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Method for Automatic Calibration of I/Q Amplitude Balance and Quadrature Skew Using GNU Radio

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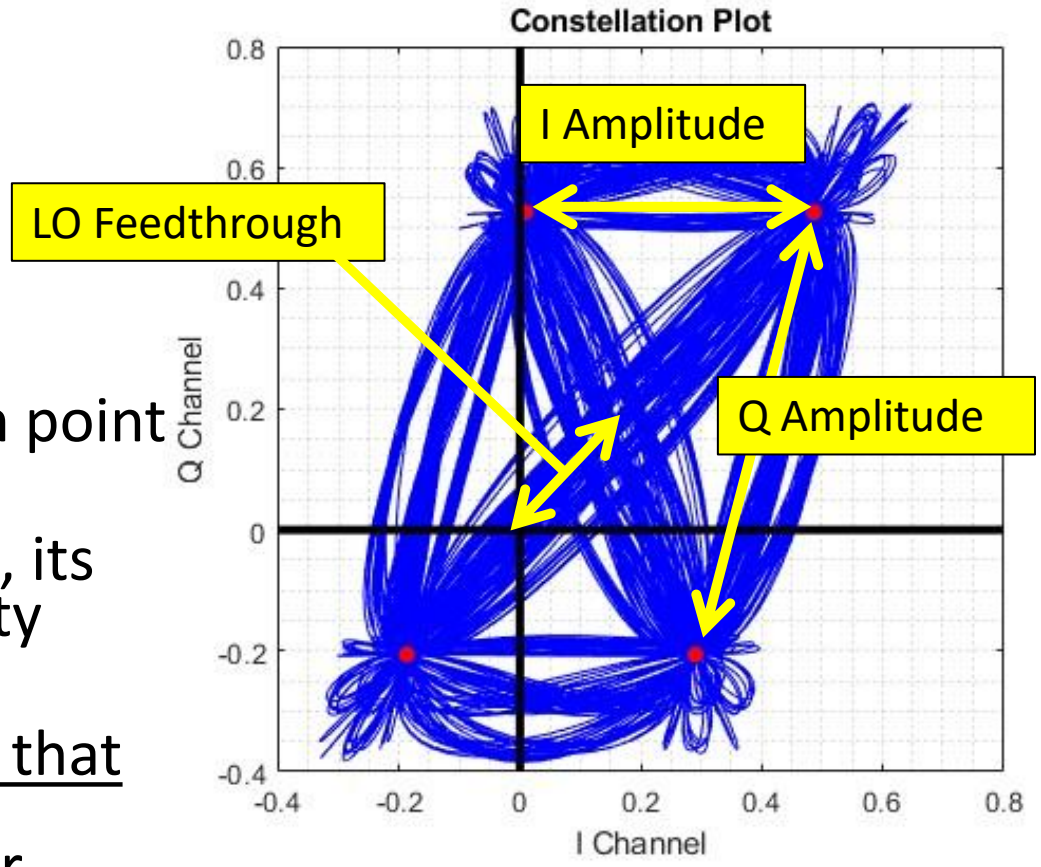
Vector Signal Analyzer (VSA) Measurements

- VSA instrument can perform measurements directly on modulated random data
- Constellation Plots
  - LO Feedthrough (sometimes called “IQ Origin Offset”)
  - I/Q Amplitude Imbalance
  - Quadrature Skew
- Measurements require finding constellation point centers, computing angles and lengths
- If VSA instrument does not know test signal, its reported amplitude imbalance has ambiguity about whether I or Q is too high
- <u>Desire an intuitive measurement technique that clearly identifies I and Q, calibrate by peak minimization using only a spectrum analyzer</u>



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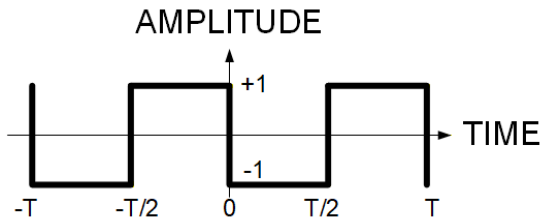
Periodic Test Signal for Measuring LO Feedthrough with Only a Spectrum Analyzer

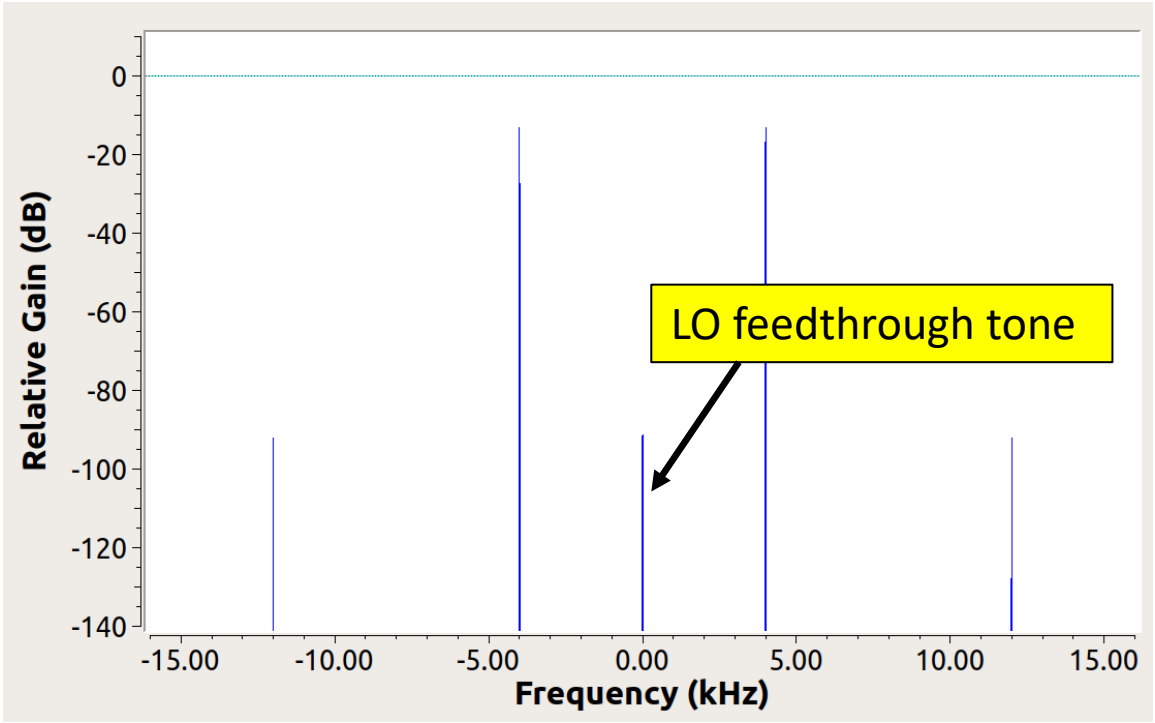
- LO Feedthrough
  - Use BPSK repeating 1010 pattern
  - Theoretical spectrum should only have odd harmonics of symbol rate
  - Center of spectrum is unmodulated carrier (LO feedthrough)



Sample Rate = 32 kHz
2 symbols / period
4 samples/ symbol
Fundamental = 4 kHz
3rd Harmonic = 12 kHz

