Characterizing PDN Pollution, Part 2

Real-time Spectral Analysis of Power Rails

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Everywhereyoulook™

Agenda

- Reminder: what is power integrity?
- Why spectral analysis?
  - What specific power integrity problems benefit from this approach?
- Time-domain vs frequency-domain analysis
  - Time-domain figures of merit
  - Basics of the Fourier transform
  - Relationships between time-domain and frequency-domain characteristics
  - FFT settings and their effects
  - Interpreting the spectrum's vertical scale
- Examples
  - Simple sine-wave generator
  - Tracking down PDN noise

What is Power Integrity (and why do we care?)

Power Integrity concerns maintaining the **quality** of power from generation to consumption. High power integrity means **noise levels** that are within tolerance.

Power Integrity is typically analyzed at:

- The PDN (Power Distribution Network)
- On-die (within devices that consume power)

Performance feature	Noise tolerance
Receiver reference voltage level shifts	~ 5% rail
Jitter on core logic gates	~ 5% rail
Jitter on data lines	~ 1-5% rail
Jitter on re-timers, clock distribution, generator circuits	~ 1-5% rail
Voltage on ADC voltage reference	< 1% rail
Voltage on analog signal circuits	< 1% rail
Voltage noise at carrier freq on rf reciever circuits	< 1% rail

Why spectral analysis?

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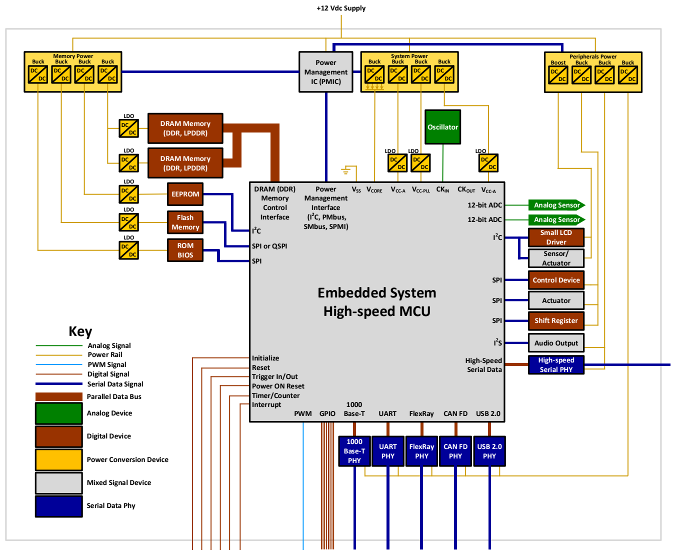
Typical embedded system block diagram

Most modern embedded systems share a similar conceptual layout to our example

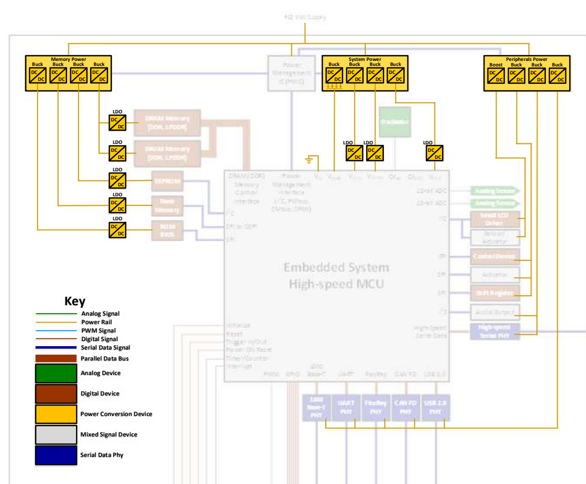
We will use this “typical” system to illustrate concepts



