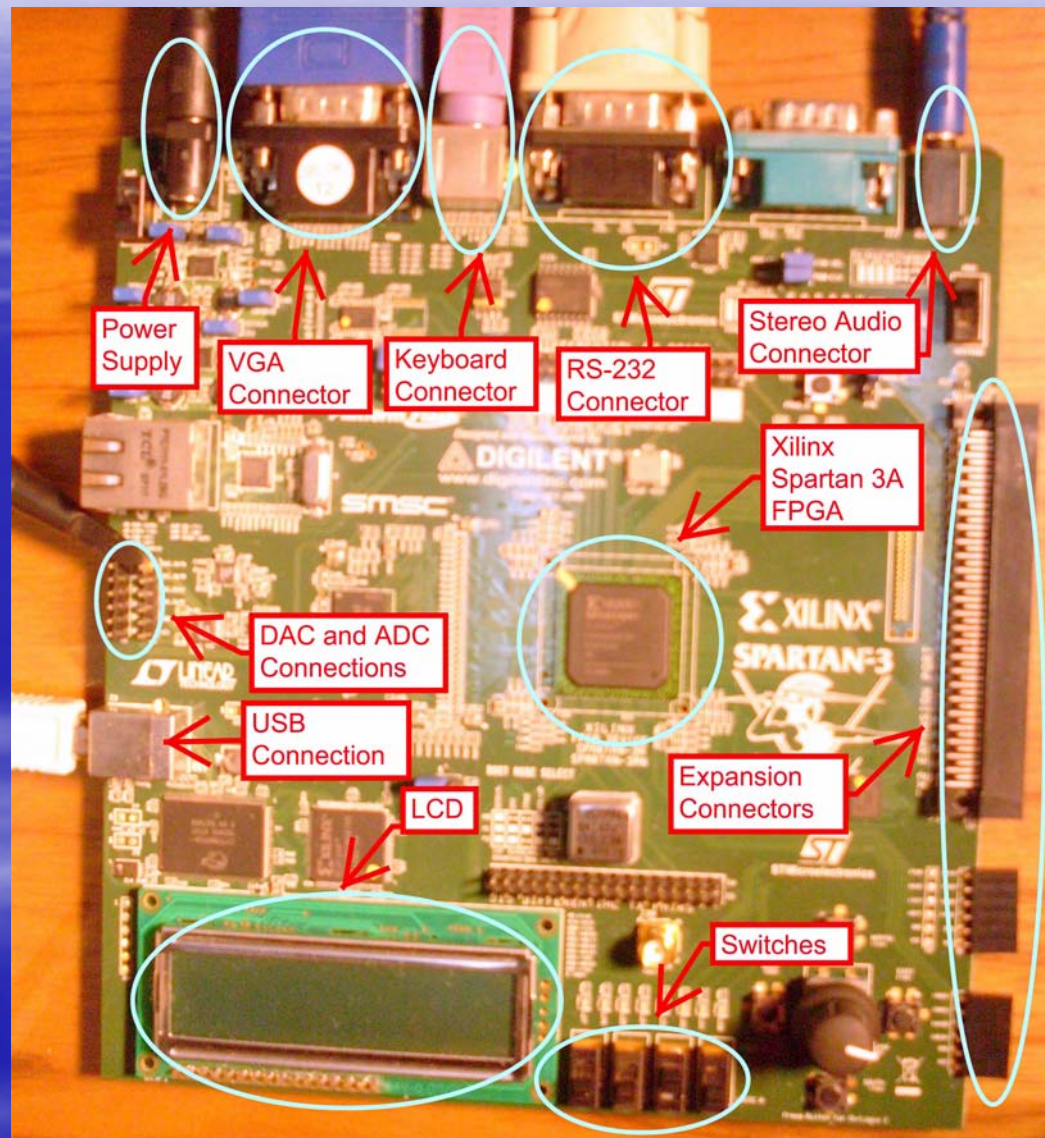
An Ultra Low Cost Software Defined Radio Laboratory for Education and Research

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Columbia, Vancouver,
Canada

Visiting Professor, Universidad
Pontificia Bolivariana,
Bucaramanga, Colombia

The Laboratory – all for under \$200!!!



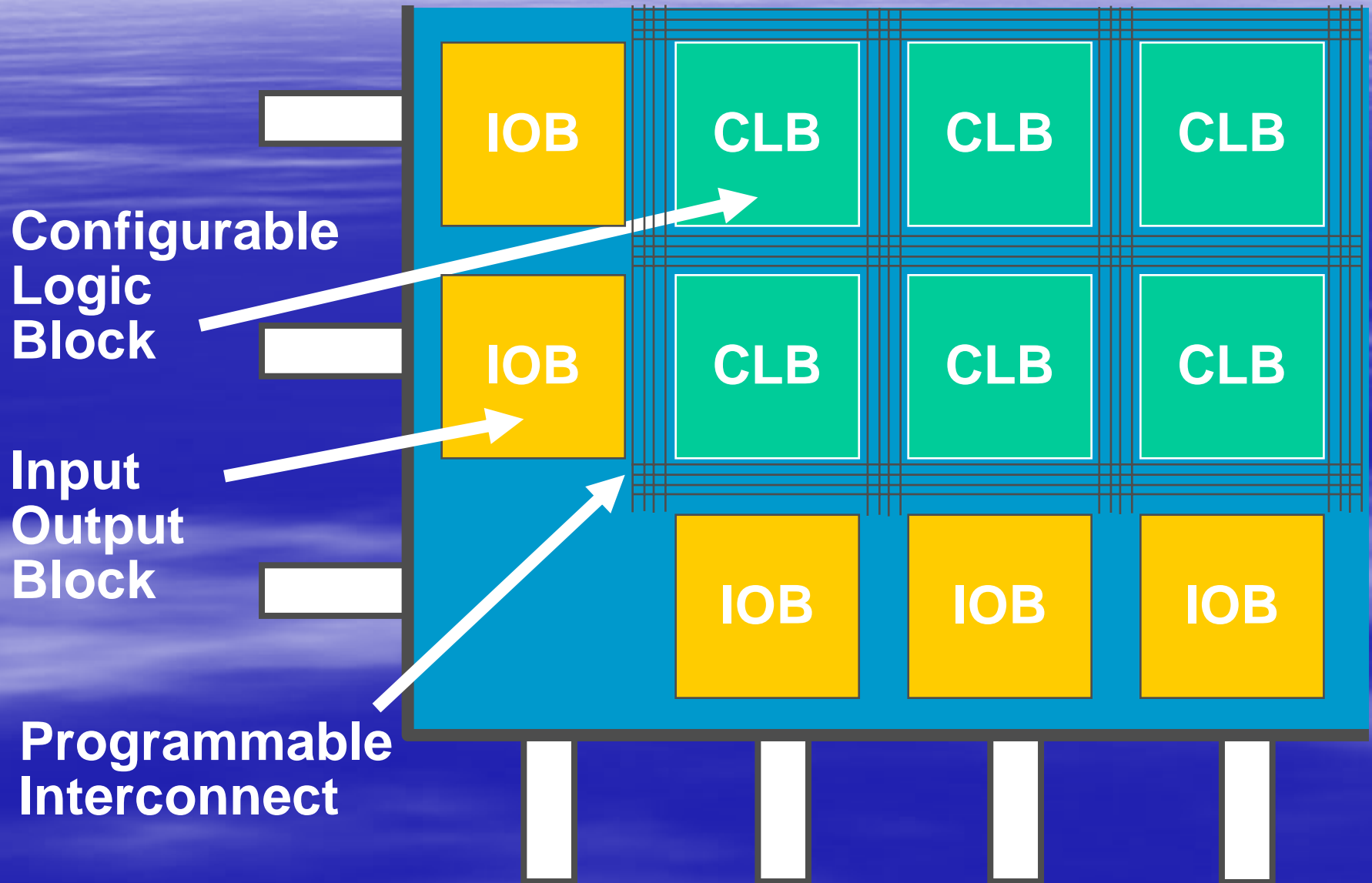
Card Components

- Xilinx Spartan 3A 700,000 Gate FPGA
- 4 push-buttons
- 8 LEDS
- 50 MHz oscillator
- 133 MHz oscillator
- External oscillator input
- Two 16 Mbit serial FLASH
- 32 Mbit parallel FLASH
- Stereo audio output
- Rotary knob/push-button
- 4-channel D/A converter
- 2-channel A/D converter
- 2-line x 16-character LCD
- Analog amplifiers
- 4 switches
- Ethernet port
- PS/2 keyboard connector
- VGA connector
- Two RS-232 ports
- 100-pin expansion connector
- 2x6-pin expansion connectors

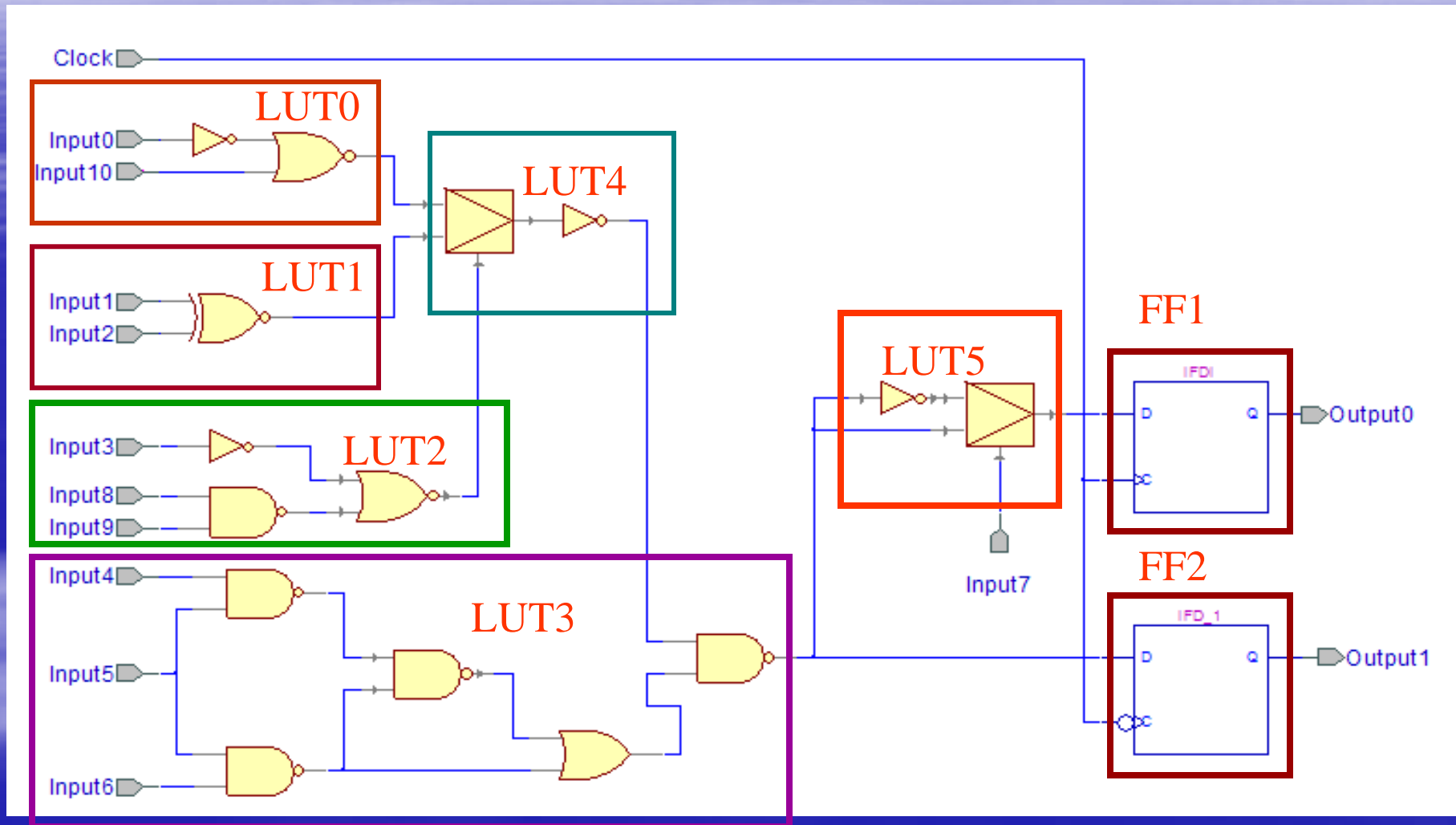
- Field Programmable Gate Array



FPGAs



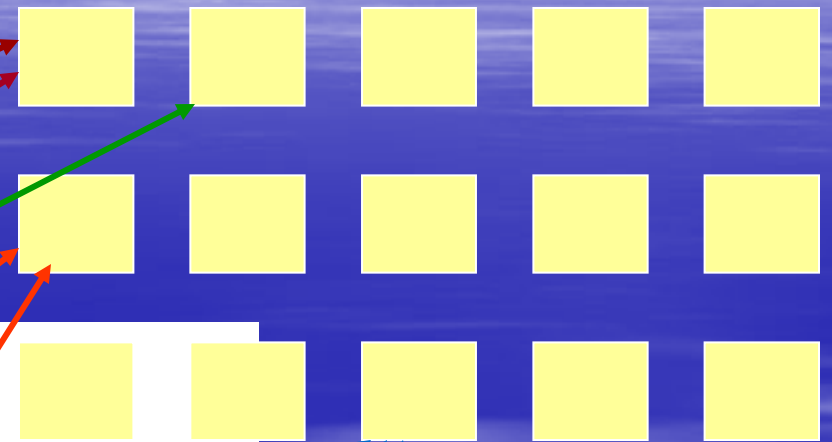
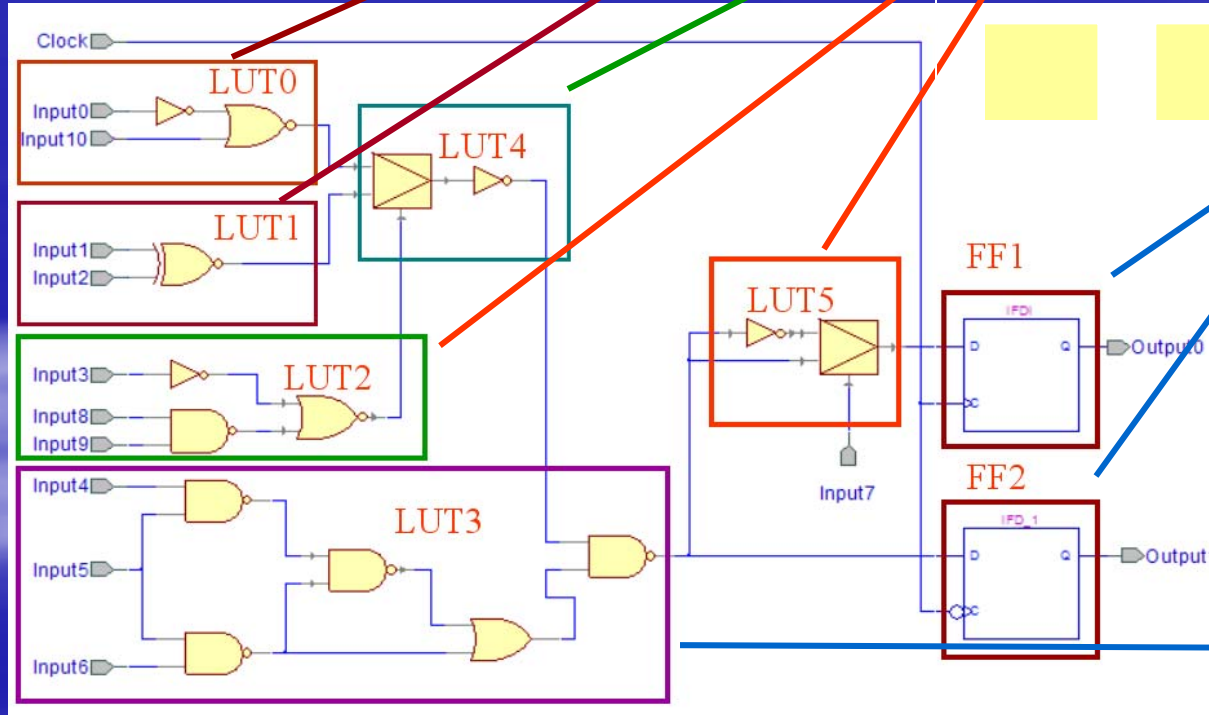
Mapping



Placing

FPGA

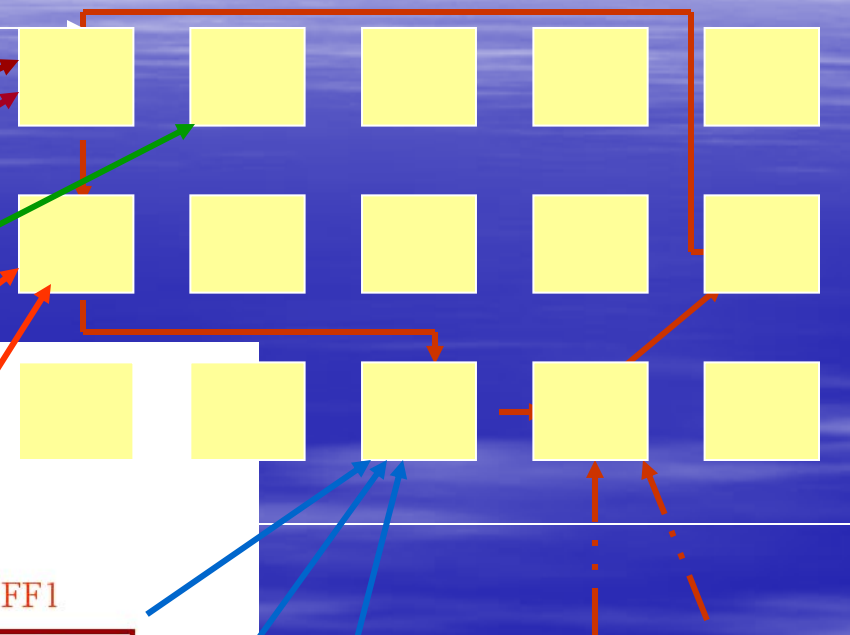
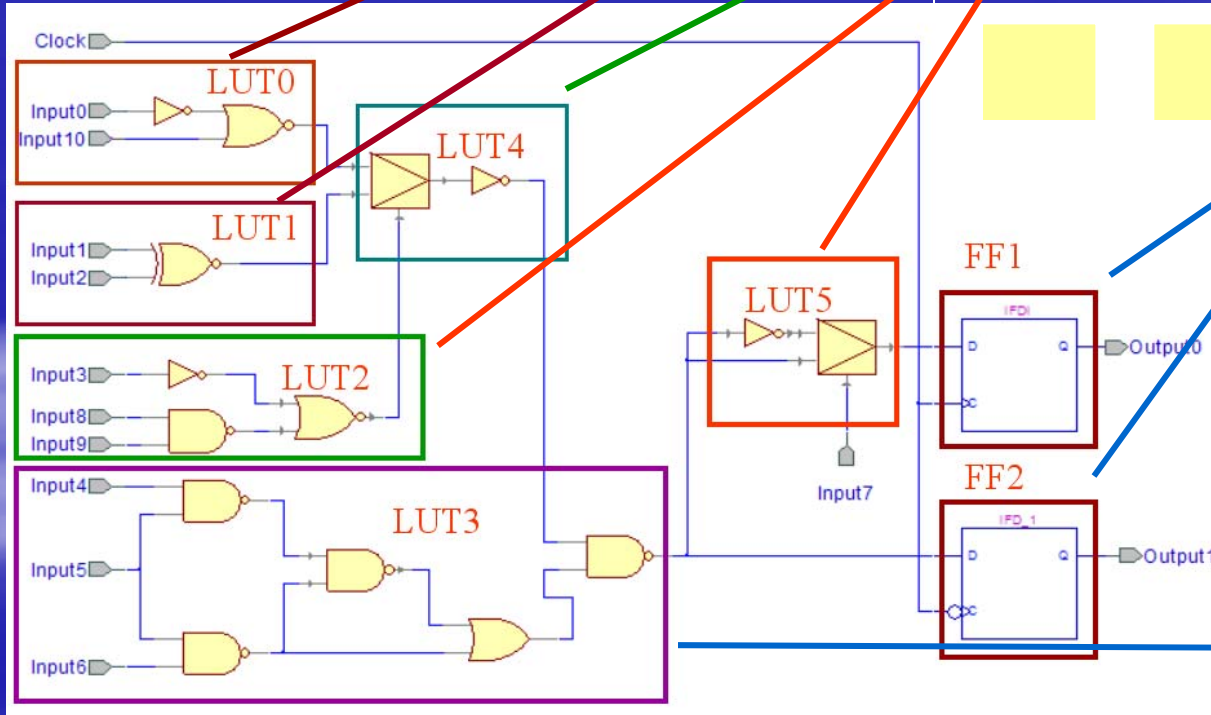
CLB SLICES



Routing

FPGA

Programmable Connections



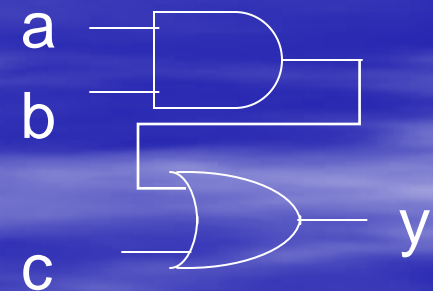
Design Entry

Design entry is done using Verilog HDL, thus allowing for large-scale circuit design

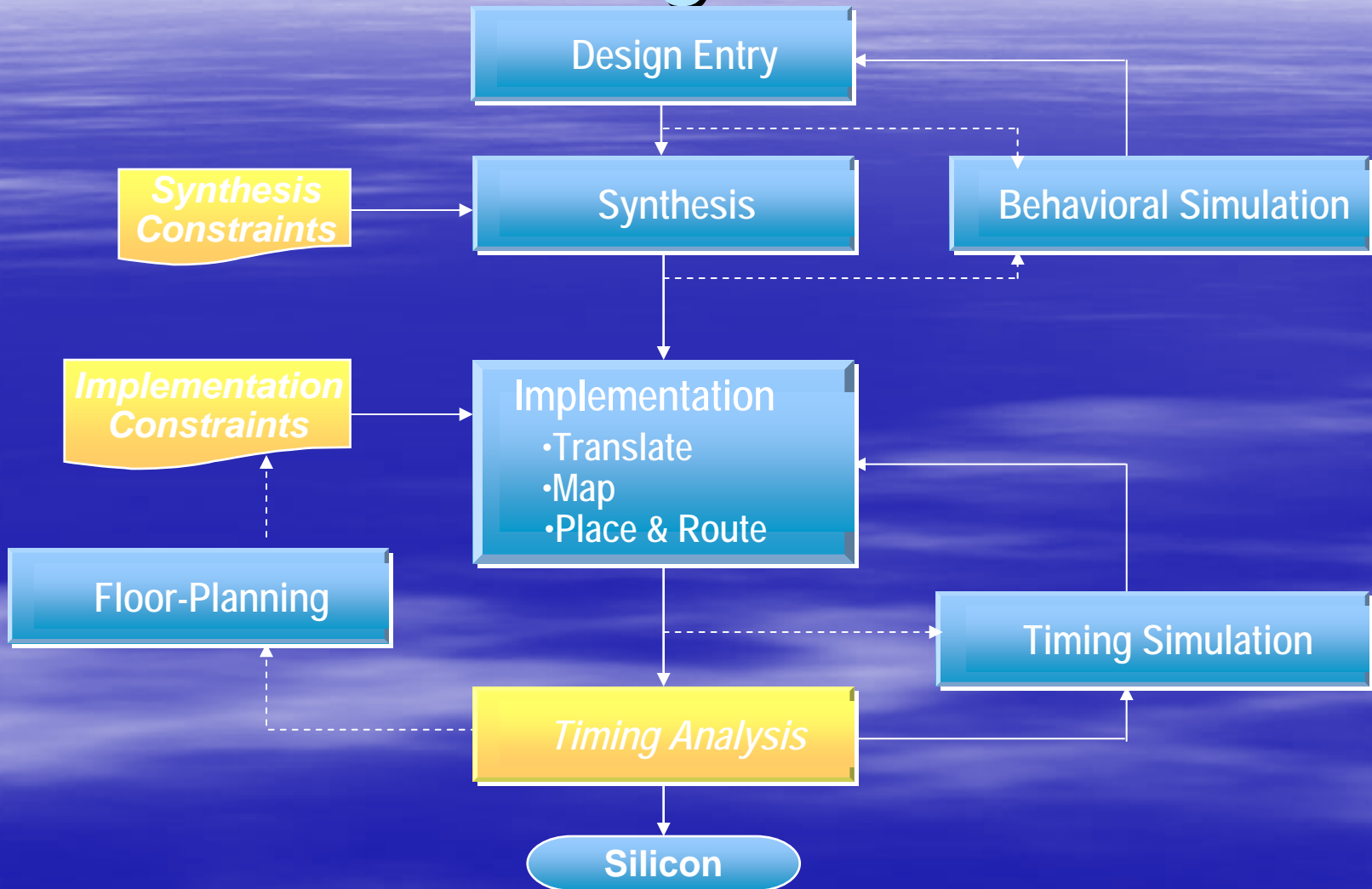
```
module example (input a, input b,  
input c, output y);  
  
wire a, b, c, y;  
  
    assign y = (a & b) | c;  
  
endmodule;
```

Síntesis

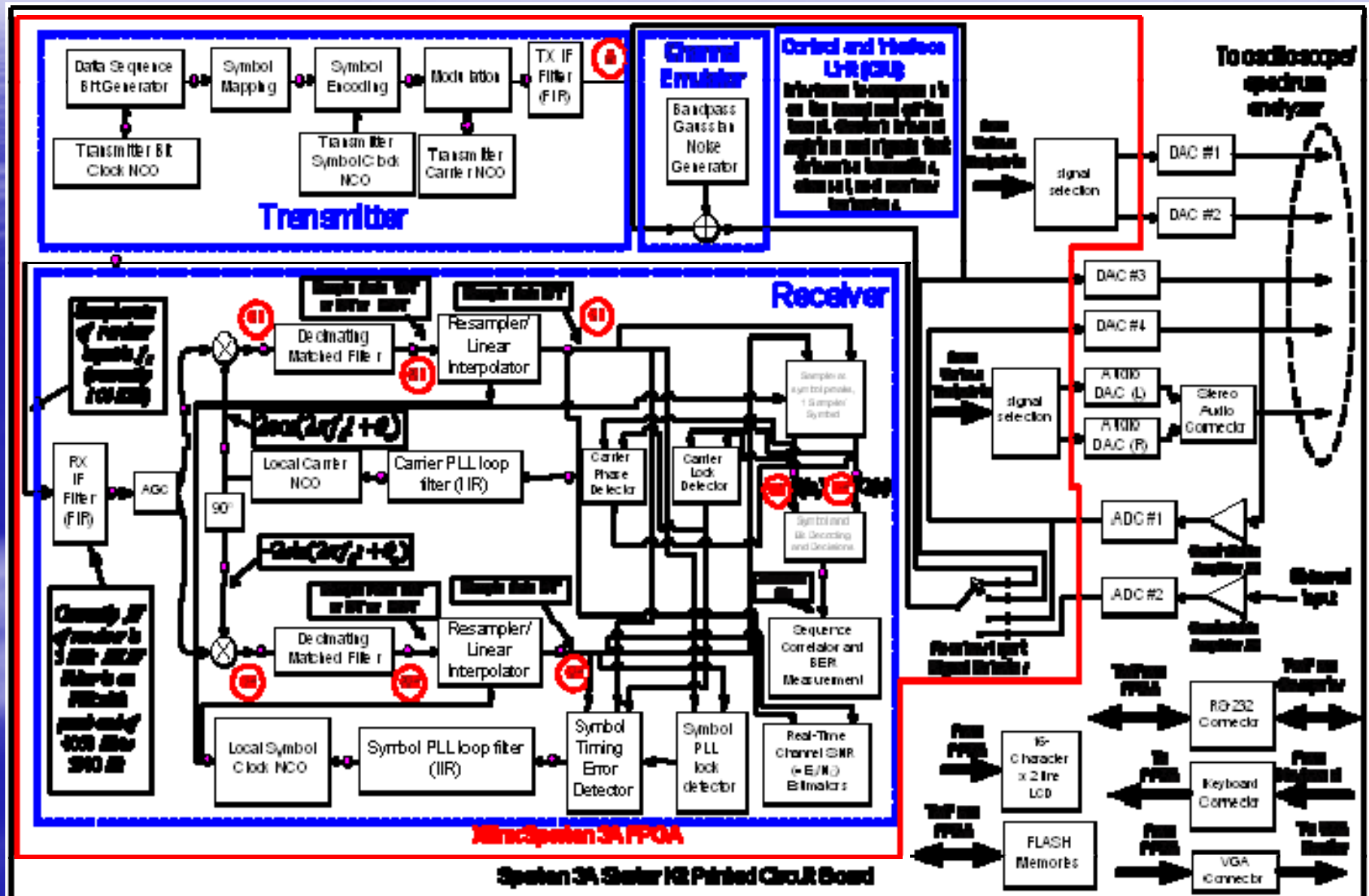
Puertas



Xilinx Design Process



The laboratory – functional diagram



Cost

- Card is a commercial FPGA card that costs under \$200
- Available worldwide
- Same card can be used for courses in digital logic, microprocessors, networking, FPGA design, etc.
- Indeed, the card has been used for this purpose by the author at UPB Bucaramanga FPGA course
- 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 developing countries
- Simple yet robust laboratory that is also useful for research

Features

- Transmitter
- Channel Emulation (AWGN), slow fading also supported
- 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
- 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

Features (cont.)

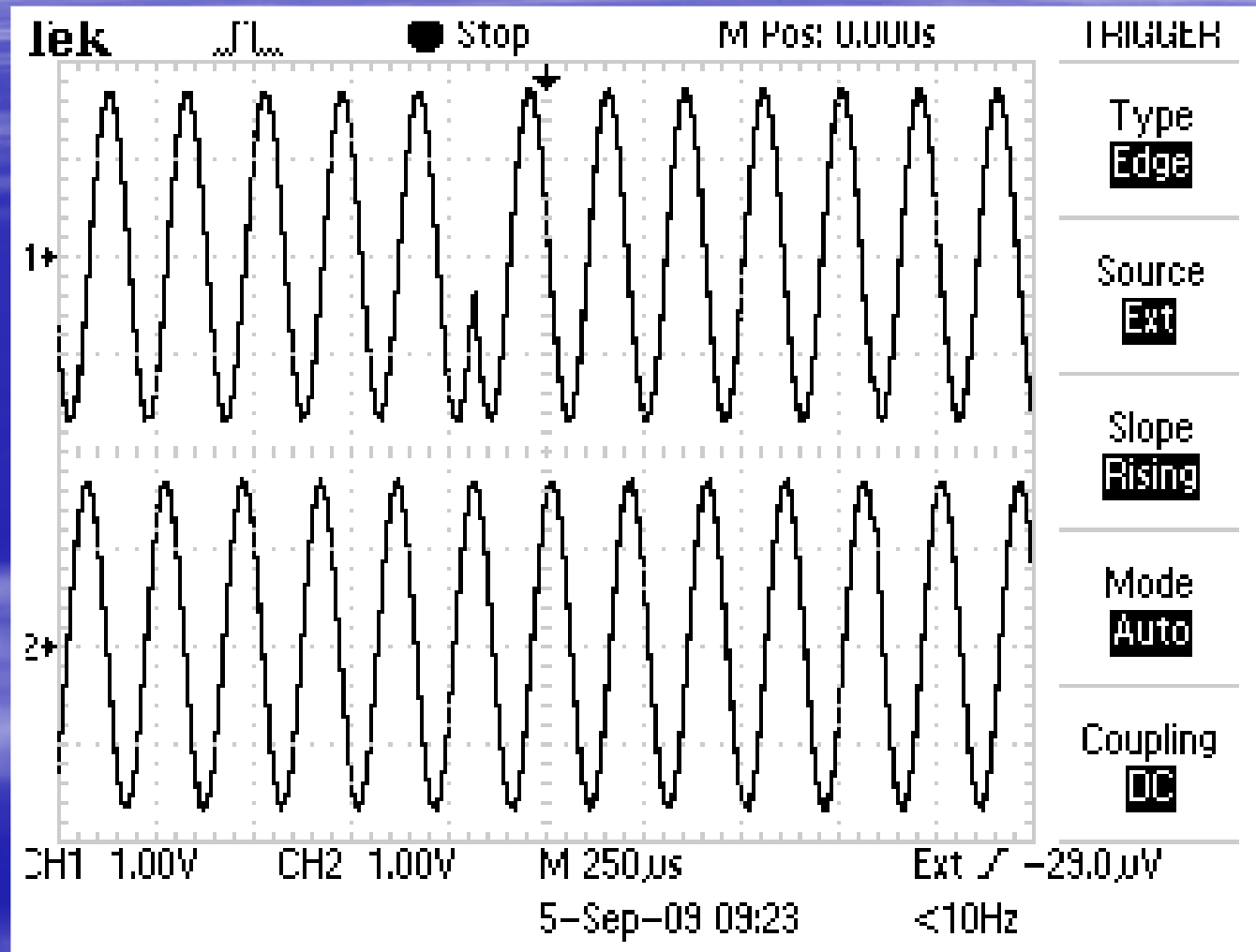
- Audio output for interface to PC-based oscilloscope and spectrum analyzer software
- 4 DAC outputs for oscilloscope use
- 2 ADC inputs
- Can be used for interface to RF components, however channel emulation makes this unnecessary
- Interface via keyboard and VGA
- Interface via hyperterminal and RS-232
- 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 use it for several courses

A Picture is worth a thousand
words.....

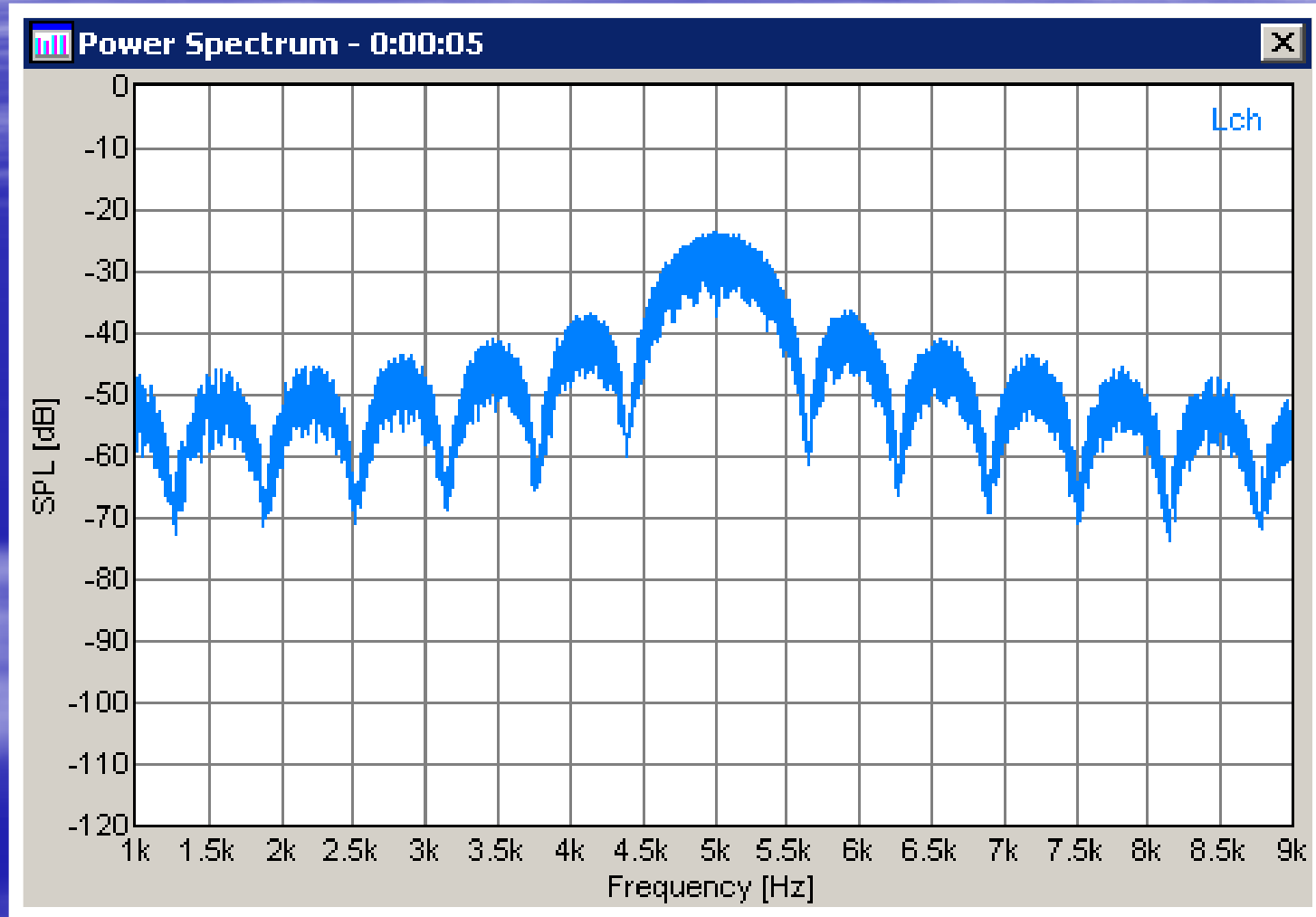
And now for some nice
pictures!!!

BPSK!!!!

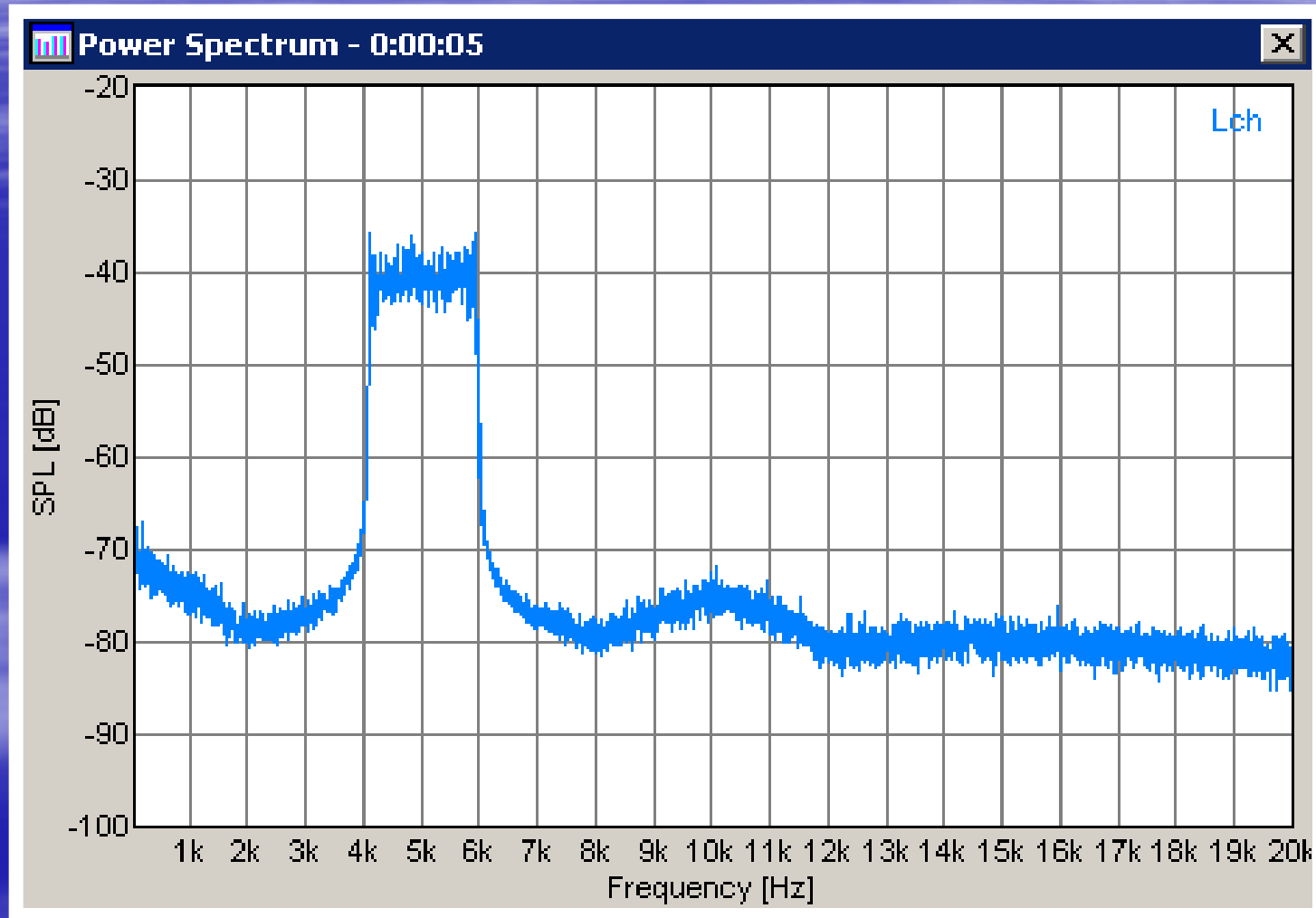
BPSK: Transmitted carrier vs. Local Oscillator



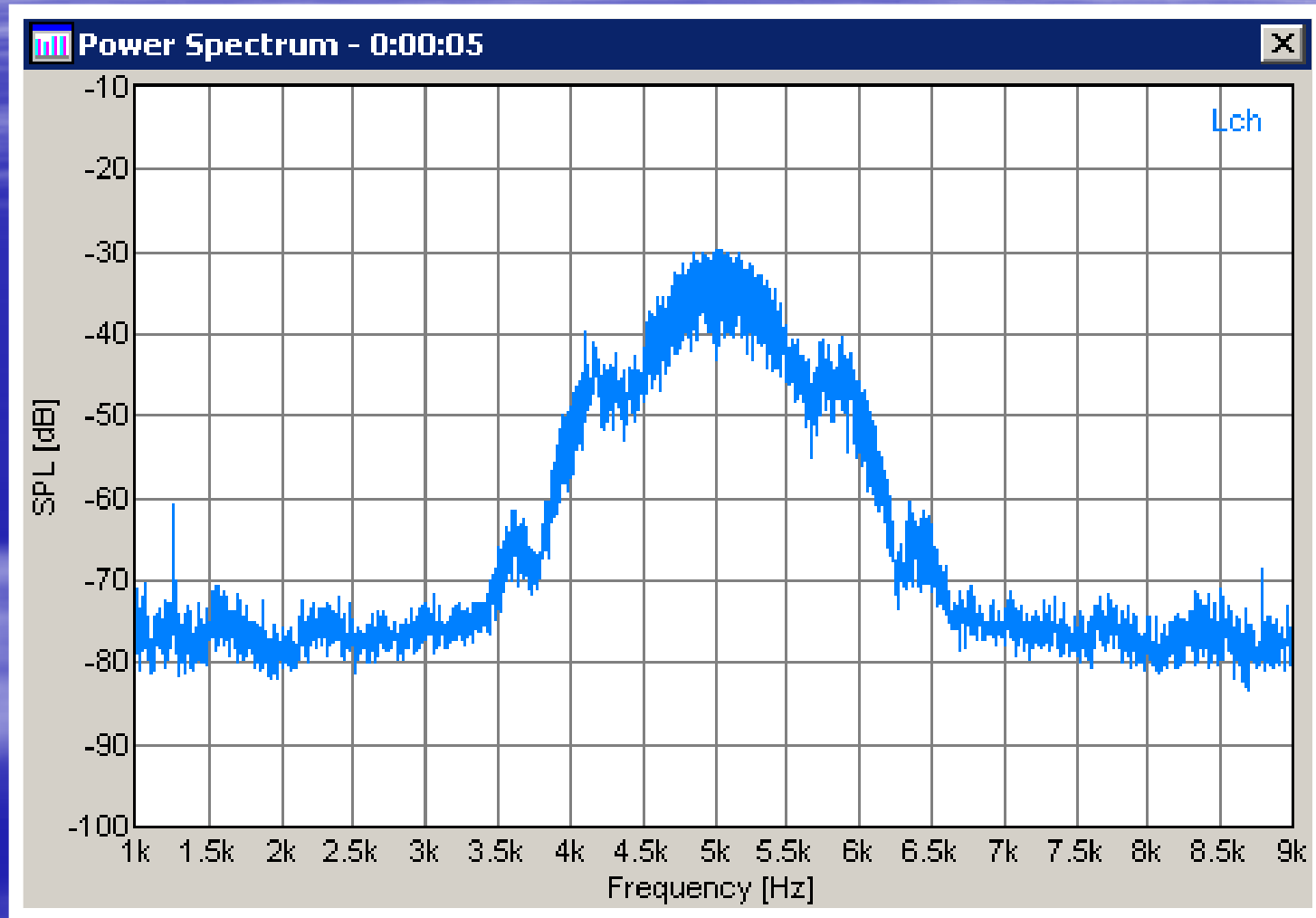
BPSK, Spectrum of Transmitted Signal before TX filter