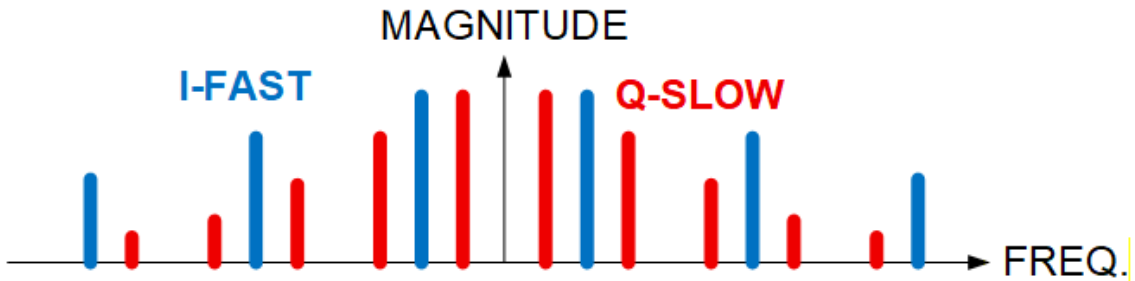
$$c_n = \frac{1}{T}\left\{\int_{-\frac{T}{2}}^{0} e^{\frac{-j2\pi nt}{T}}\,dt - \int_{0}^{\frac{T}{2}} e^{\frac{-j2\pi nt}{T}}\,dt\right\}$$

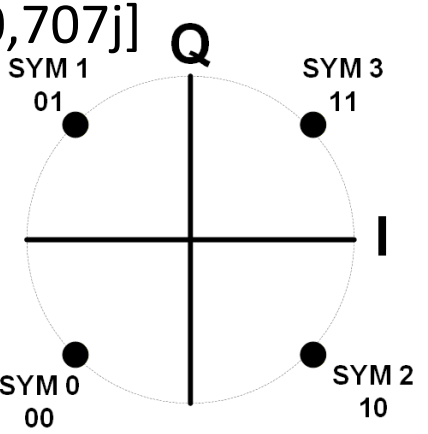
$$= \frac{2((-1)^n - 1)}{j2\pi n} = \begin{cases} 0, & n\ even \\ \frac{j2}{\pi n}, & n\ odd \end{cases}$$



Can We Measure I/Q Amplitude Imbalance with Only a Spectrum Analyzer?

- We need a way to do the following:
  - Generate periodic sequences of I and Q to move them away from the LO feedthrough
  - Arrange them so that the peaks of I occur in the nulls of Q and vice versa
- The way to do that is to have 1010 patterns on both I and Q, <u>but generate one of them at half the rate of the other</u>
  - Peaks of one will be in the nulls of the other
- Define Constellation Rect.
  - Symbol Map: [0, 1, 2, 3]
  - Constellation Points: [-0.707-0.707j, -0.707+0.707j, 0.707-0.707j, 0.707+0,707j]
- Test Signals defined with “Vector Source”
  - I-channel 1010, Q-channel 1100 “I-fast, Q-slow”
    - GNU Radio represents this as the following IQ pairs: 11 01 10 00 = 216 in decimal
  - I-channel 1100, Q-channel 1010 “I-slow, Q-fast”
    - GNU Radio represents this as the following IQ pairs: 11 10 01 00 = 228 in decimal





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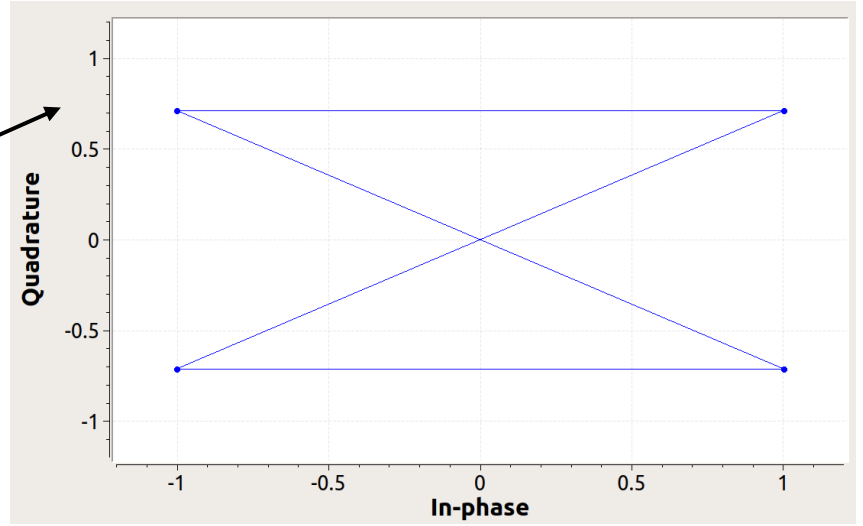
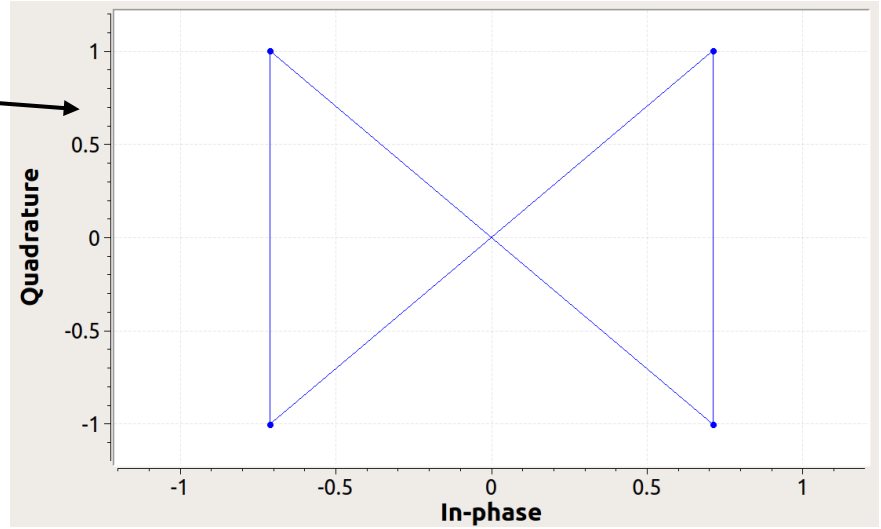
Constellations of Test Signals

- Constellation Modulator
  - Differential Encoding = No
  - 4 Samples/Symbol
- Constellation Sink
  - Default Settings
- Repeating 216 (I-Fast, Q-Slow)
  - Use a vector source with a repeat of 216 as the input to the Constellation Modulator
- Repeating 228 (I-Slow, Q-Fast)
  - Use a vector source with a repeat of 228 as the input to the Constellation Modulator
- The way to read these is to know that the fat end of the figure-8 is always aligned with the slow channel – the one that changes only every other symbol





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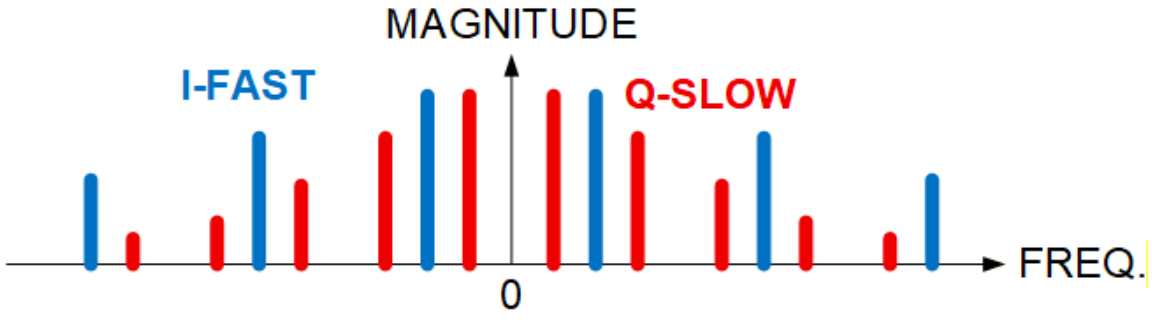
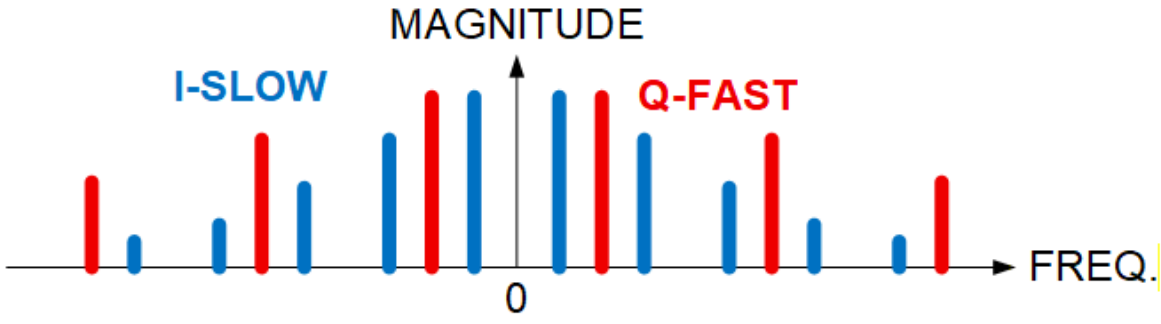
Do We Need Both I-Fast,Q-Slow and I-Slow,Q-Fast? Yes