The Power Distribution Network

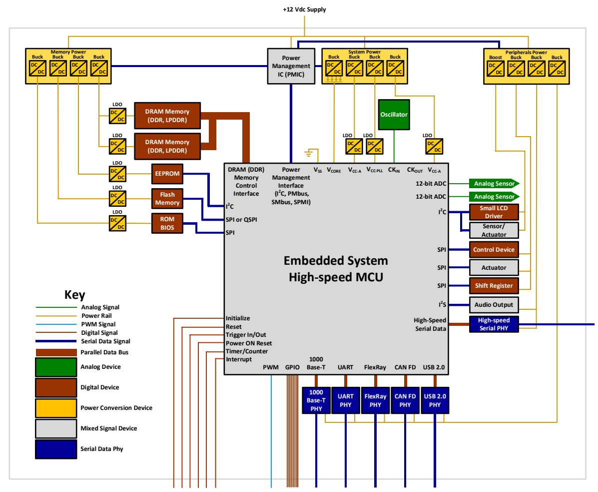
The board-level Power Distribution Network (PDN) consists of:

- Regulation modules (VRMs) between the bulk supply and components that consume power
- Board interconnects (traces, planes) distributing power from VRMs to devices
- Capacitors



The 12 types of PDN noise

- Self aggression noise
  - From VRM on VRM
  - From Vcc on Vcc
  - From Vdd on Vdd
  - From signals on signals
- "Pollution" of the board/pkg interconnects
  - From VRM
  - From I/O
  - From core
  - From signals
- Mutual aggressors: cross talk coupling from the PDN
  - To VRM
  - To I/O
  - To core
  - To signals



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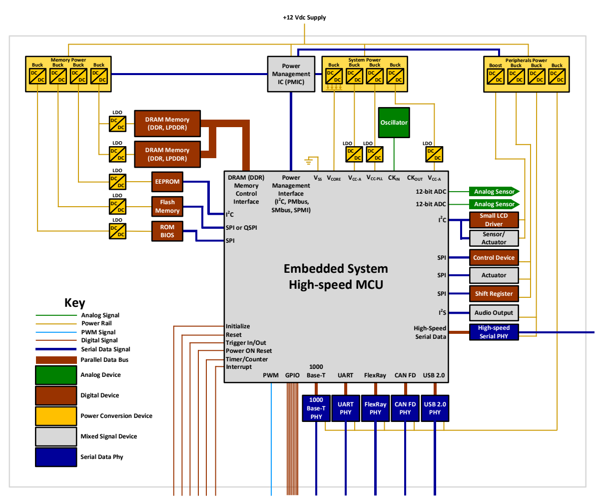
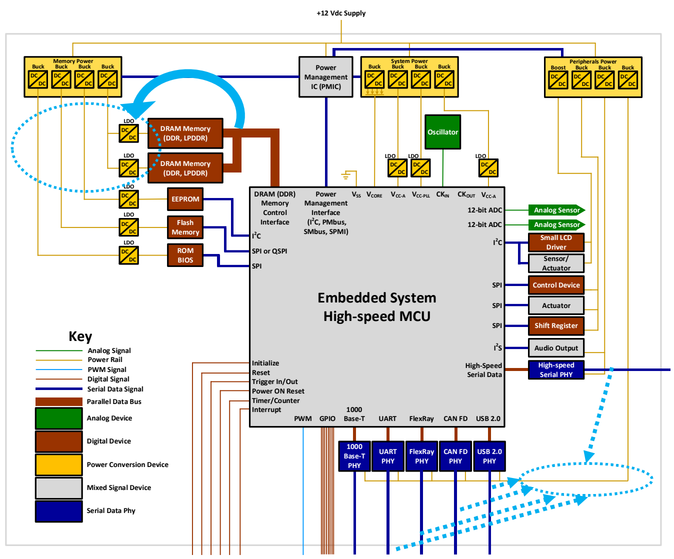


Board/Interconnect Pollution

- From VRM
- From I/O
- From core
- From signals



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Time-domain vs frequency-domain analysis