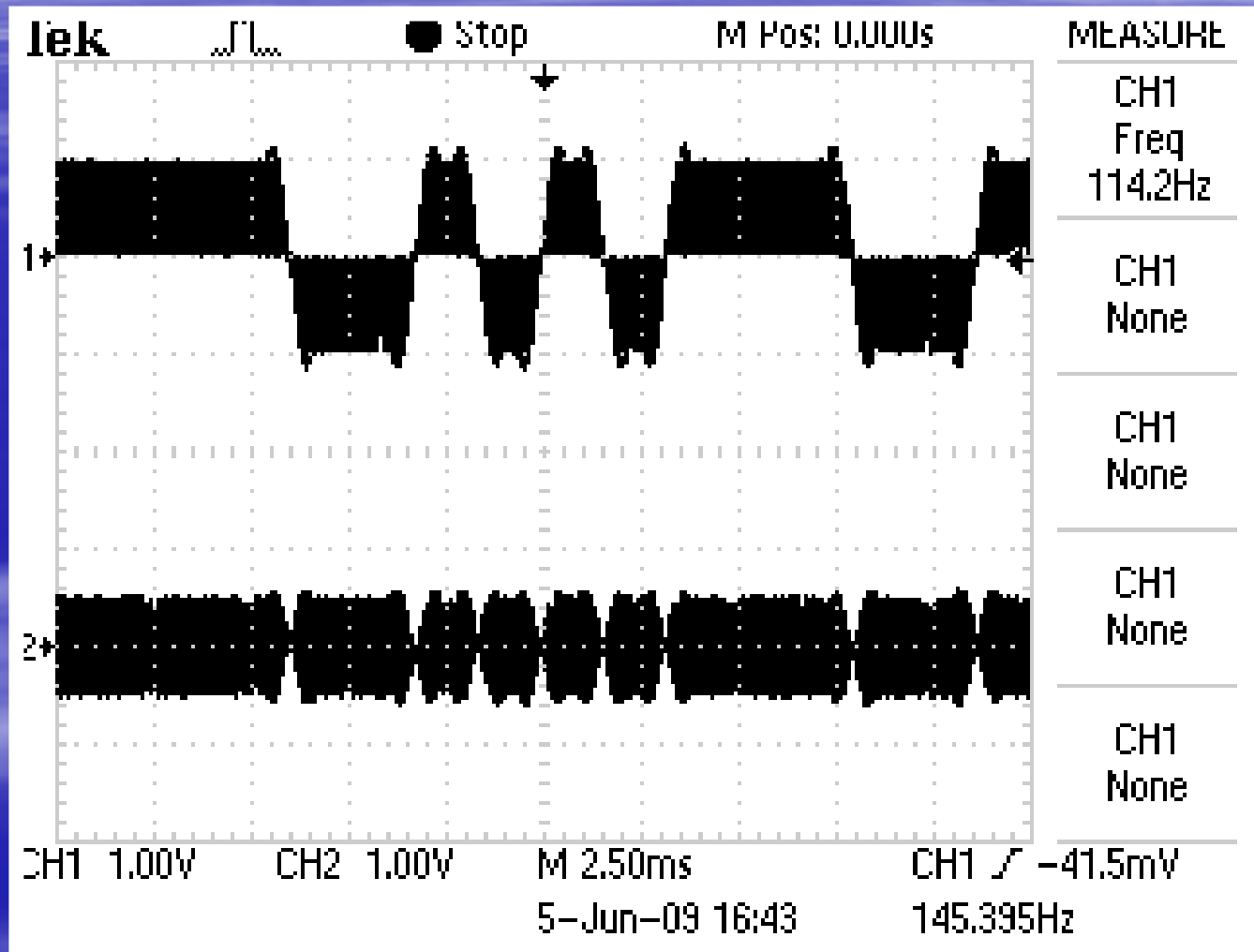
Noise Spectrum around 5 KHz, new Gaussian noise generation method



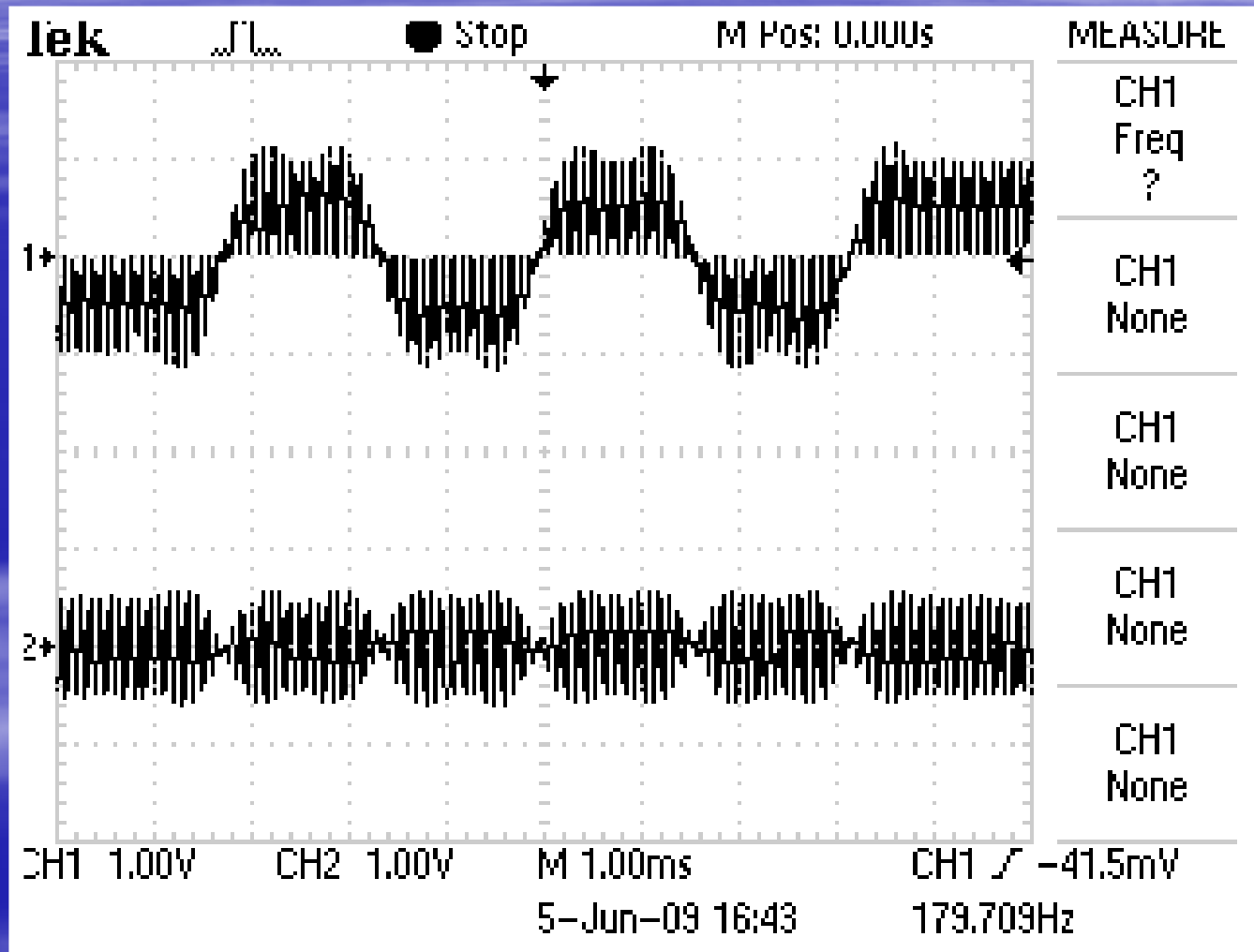
BPSK receiver signal after RX filter, $\text{SNR} = 12 \text{ dB}$



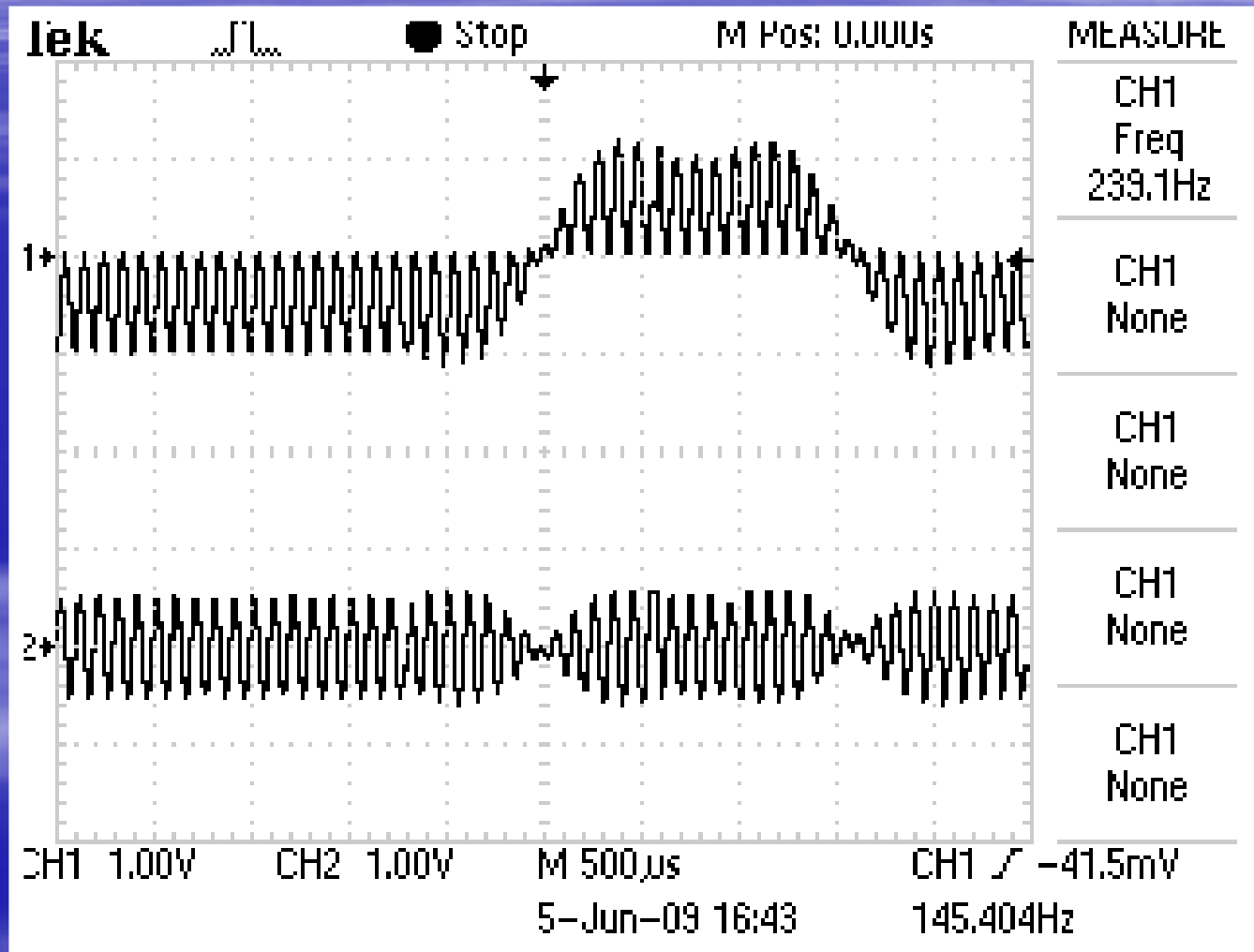
BPSK: post-IQ demodulator, no noise



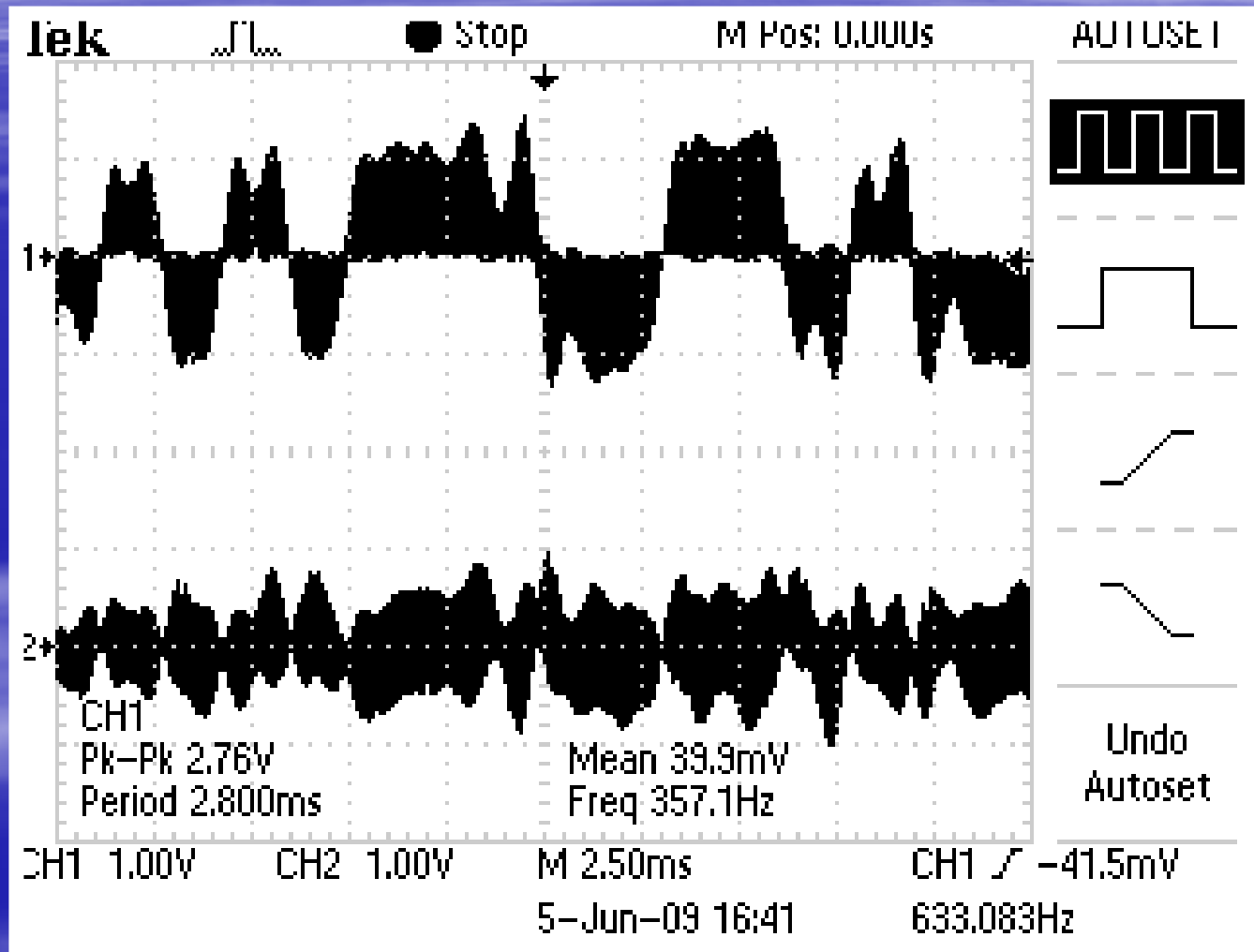
BPSK: post-IQ demodulator, no noise, zoom



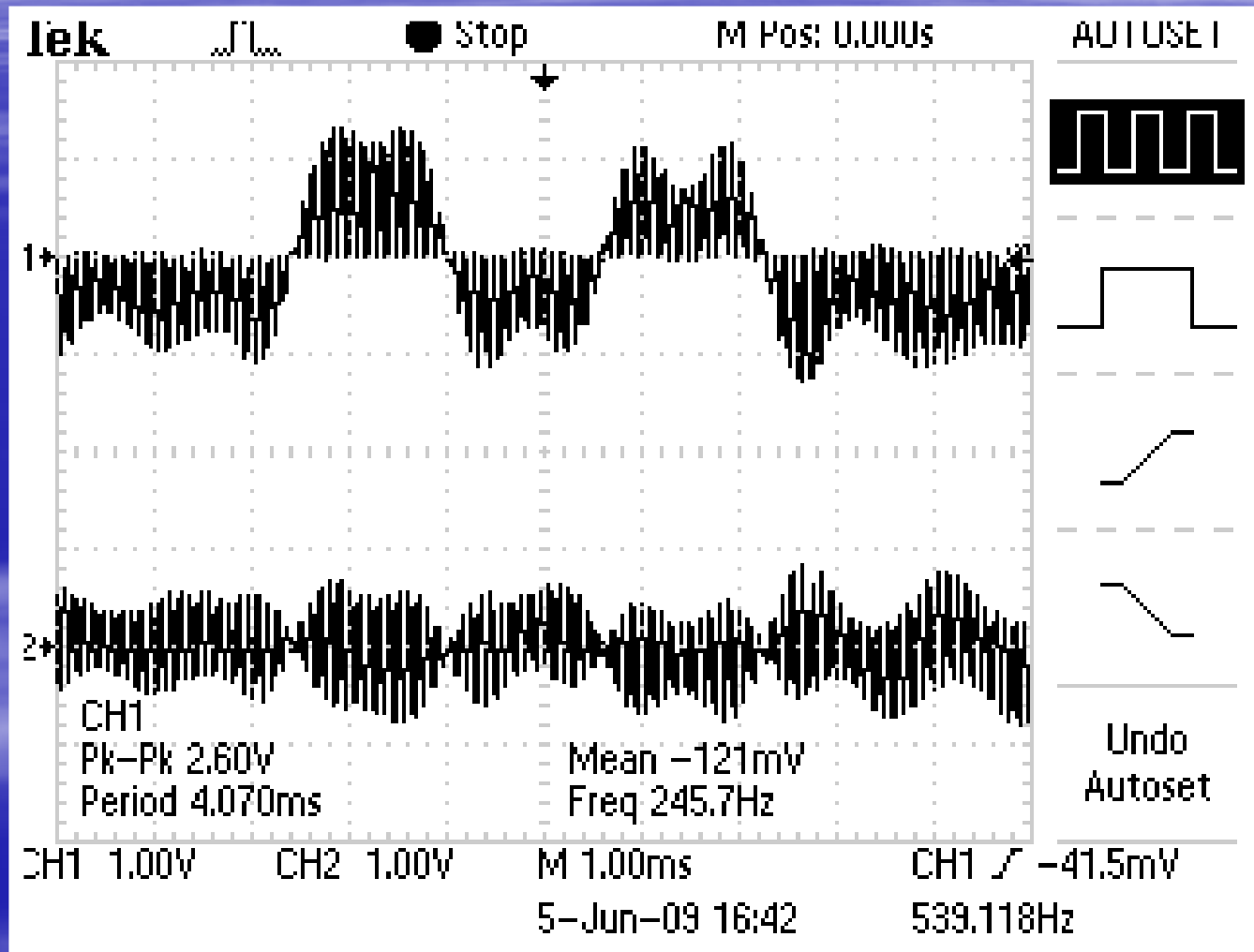
BPSK: post-IQ demodulator, no noise, more zoom



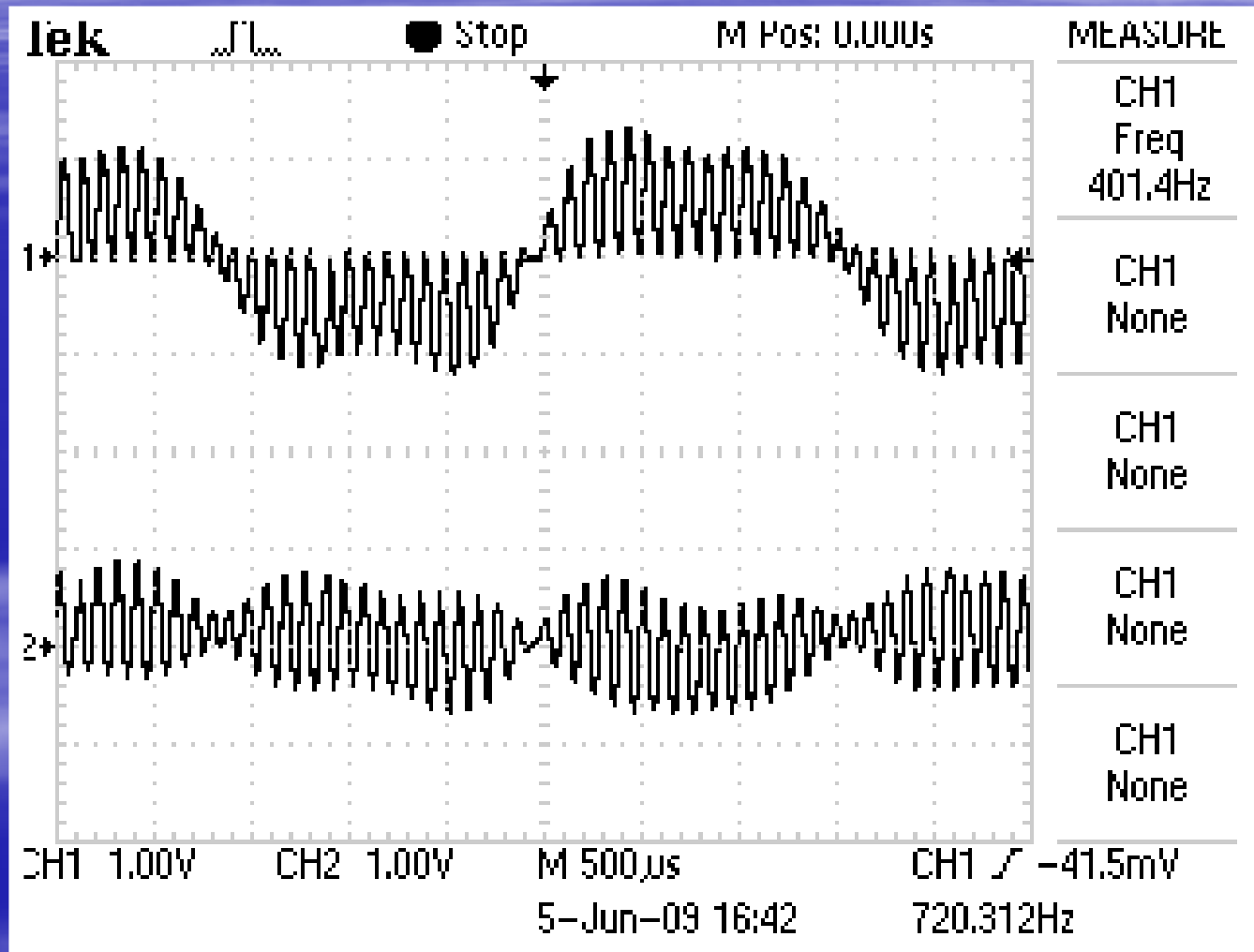
BPSK: post-IQ demodulator, SNR=12dB



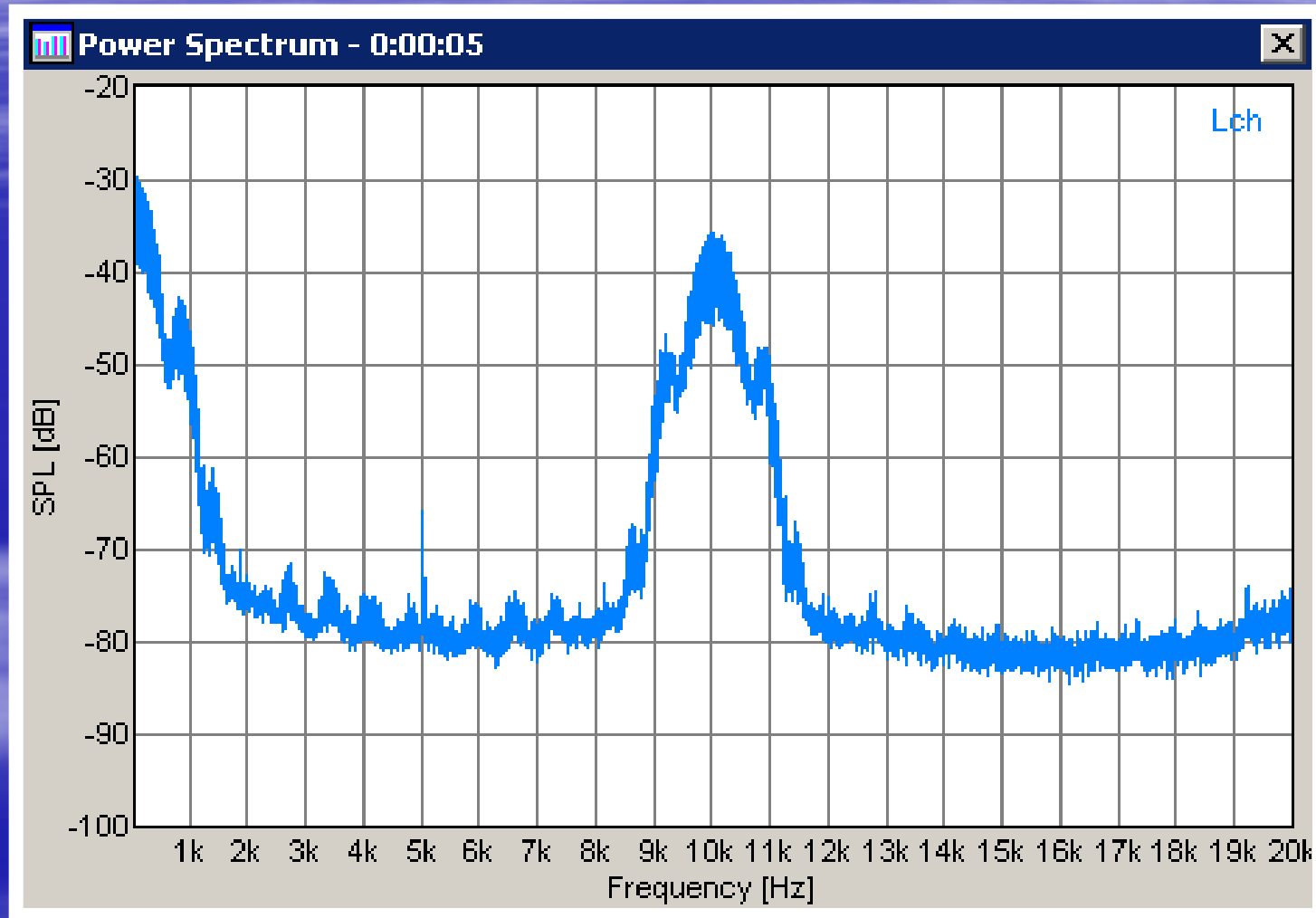
BPSK: post-IQ demodulator, SNR=12dB, zoom



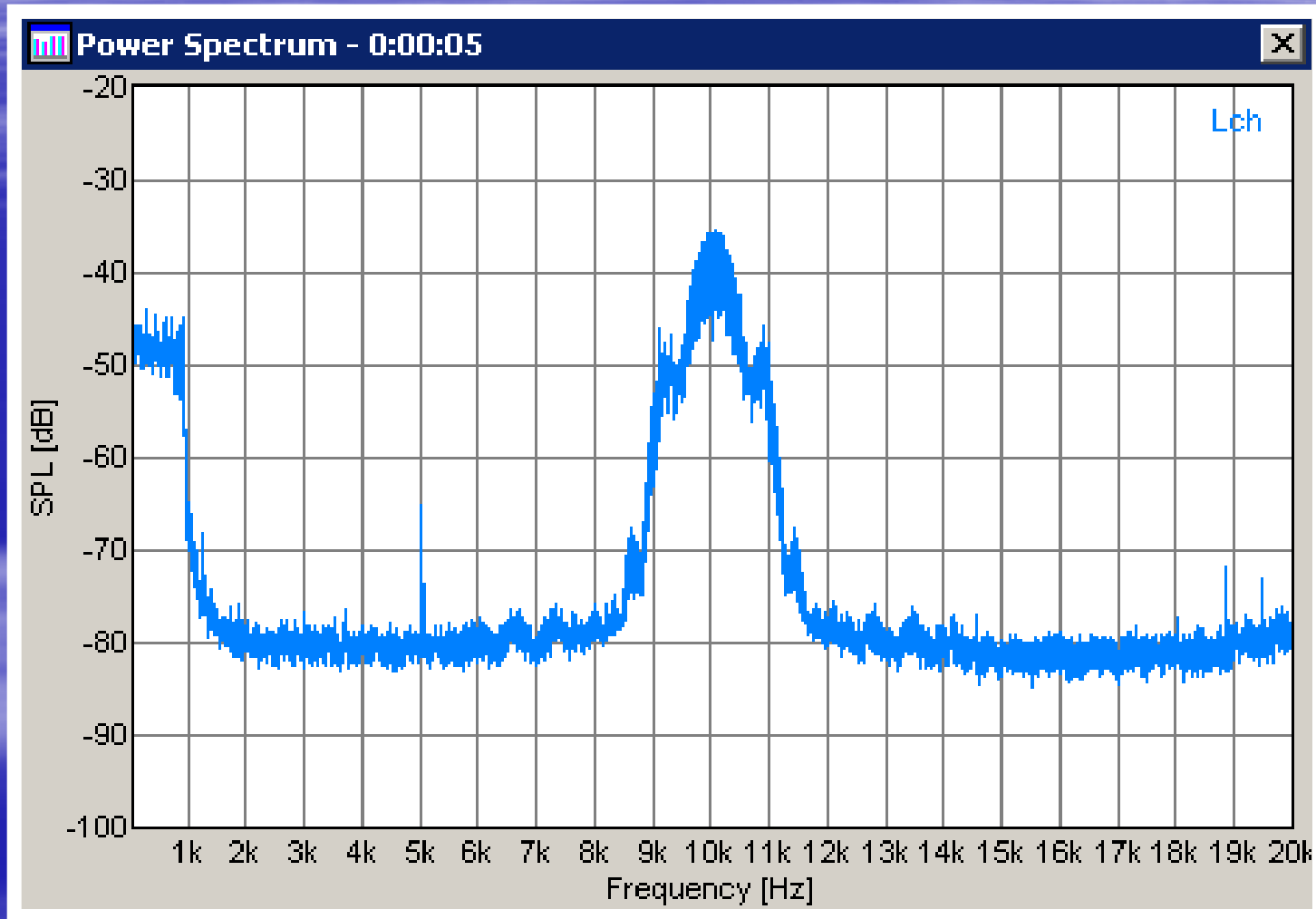
BPSK: post-IQ demodulator, SNR=12dB, more zoom



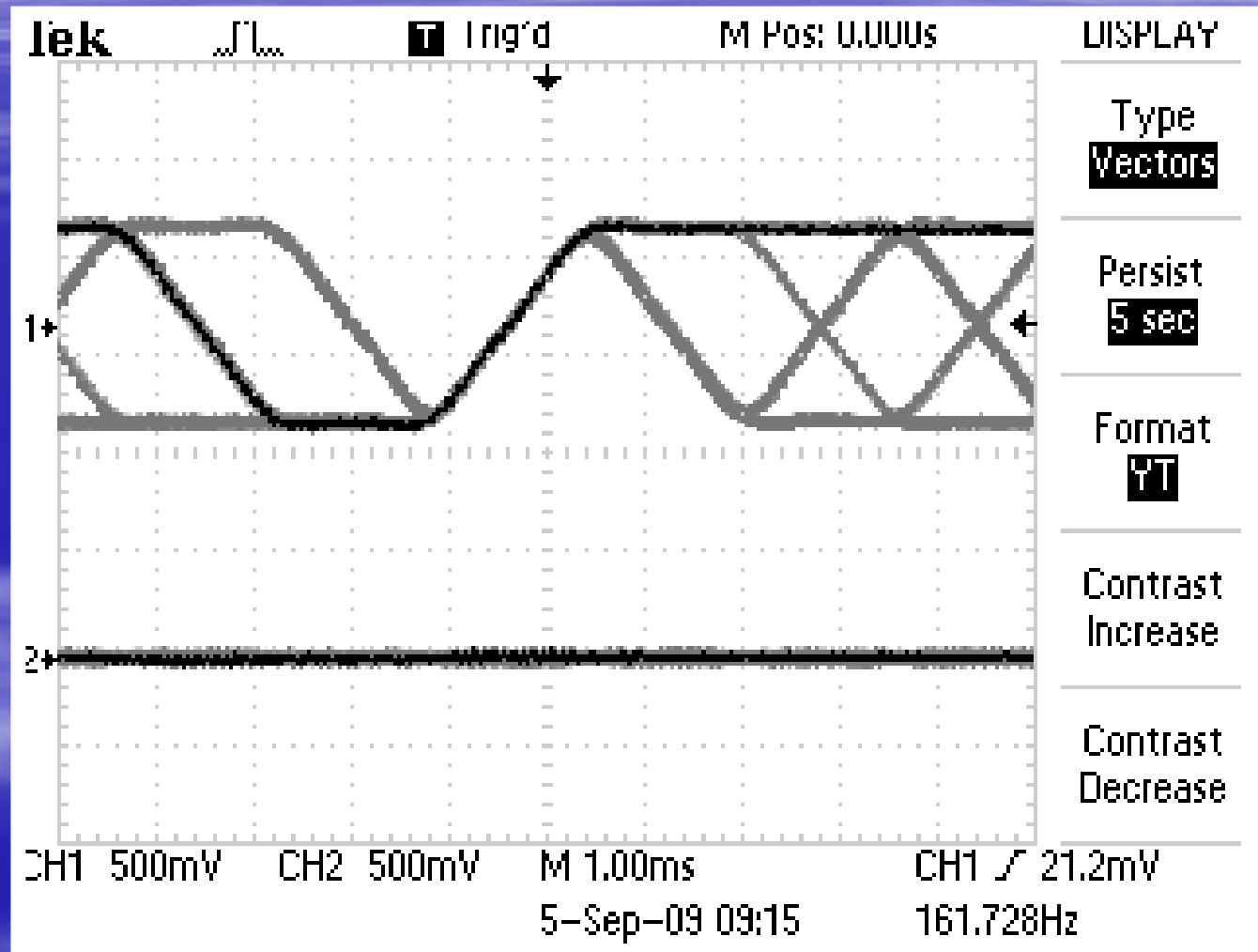
BPSK, I channel after I-Q Demodulator



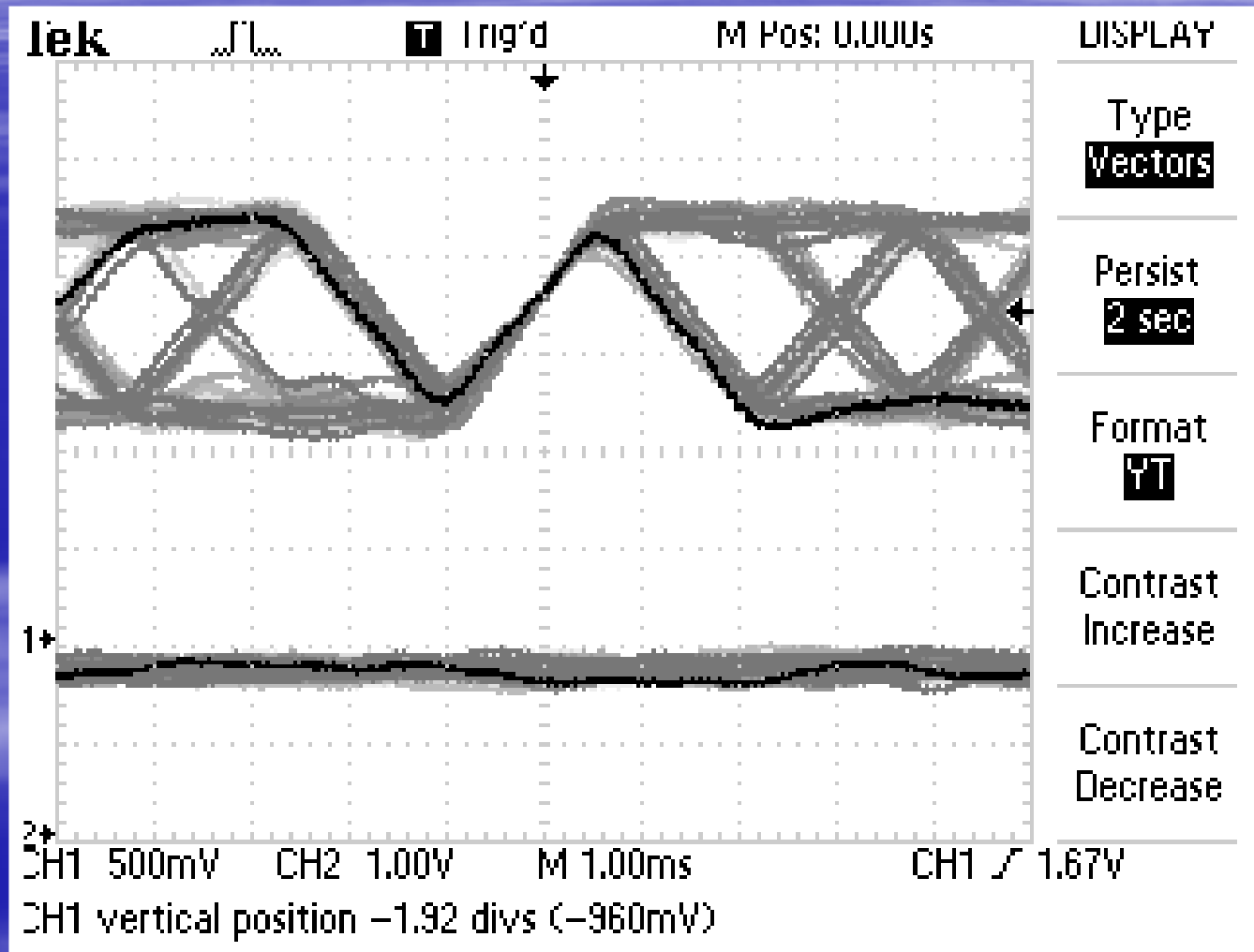
BPSK, Q channel after I-Q Demodulator



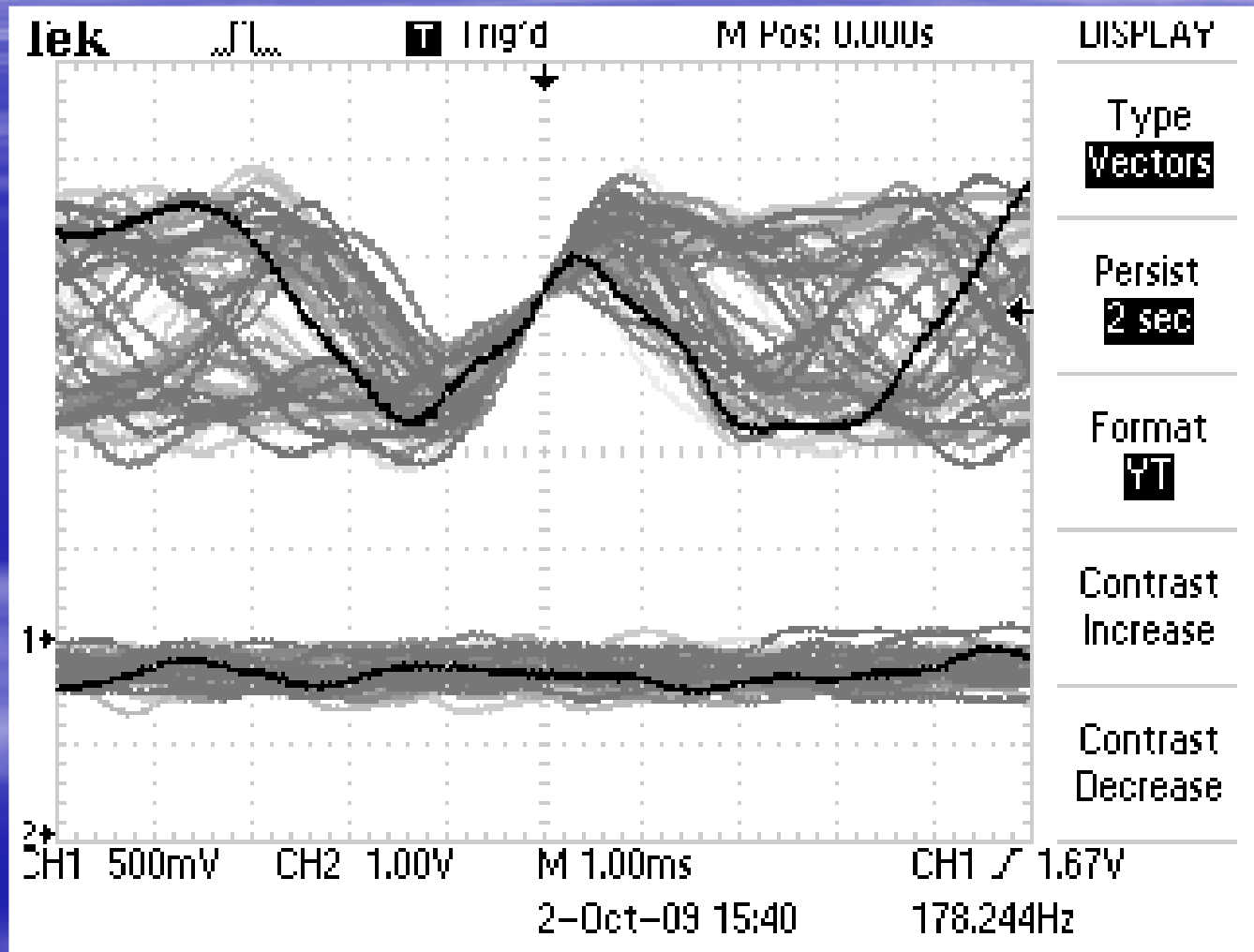
BPSK – In receiver after matched filter – no noise