- DAC Sample-and-Hold Rolloff $\text{Sin}(\text{pi}*f/f_{CLK}) / (\text{pi}*f/f_{CLK})$
  - 4 samples per symbol, 2 syms / cycle fast, 4 syms / cycle slow
  - Fast tones at (sample rate)/8, slow tones at (sample rate)/16 = 0.17 dB difference
- Ripple in the digital shaping filters of the modulator
- Switch between I-Fast,Q-Slow and I-Slow,Q-Fast signals for direct comparisons between I and Q amplitude levels at same frequencies





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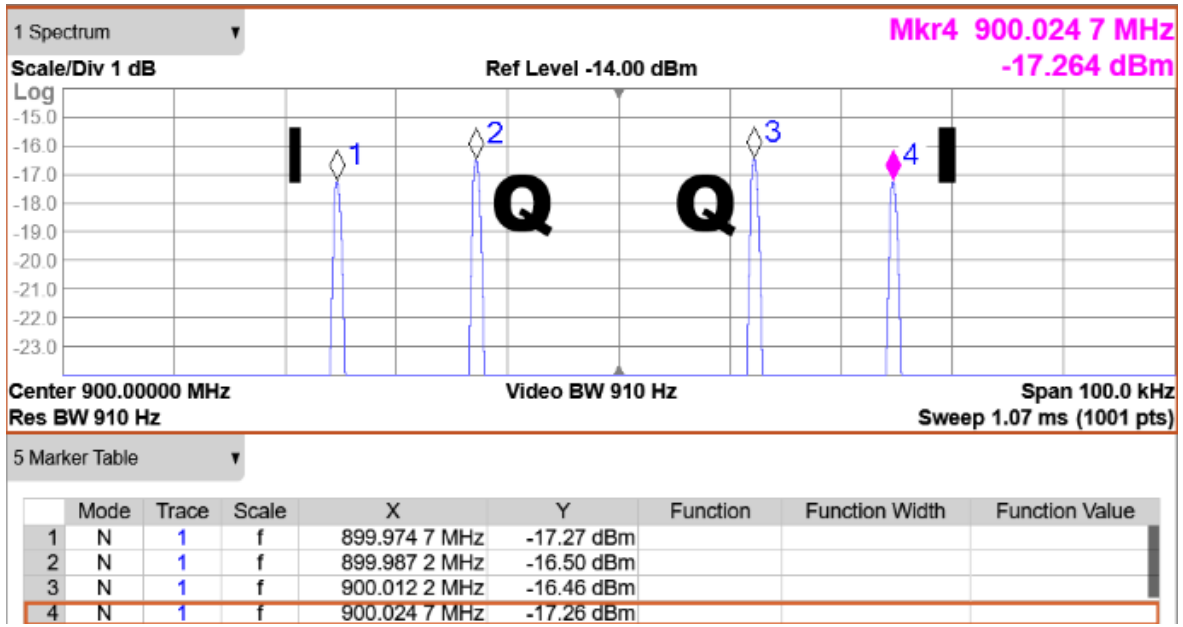
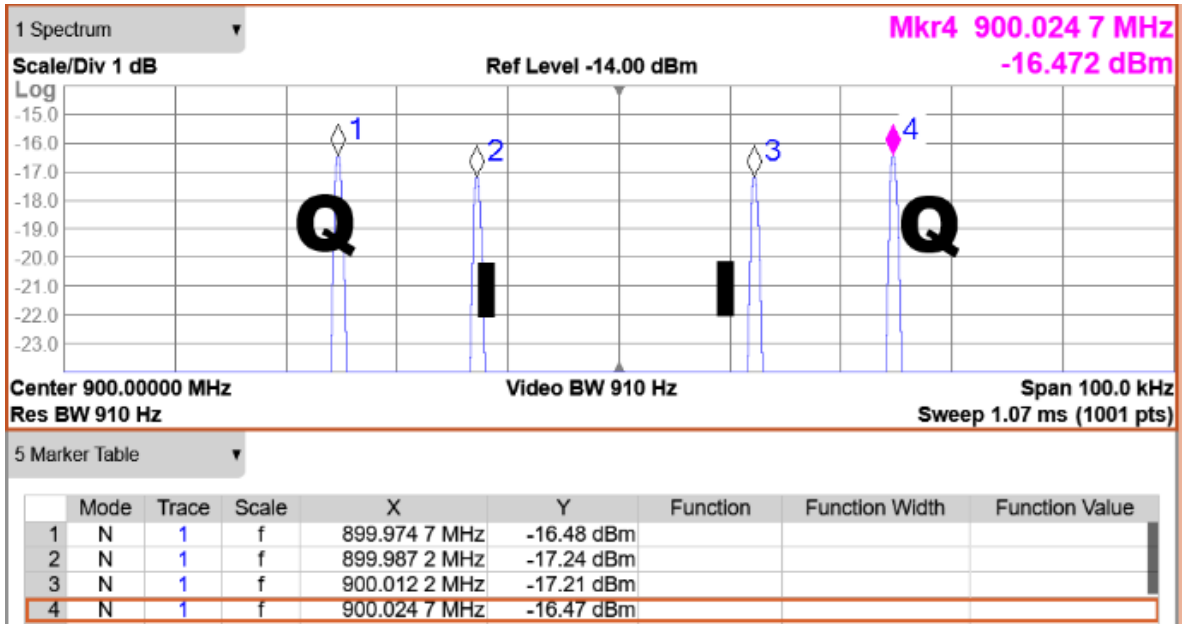
Example of I/Q Amplitude Imbalance Measurement for QPSK





- 899.9750 MHz: I = -17.27 dBm, Q = -16.58 dBm; Q-I = 0.79 dB
- 899.9875 MHz: I = -17.24 dBm, Q = -16.50 dBm; Q-I = 0.74 dB
- 900.0125 MHz: I = -17.21 dBm, Q = -16.46 dBm; Q-I = 0.75 dB
- 900.0250 MHz: I = -17.26 dBm, Q = -16.47 dBm; Q-I = 0.79 dB