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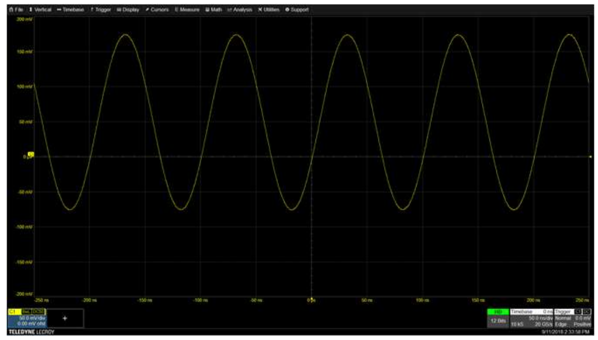
Signals in the time domain

- **Figures of merit** take a complex behavior and extract a few terms that characterize it.
- What are the figures of merit that describe a signal?



Signals in the Time Domain and Their Figures of Merit

- Example:
  - Frequency
  - Amplitude
  - Peak to peak
  - Average
  - Offset
  - Peak = Max
  - RMS
  - Standard deviation

General Signals

$$\text{Average} = \frac{1}{T}\int_{\text{start}}^{\text{finish}} V(t)dt$$

$$\text{RMS} = \sqrt{\frac{1}{T}\int_{\text{start}}^{\text{finish}} V^2(t)dt}$$

$$\text{Standard deviation} = \sigma = \sqrt{\frac{1}{T}\int_{\text{start}}^{\text{finish}} \left(V(t) - \langle V(t)\rangle\right)^2 dt}$$

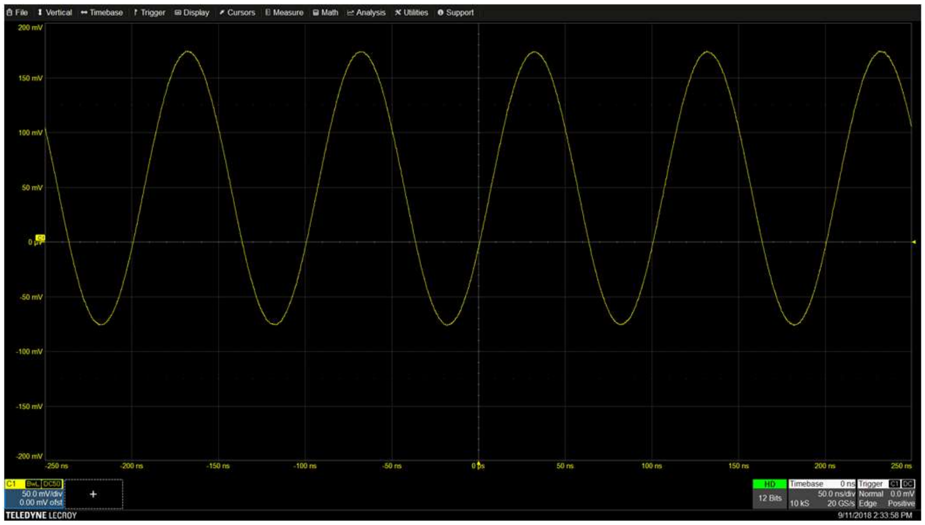
Special case of a sine wave

$$\text{RMS} = \sqrt{\text{Average}^2 + \frac{1}{2}\text{Amplitude}^2}$$

$$\sigma = \sqrt{\frac{1}{2} \times \text{Amplitude}^2} = 0.707 \times \text{Amplitude}$$