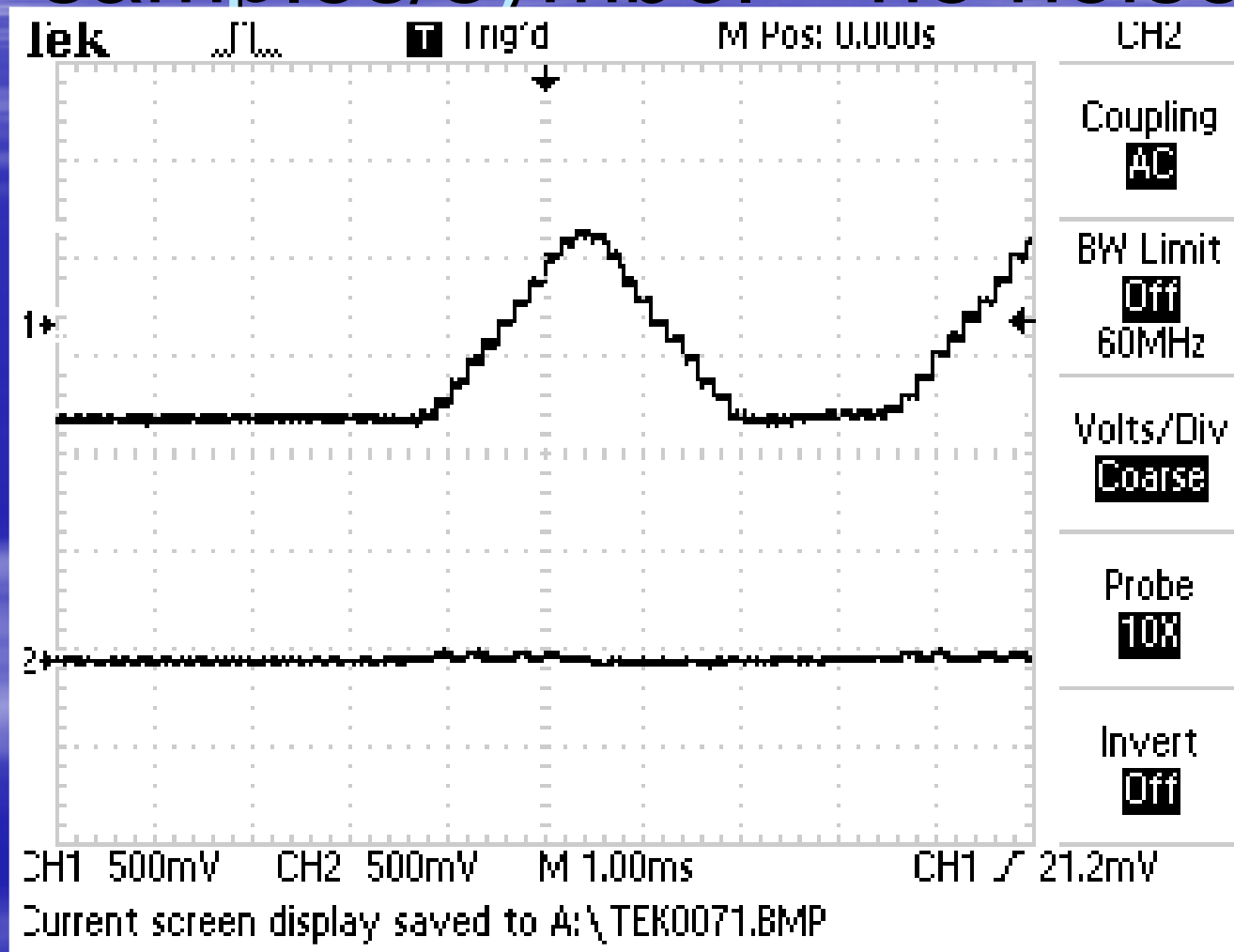
BPSK eye diagram – high SNR



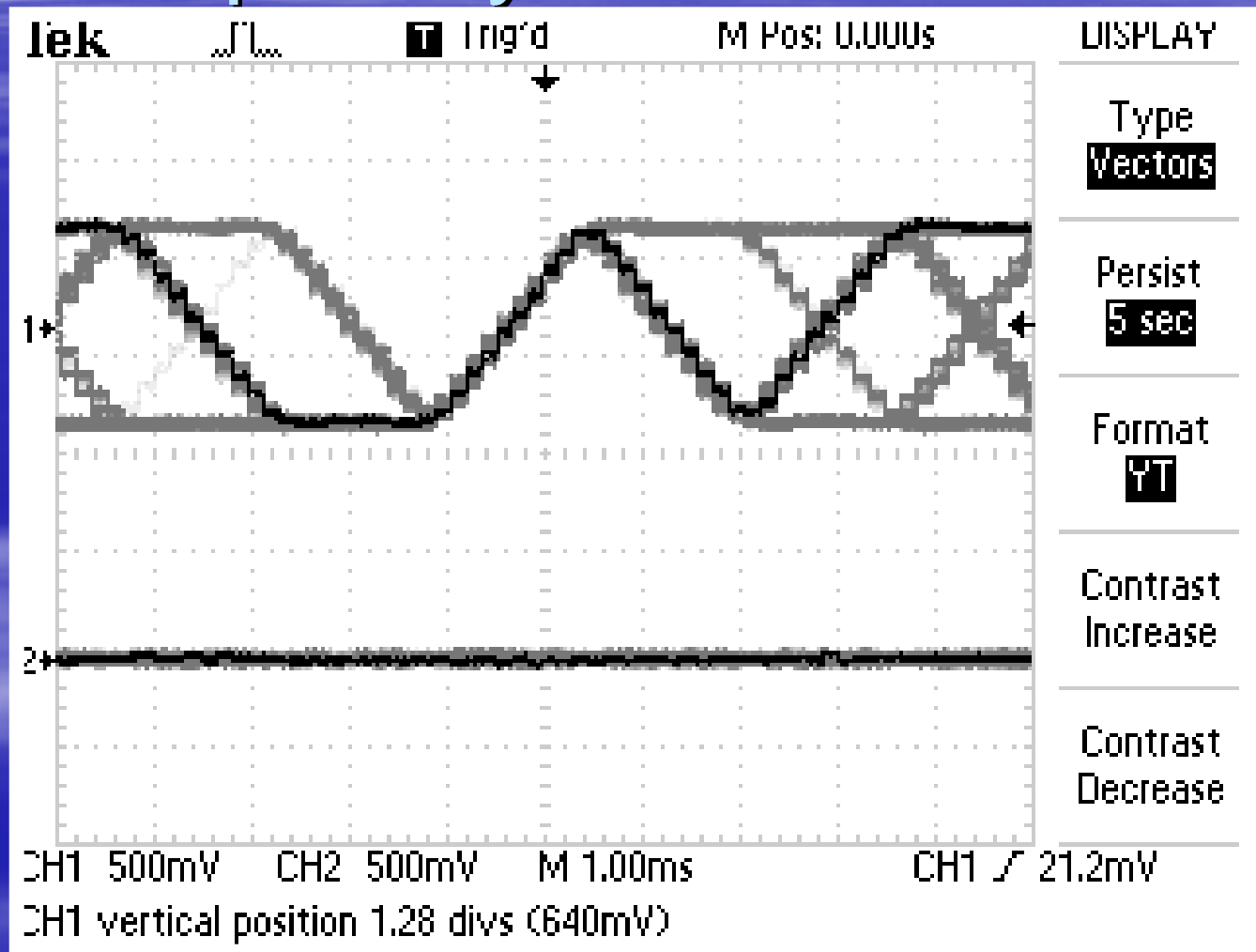
BPSK eye diagram – low SNR



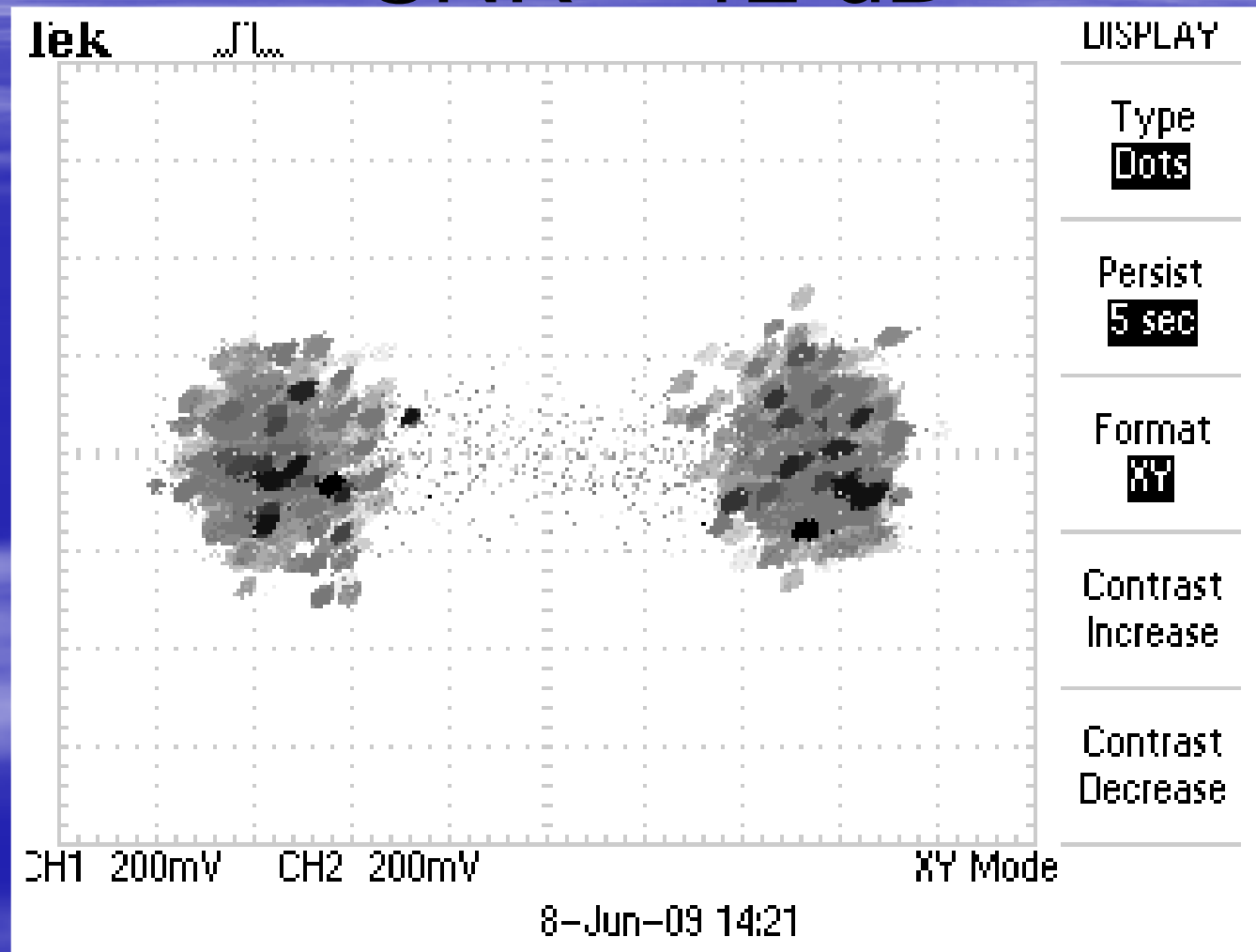
BPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



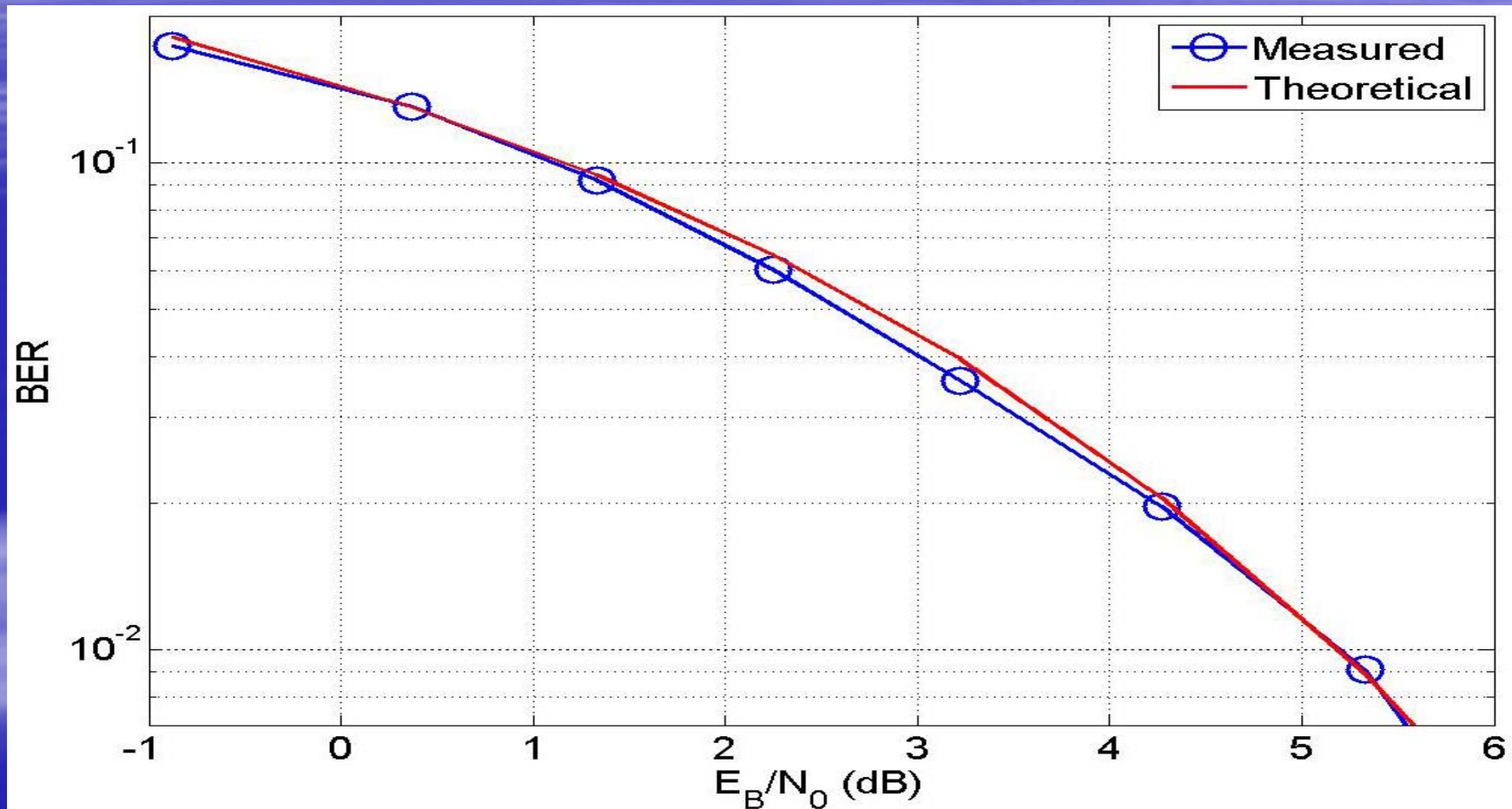
BPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



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



BER measurements using LAB: DEBPSK



VGA Terminal, BPSK, Differential coding, Coherent Detection, SNR = 2.25 dB



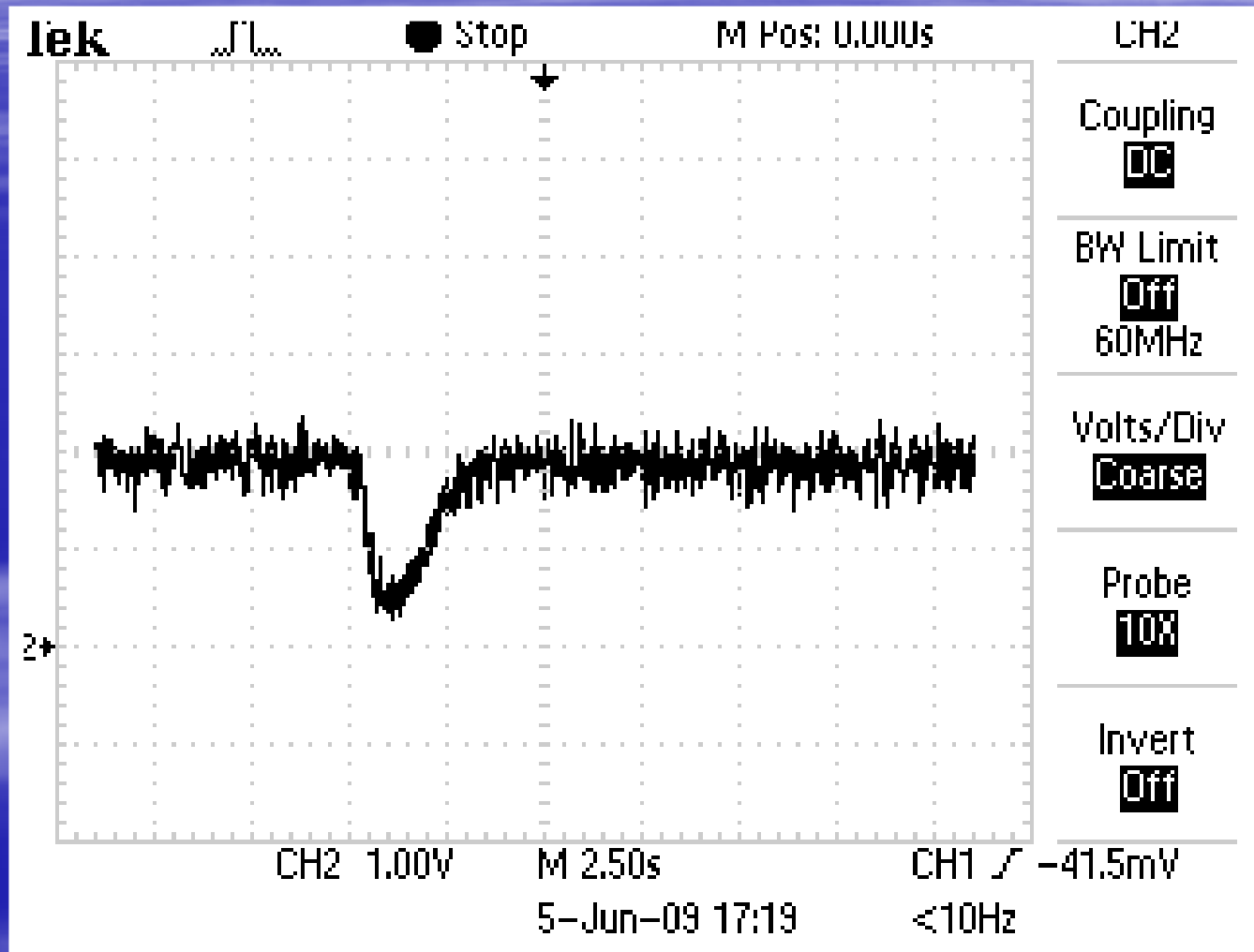
VGA Terminal, BPSK, Differential coding, Coherent Detection, SNR = 2.125 dB



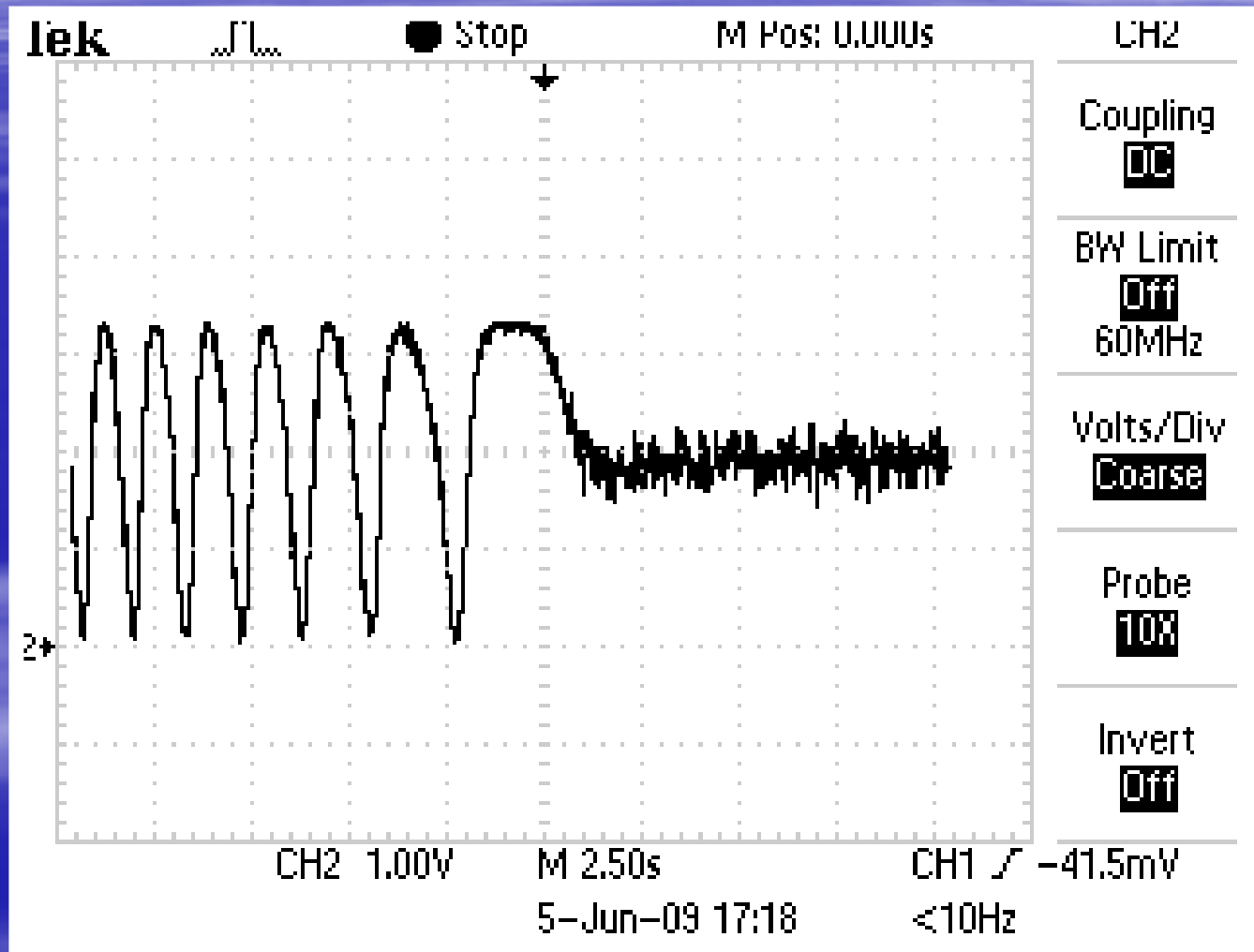
VGA Terminal, BPSK, Differential coding, Coherent Detection, SNR = -2 dB



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

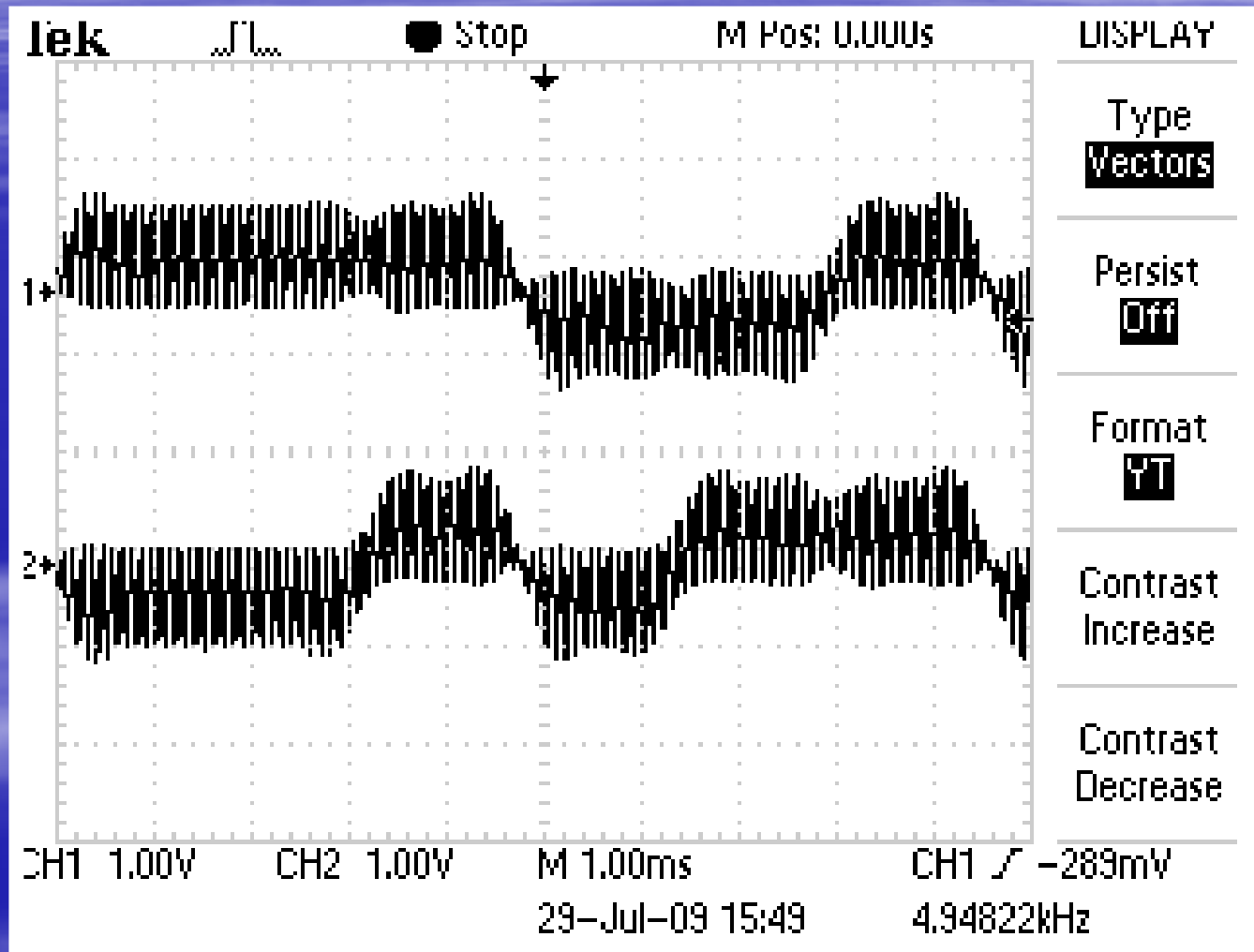


BPSK, carrier PLL phase detector output, pull-in process

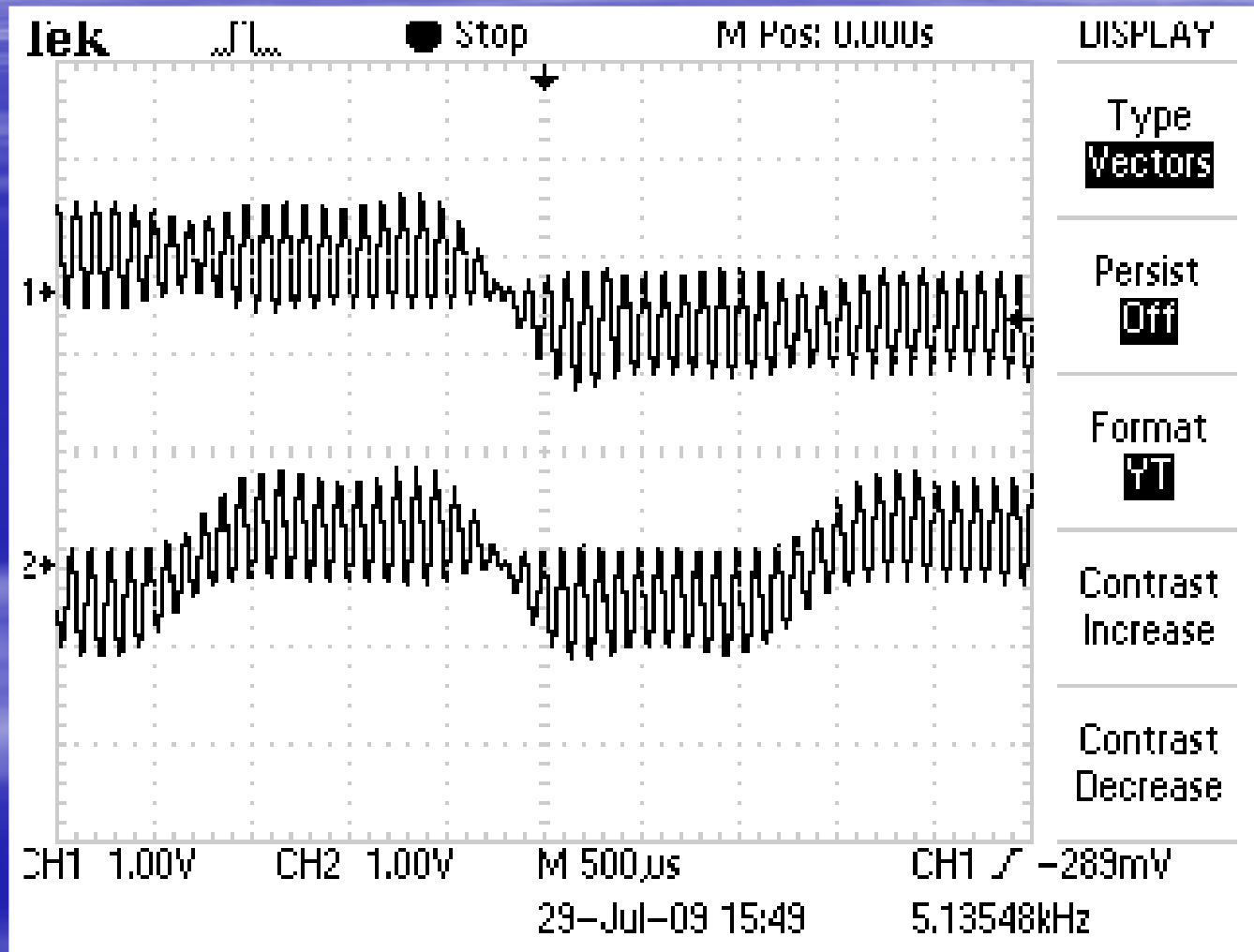


QPSK!!!!

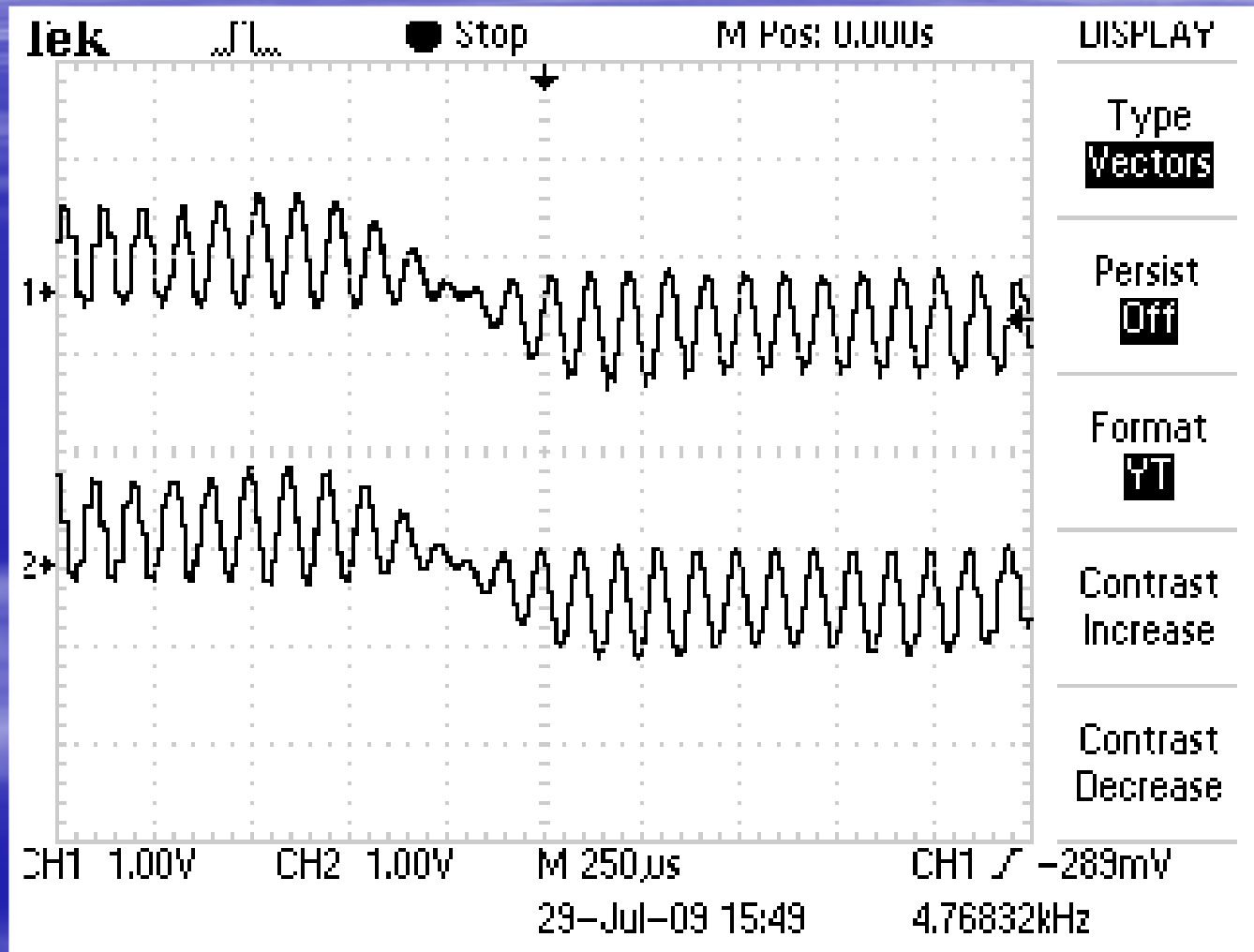
QPSK: post-IQ demodulator, SNR = 12dB



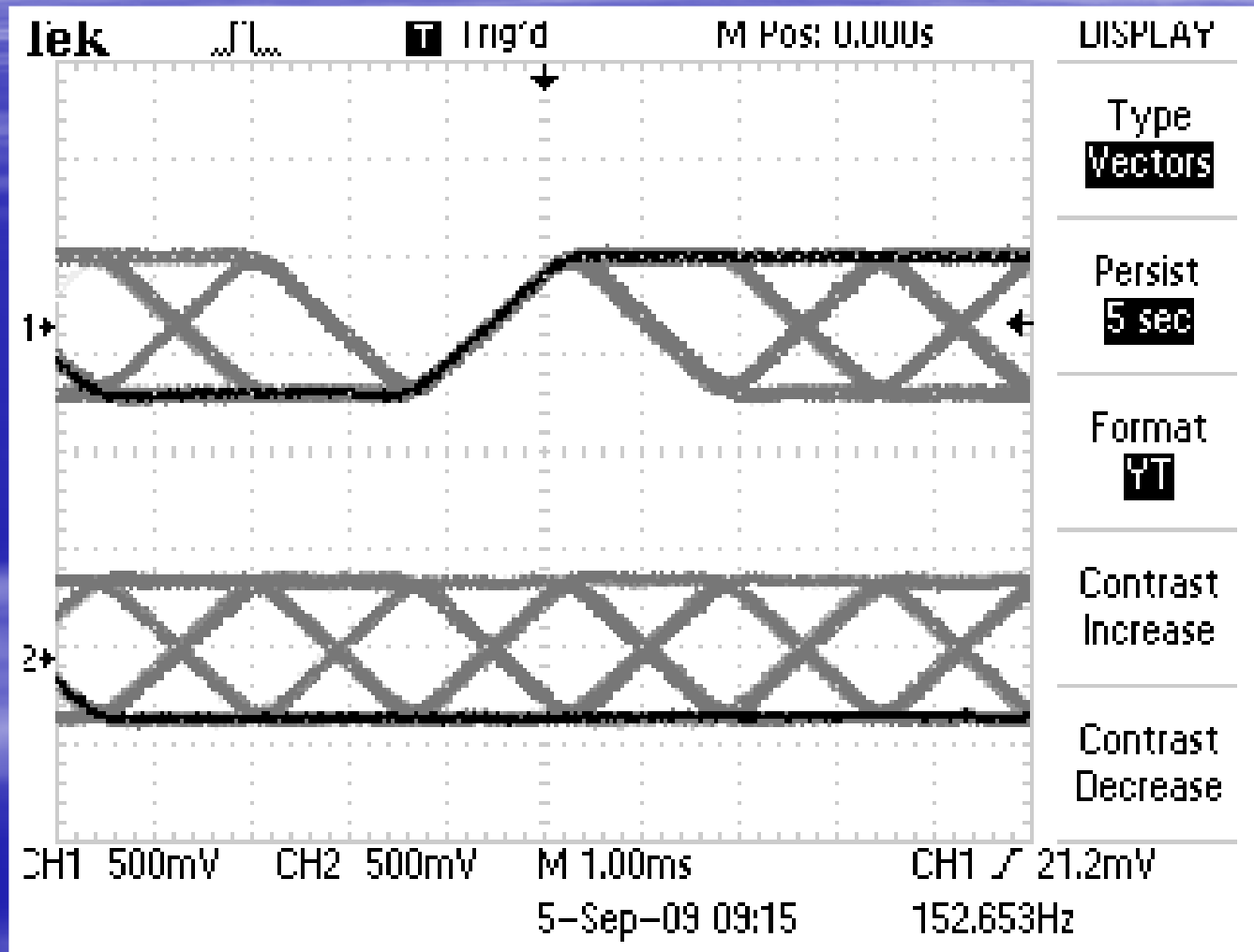
QPSK: post-IQ demodulator, SNR = 12dB, Zoom In



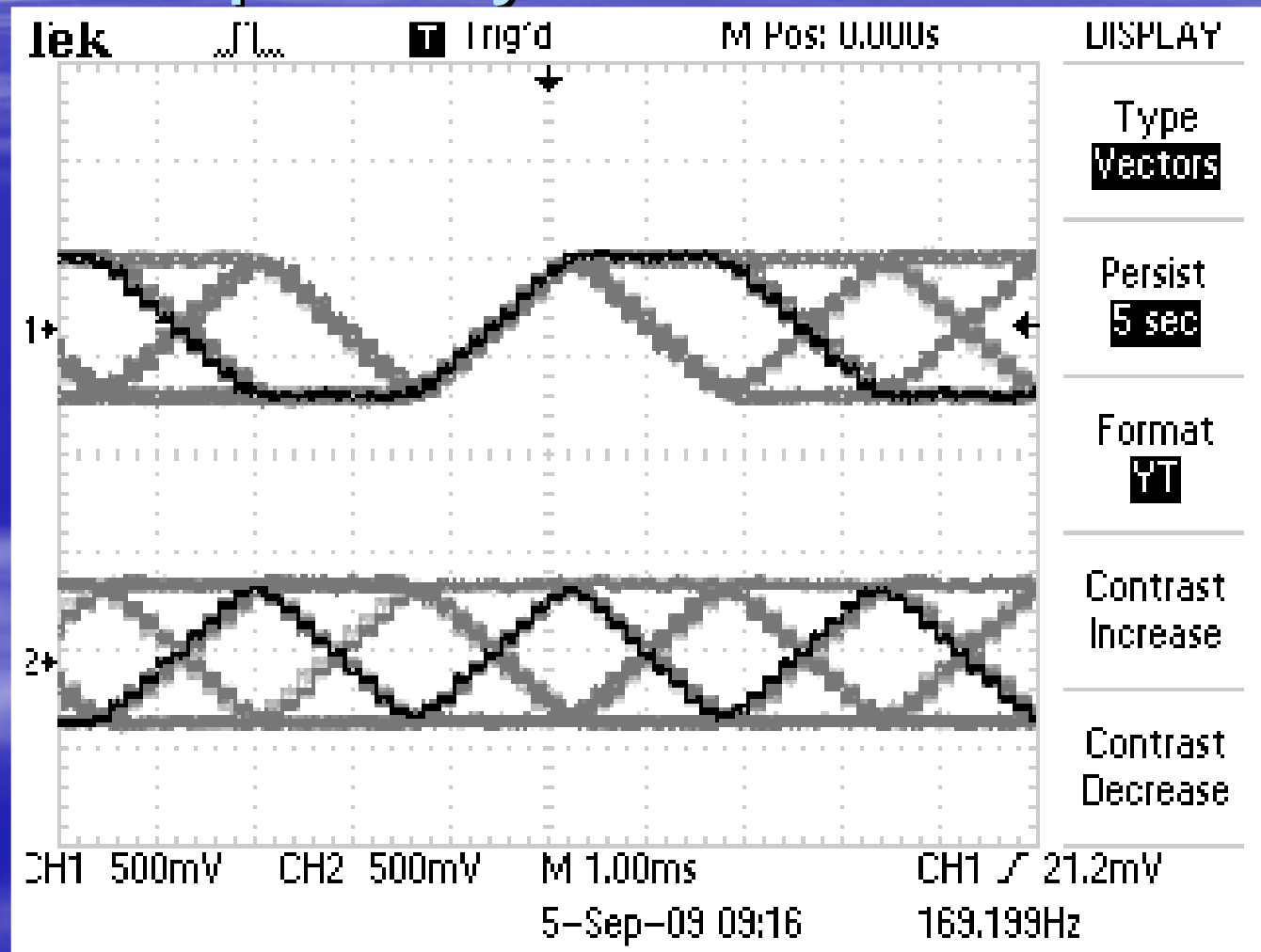
QPSK: post-IQ demodulator, SNR = 12dB, More zoom



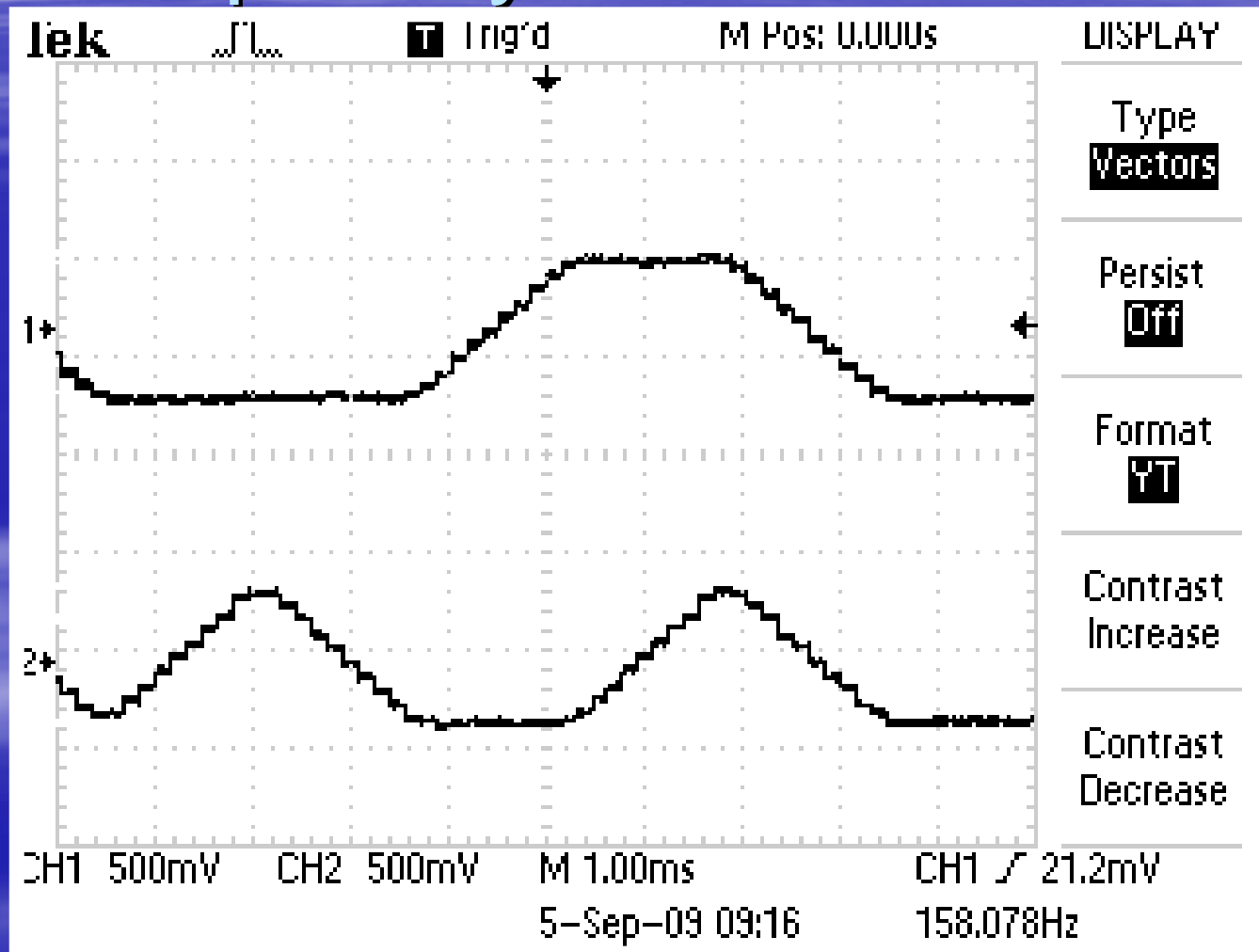
QPSK – In receiver after matched filter – no noise