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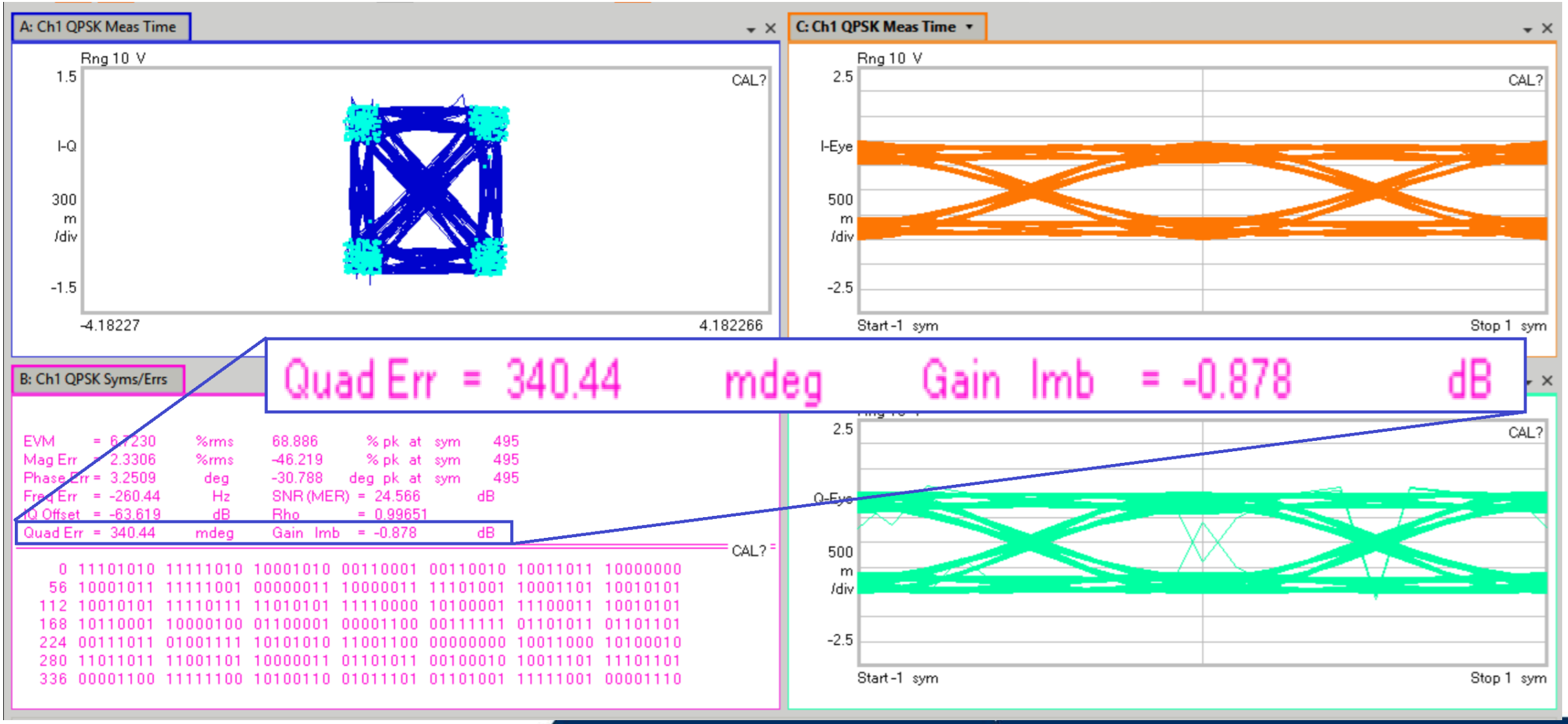
VSA Measurement of Same System



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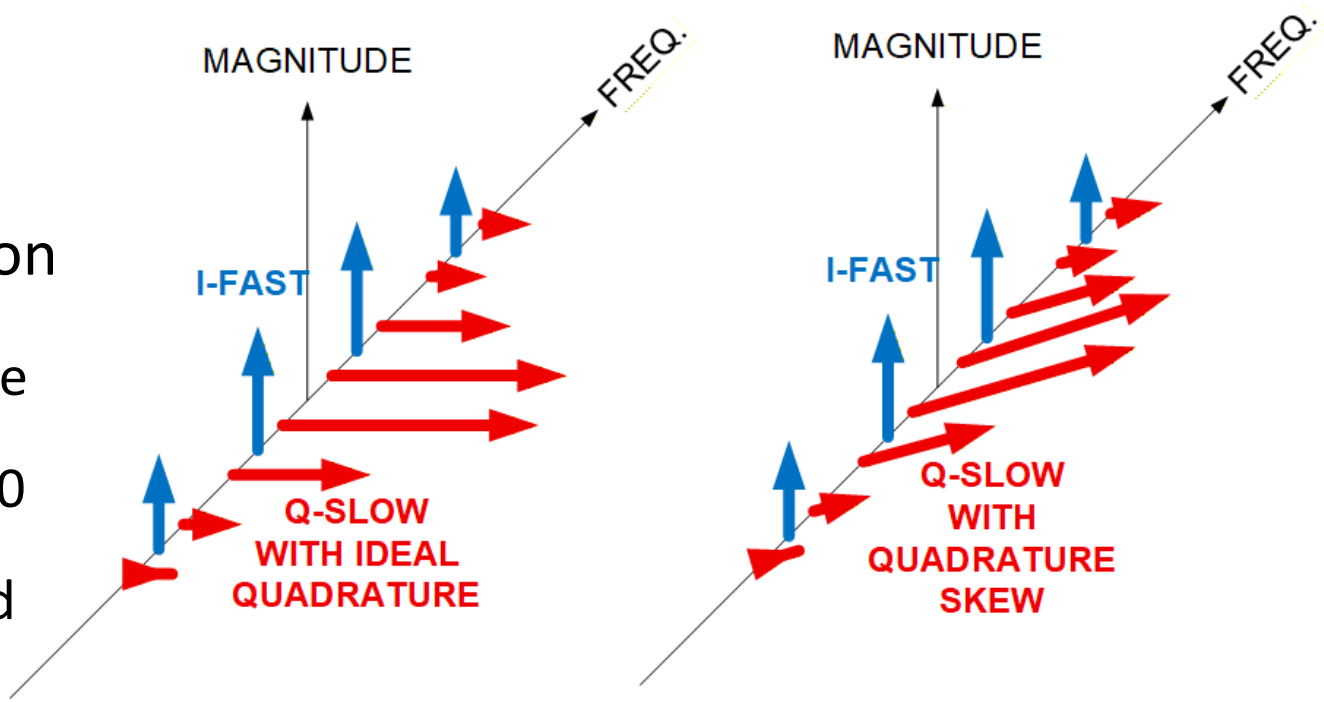
Amplitude Imbalance Measurement is Insensitive to Quadrature Skew

- Quadrature skew causes crosstalk between I and Q in the time domain
  - Real() and Imaginary() operators cannot separate signal components
- Spectrum analyzer separates information according to frequency
  - Peaks of I are in nulls of Q, peaks of Q are in nulls of I
  - Perfect quadrature means Q is rotated 90 degrees with respect to I
  - Imperfect quadrature means Q is rotated differently, but magnitude is same
  - No matter the angle, spectrum shows same amplitude imbalance



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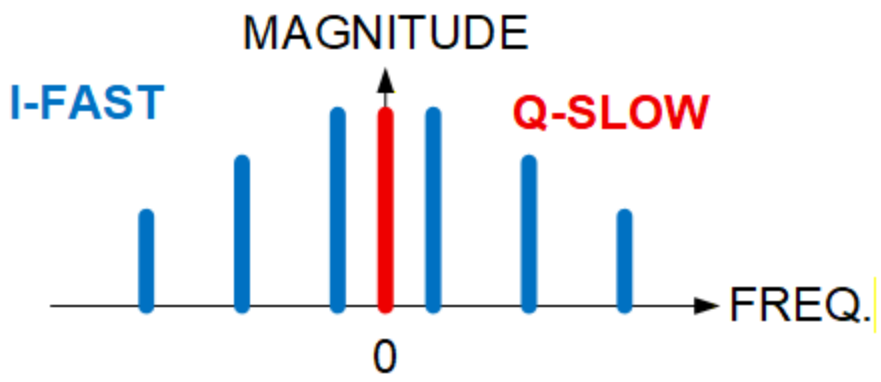
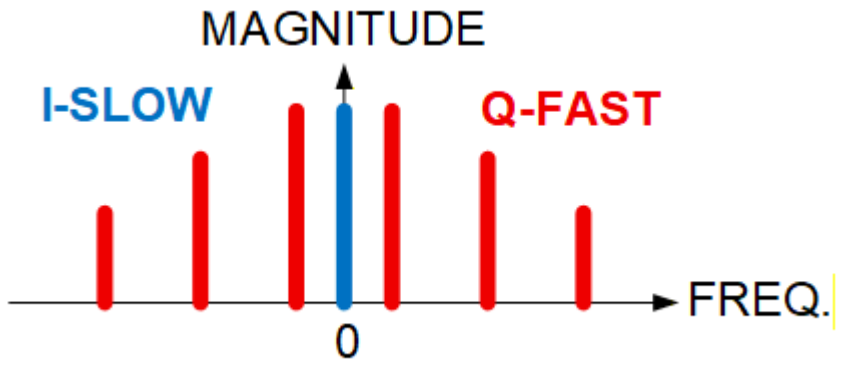
I/Q Amplitude Imbalance Measurement for Offset QPSK Constellation