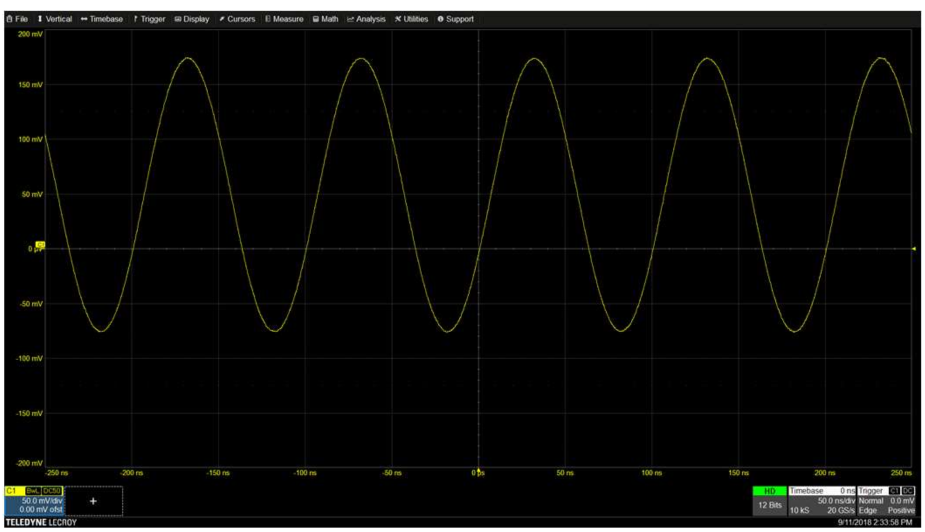
Figures of merit: visual/cursor measurements

- On a simple signal, some vertical figures of merit can be easily assessed visually:
  - Amplitude
  - PkPk
  - Offset
- Others require more analysis:
  - Average
  - RMS
  - Standard deviation



Figures of merit: visual/cursor measurements

- On a simple signal, some horizontal figures of merit can be easily assessed visually:
  - Frequency
  - Period
- Others require more analysis:
  - Phase relationships
  - Relative amplitudes of frequency components



Figures of merit: Analytical measurements in the time domain

- When the signal is simple, analysis of basic figures of merit is fairly trivial in the time domain

Figures of merit: Analytical measurements in the time domain

- But what happens when the signal becomes more complicated?

How do we go from the time domain to the frequency domain“?

- The Fourier Integral:

$$F(f) = \int_{-\infty}^{+\infty} f(t) e^{-j2\pi ft} dt$$

- The discrete Fourier transform:
  - ONLY applies to periodic waveforms with period T_0
  - Each frequency component is n x $1/T_0$

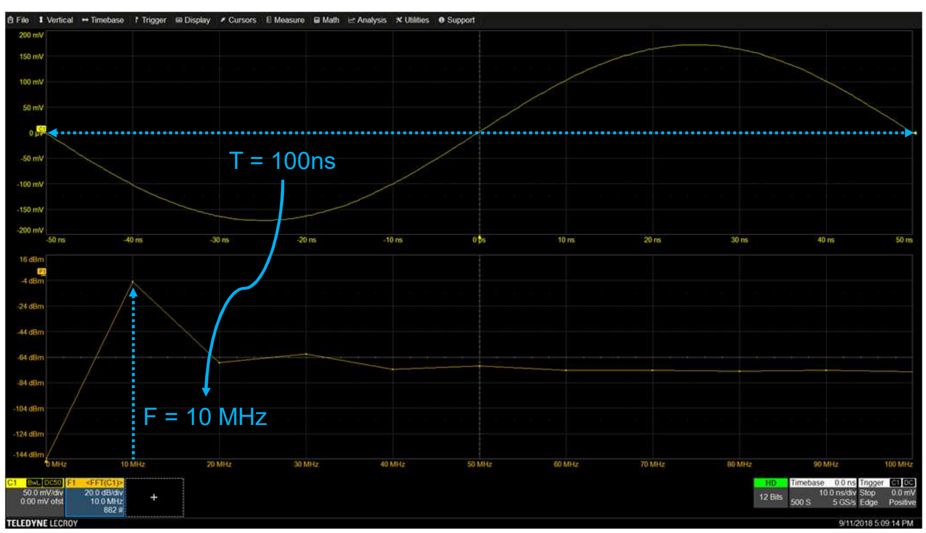
$$a_0 = \frac{1}{T_0}\int_0^{T_0} V(t)\,dt \qquad a_n = \frac{2}{T_0}\int_0^{T_0} V(t)\cos\left(\frac{2\pi}{T_0}nt\right)dt \qquad b_n = \frac{2}{T_0}\int_0^{T_0} V(t)\sin\left(\frac{2\pi}{T_0}nt\right)dt \qquad \text{Amplitude}_n = \sqrt{a_n^2 + b_n^2}$$