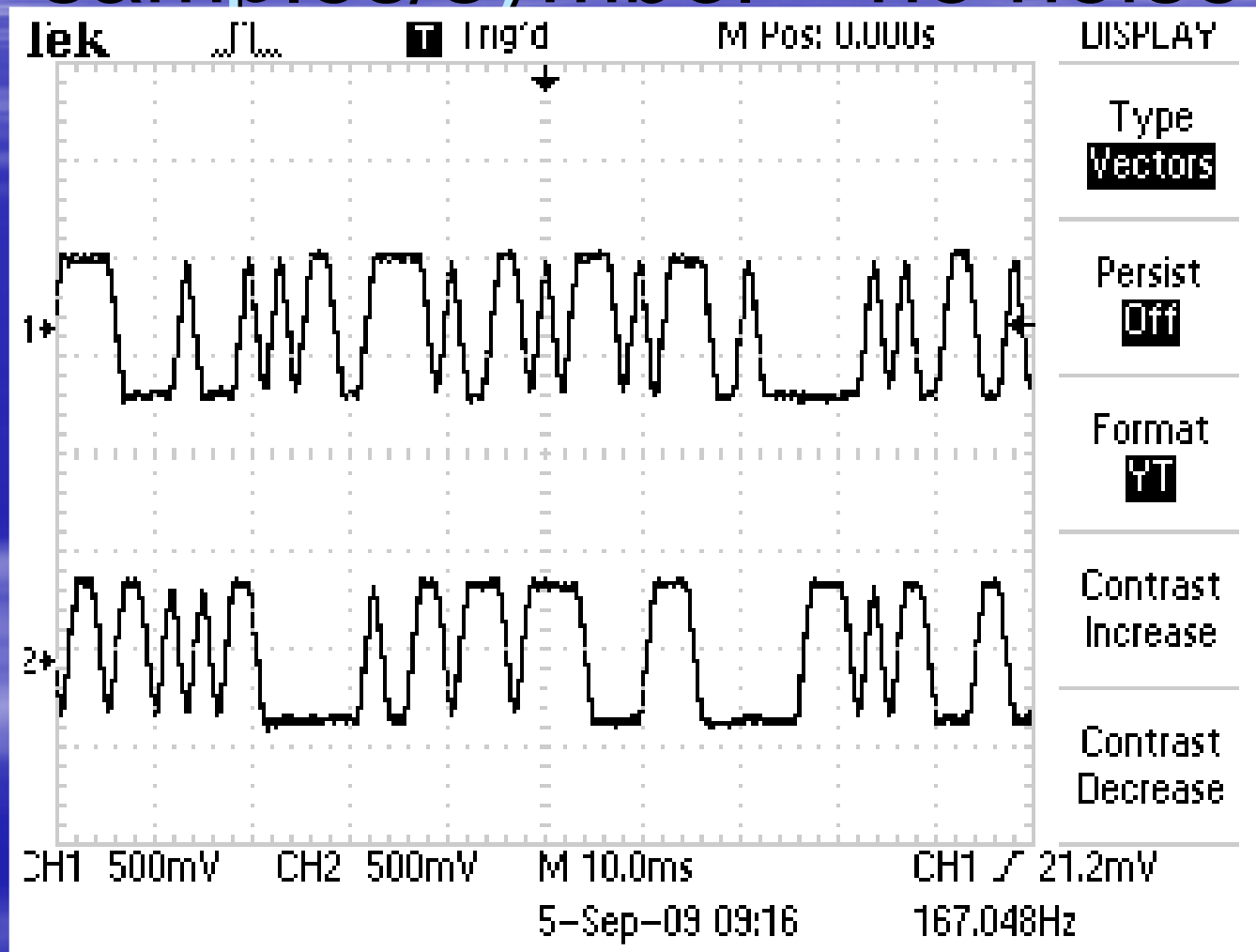
QPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



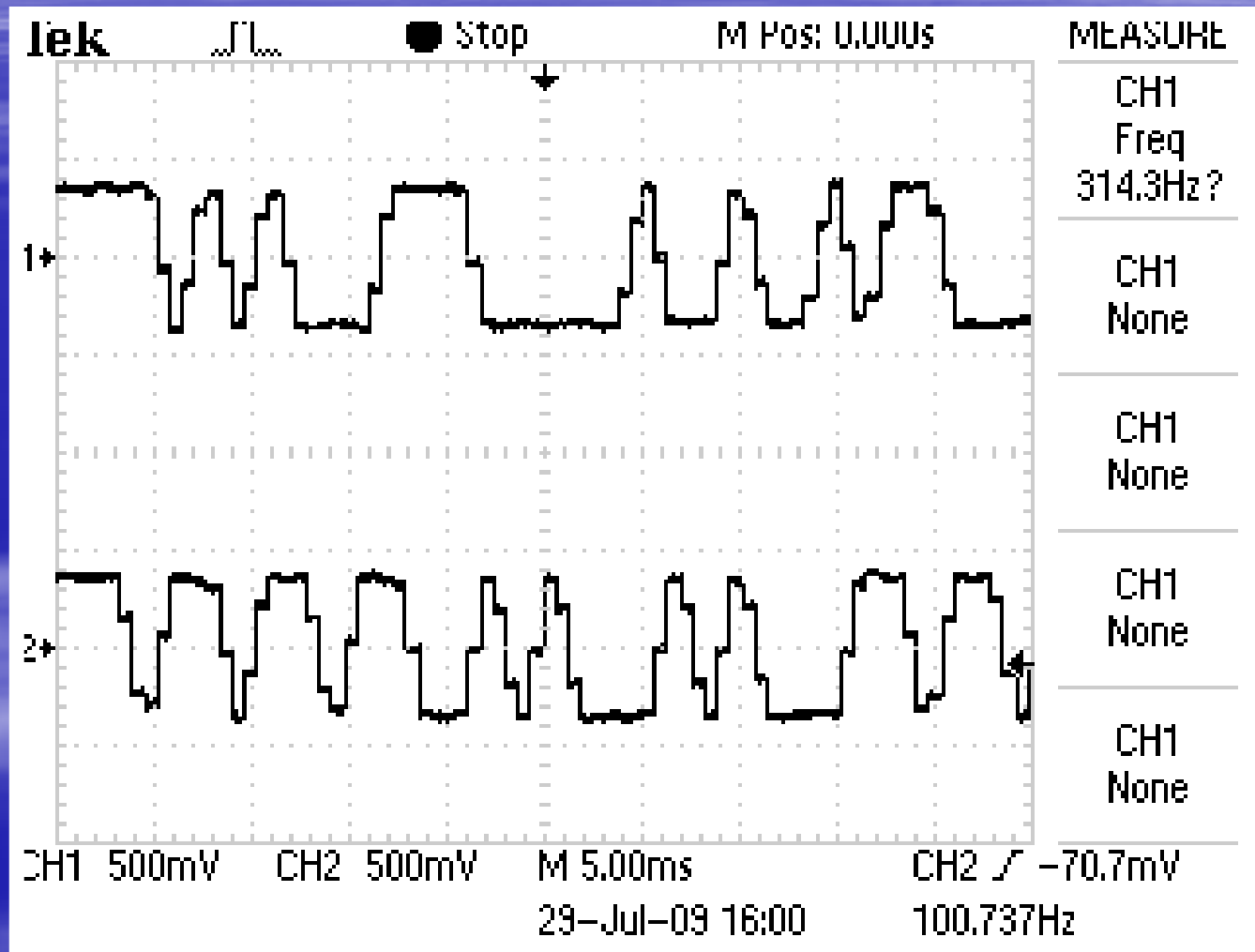
QPSK – In receiver after matched filter – After downsampling to 10 samples/symbol – no noise



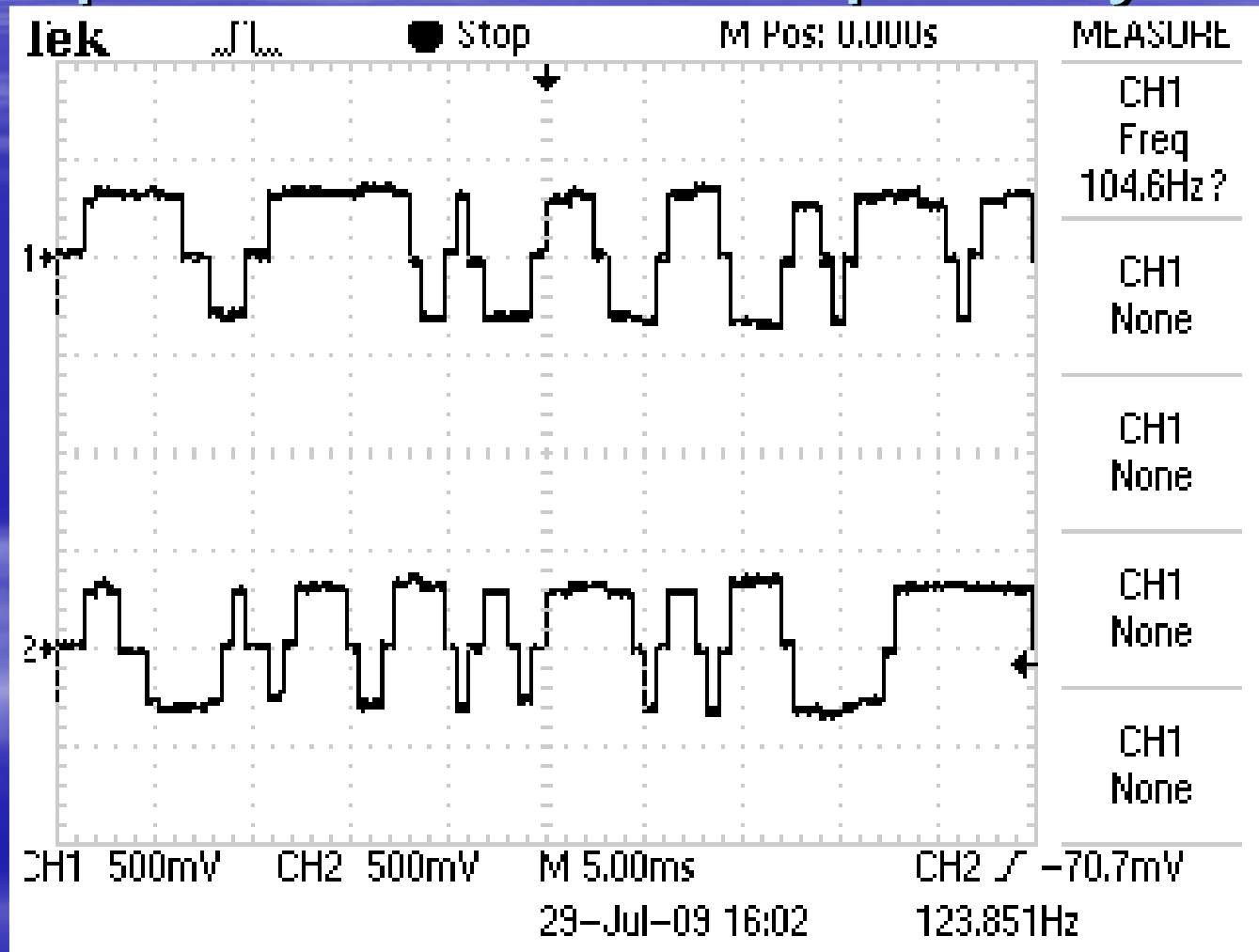
QPSK – In receiver after matched filter – After downsampling to 5 samples/symbol – no noise



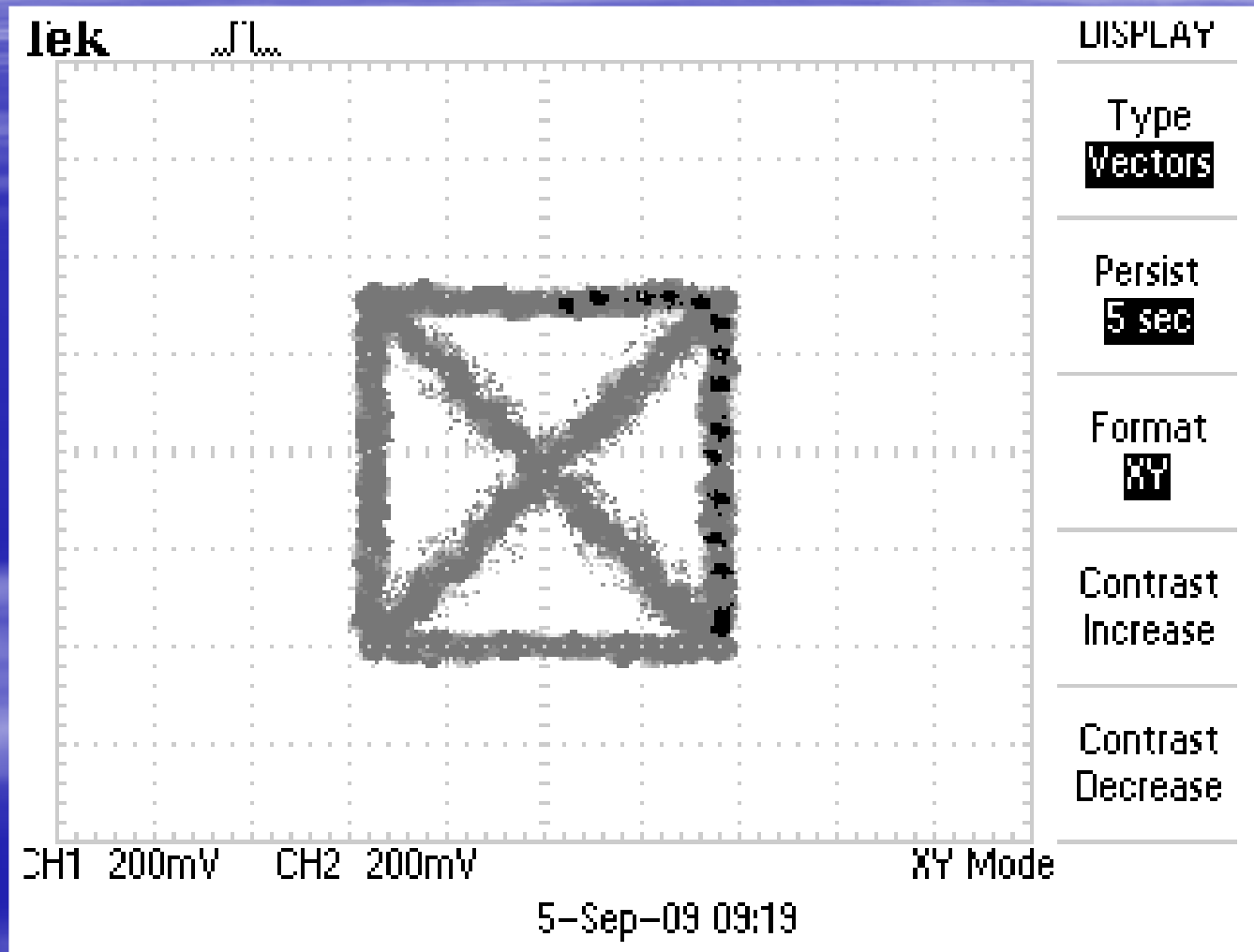
QPSK: after matched filter, carrier synchronized, 2.5 samples/symbol



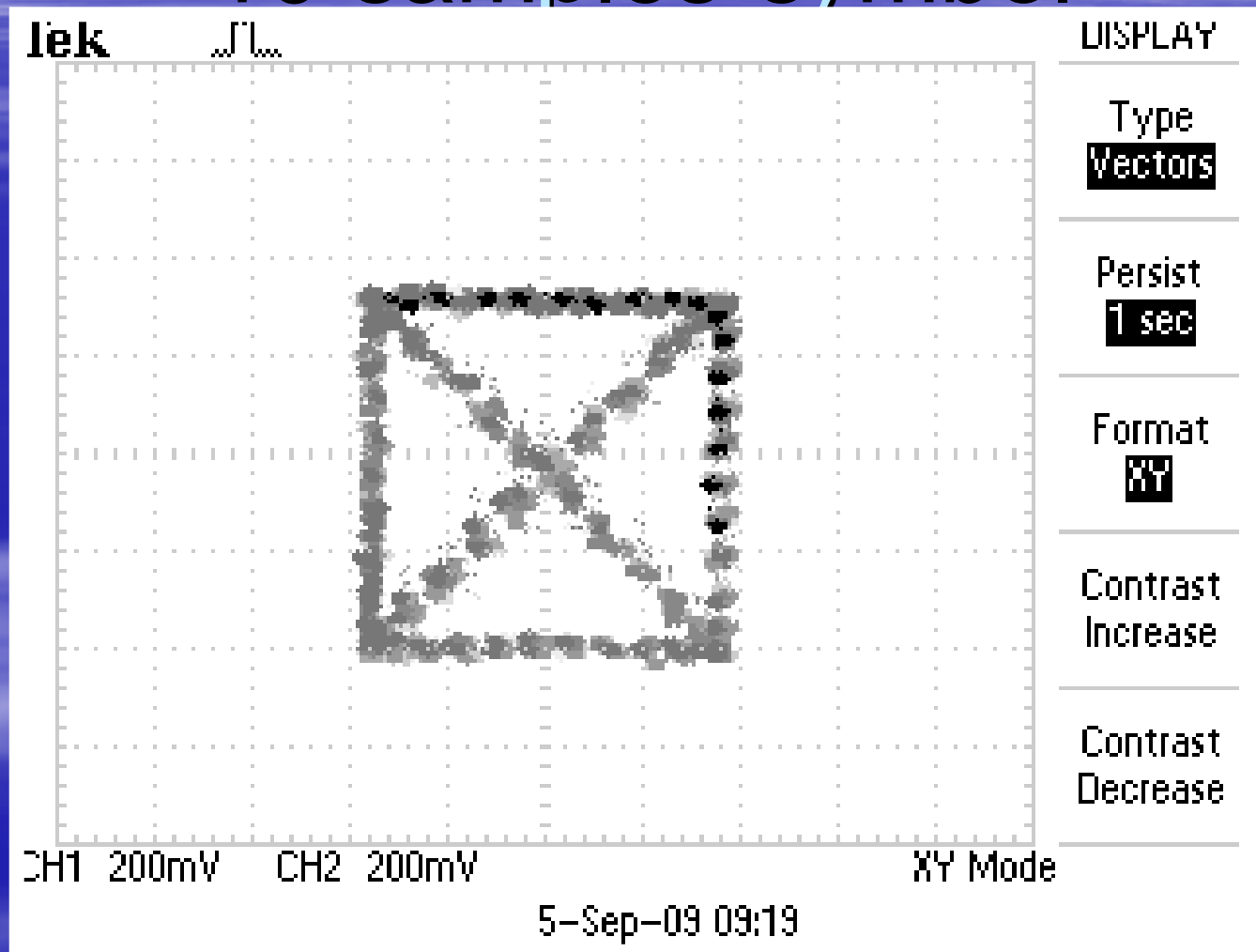
QPSK – I and Q at receiver, after synchronization and resampling interpolation to 2-samples/symbol



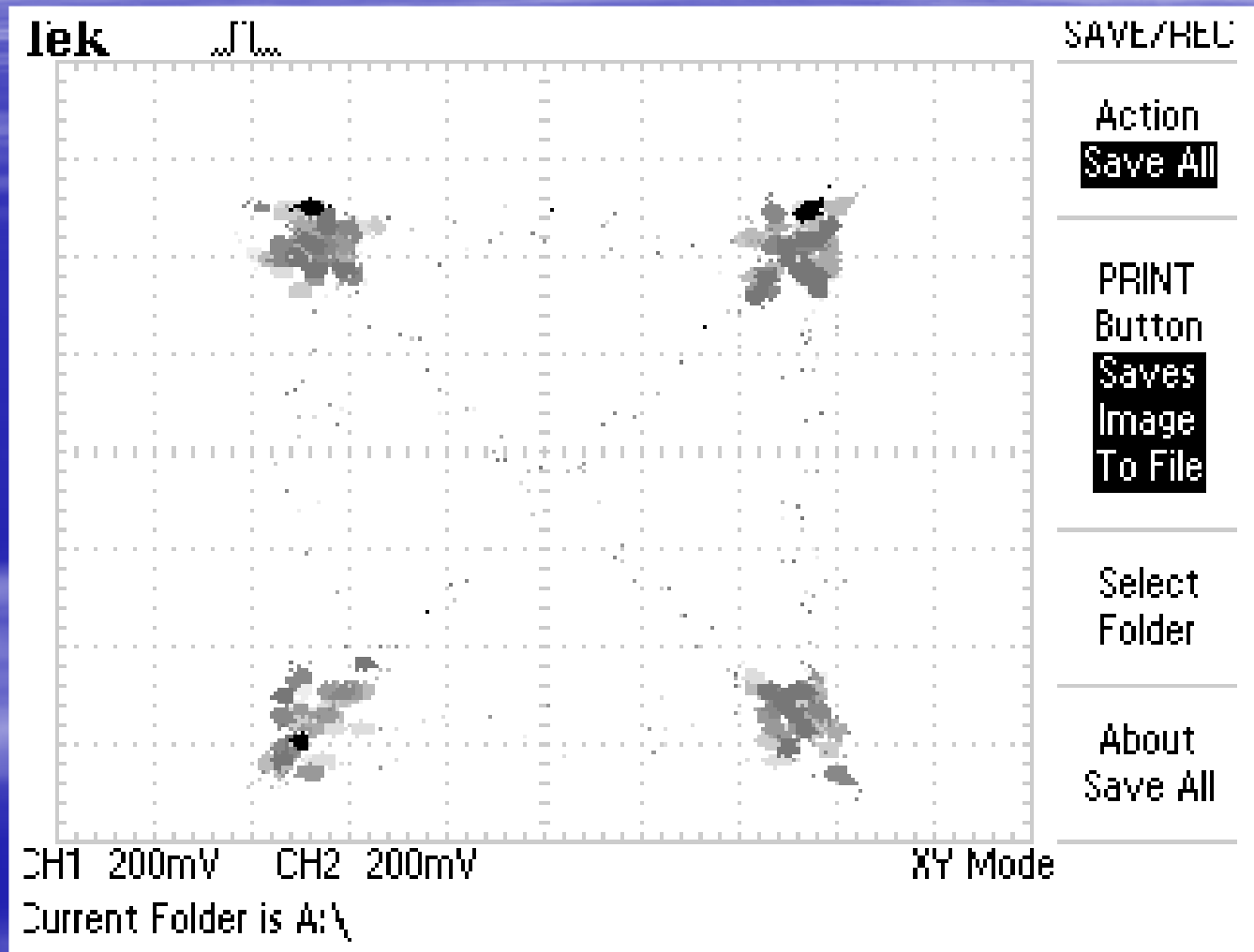
QPSK, X-Y graph of I vs. Q after matched filter



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

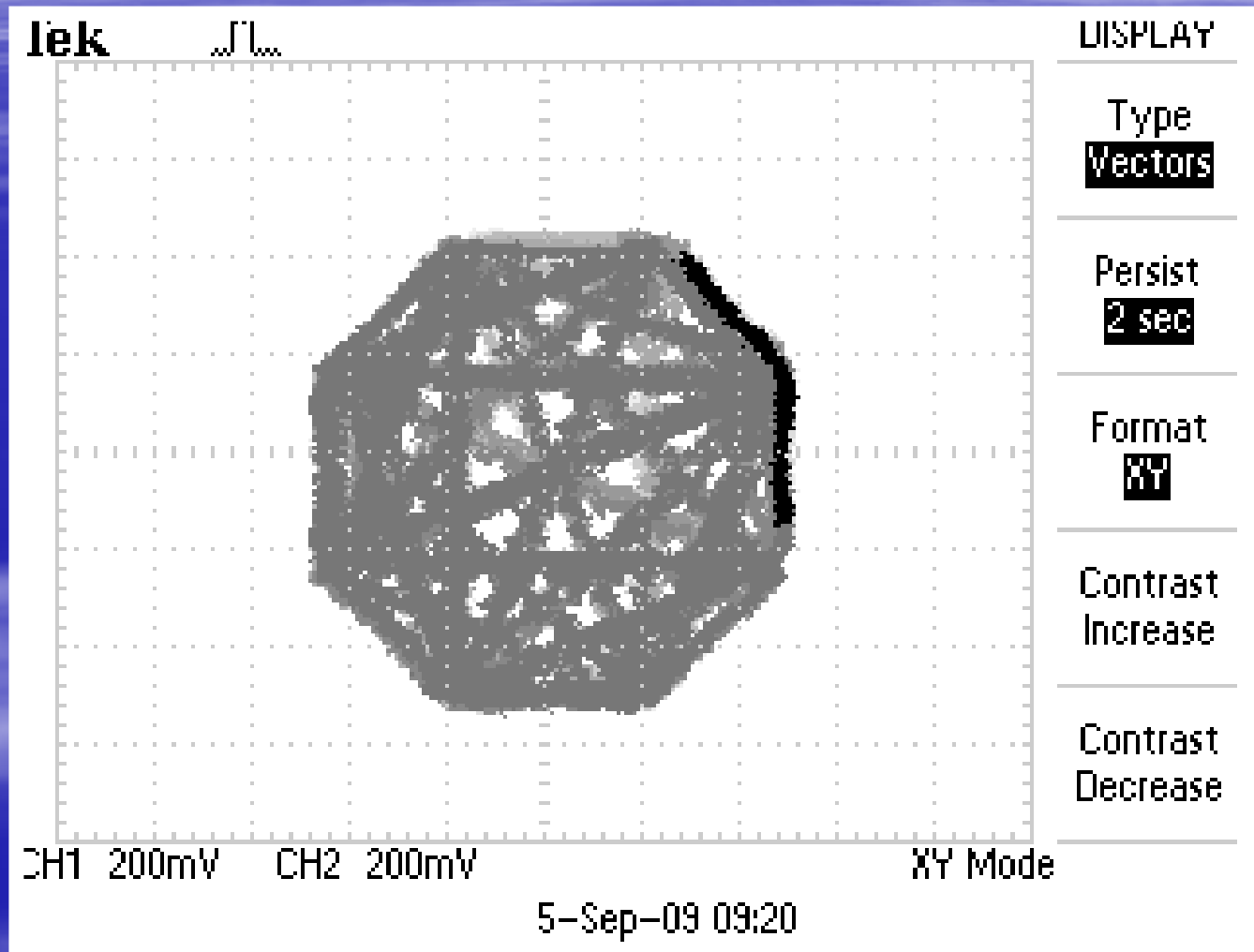


QPSK – at output of receiver, SNR = 12 dB, 1 sample/symbol

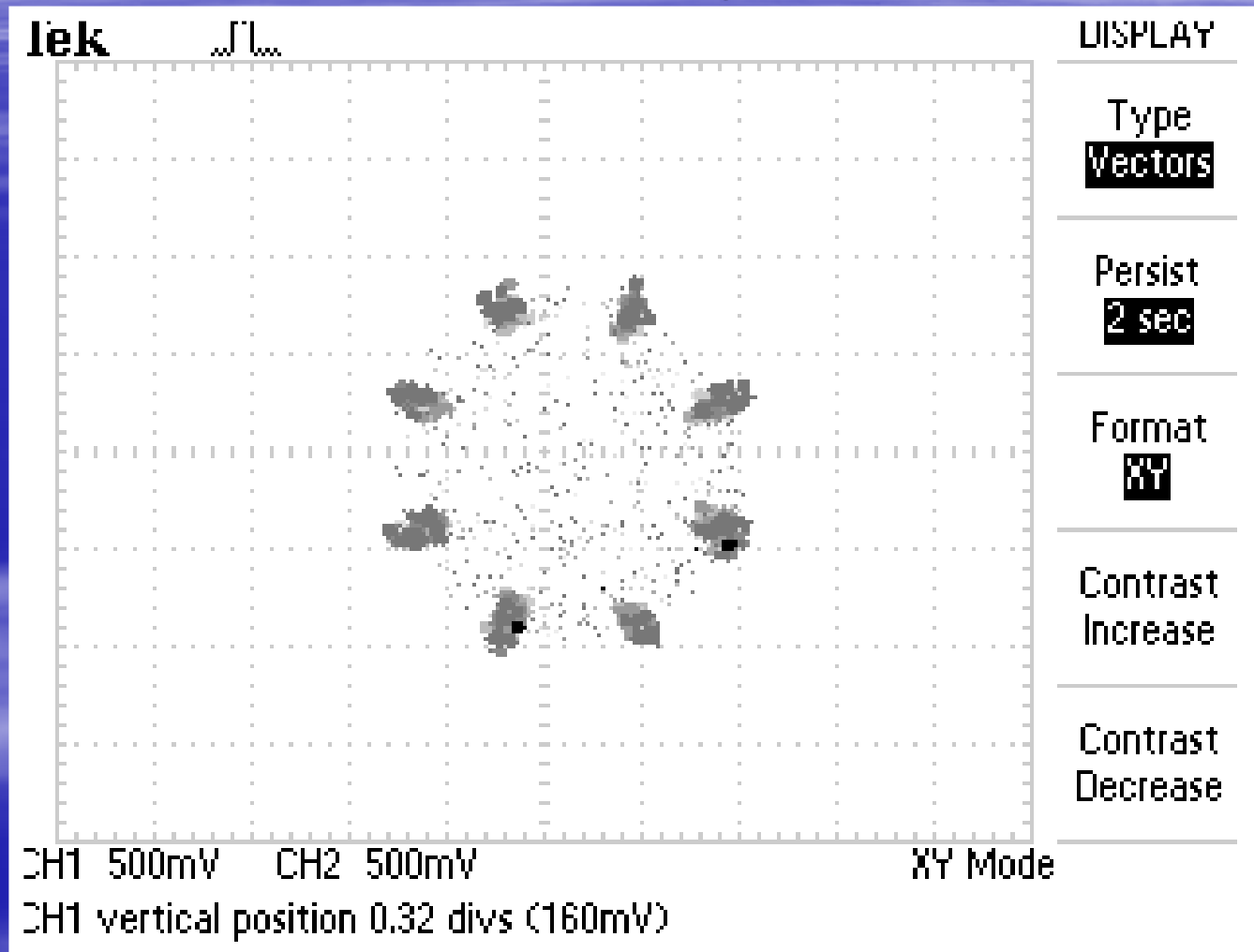


8-PSK

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

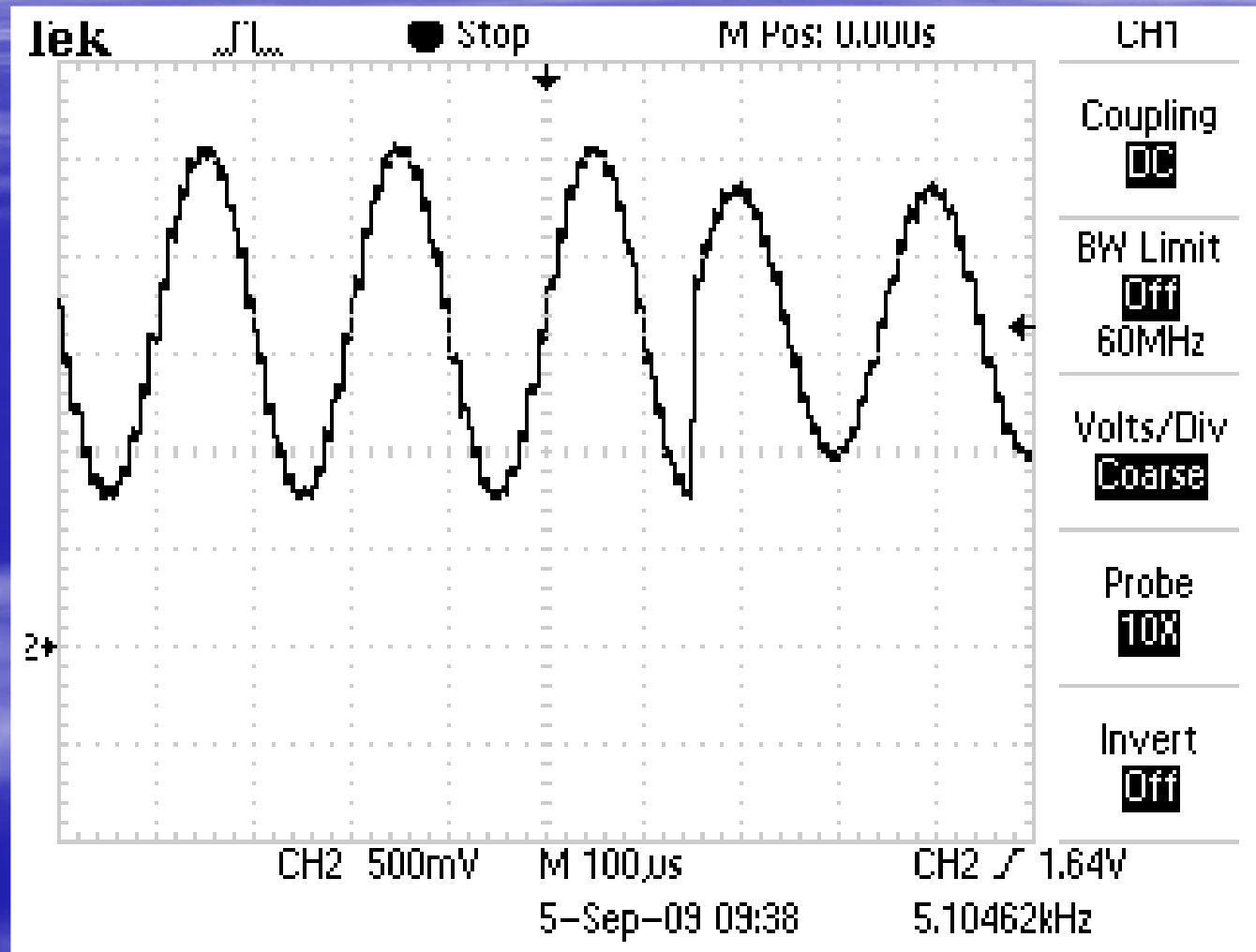


8-PSK after demodulation, 1 sample/symbol

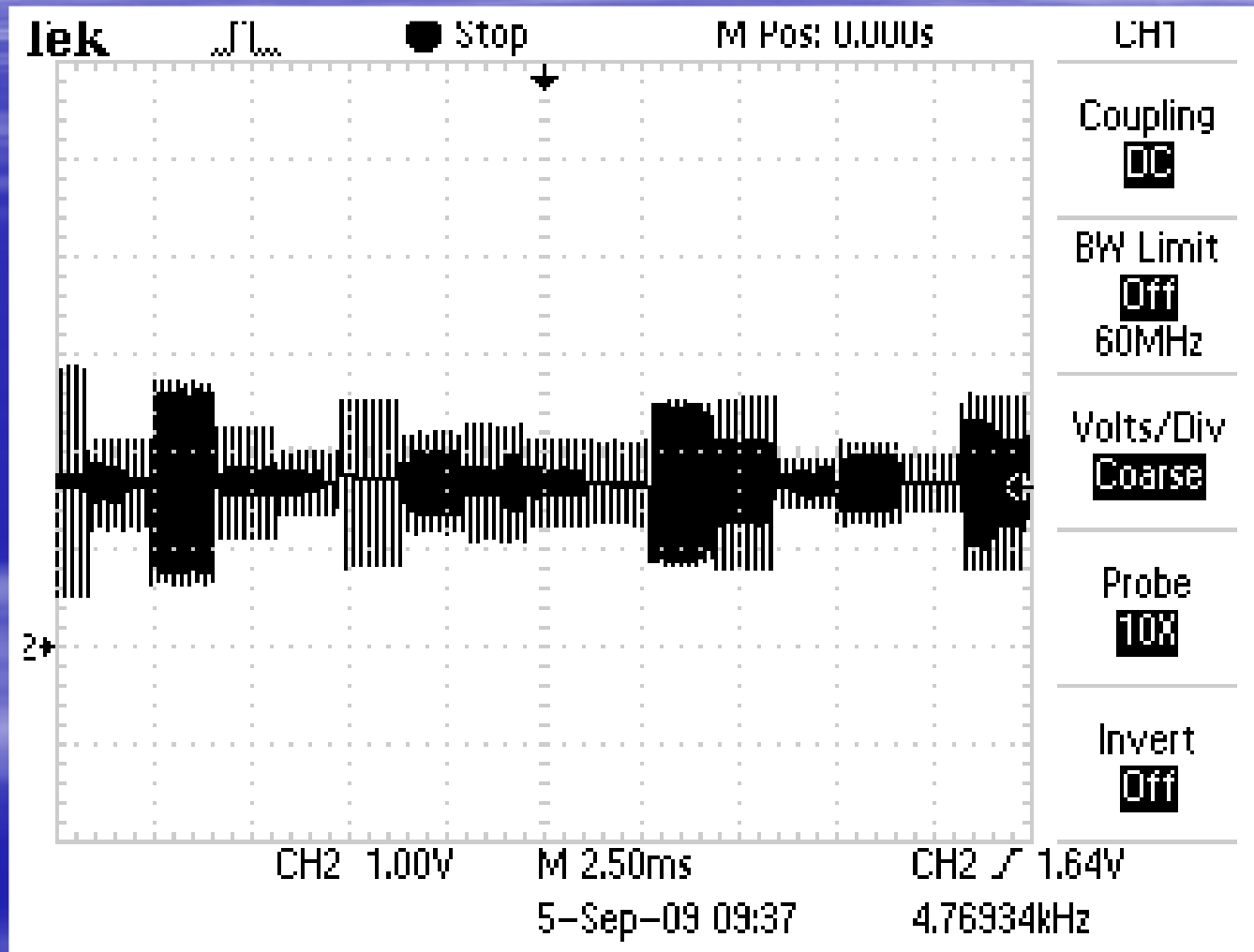


QAM

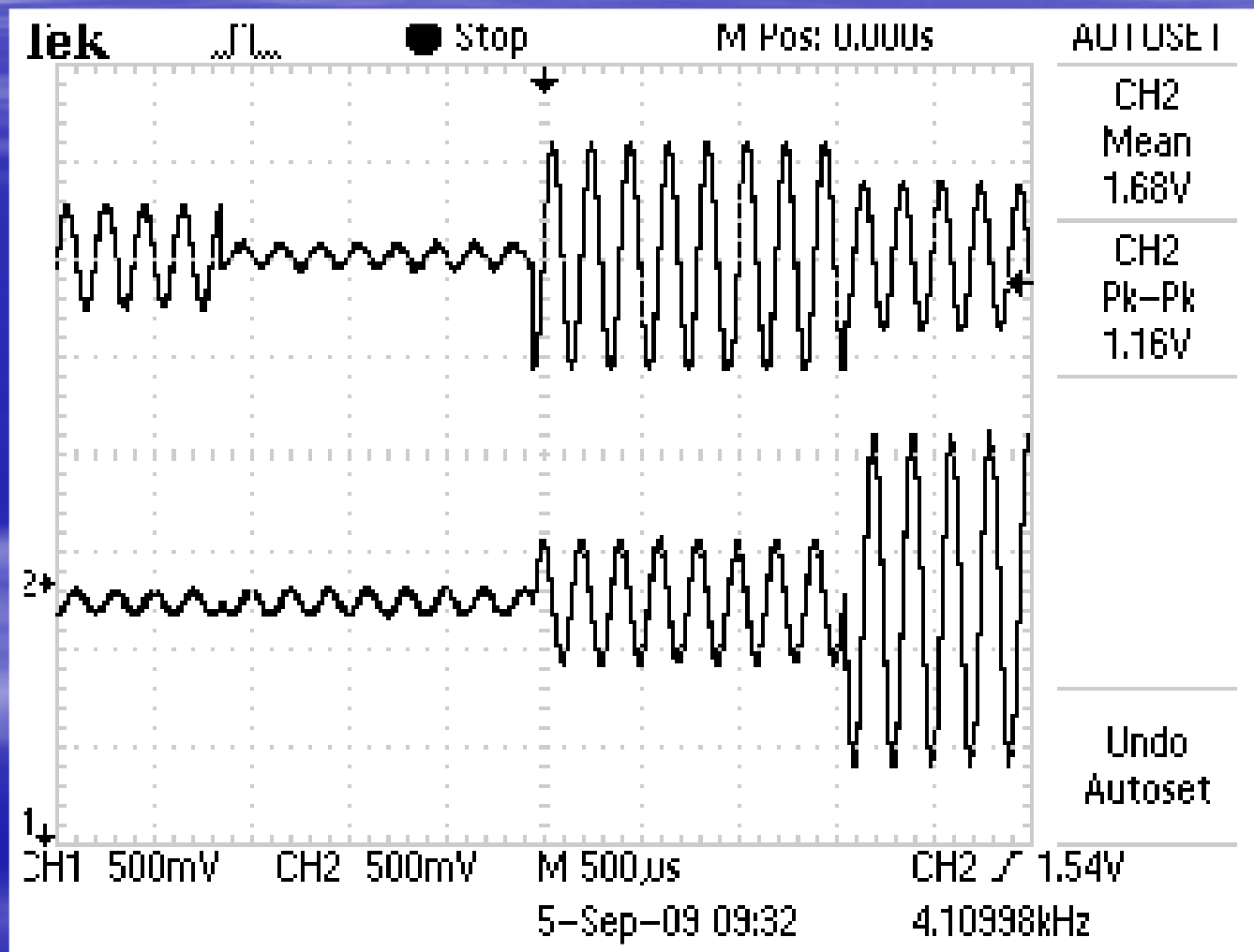
Transition in transmitted wave – 16-QAM modulation