- Offset QPSK requires that there is a half sample delay between the I channel and the Q channel
  - Ensures that I and Q never change at same time – limits sidelobes
  - "Slow" will now mean CONSTANT. This channel's output will only show up in the center of the spectrum
  - I-Fast, Q-Slow is now 11011101 = 221
  - I-Slow, Q-Fast is now 11101110 = 238





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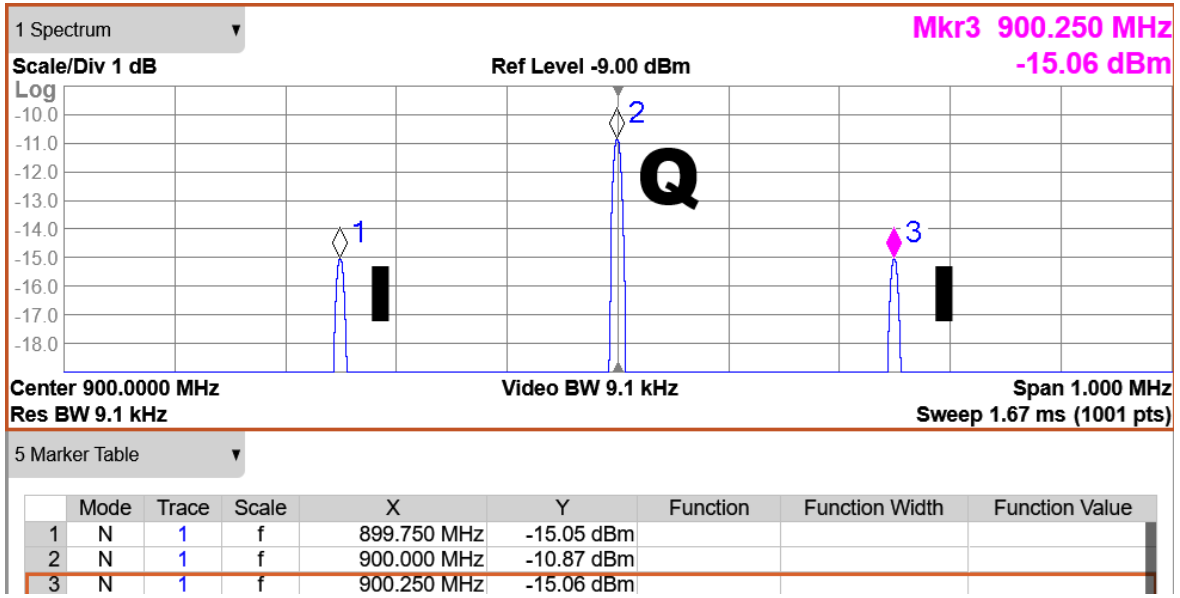
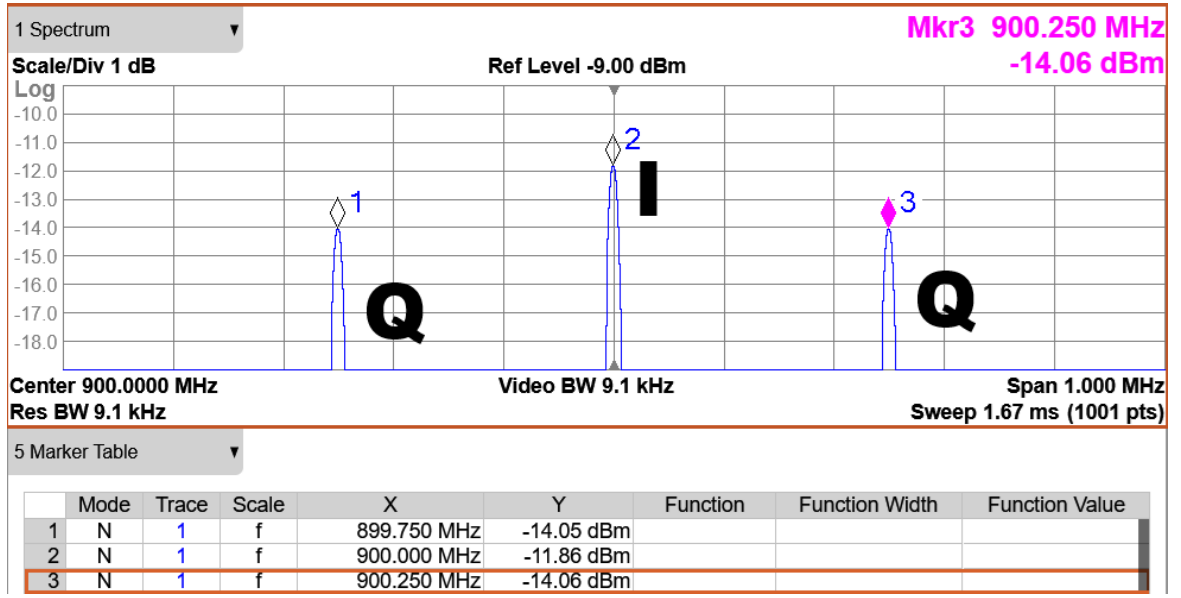
Example of I/Q Amplitude Imbalance Measurement for OQPSK





- 899.975 MHz: I = -15.05 dBm, Q = -14.05 dBm; Q-I = 1.00 dB
- 900.000 MHz: I = -11.86 dBm, Q = -10.87 dBm; Q-I = 0.99 dB
- 900.025 MHz: I = -15.06 dBm, Q = -14.06 dBm; Q-I = 1.00 dB