- Fast Fourier Transform (FFT): same as DFT, but limited to 2^n points

FFT bins represent harmonics of $1/T_0$

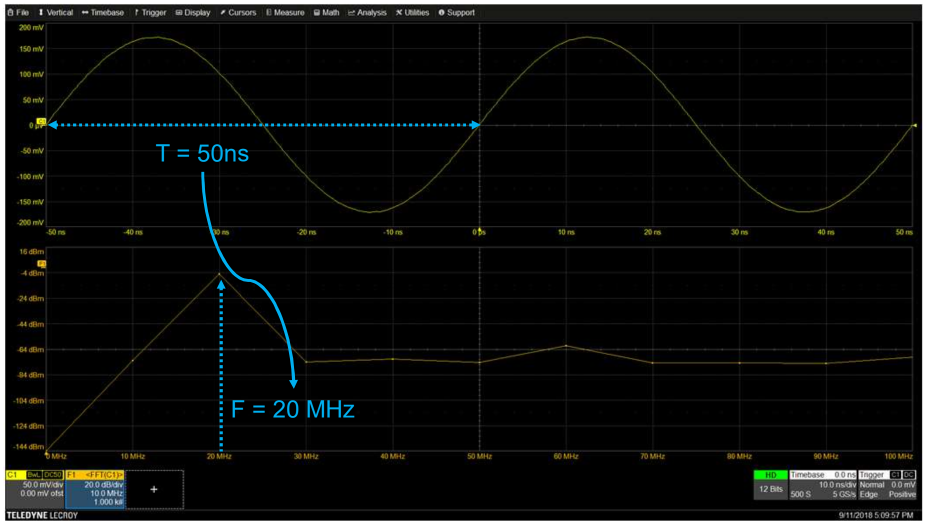
- 1^{st} harmonic frequency:
  $f_0 = 1/T_0$

- Signal energy at 10 MHz goes into the 10 MHz “bin”



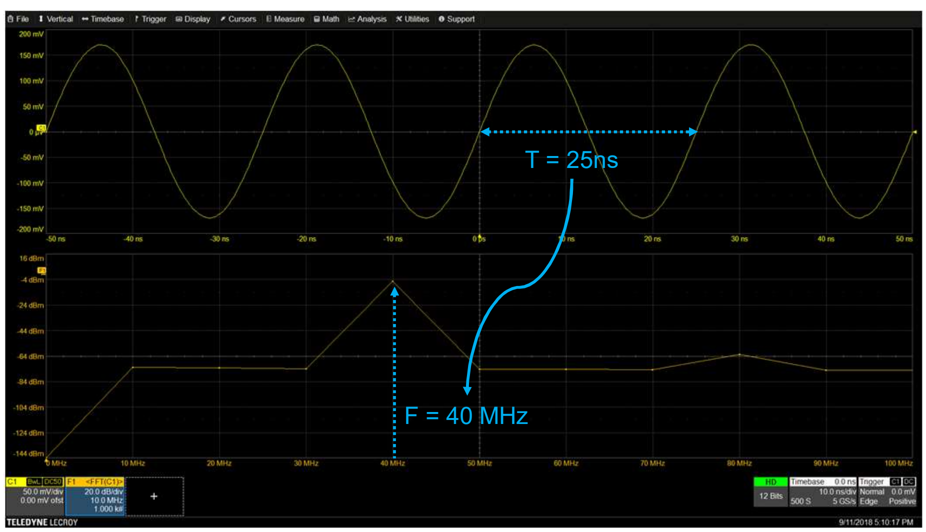
FFT bins represent harmonics of $1/T_0$

- 2^{nd} harmonic frequency:
  $f_1 = 1/T_1$
- Signal energy at 20 MHz goes into the 20 MHz bin