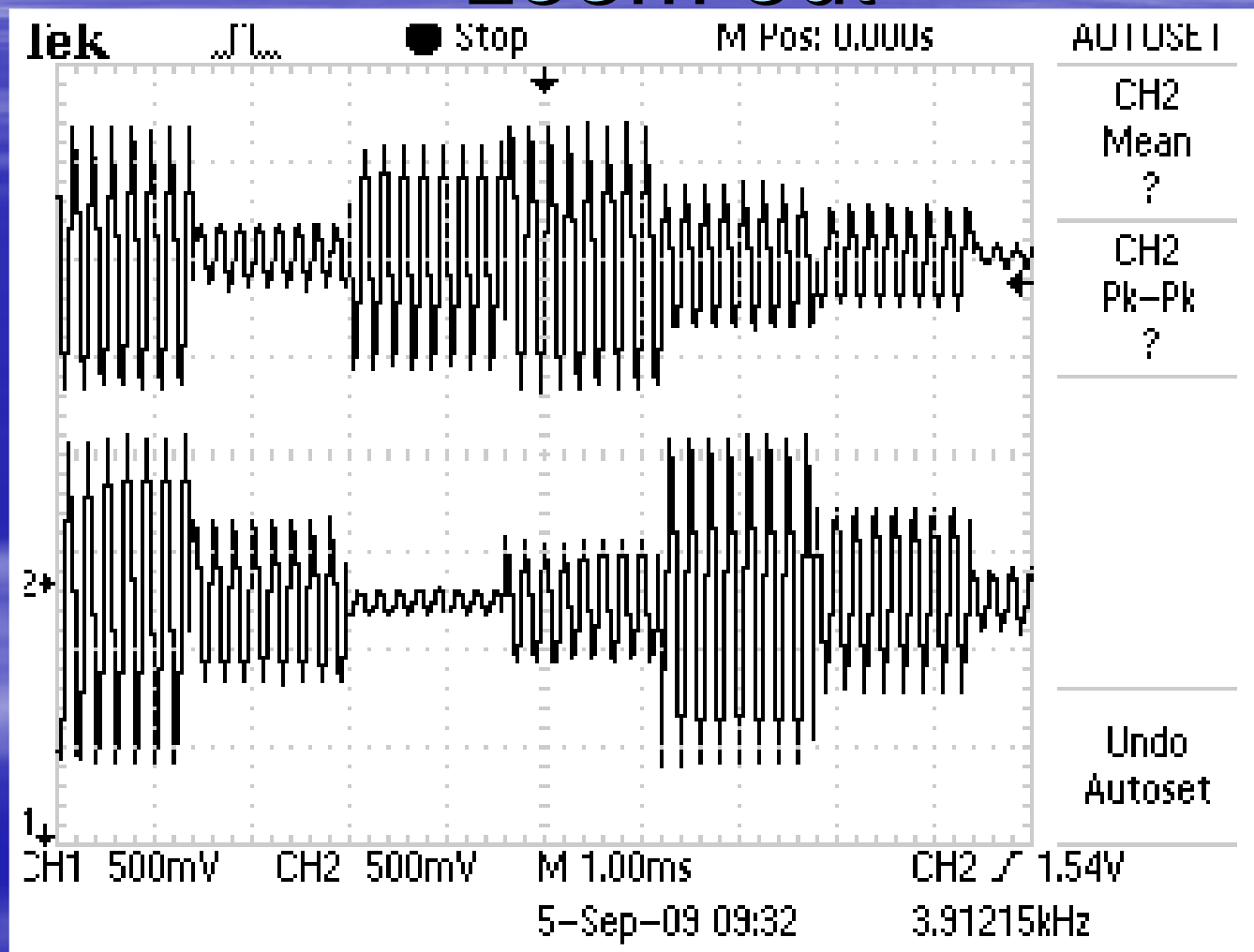
16-QAM Transmitted wave -



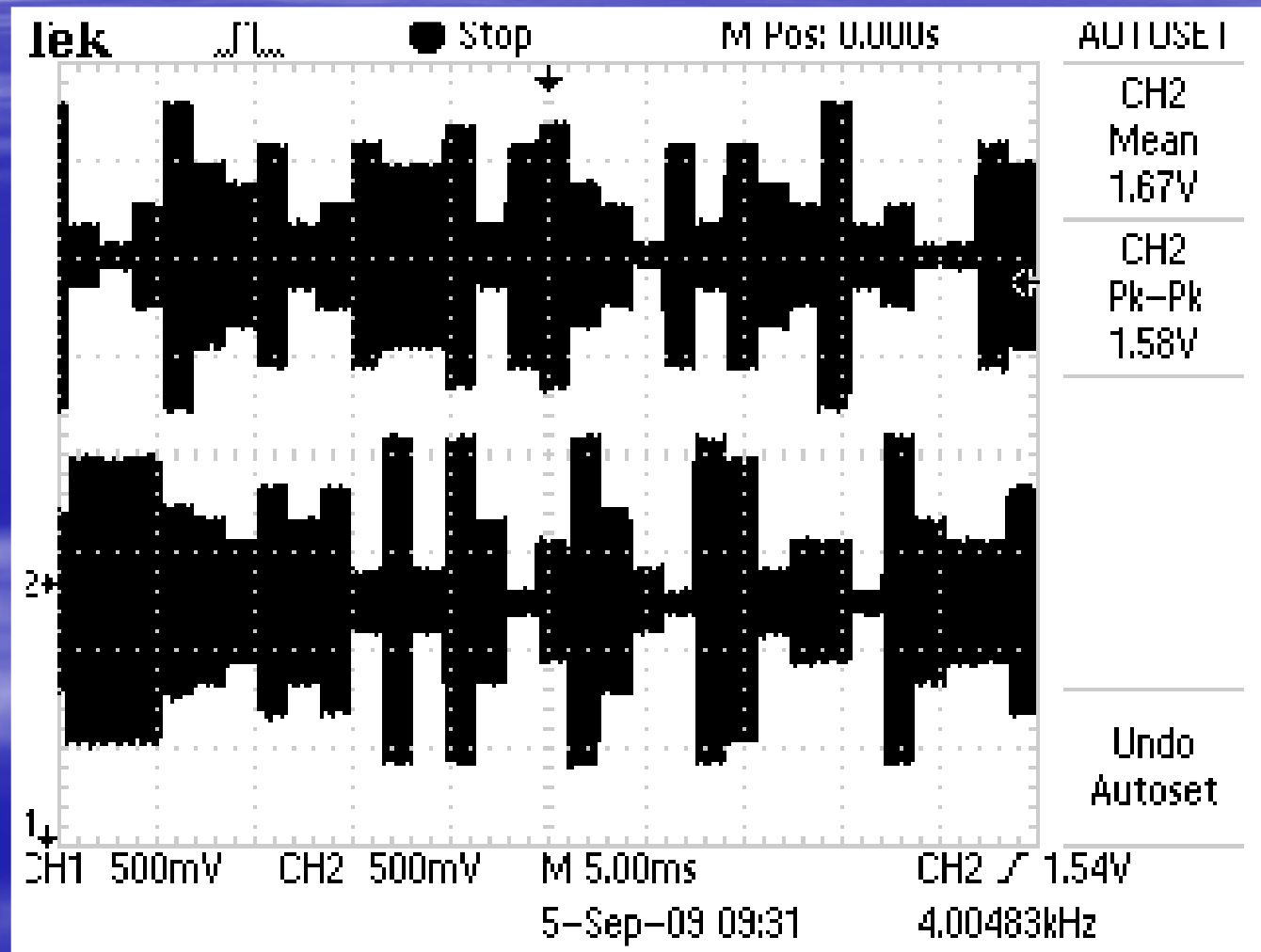
64-QAM I and Q arms before addition in transmitter



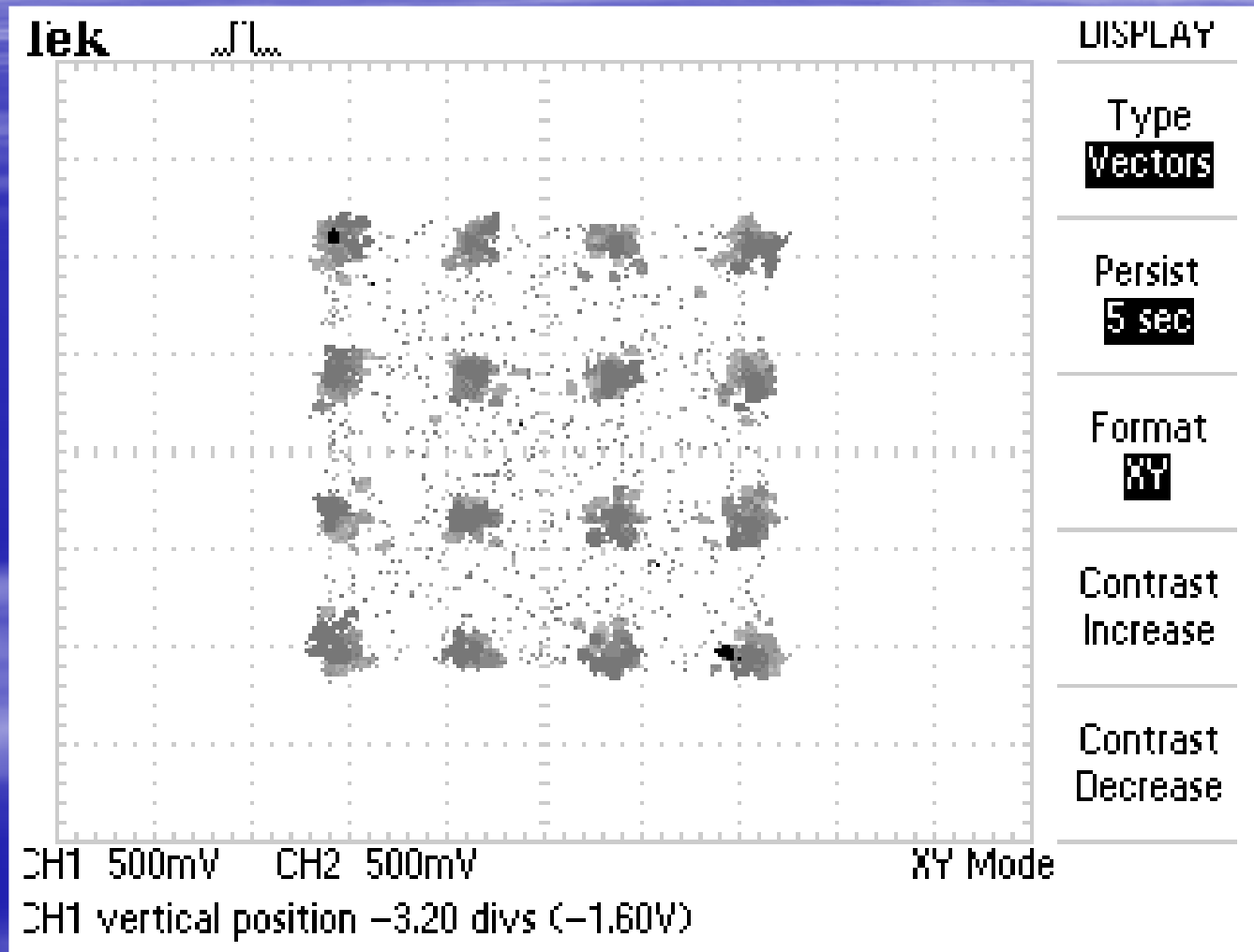
64-QAM I and Q arms before addition in transmitter - zoom out



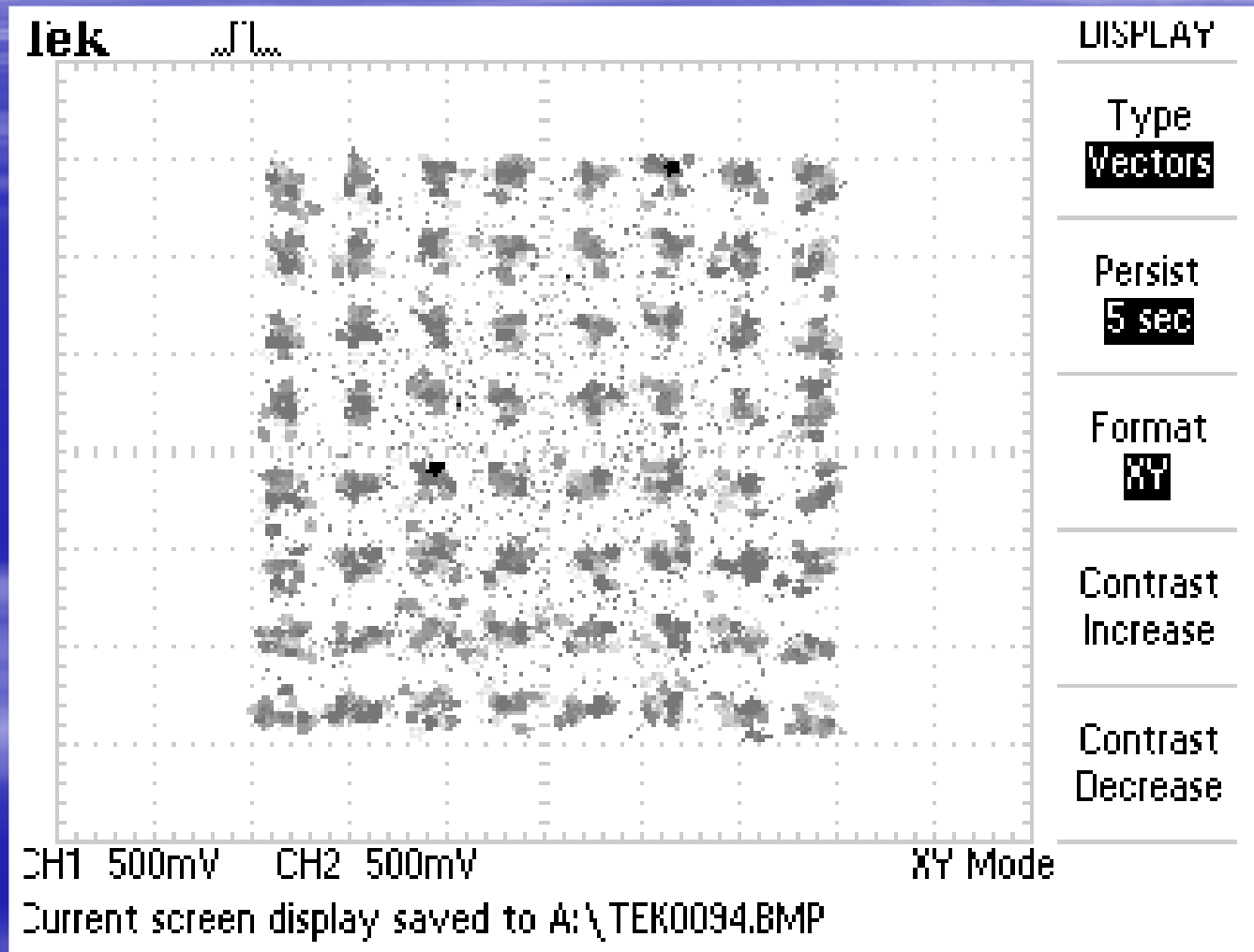
256-QAM I and Q arms before addition in transmitter - zoom out



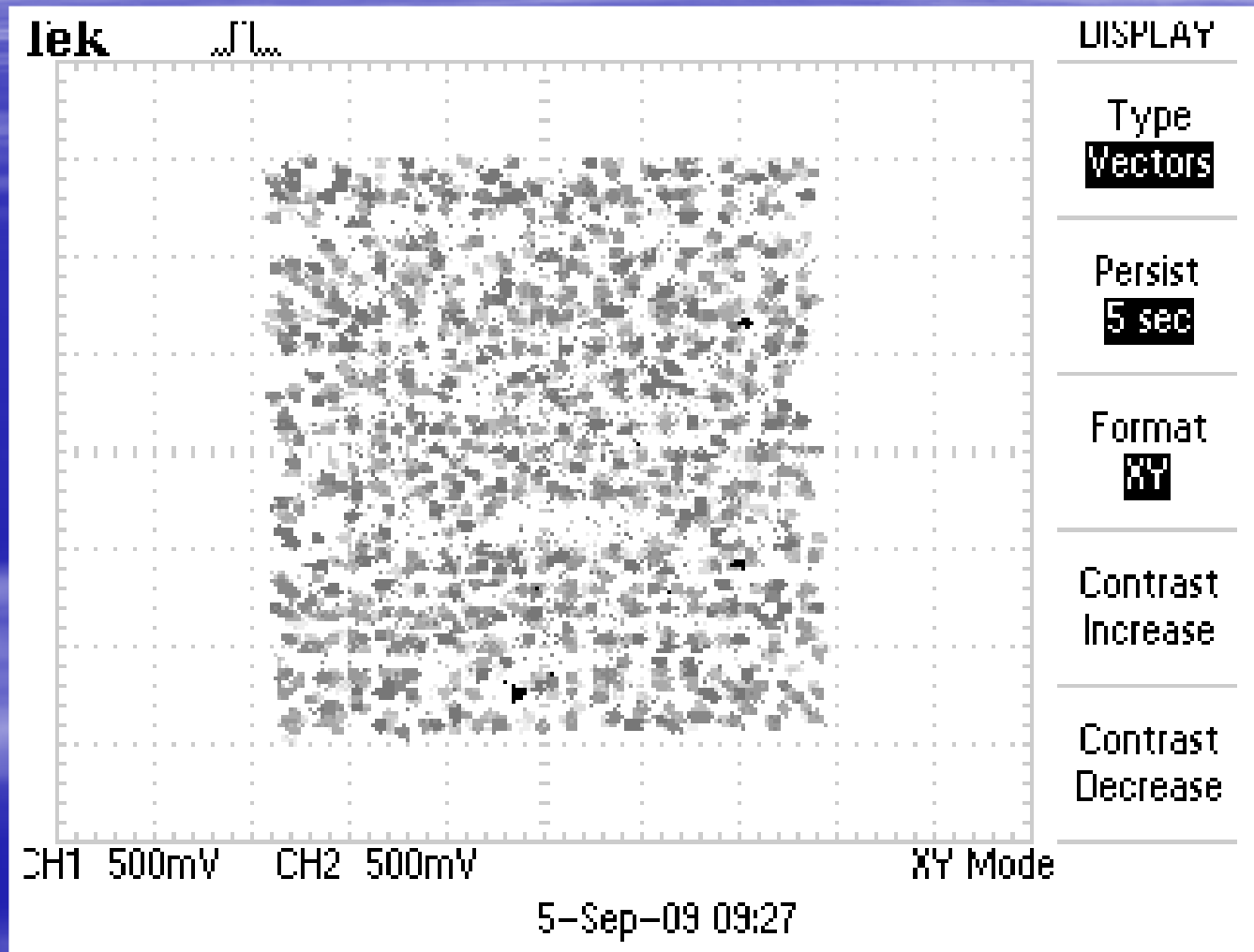
16-QAM received constellation



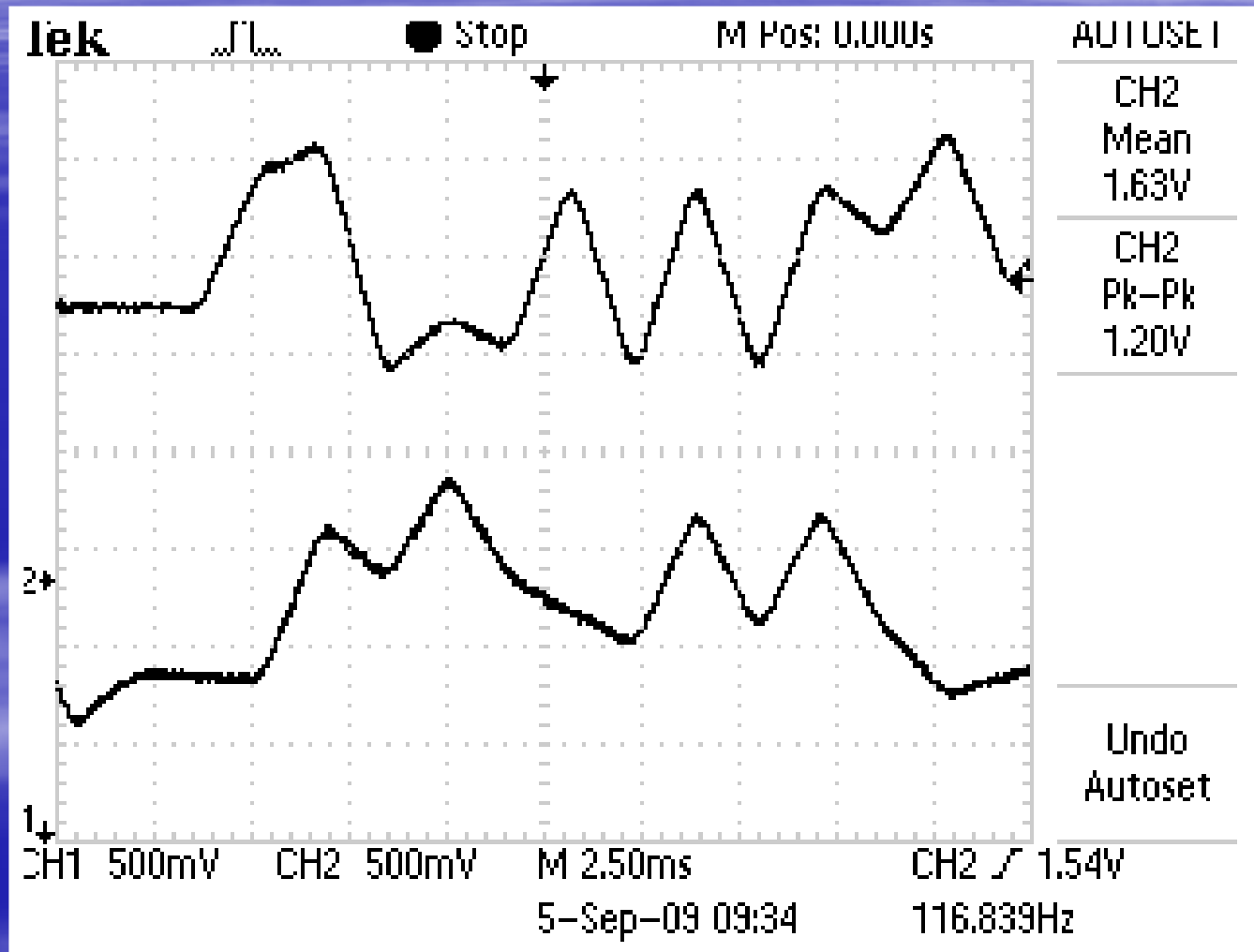
64-QAM received constellation



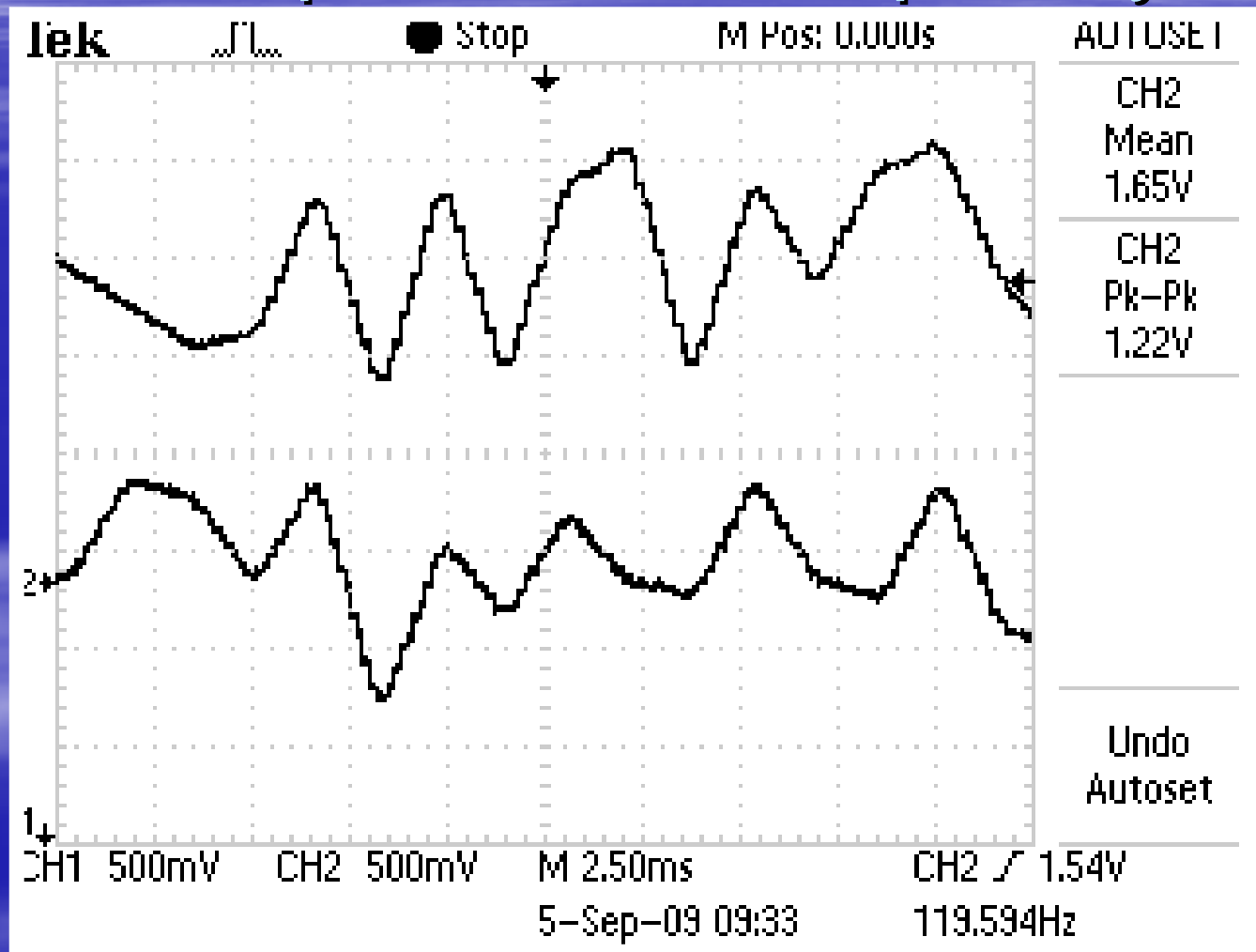
256 QAM received constellation – with slight carrier phase error



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

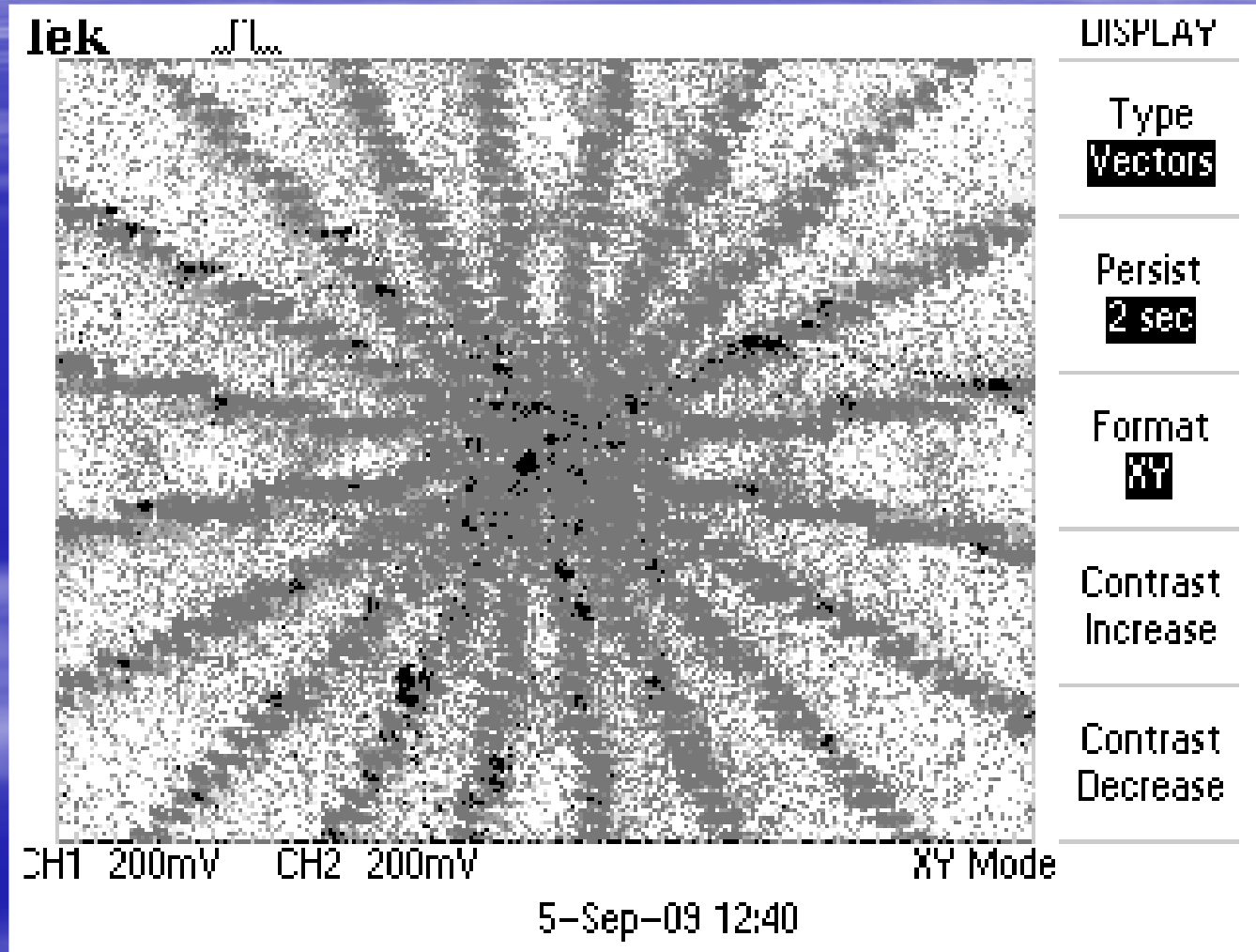


Demodulated post-matched-filter 256-QAM I and Q, no noise downsampled to 10-samples/symbol

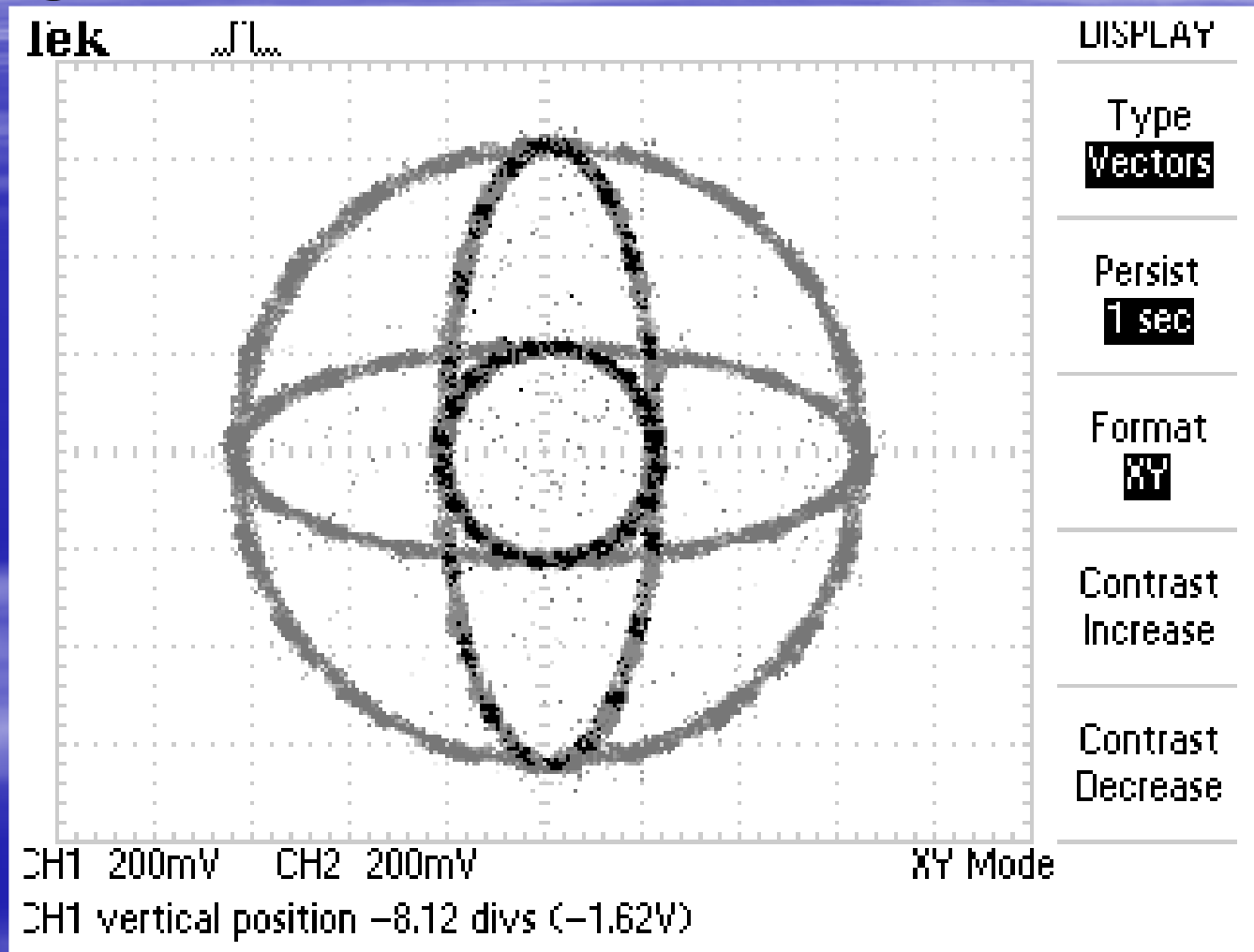


Various nice pictures....

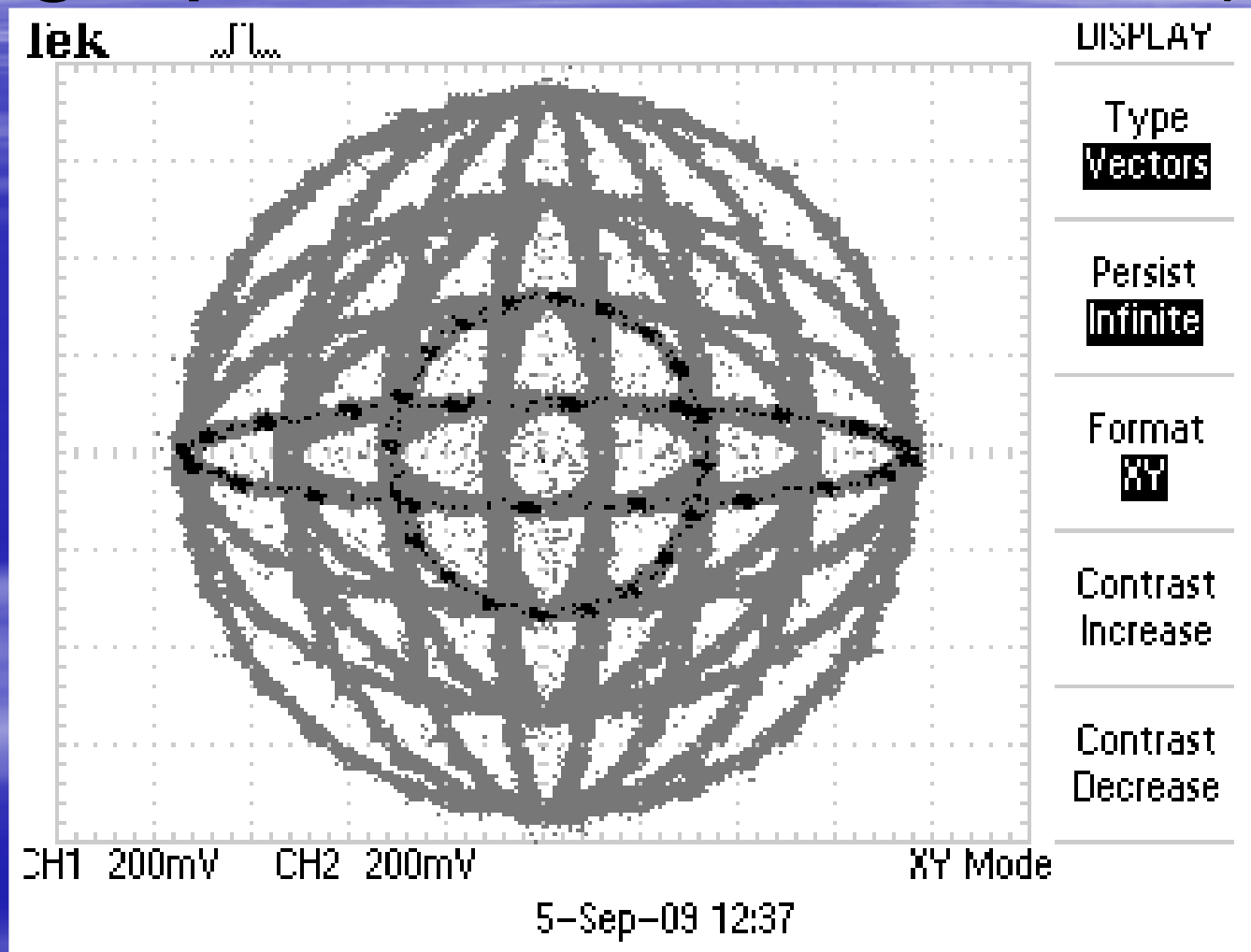
I-Q graph of post I-Q Demod (pre-matched filter)



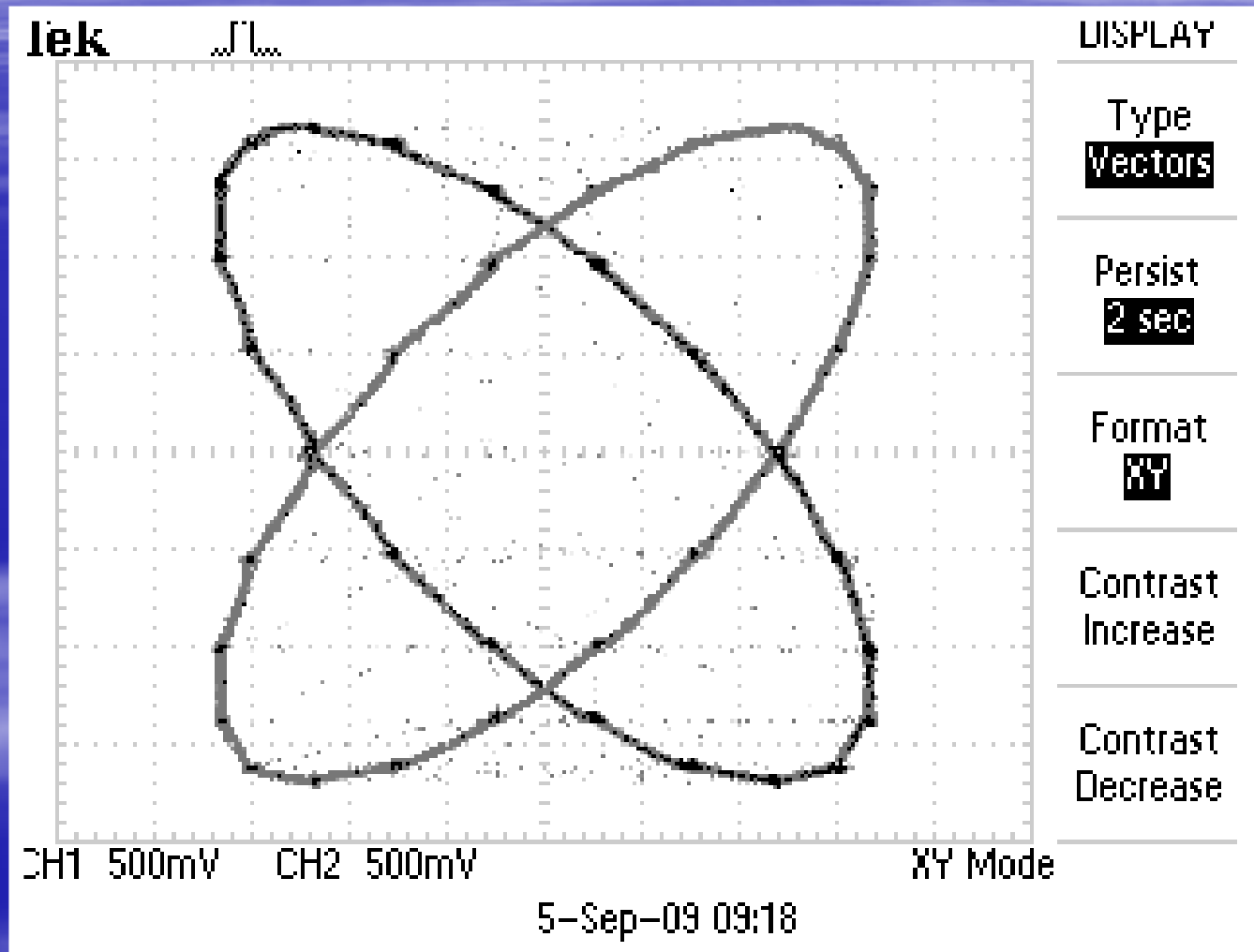
16-QAM Transmission (X-Y graph of I vs. Q TX arms)



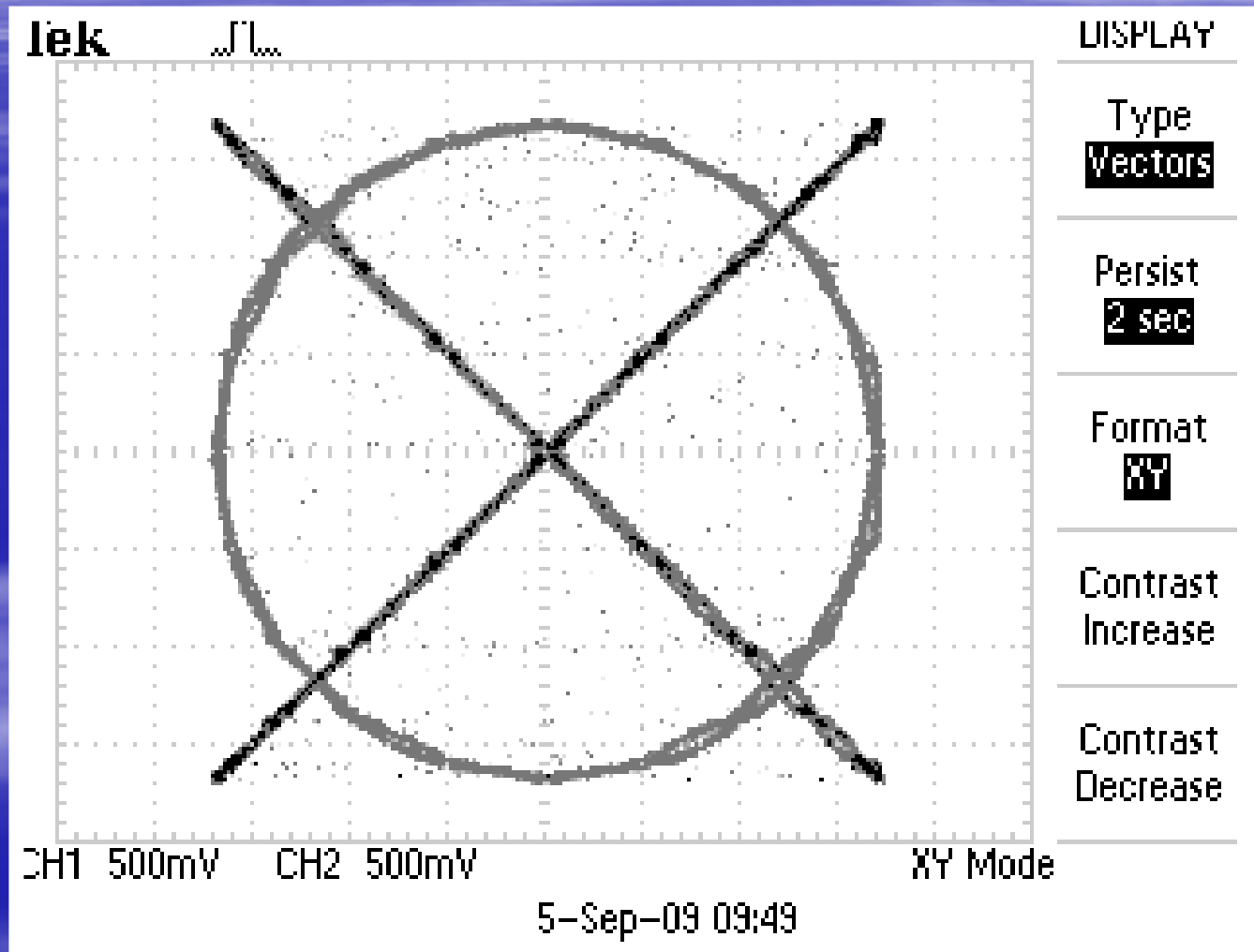
64-QAM Transmission (X-Y graph of I vs. Q TX arms)



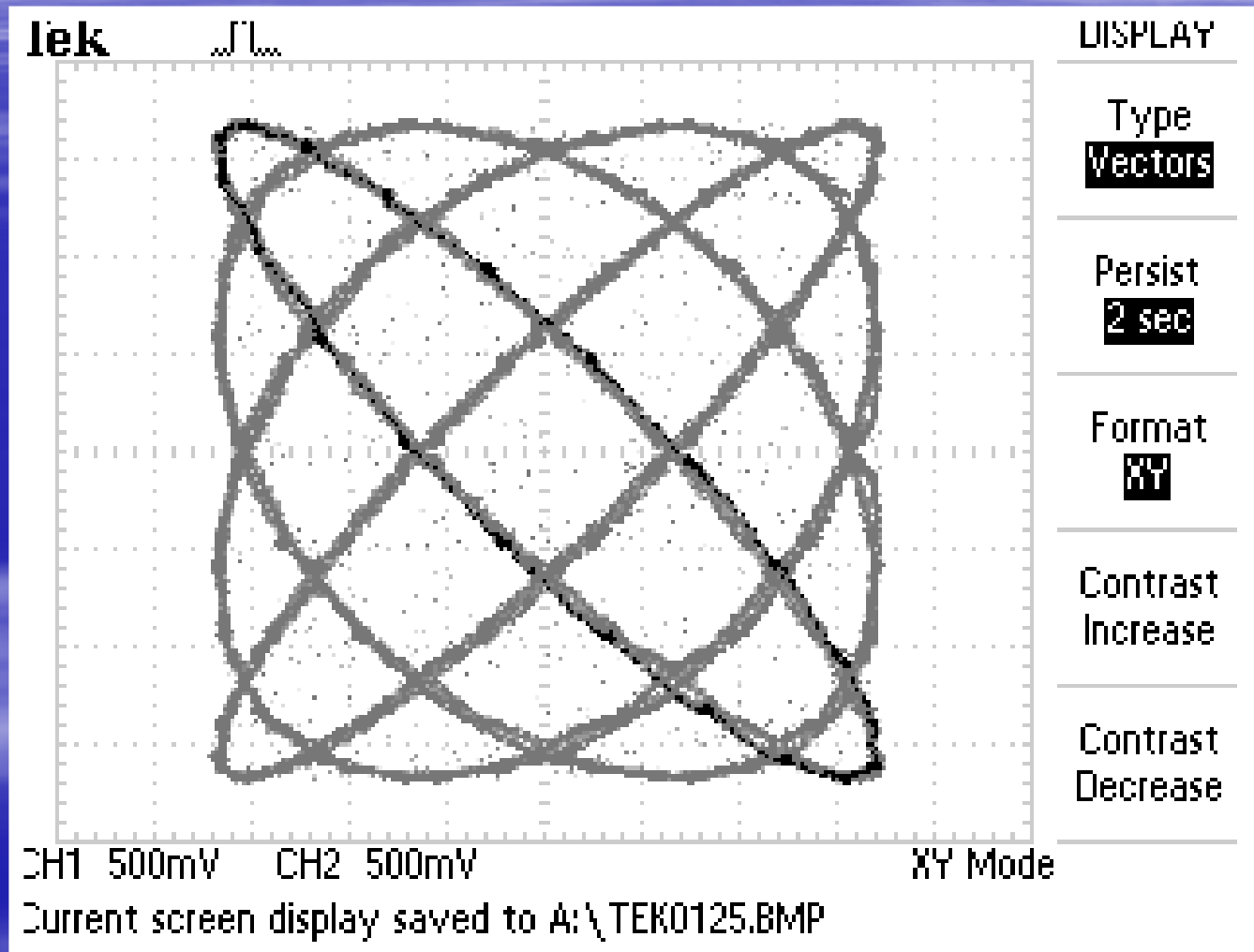
BPSK: Synchronized Local carrier vs. Transmitted Signal