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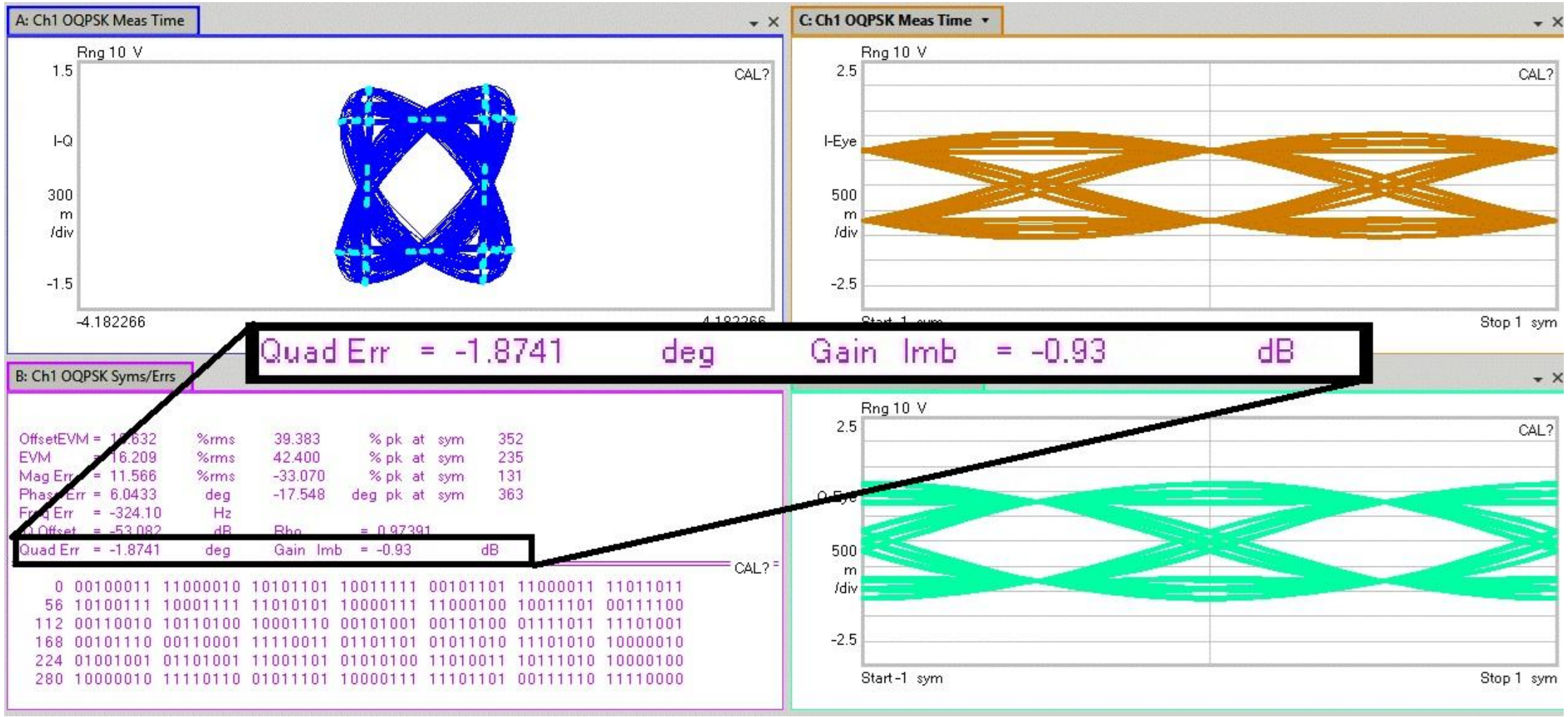
VSA Measurement of Same System for OQPSK



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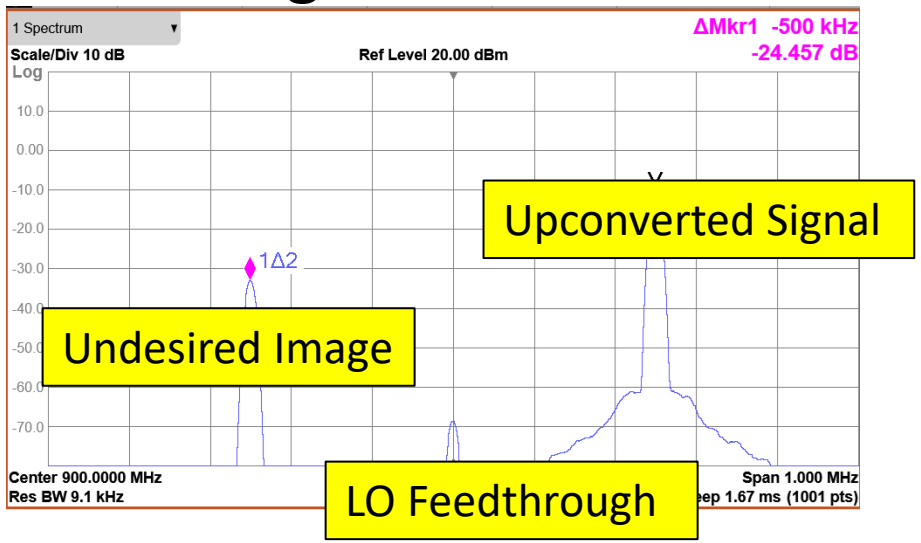
Quadrature Skew Measurement with Spectrum Analyzer

- Main effect of quadrature skew is crosstalk between I and Q
  - Can't separate using Real{} and Imag{} operators
- Deliberately introduce crosstalk with the opposite sign
- If we put a complex sinusoid on I and Q (I=cosine, Q=sine), the output of the vector modulator should be a single tone
- Imperfection in Vector Modulator Phase Shift Causes Image
- $IRR = \frac{1+2\alpha+\alpha^2(1+\epsilon^2)}{1-2\alpha+\alpha^2(1+\epsilon^2)}$ Image Rejection Ratio
  - Epsilon: quadrature skew (radians)
  - Alpha: ratio of Q-amplitude to I-amplitude
  - Knowing IRR and alpha, solve for epsilon squared
  - Try both positive / negative values as corrections



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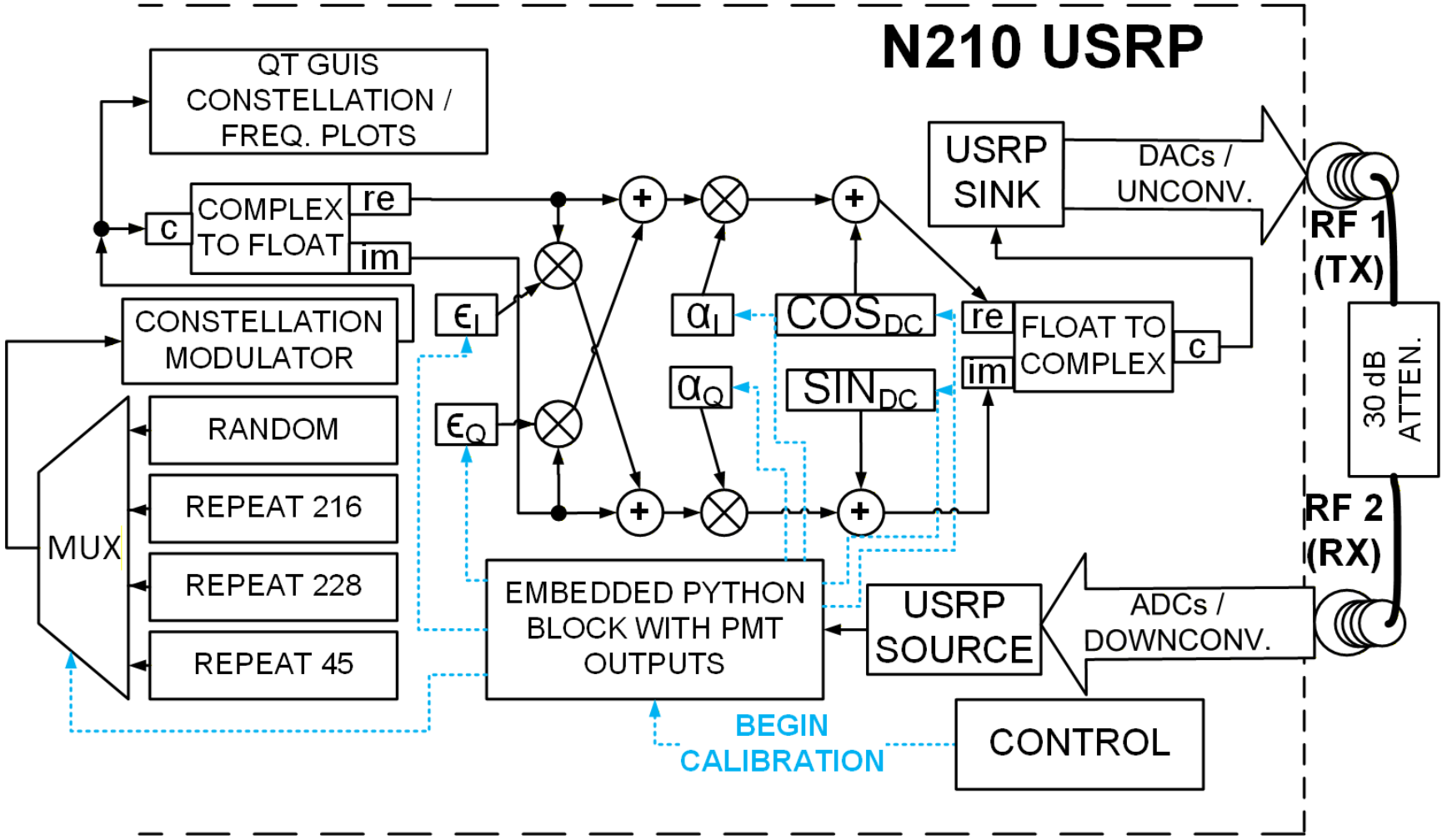
Auto-Calibration of QPSK in GNU Radio