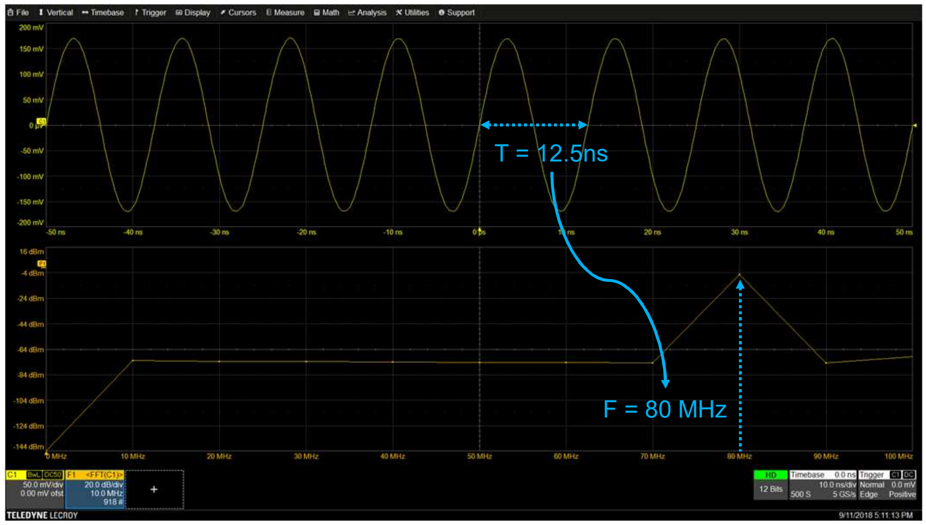
FFT bins represent harmonics of $1/T_0$

- 4^{th} harmonic frequency:
  $f_3 = 1/T_3$
- Signal energy at 40 MHz goes into the 40 MHz bin



FFT bins represent harmonics of $1/T_0$

- 8^{th} harmonic frequency:
  $f_7 = 1/T_7$
- Signal energy at 80 MHz goes into the 80 MHz bin



Translating from time domain to frequency domain

Time domain characteristic	Frequency domain characteristic
T_0: Timebase or FFT window (in seconds)	Frequency resolution (in Hz) FFT bin size (in Hz) Lowest (non-DC) frequency point (in Hz
F_S: Sample rate, S/sec	Highest frequency value: f_{max} = ½ Sample rate (Nyquist frequency of sample rate)
Bandwidth of the scope's amplifier	Frequency where response is – 3 dB down from pass band value

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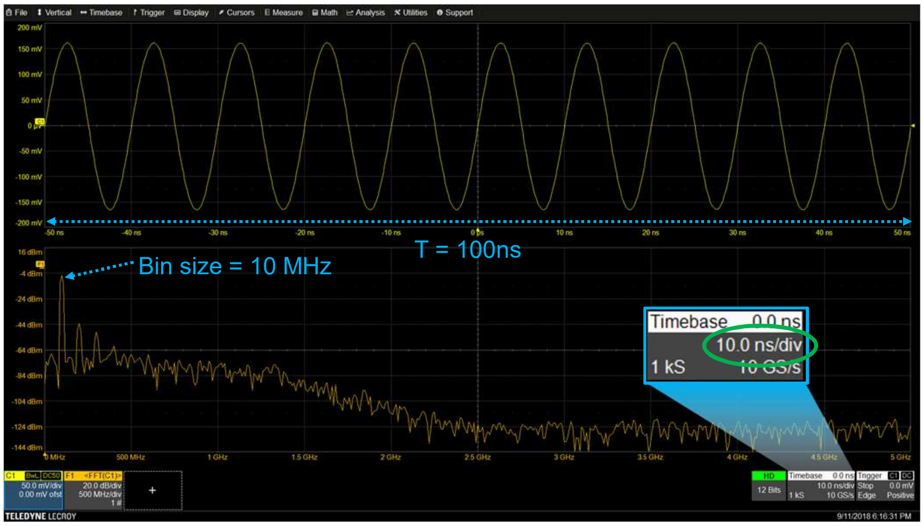
Effect of timebase on FFT