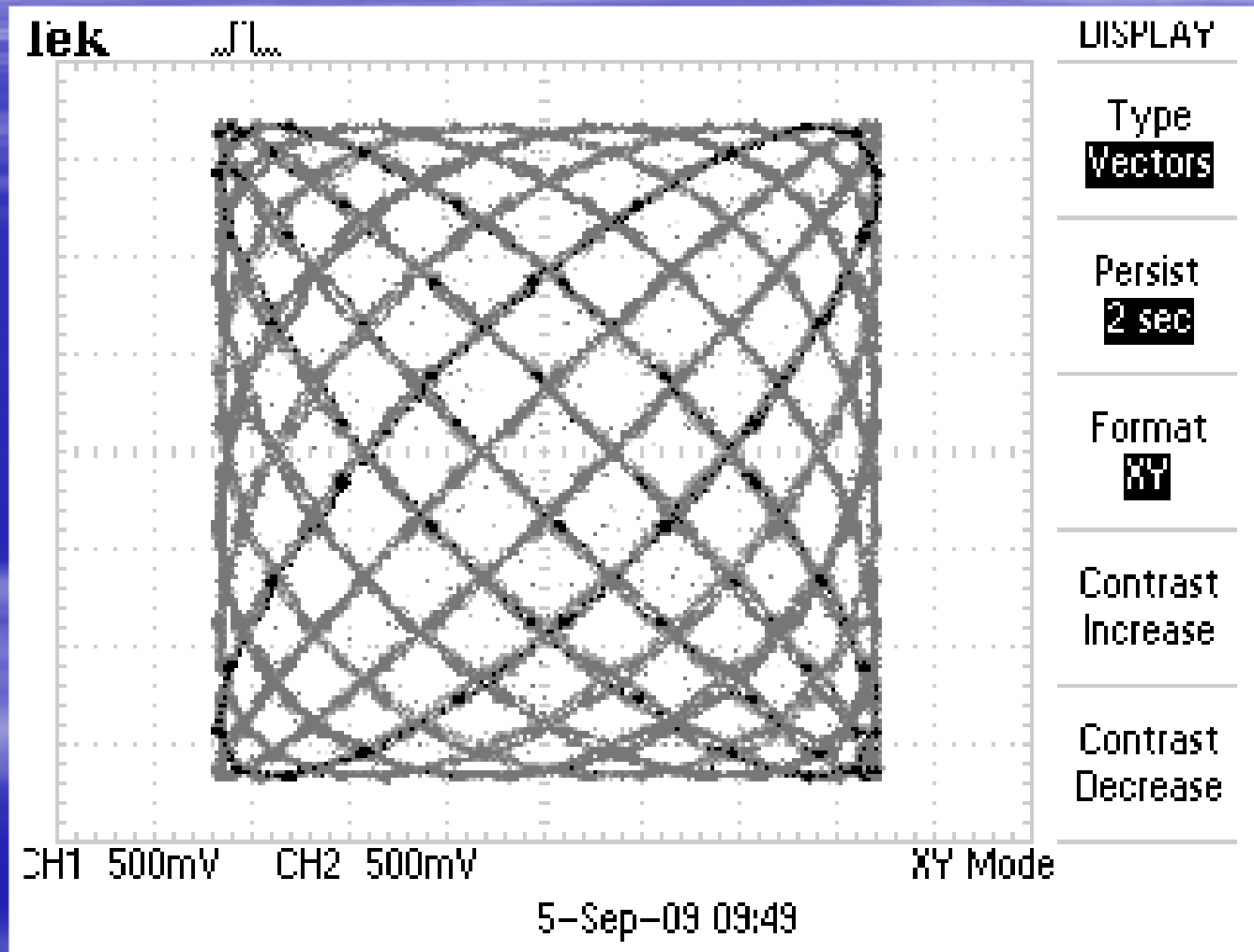
QPSK: Synchronized Local carrier vs. Transmitted Signal



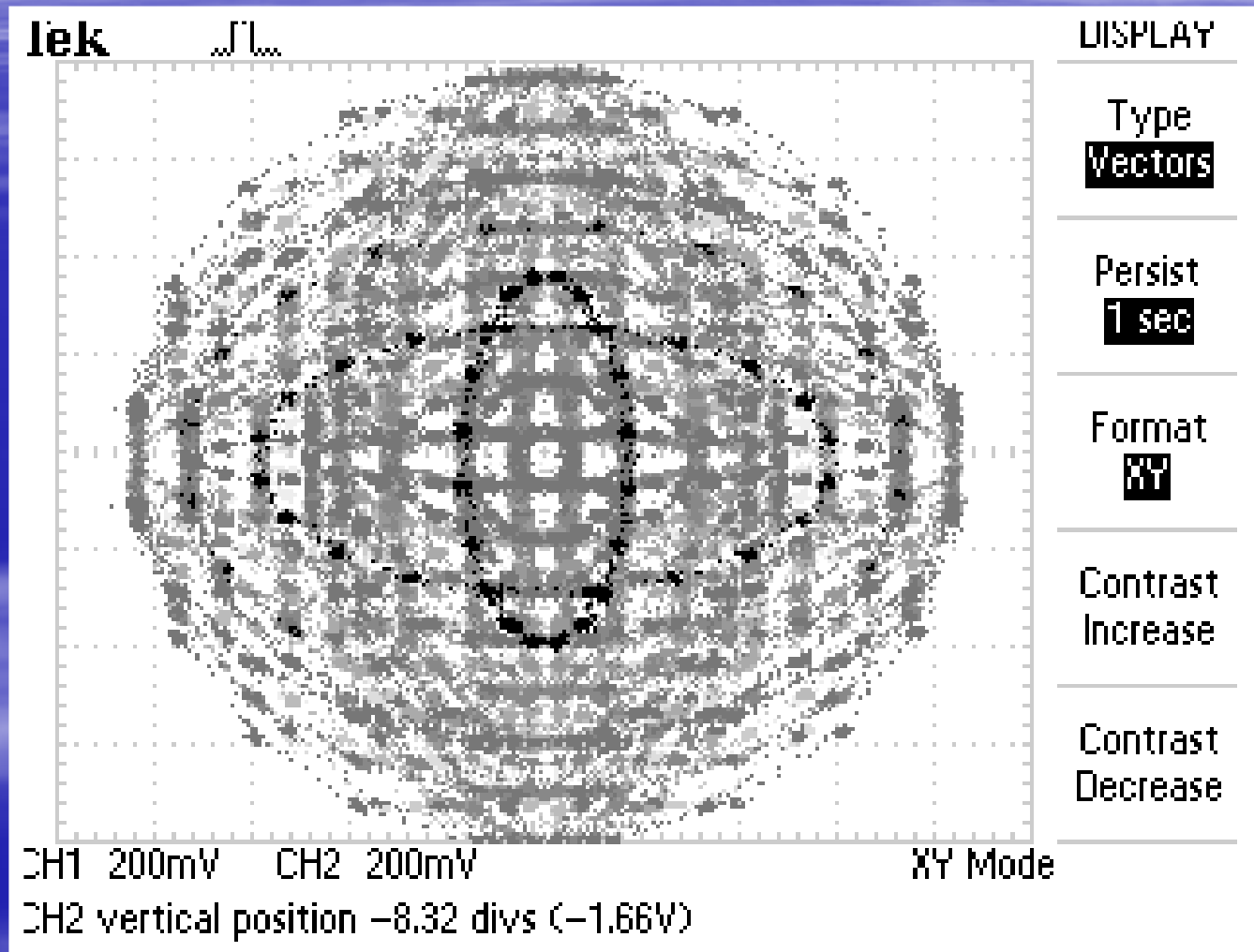
8-PSK: Synchronized Local carrier vs. Transmitted Signal



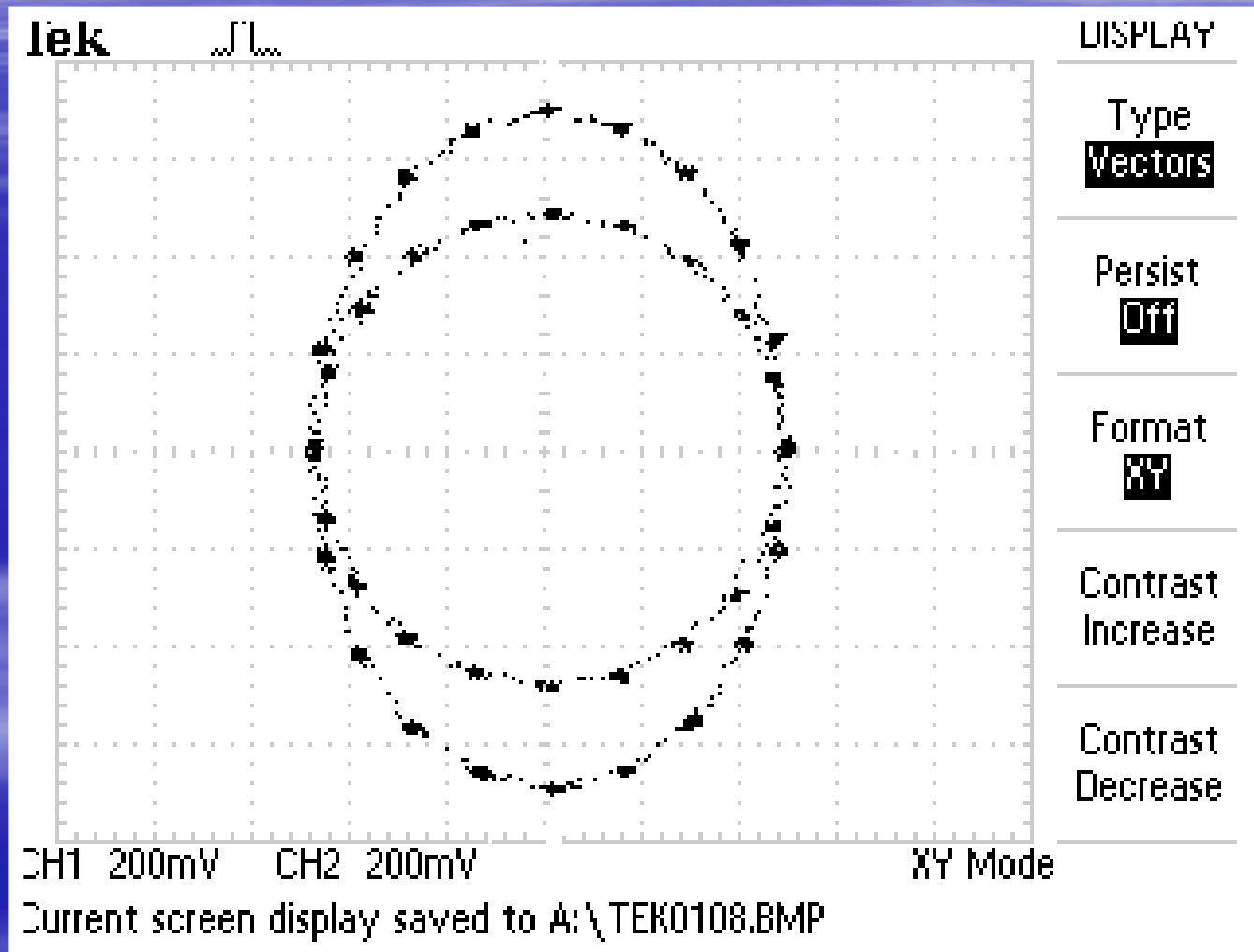
16-PSK: Synchronized Local carrier vs. Transmitted Signal



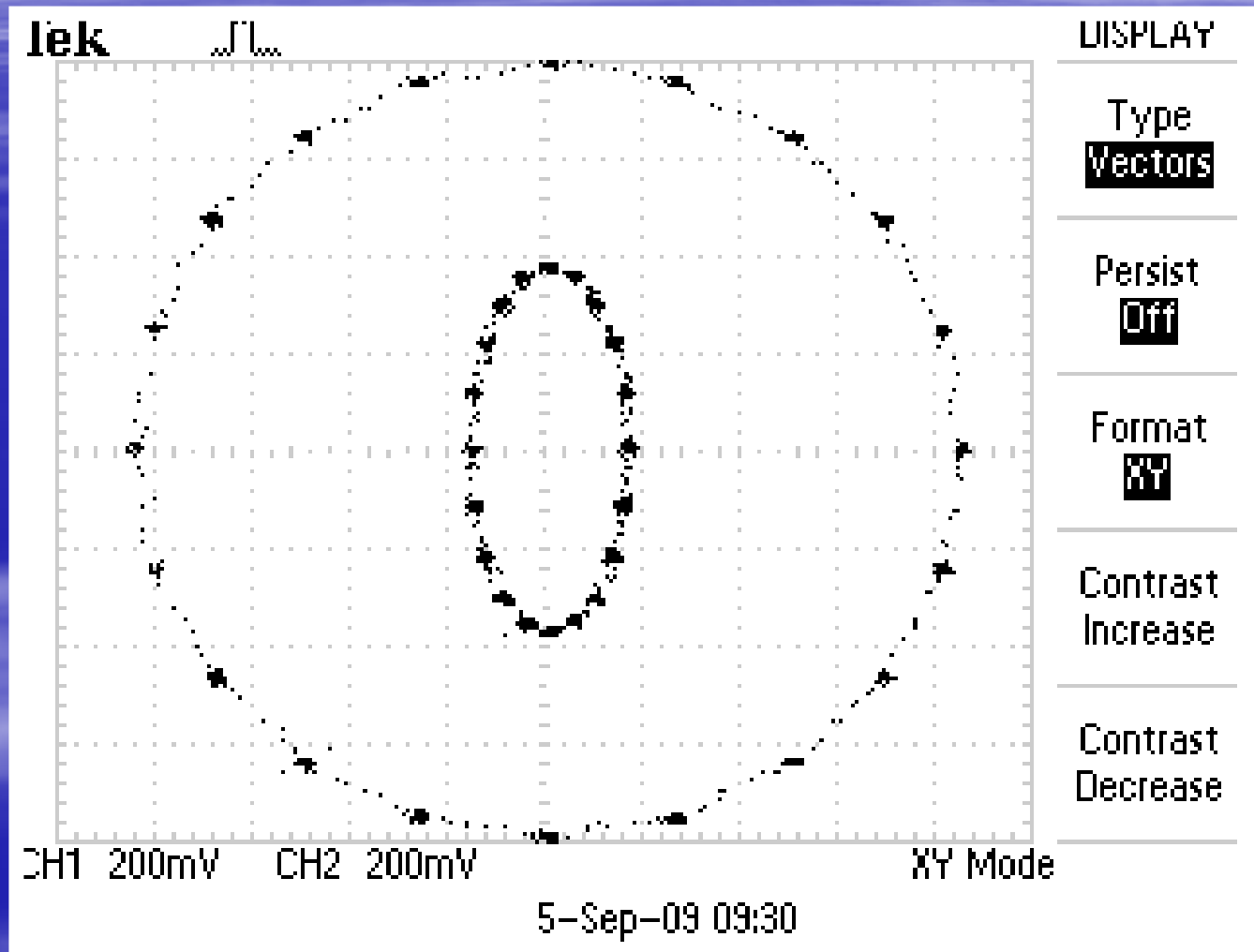
What's this?



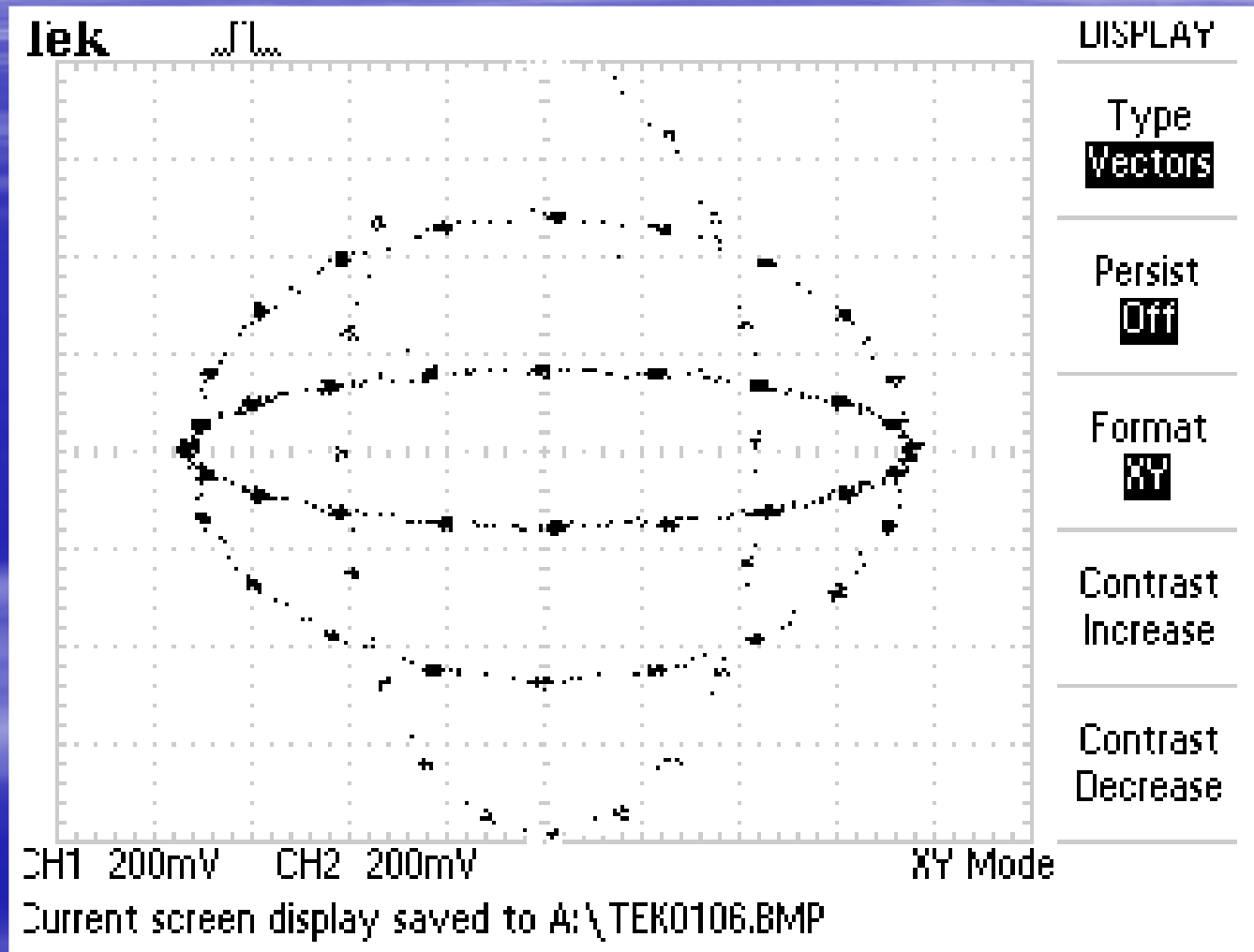
256-QAM X-Y graph of I and Q arms in Transmitter



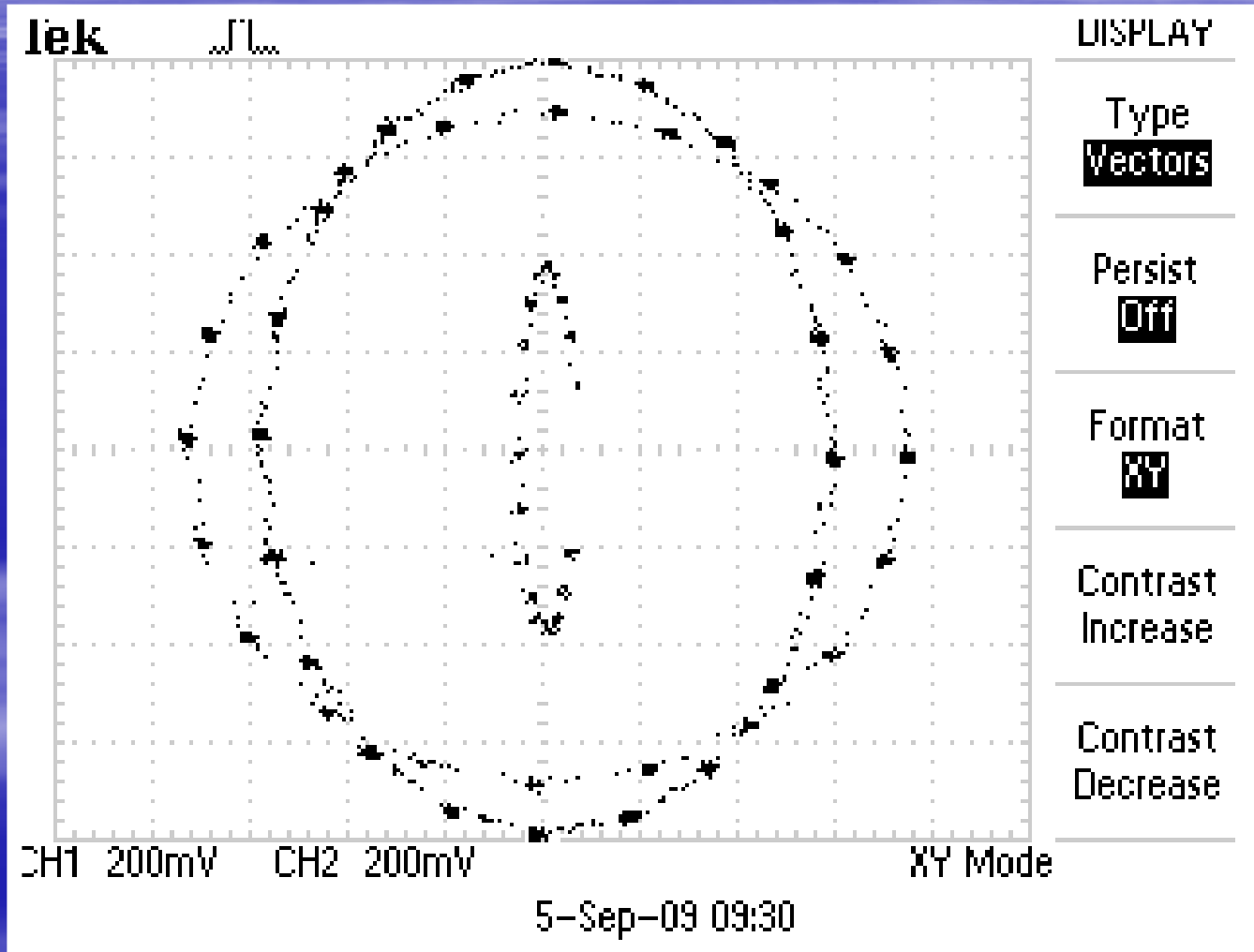
256-QAM X-Y graph of I and Q arms in Transmitter



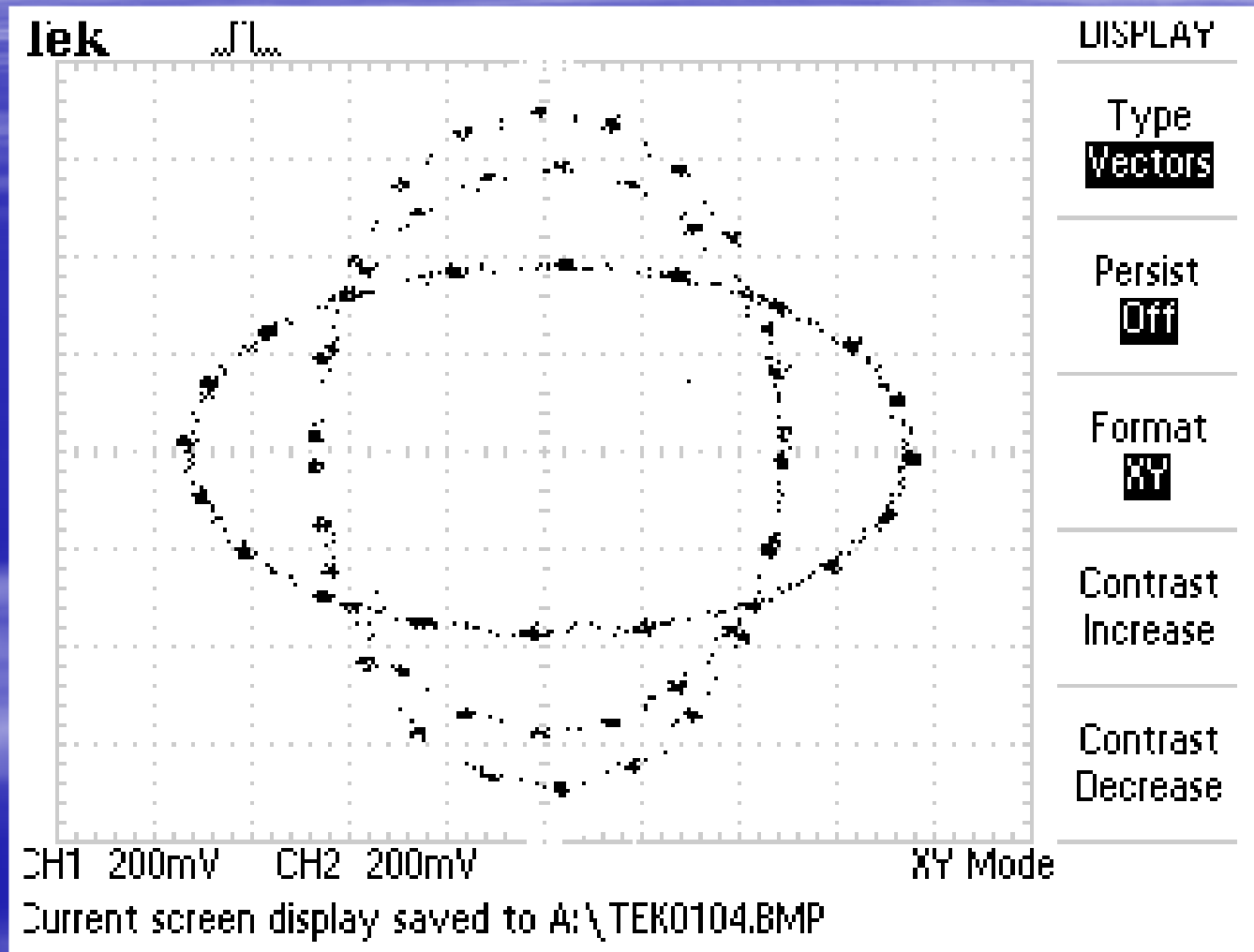
256-QAM X-Y graph of I and Q arms in Transmitter



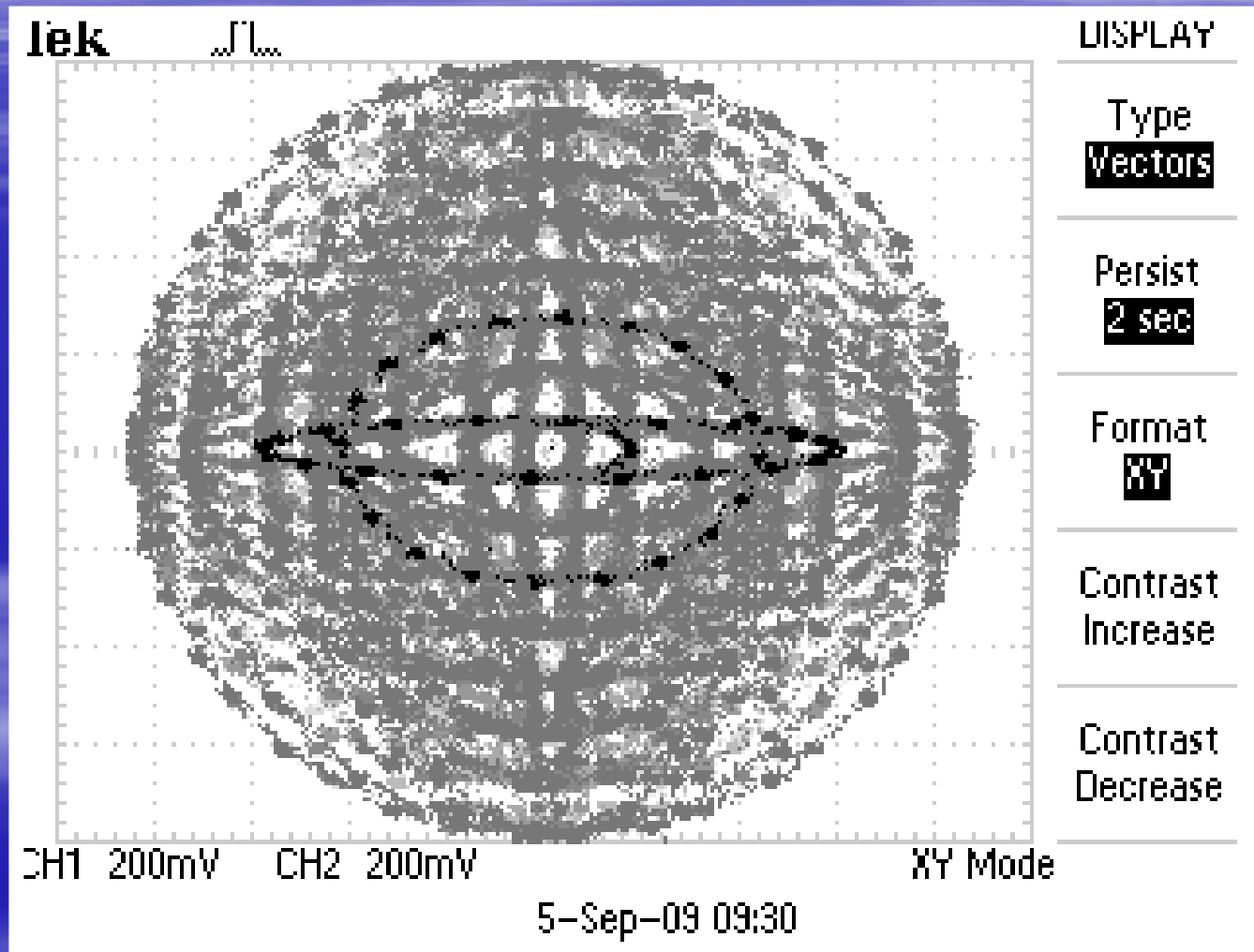
256-QAM X-Y graph of I and Q arms in Transmitter



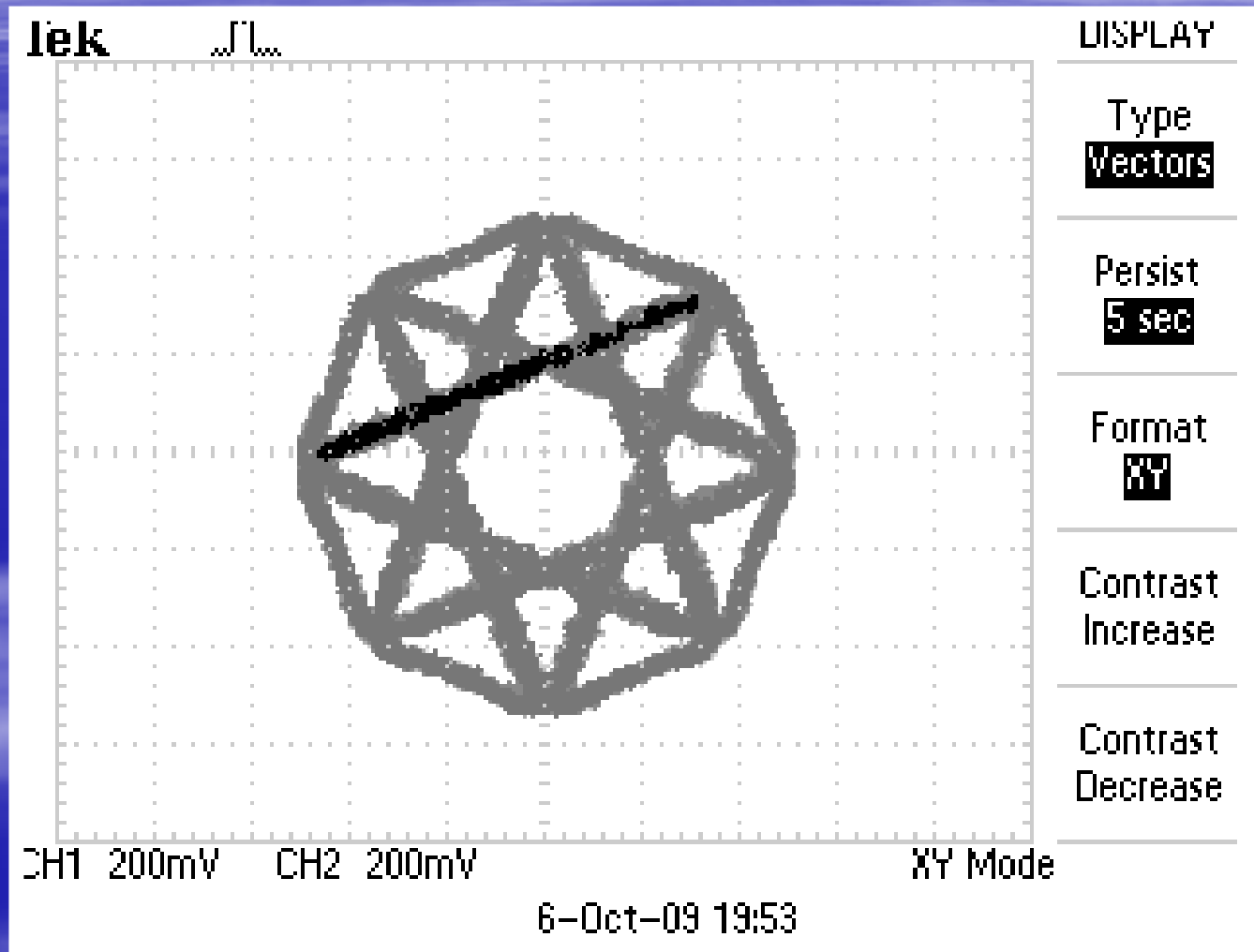
256-QAM X-Y graph of I and Q arms in Transmitter



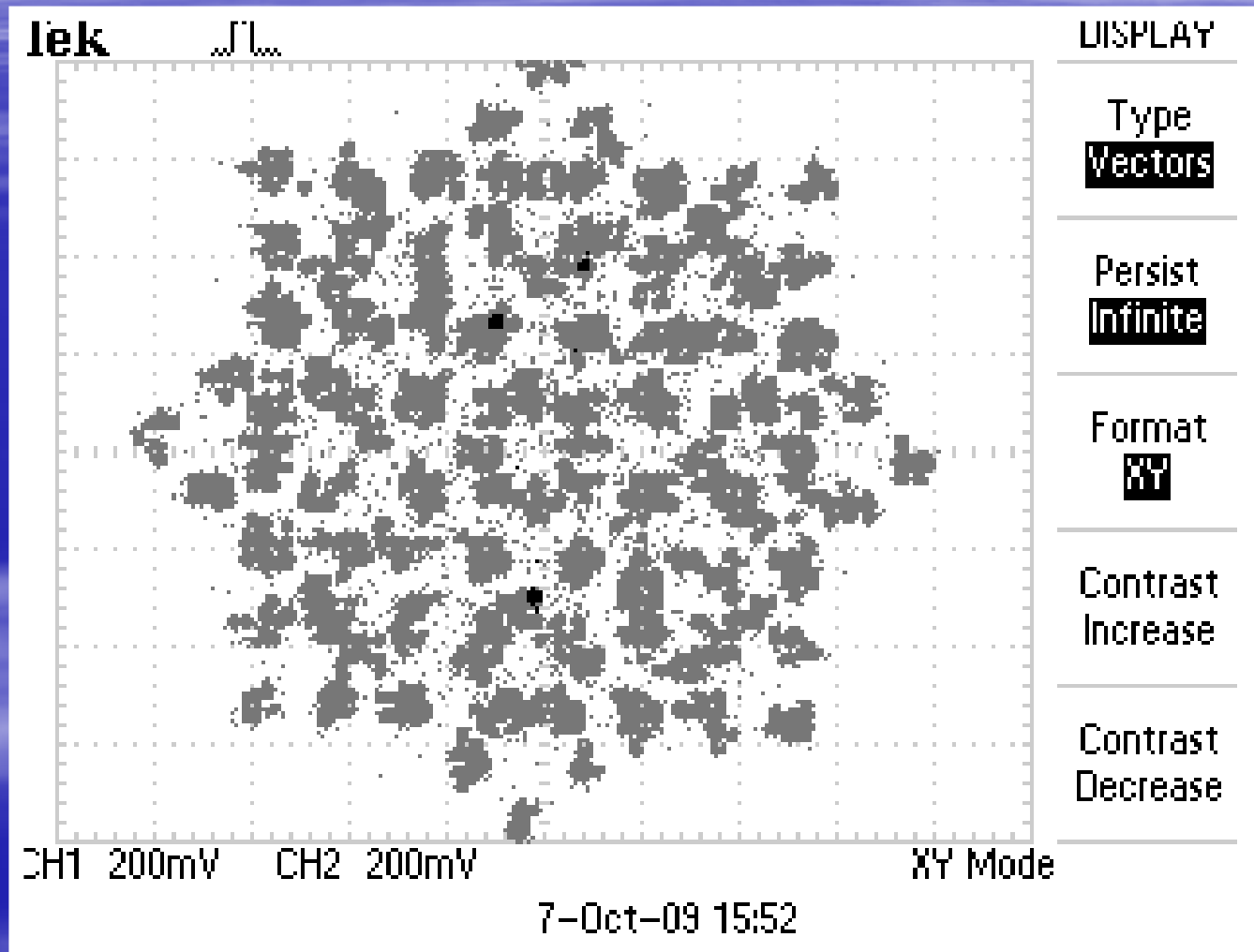
256-QAM X-Y graph of I and Q arms in Transmitter - Overlay