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Calibration Implementation in GNU Radio

- Embedded Python Block
  - Starts with normal random signal, waits for control input to start calibration
  - Alternates between I-Fast,Q-Slow vector (216) and I-Slow,Q-Fast (228) vector to measure and correct α_I and α_Q
  - Switches to Quad Skew vector (45) to measure IRR and correct quadrature skew ϵ_I or ϵ_Q (and any additional residual amplitude imbalance)
    - Also corrects LO Feedthrough by adjusting COS_{DC} and SIN_{DC}
- Polymorphic Type (PMT) messages update α_I α_Q ϵ_I ϵ_Q COS_{DC} SIN_{DC}

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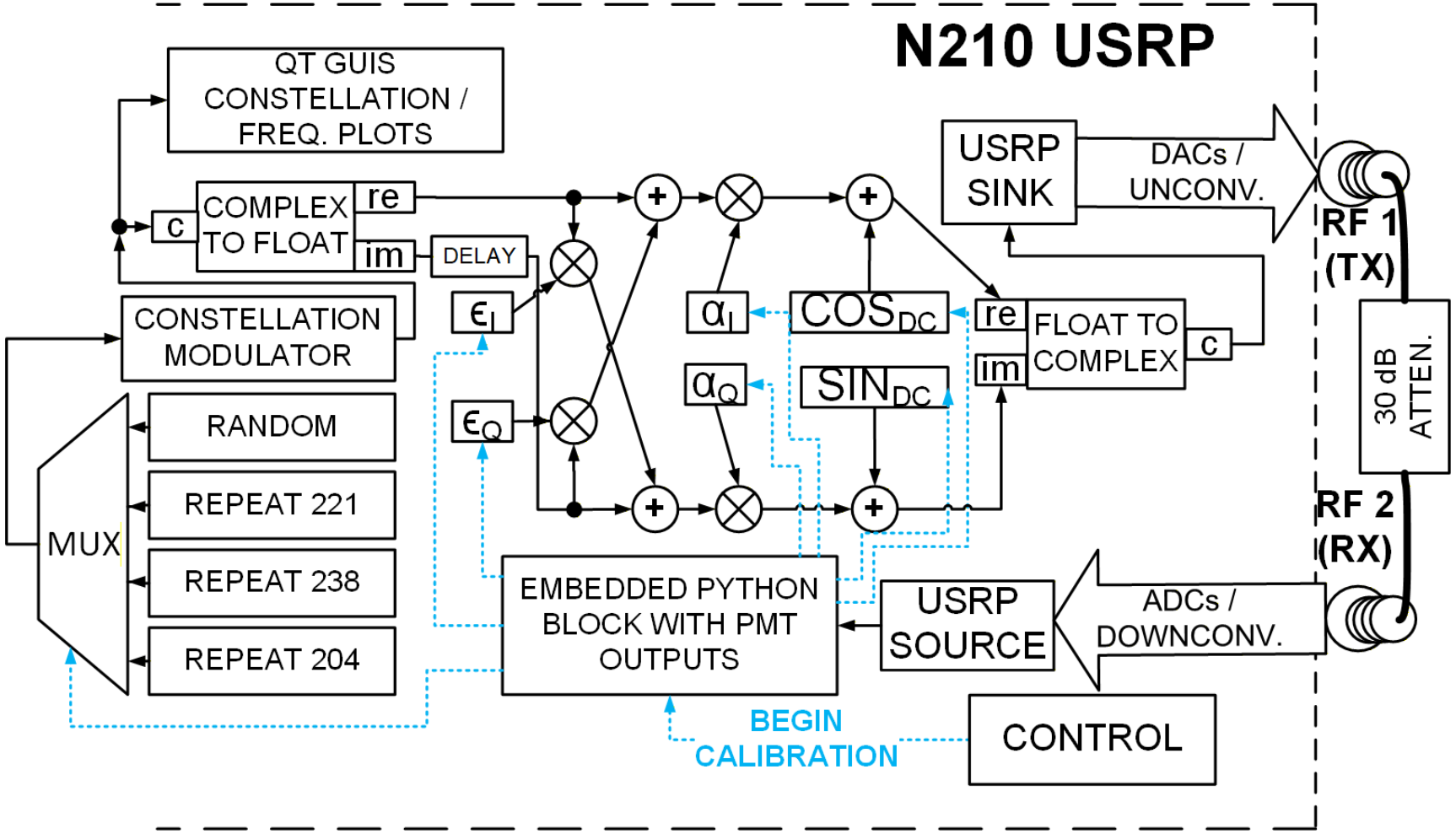
Auto-Calibration of OQPSK in GNU Radio



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Summary of Differences Between Diagrams for QPSK and OQPSK

- OQPSK has ½ samples per symbol delay on imaginary path
- QPSK
  - Amplitude Imbalance:
  - I-Fast Q-Slow: 216
  - I-Slow Q-Fast: 228
  - Quad Skew: 45
- OQPSK
  - Amplitude Imbalance:
  - I-Fast Q-Slow: 221
  - I-Slow Q-Fast: 238
  - Quad Skew: 204

- Questions?