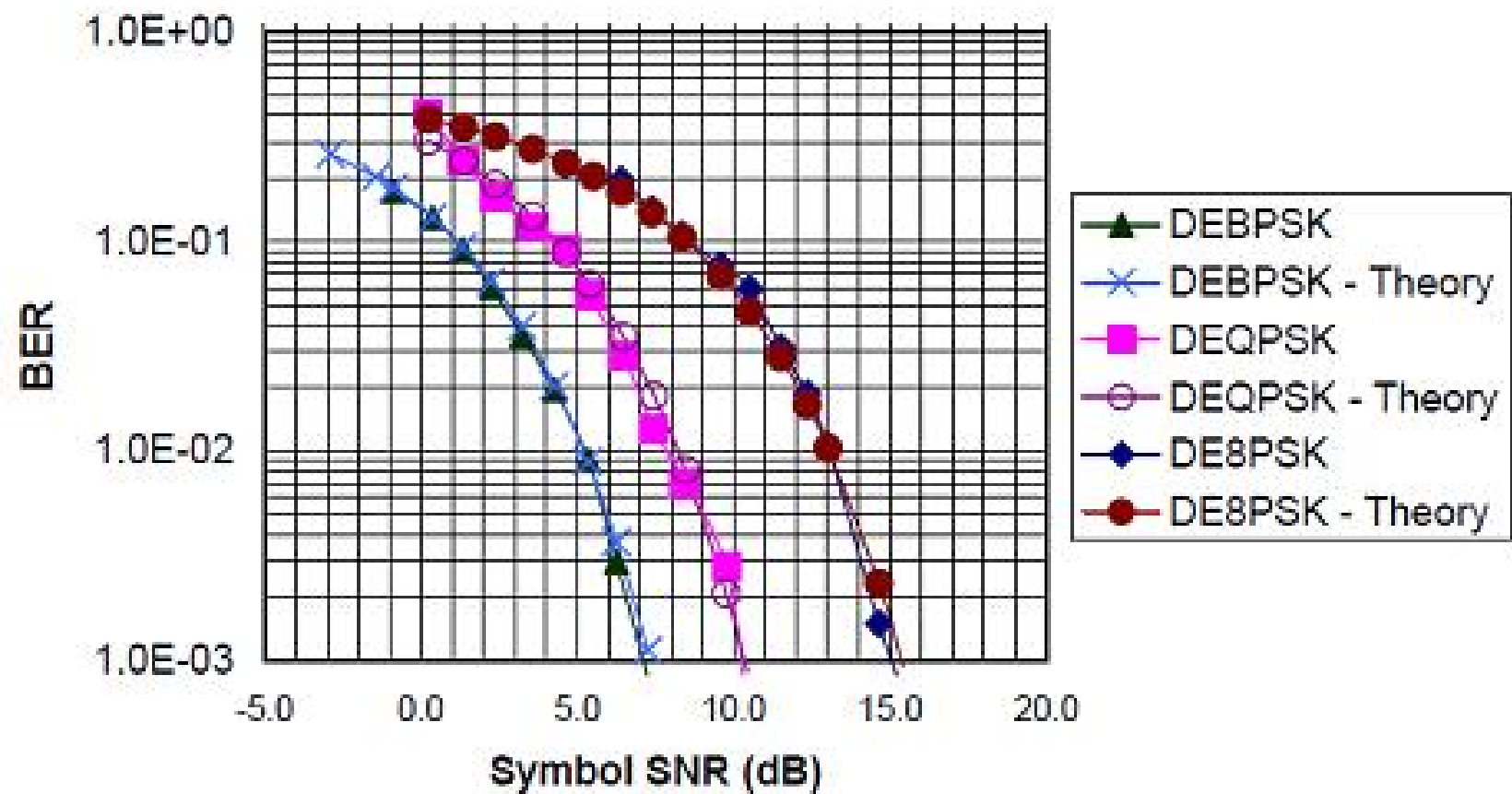
pi/4-QPSK reception



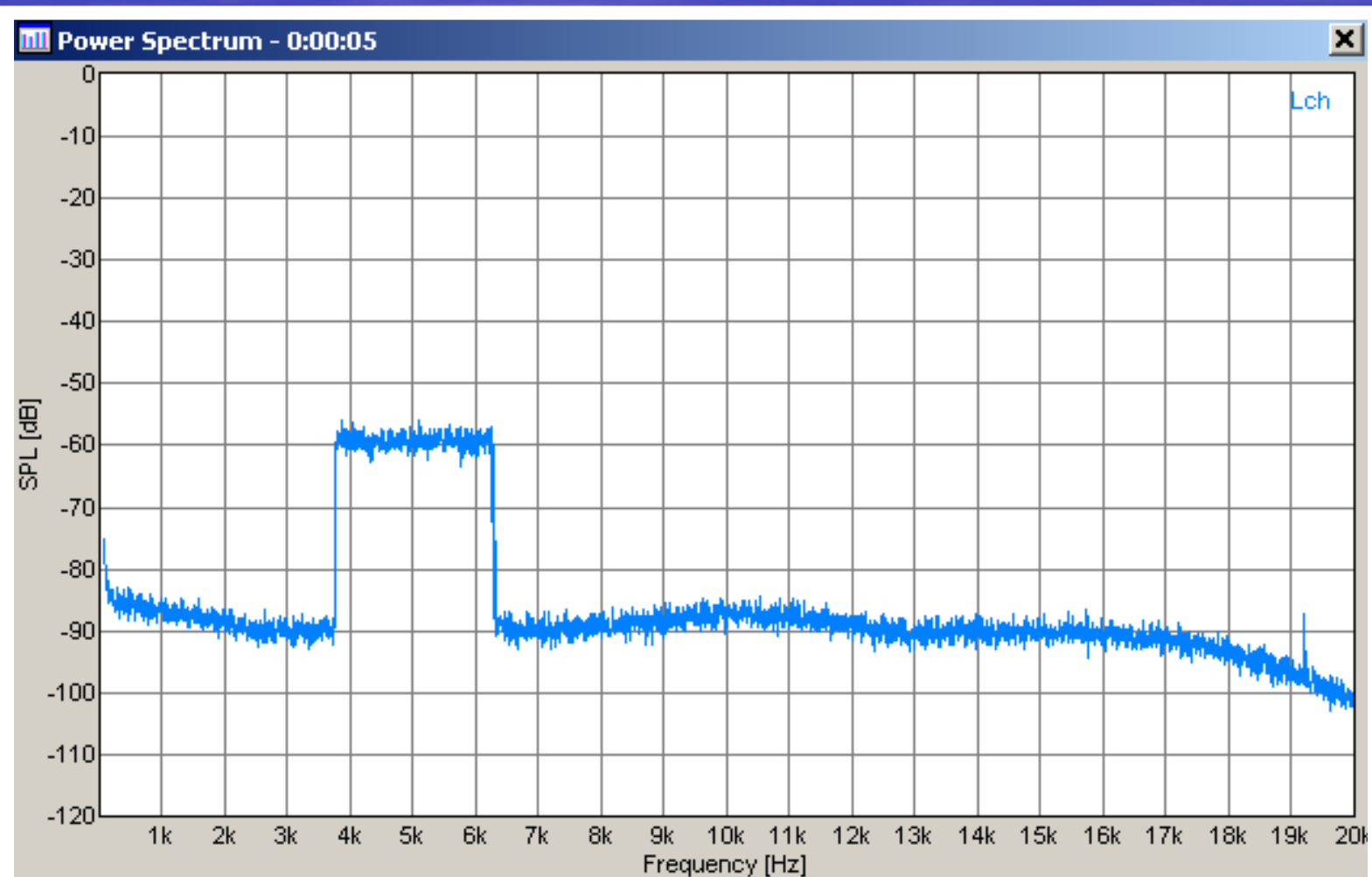
pi/4-QAM-64 reception



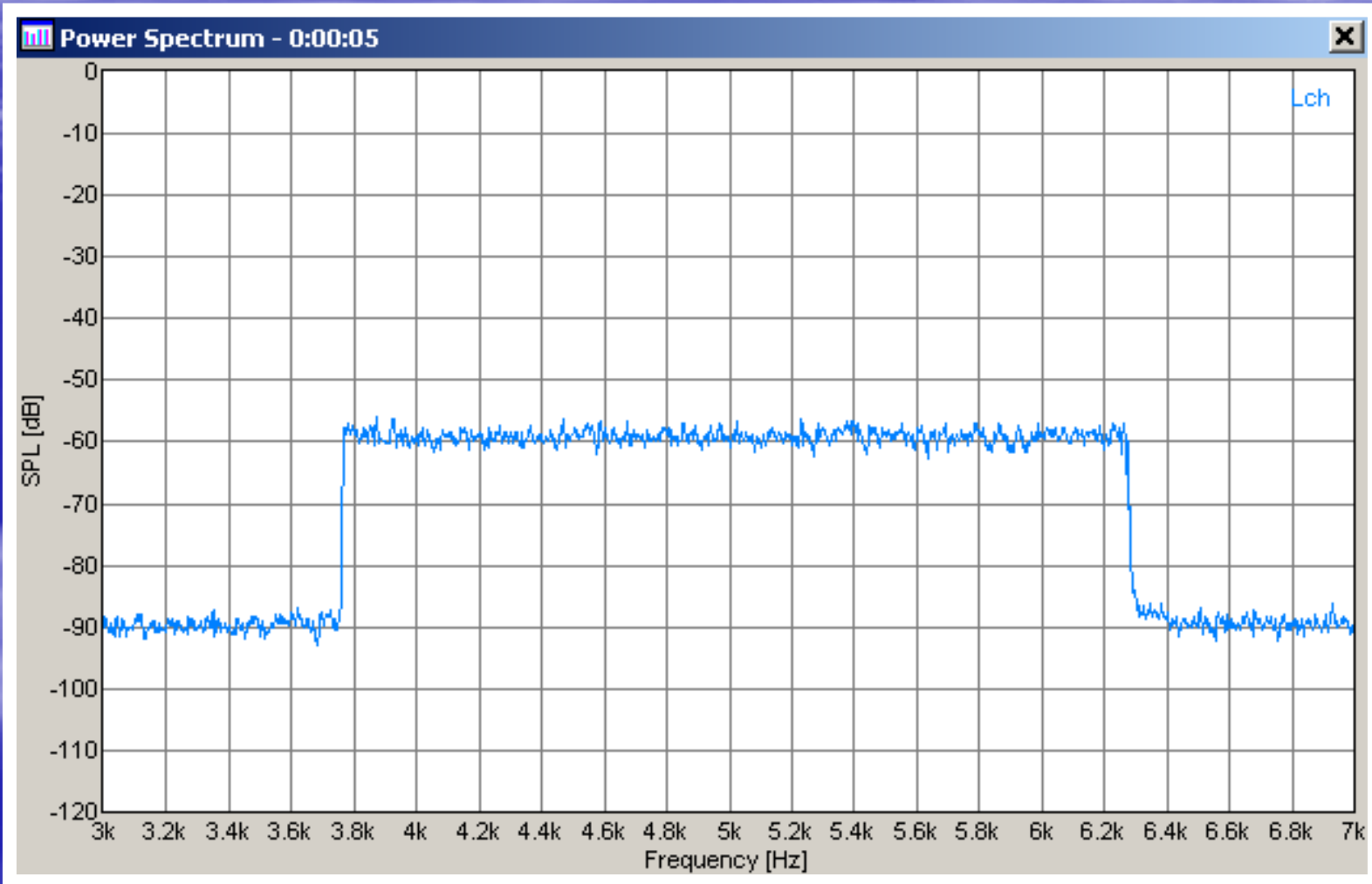
BER Measurements



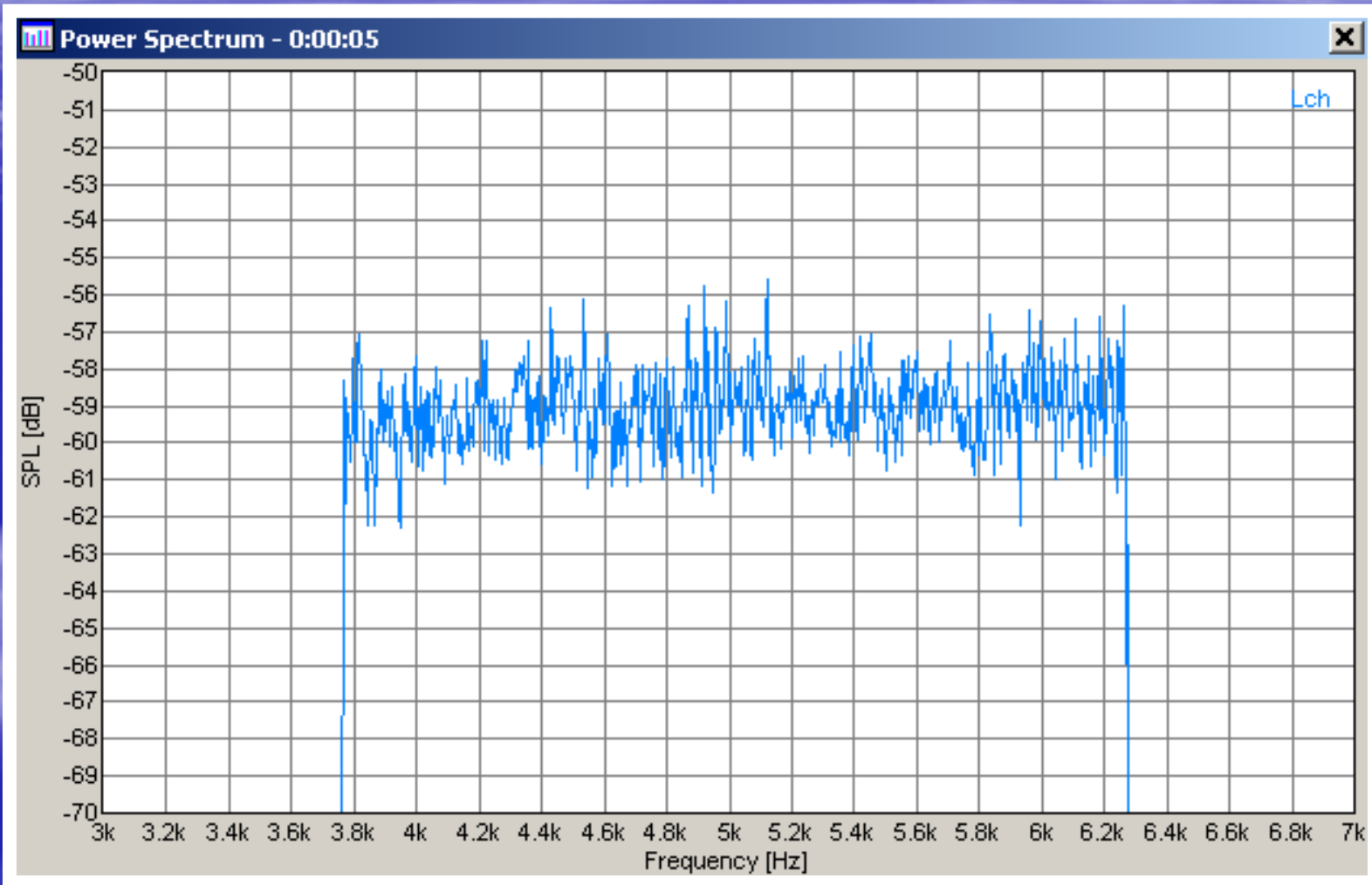
Bandpass Noise Generation For Channel Emulation



Bandpass Noise Generation (zoom in frequency)



Bandpass Noise Generation (zoom in frequency and in amplitude)



Conclusions

- We presented a laboratory that costs less than \$200
- Based on a commercial 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!

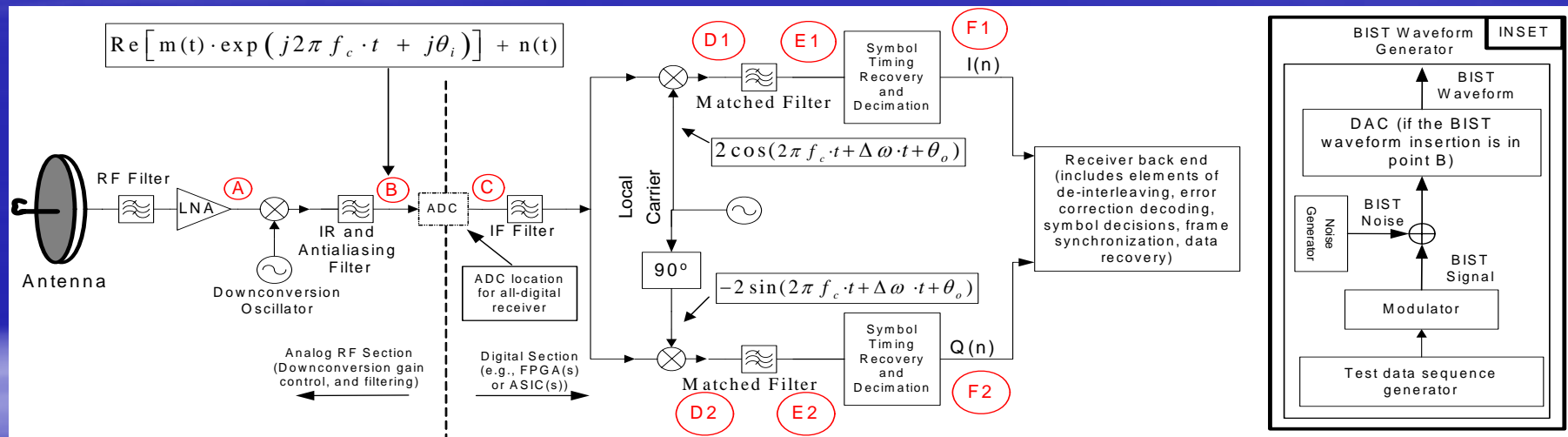
Thank you!!!!

Questions? Comments?

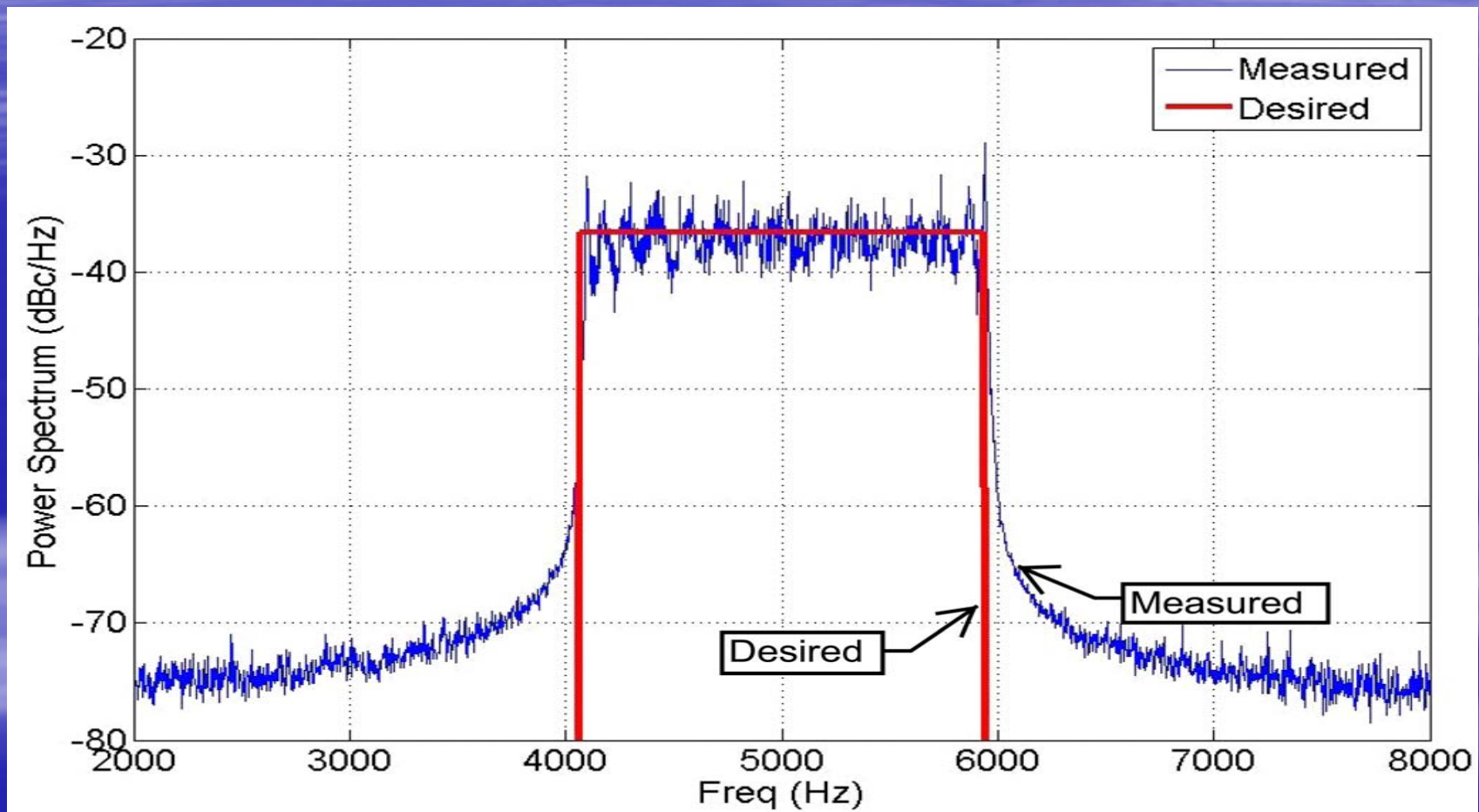
yairlinn@gmail.com

<http://yairlinn.googlepages.com>

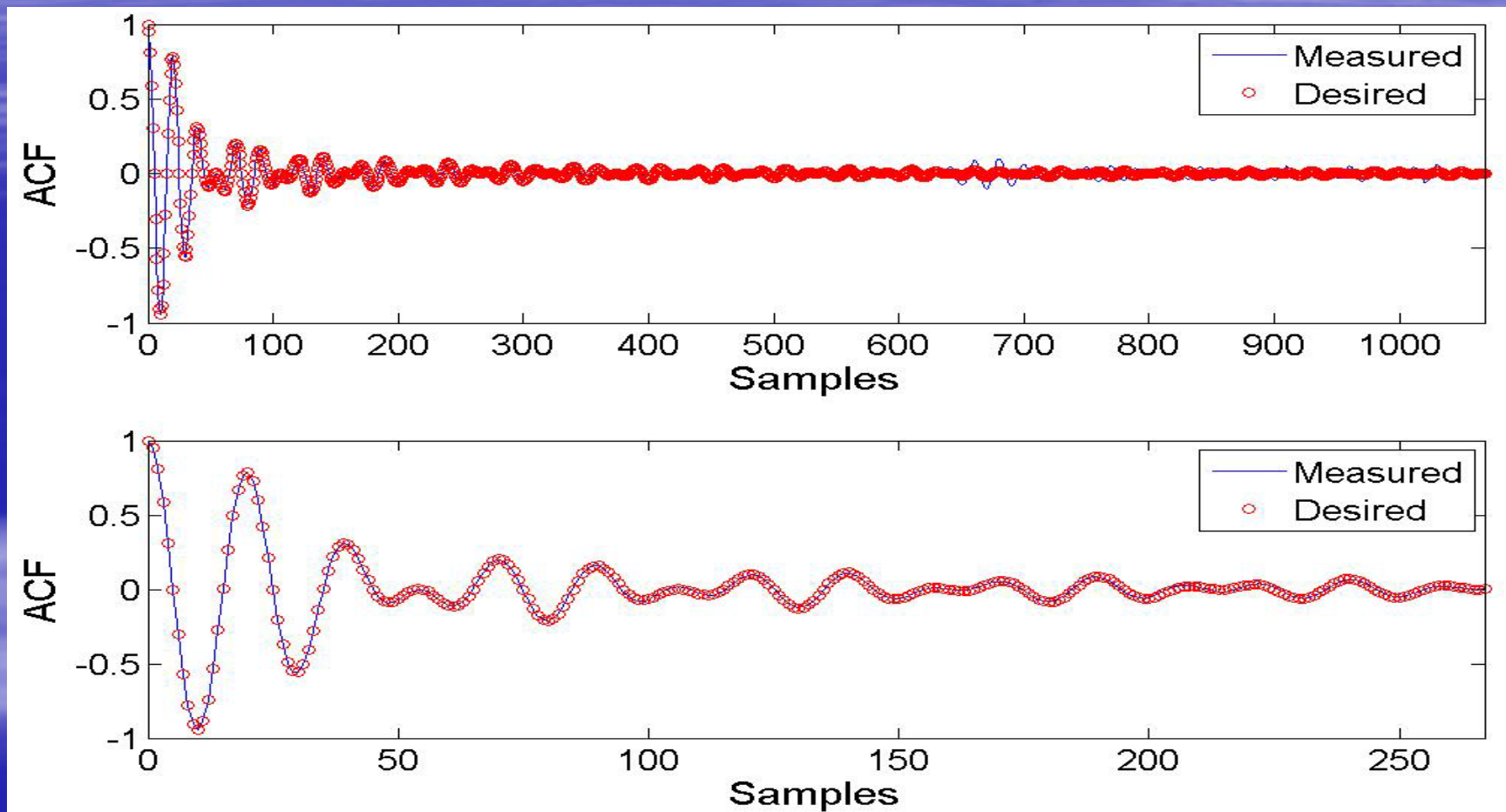
BIST – Where to insert the test signal



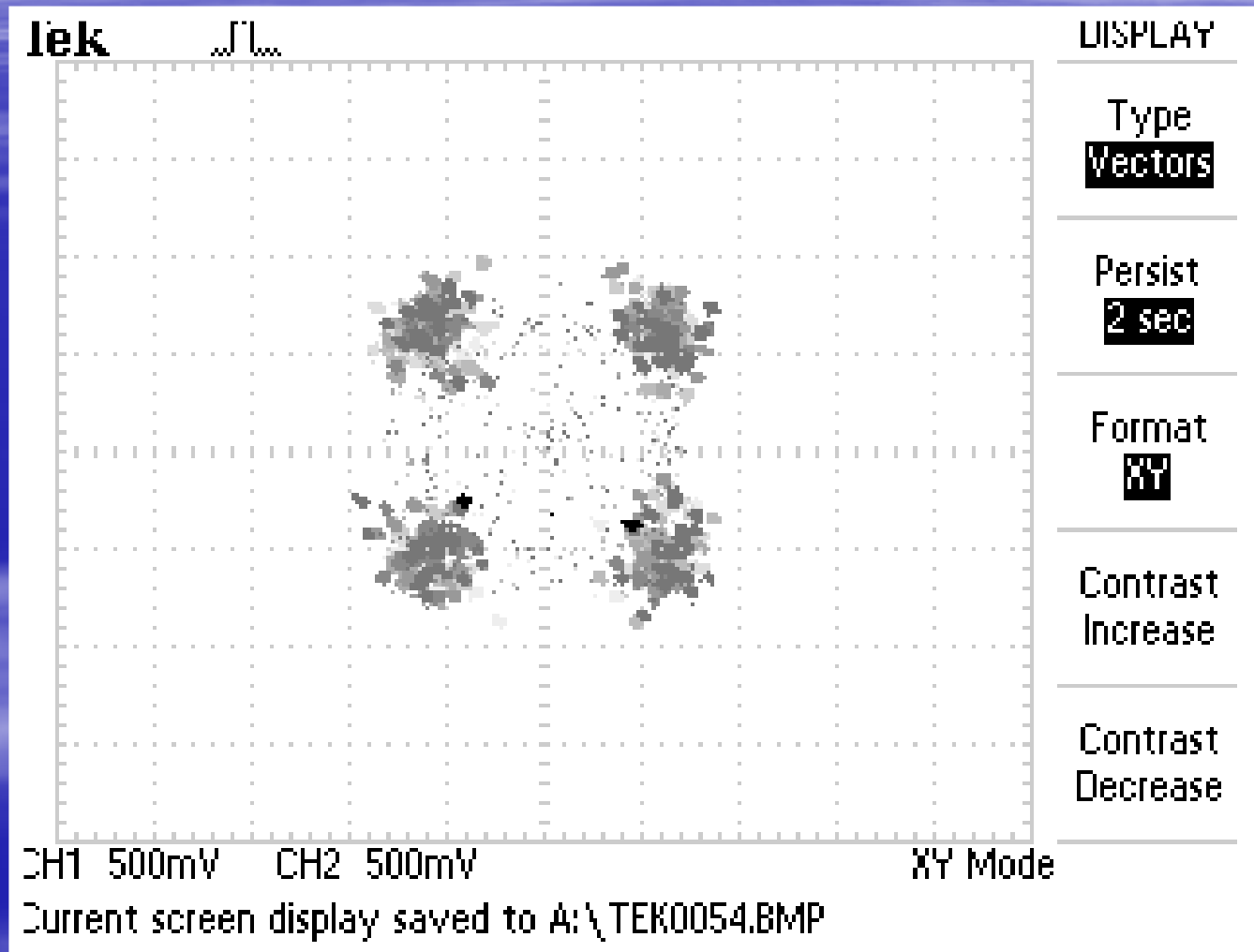
Noise Spectrum: Measured Vs. Desired, $p=534$



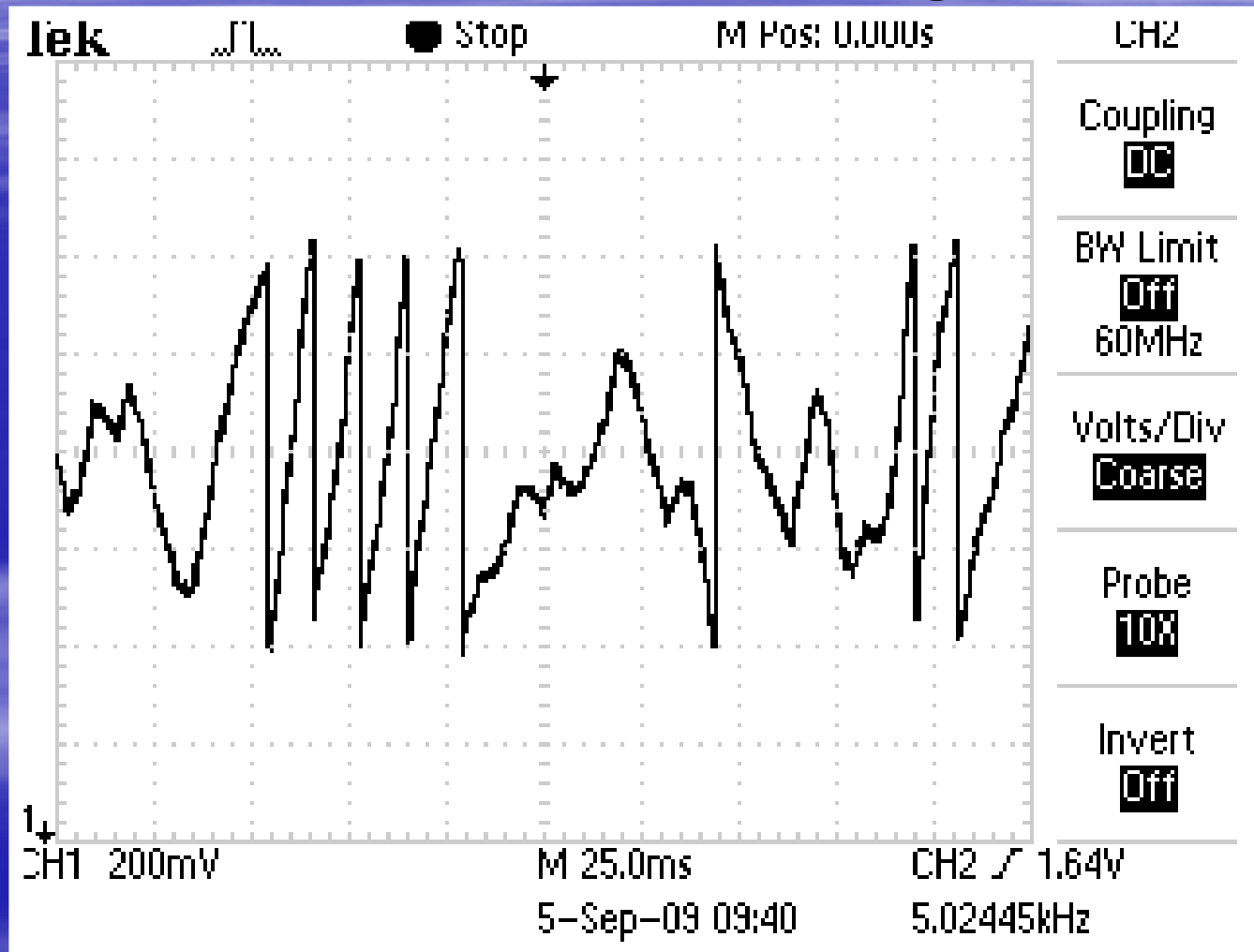
ACF function, measure vs. desired, $p=534$



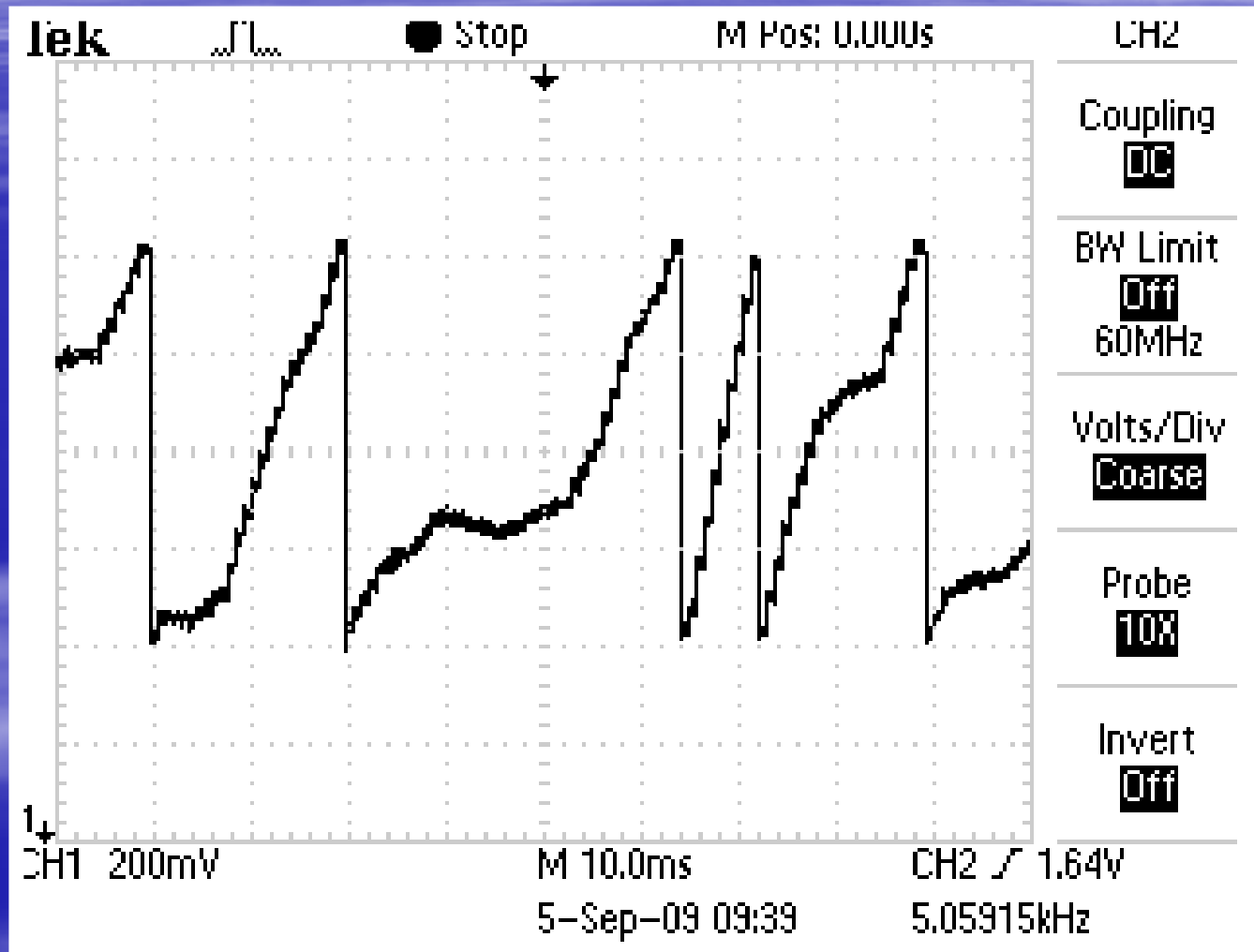
QPSK – at output of receiver, SNR = 12 dB, 1 sample/symbol



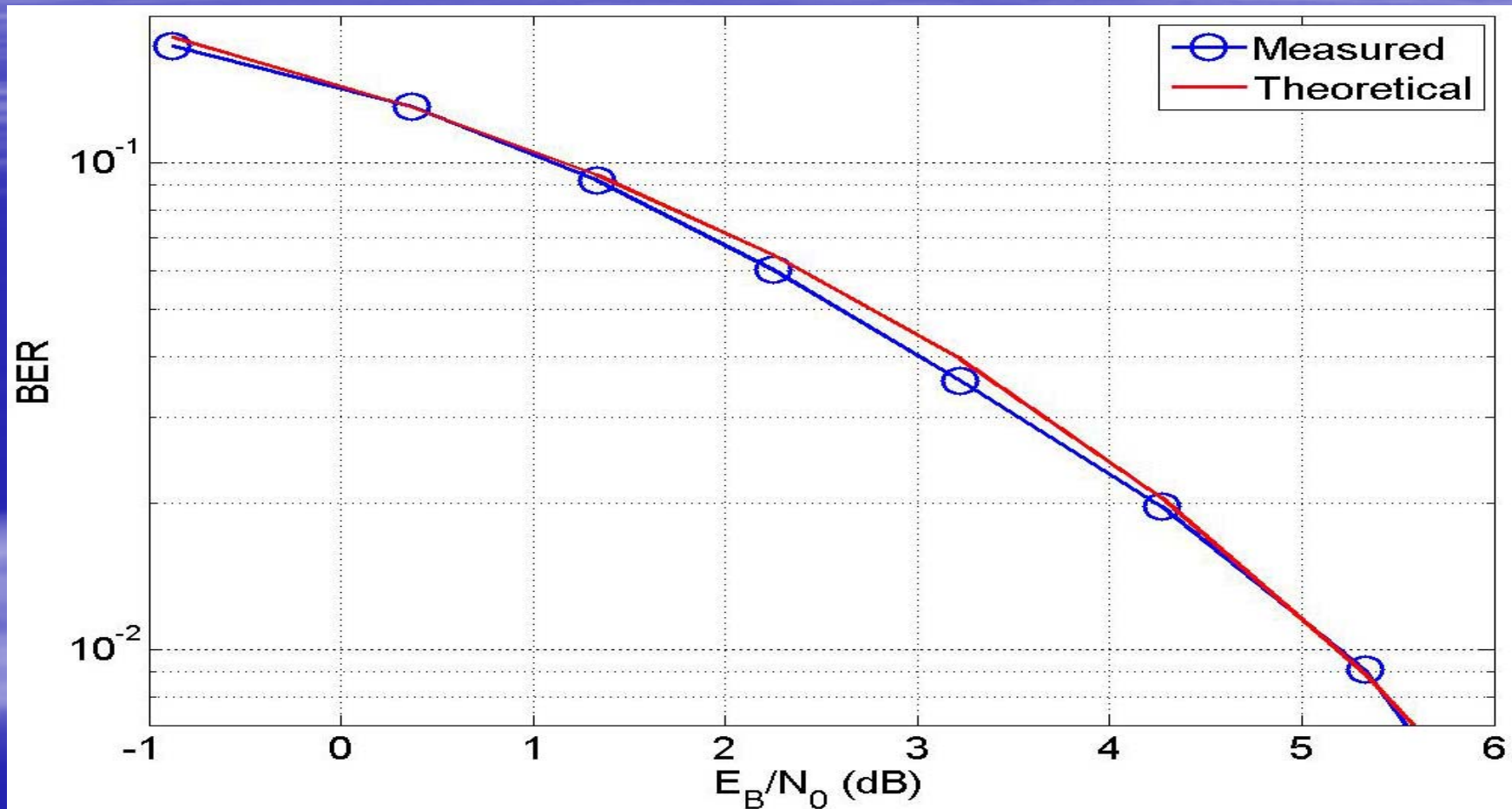
Interpolation mu vs. time for 10x oversampling



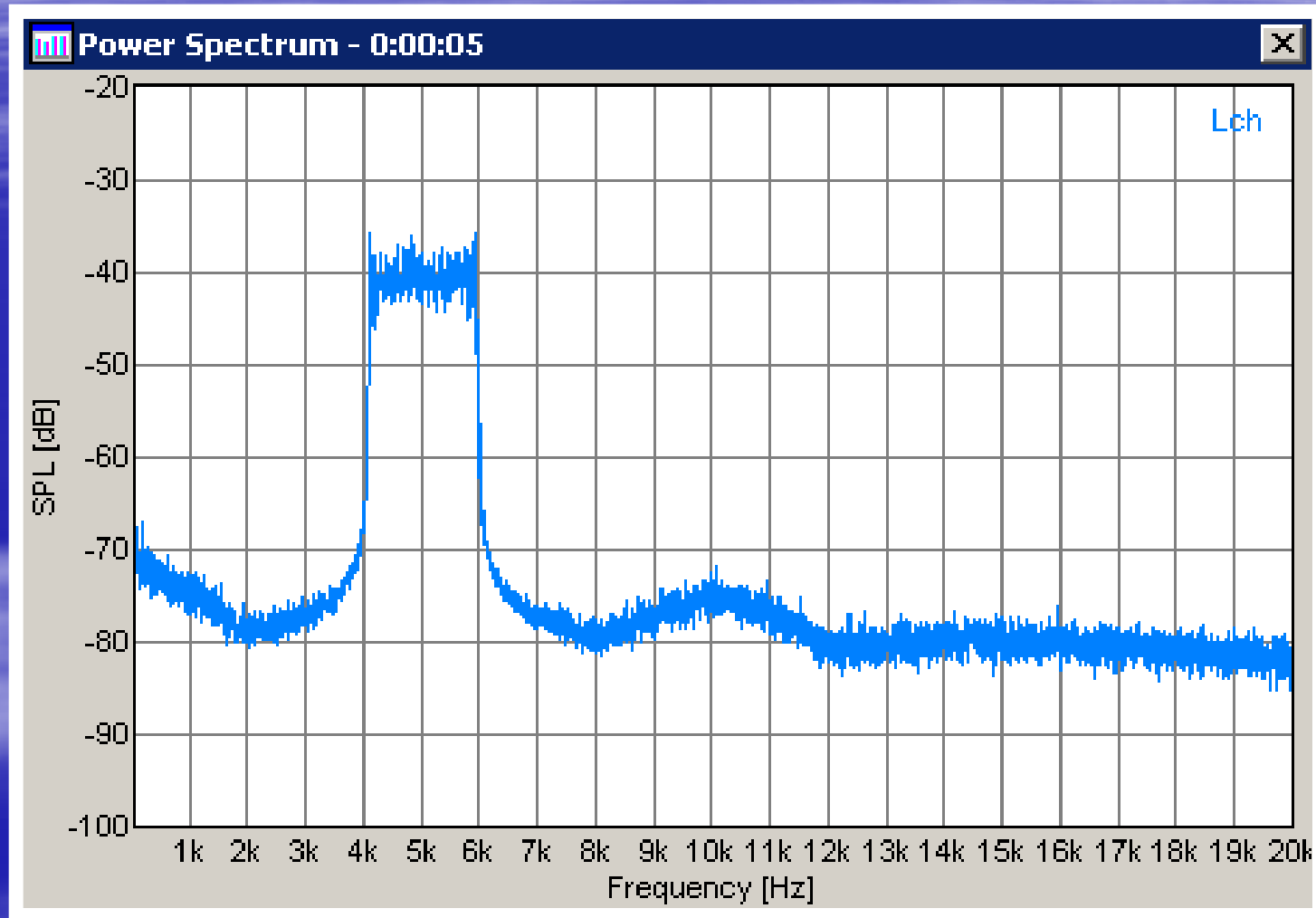
Interpolation mu vs. time for 10x oversampling - zoom



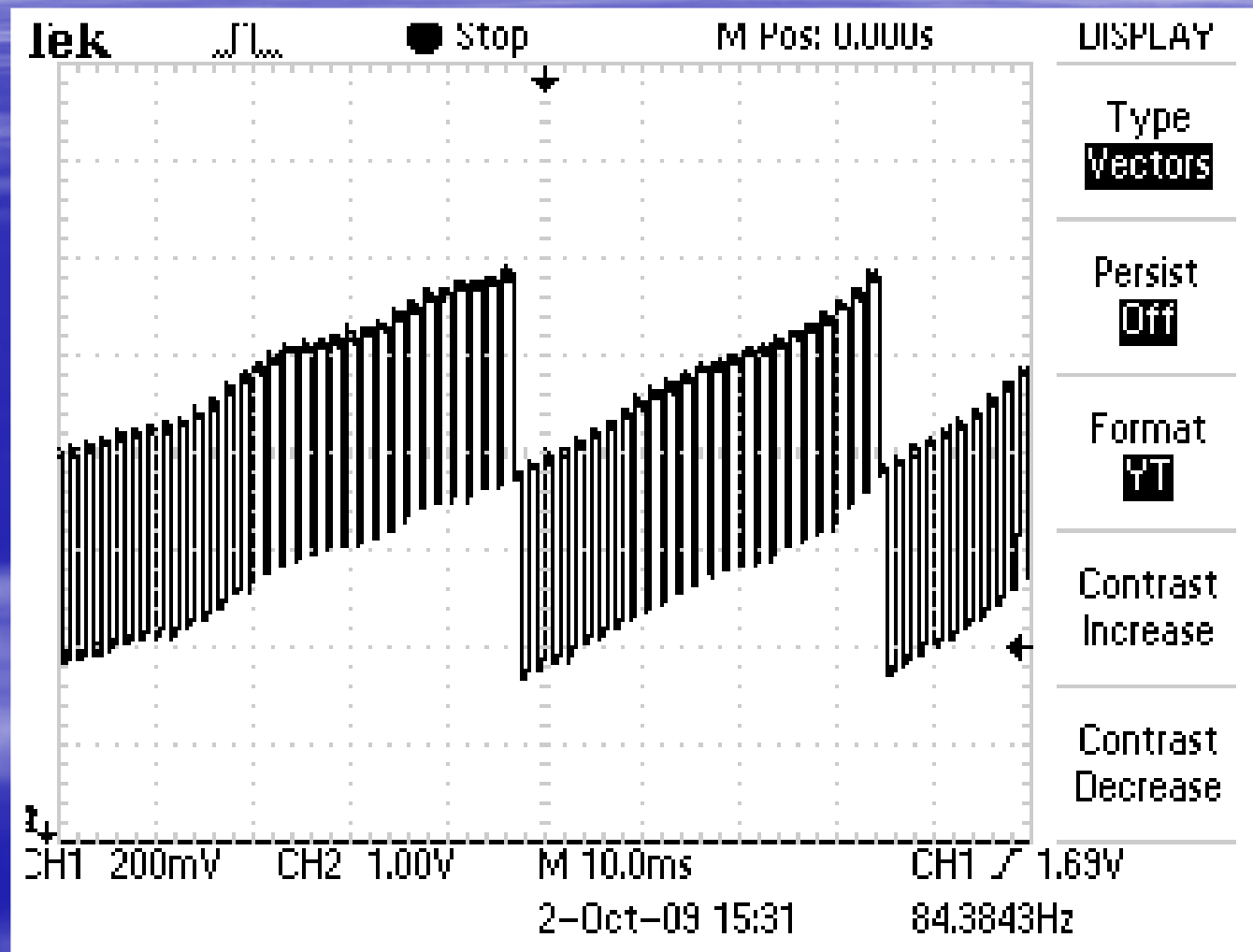
BER laboratory measurements for DEBPSK



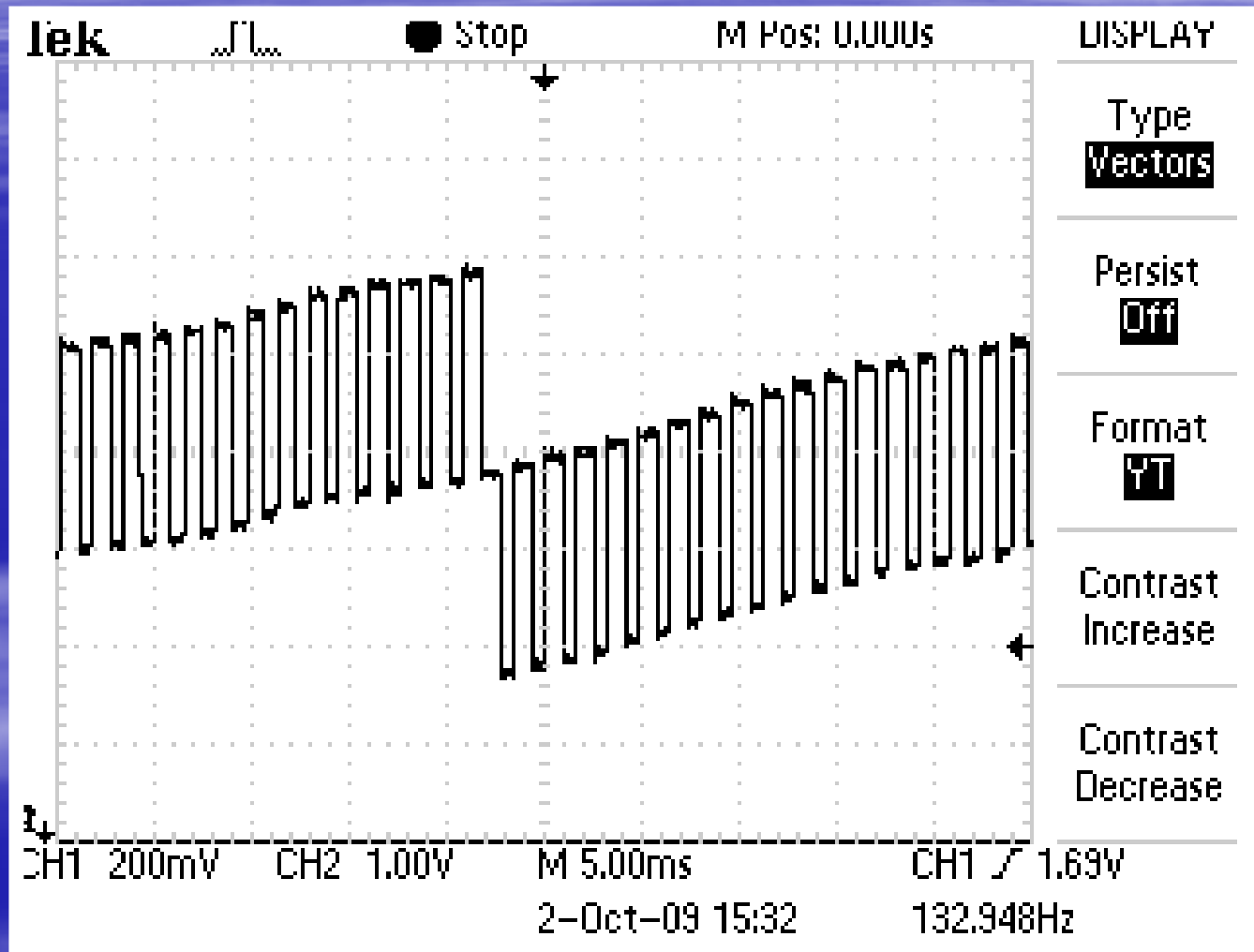
Noise Spectrum around 5 KHz, new Gaussian noise generation method



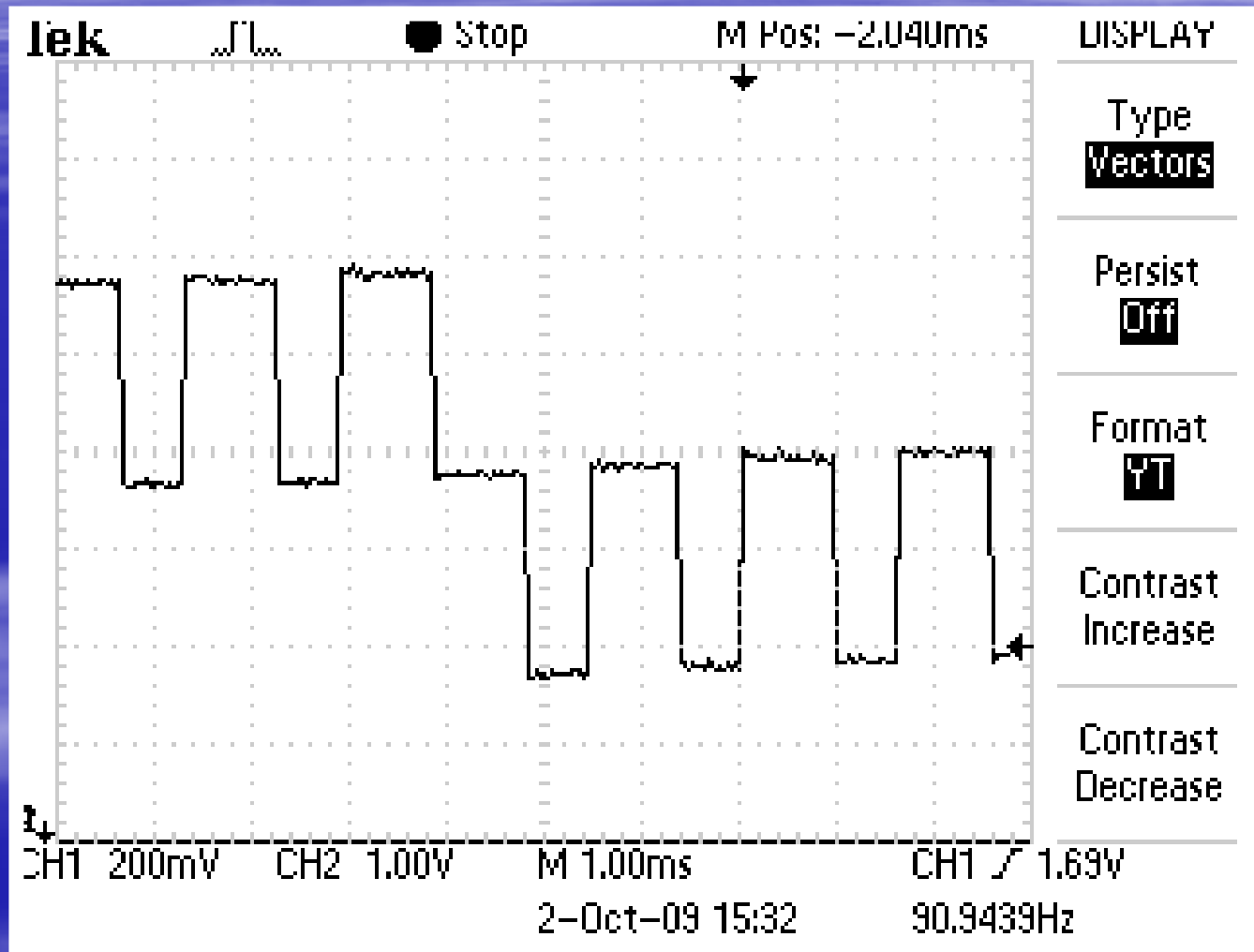
Interpolation mu variable behavior



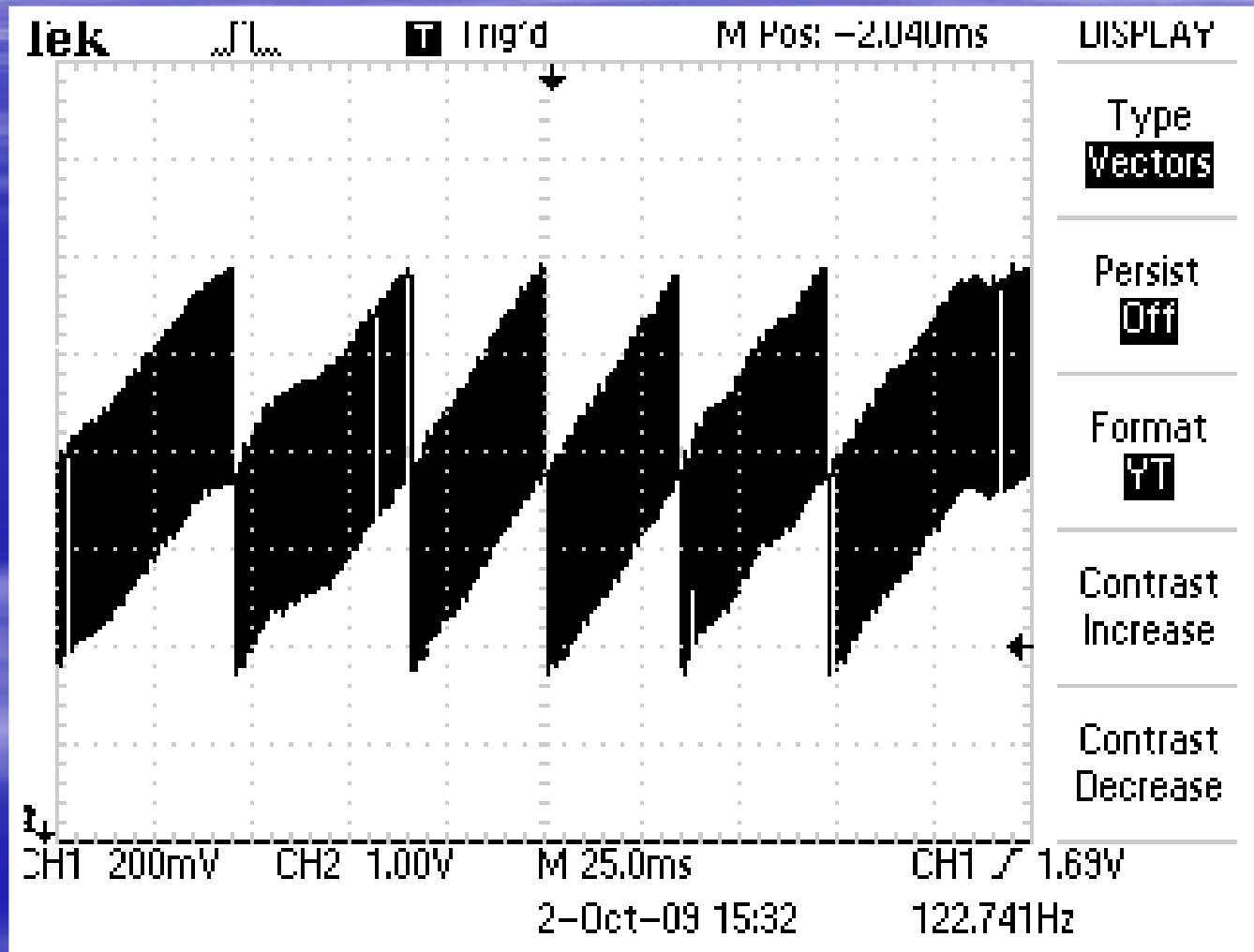
Interpolation mu variable behavior



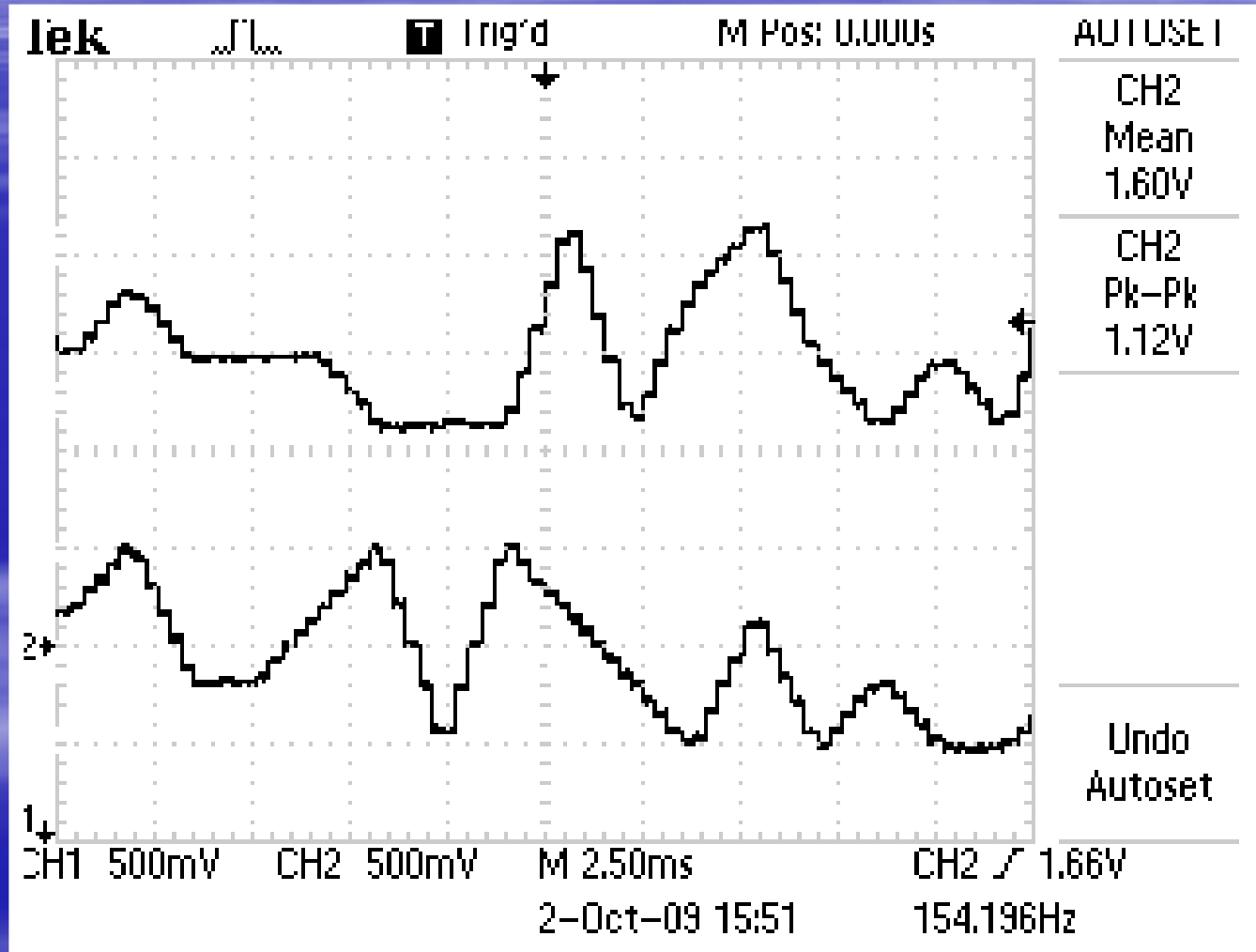
Interpolation mu variable behavior



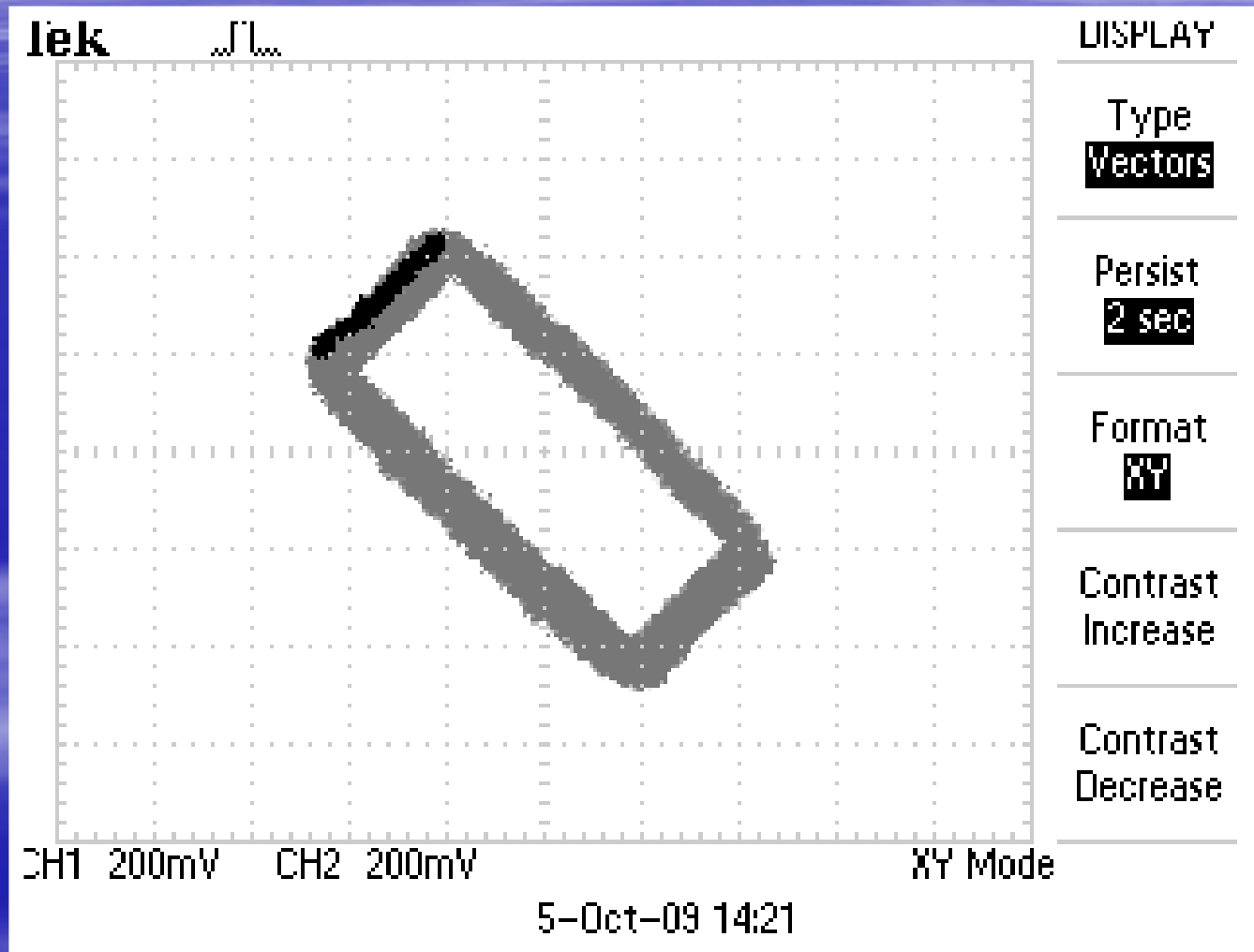
Interpolation mu variable behavior



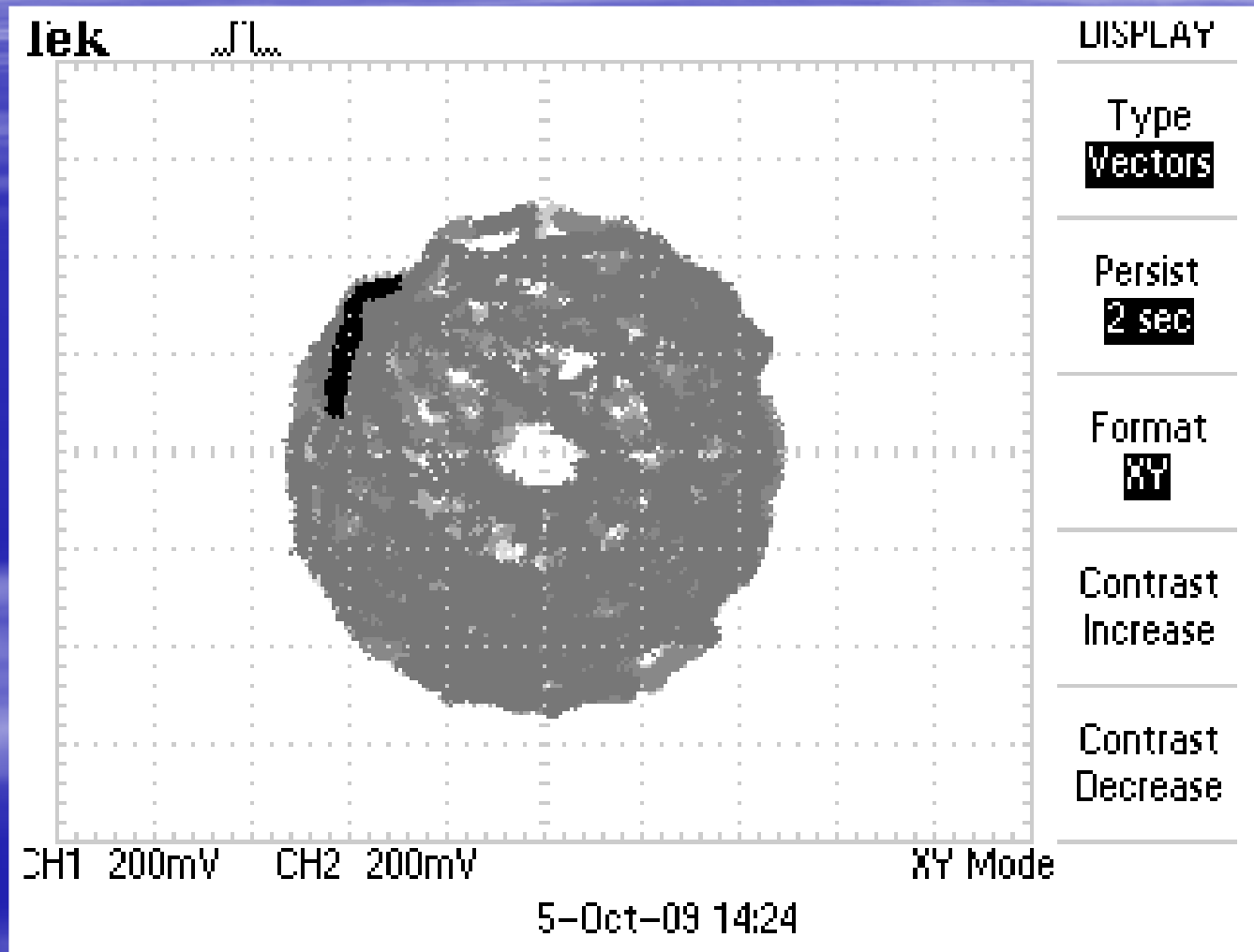
QAM-256 after matched filter and downsampling to 5 samples/symbol



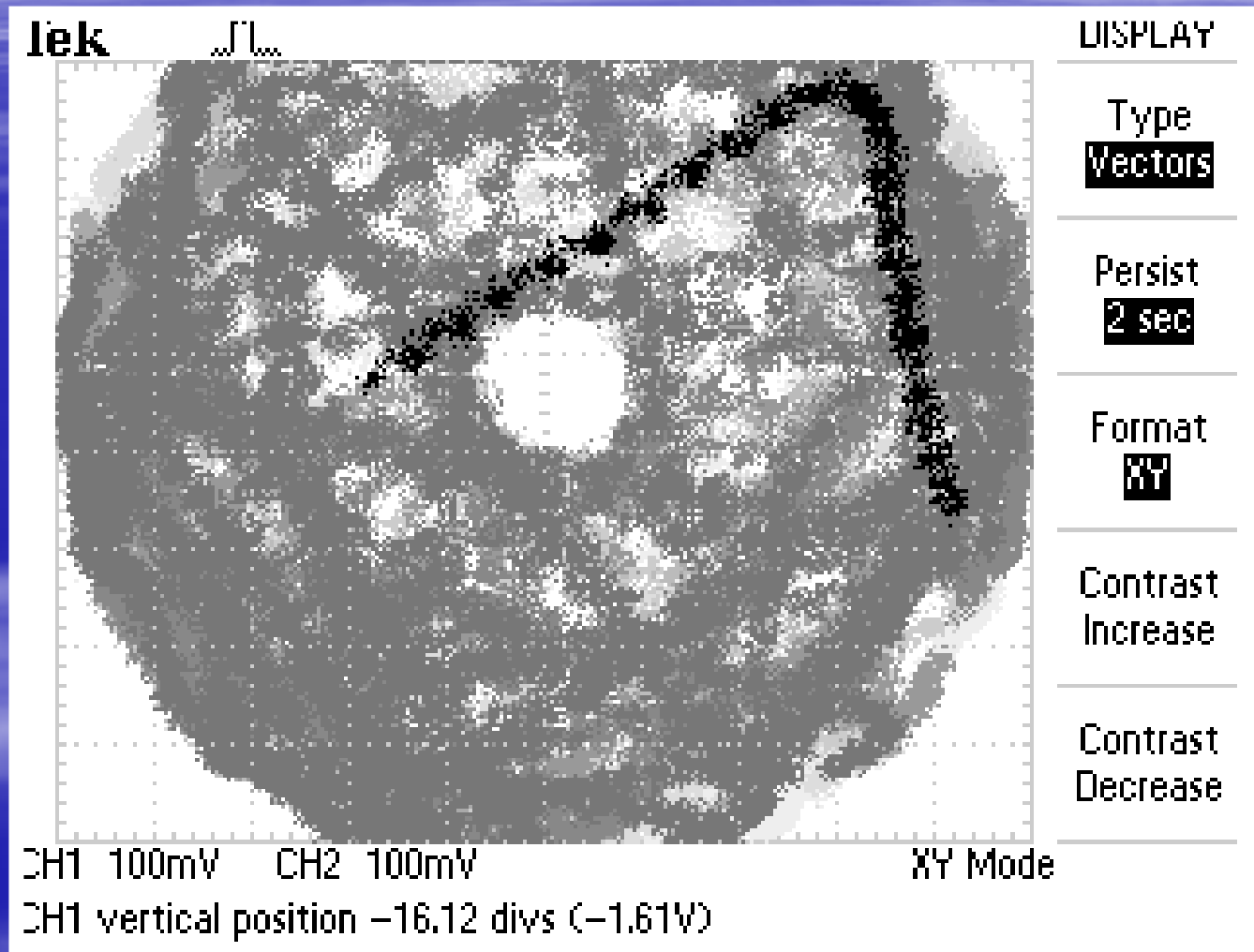
$\pi/4$ -BPSK reception



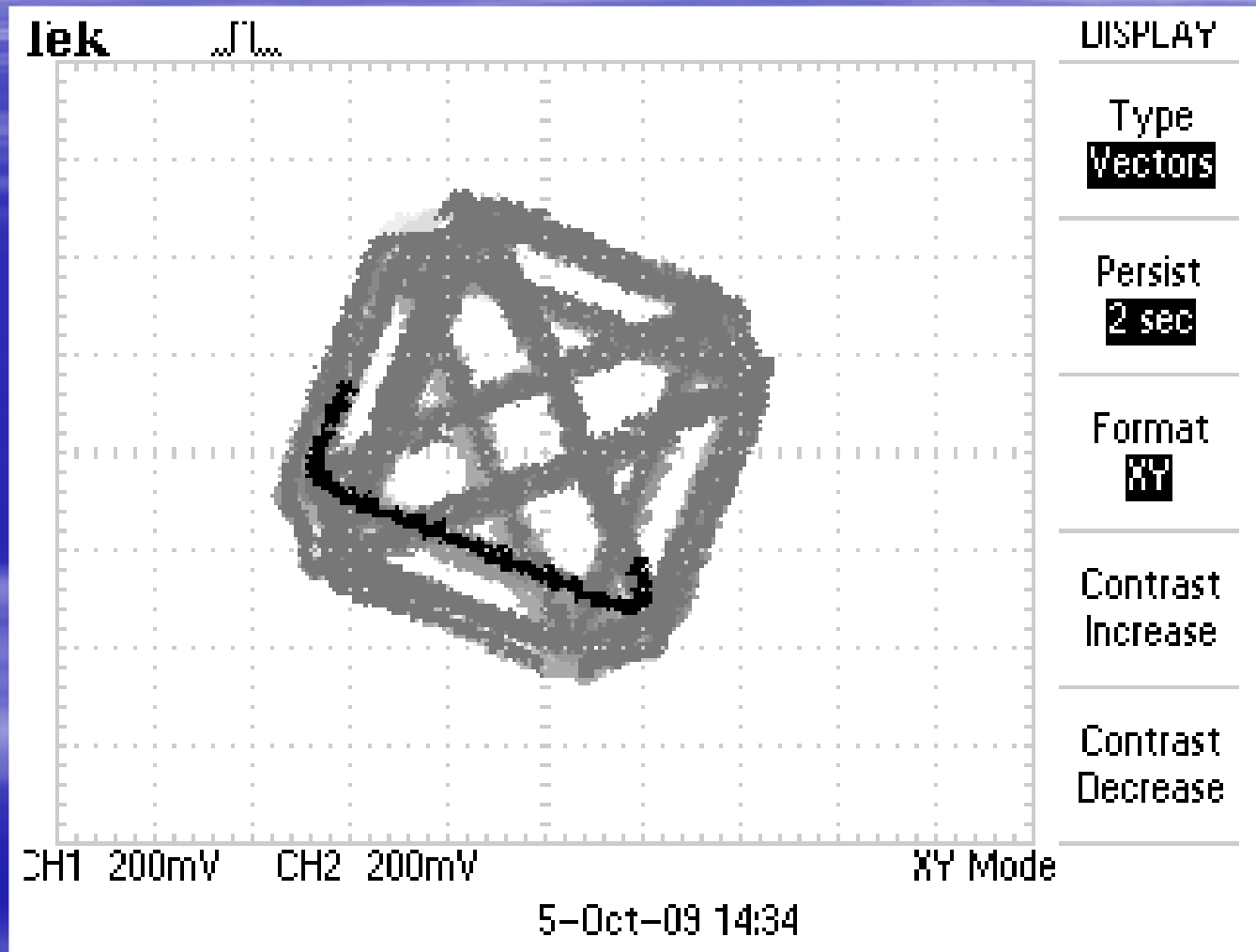
pi/8-8PSK reception



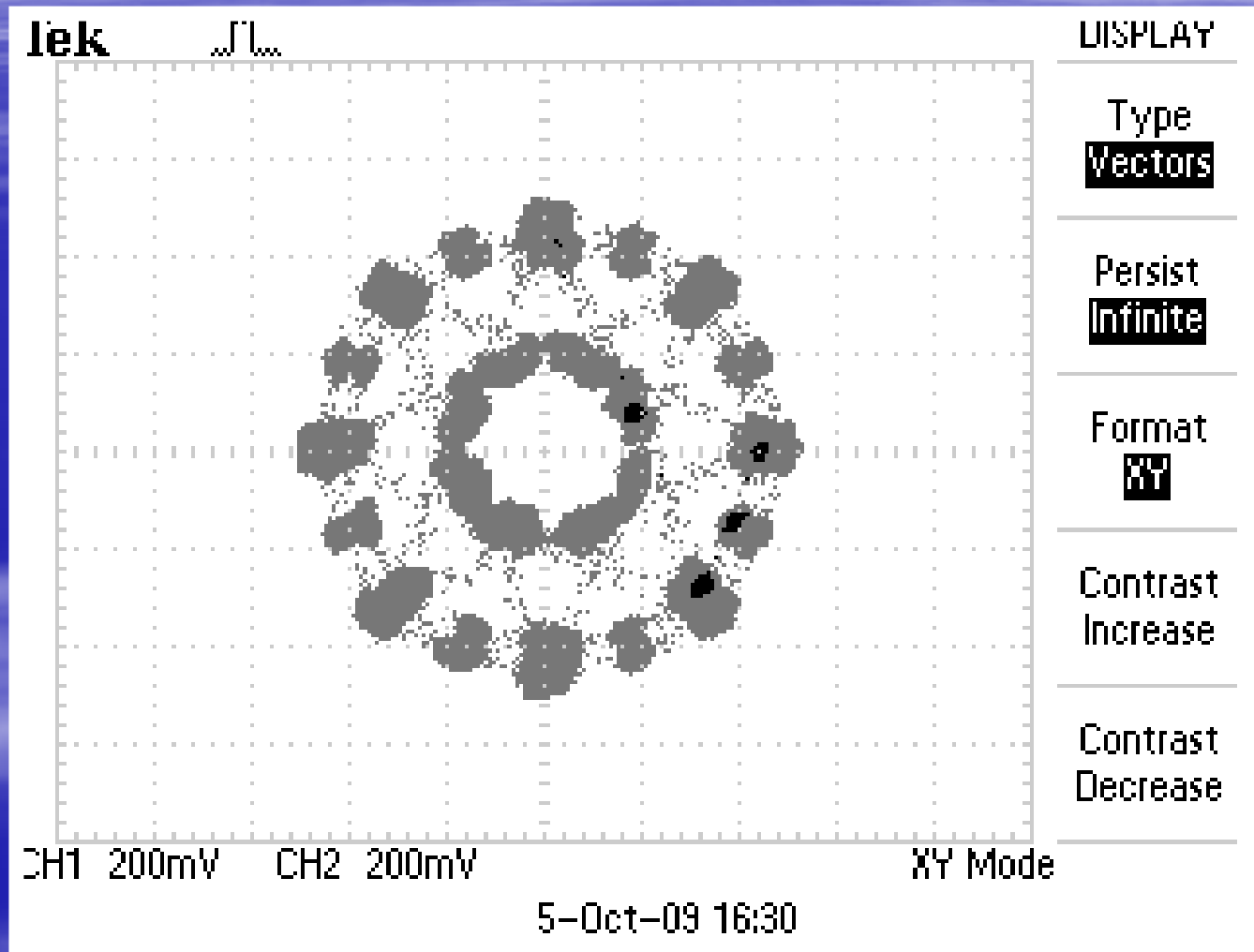
pi/8-8PSK reception



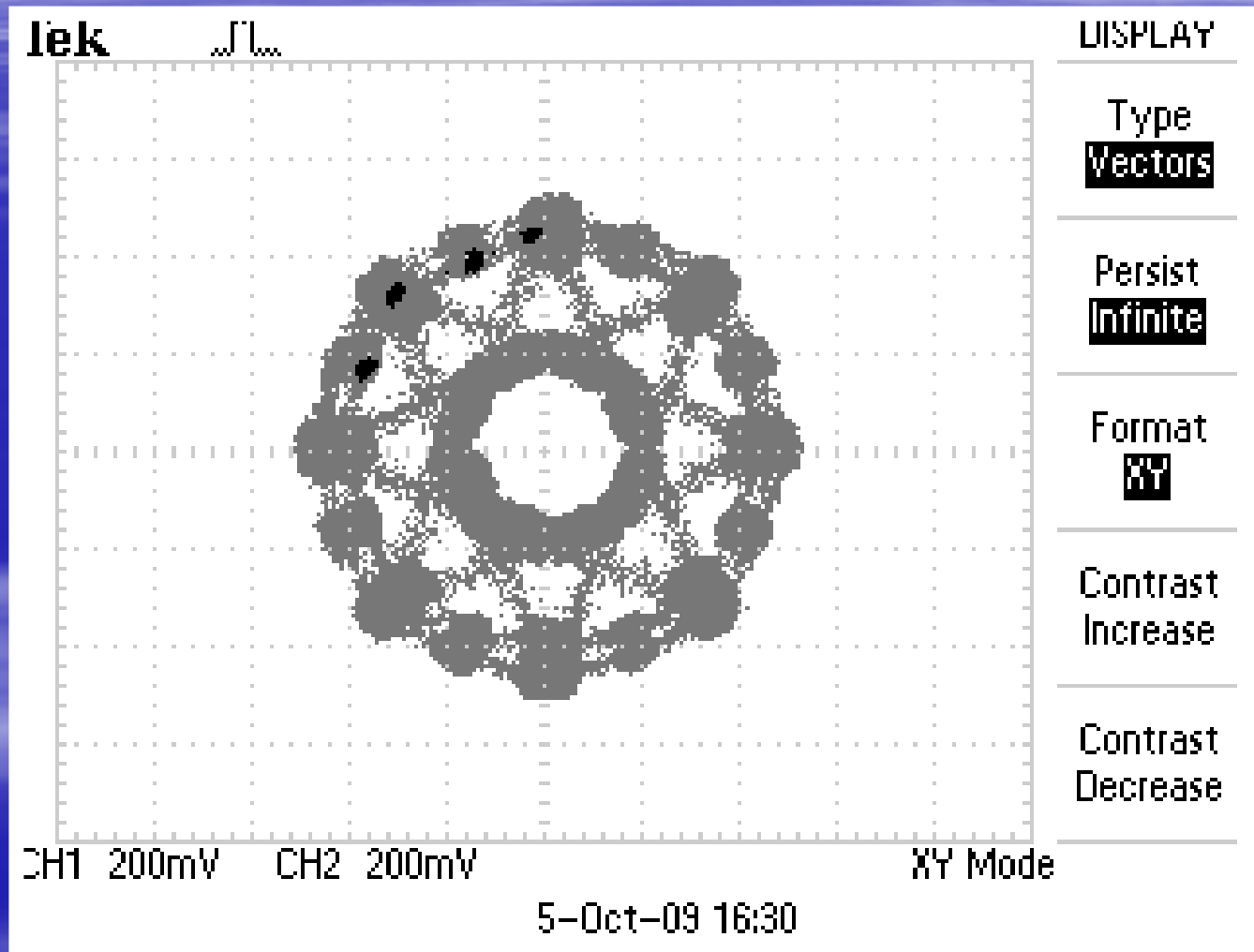
pi/8-QPSK reception



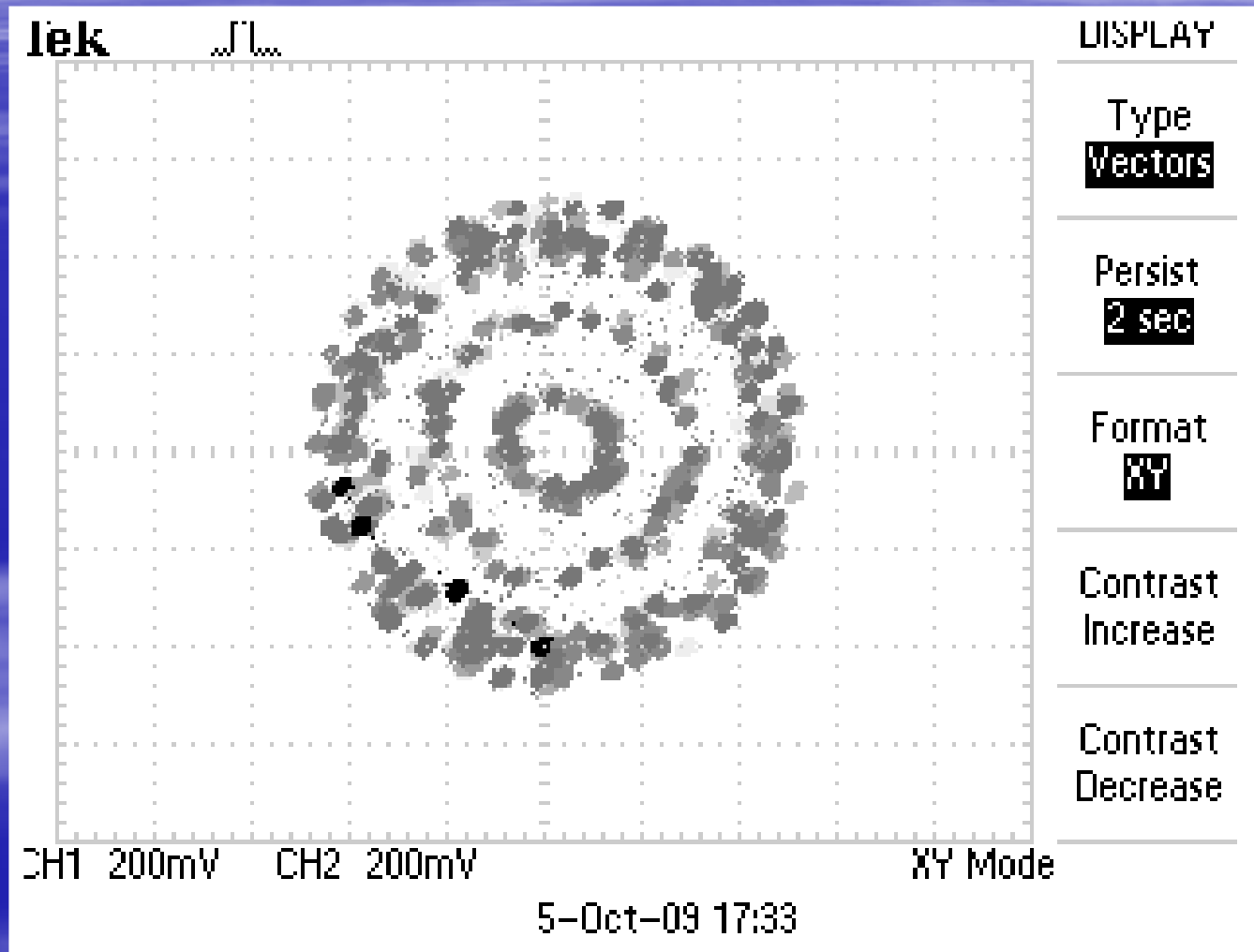
pi/8-8PSK after interpolator



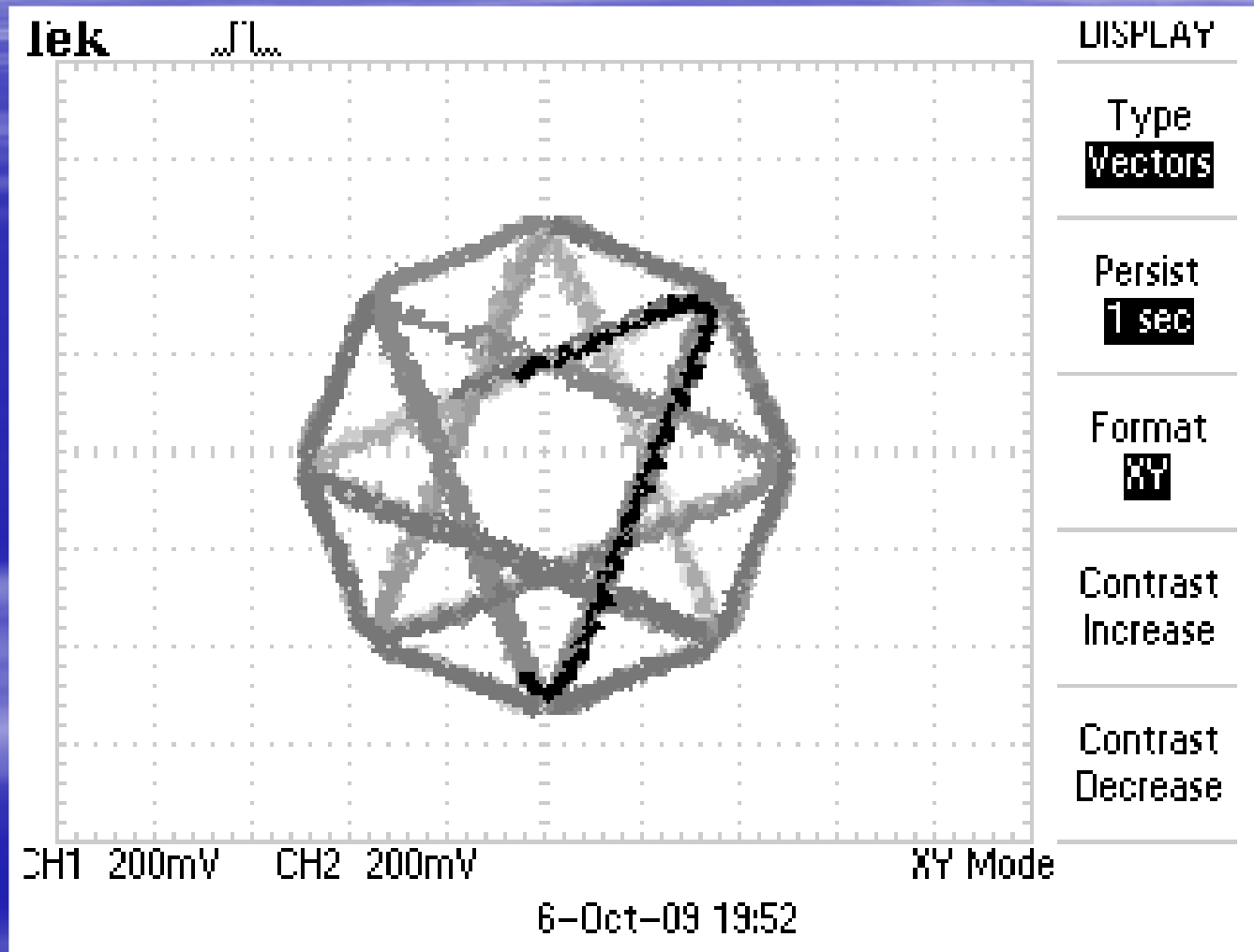
pi/8-8PSK after interpolator



pi/8-8PSK after interpolator



pi/4-QPSK reception



pi/4-QAM-64 reception