- Backup Slides

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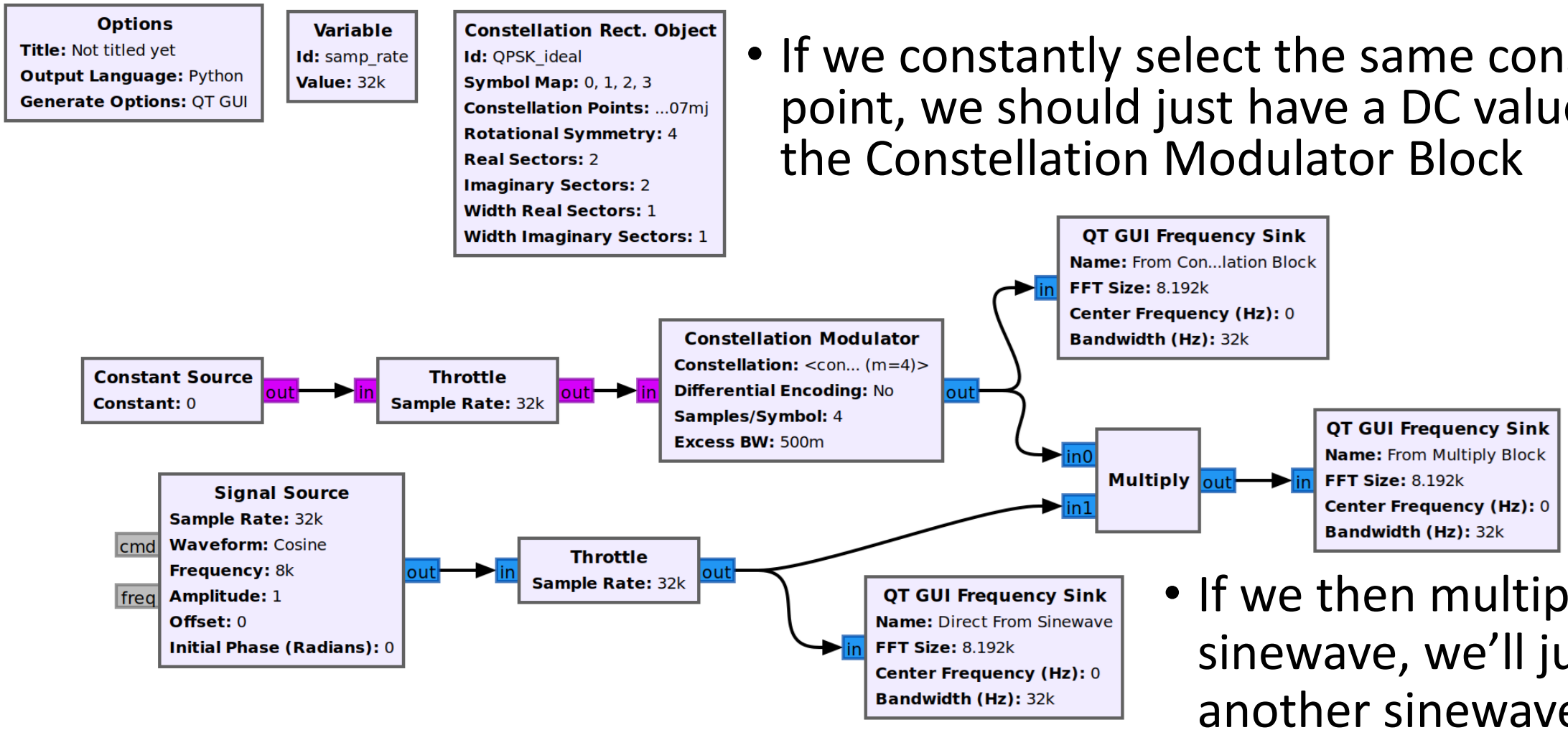
Quad Skew Correction Test Signal: How NOT To Generate It



- If we constantly select the same constellation point, we should just have a DC value out of the Constellation Modulator Block

- If we then multiply by a sinewave, we'll just have another sinewave, RIGHT?

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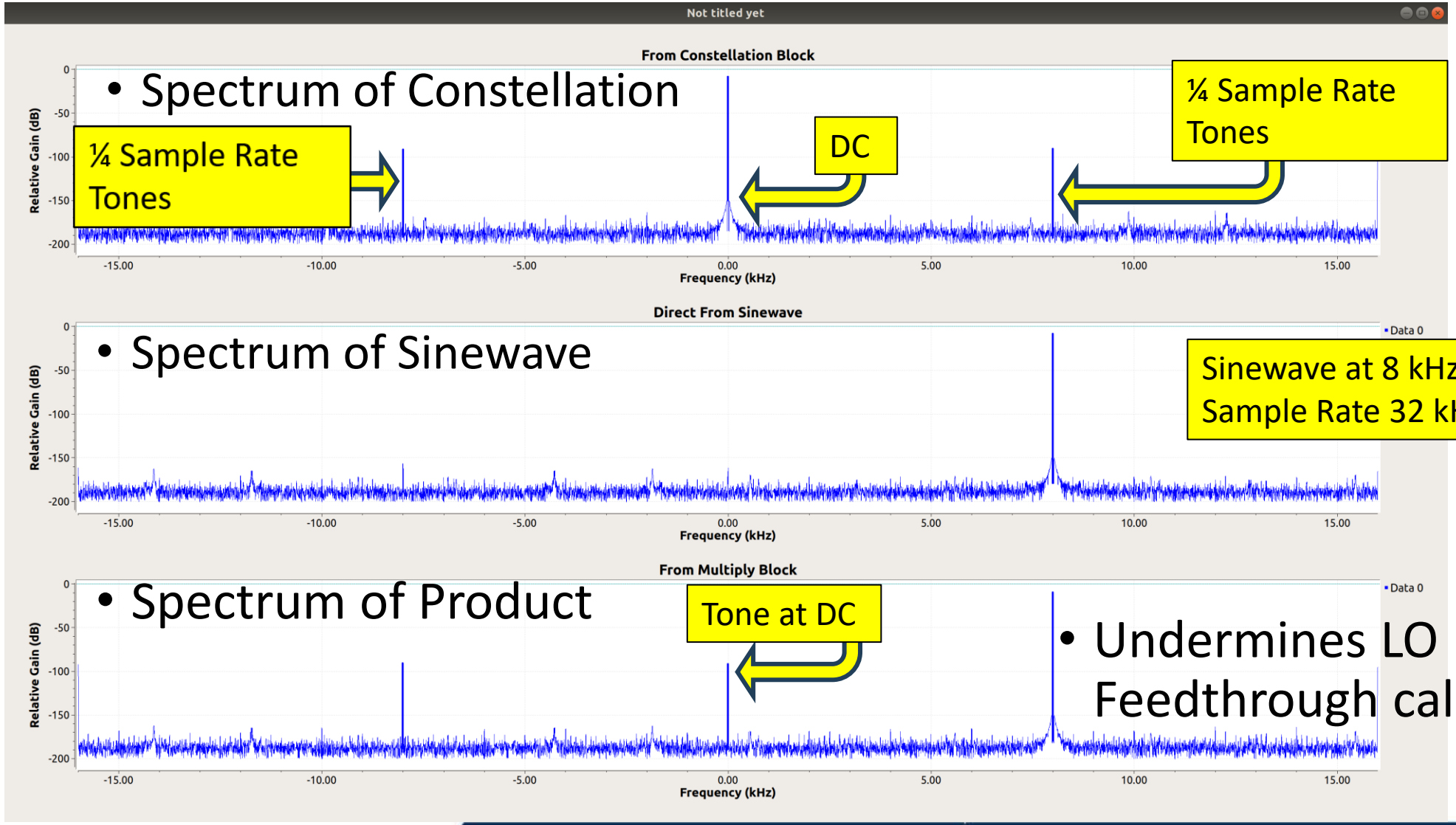
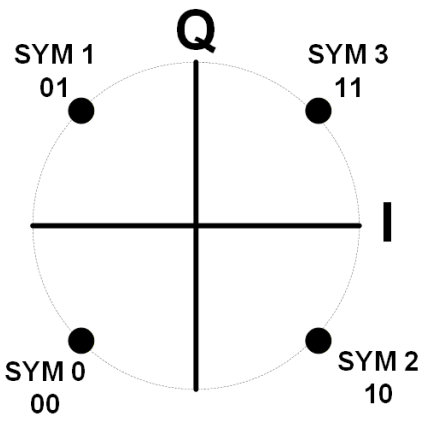
Quad Skew Correction Test Signal: How NOT To Generate It, Part 2



Quad Skew Correction Test Signal: How To Generate It

Sample Rate = 32 kHz
4 symbols / period
4 samples/ symbol
Fundamental = 2 kHz
3rd Harmonic = 6 kHz

- The RIGHT way is to create a vector source that cycles around the unit circle
  - Positive freq. offset: 00 10 11 01 = 45 decimal
  - Negative freq. offset: 00 01 11 10 = 30 decimal
- With 4 samples / symbol in the constellation block, and 4 symbols per cycle, the resulting frequency will be 1/16 of the sample rate
- Undesired image on other side of 0 Hz is caused by quadrature skew



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Other Consequences of Modulating Baseband onto Sine / Cosine

- Even if there is amplitude imbalance between I and Q channels
- Even if there is quadrature skew
- The constellation on either sideband will have quadrature skew and amplitude imbalance REMOVED
- Just use an analog filter to remove the undesired sideband