- 10 ns/div = 100 ns timebase (T_0)
- 1/100ns means frequency resolution of 10 MHz (depending on algorithm used)



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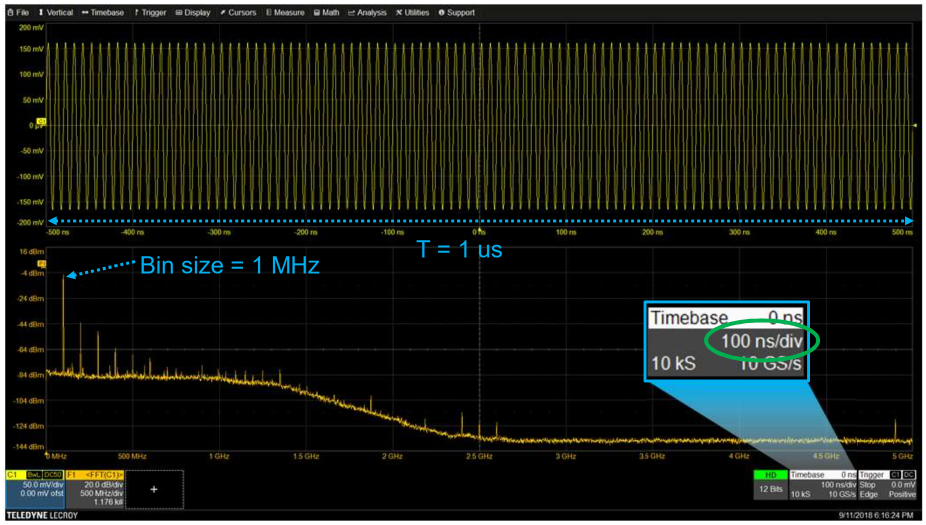
Effect of timebase on FFT

- 100 ns/div = 1 us timebase (T_0)
- 1/1us means frequency resolution of 1 MHz (depending on algorithm used)



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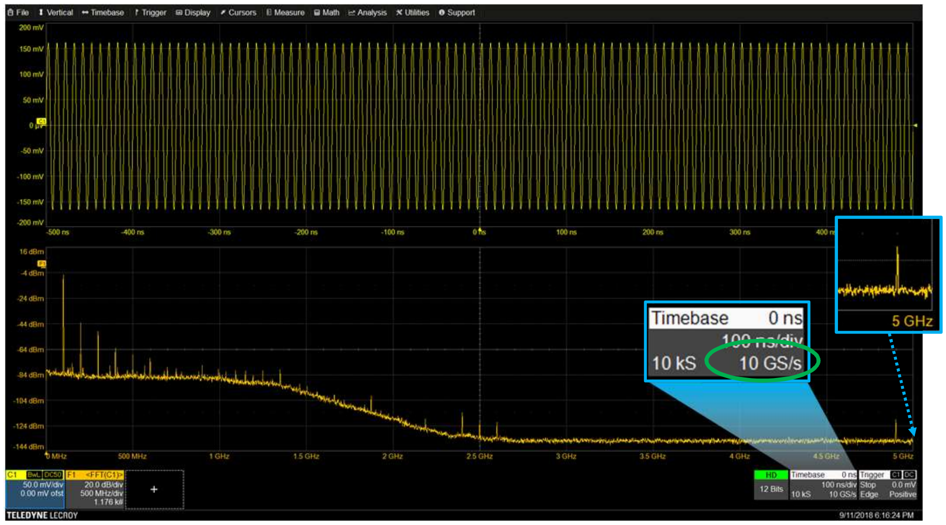
Effect of sample rate on FFT

- Nyquist dictates the upper limit of the FFT is $F_S/2$
- Here, we are sampling at 10 GS/s, so the FFT's upper frequency limit is 5 GHz



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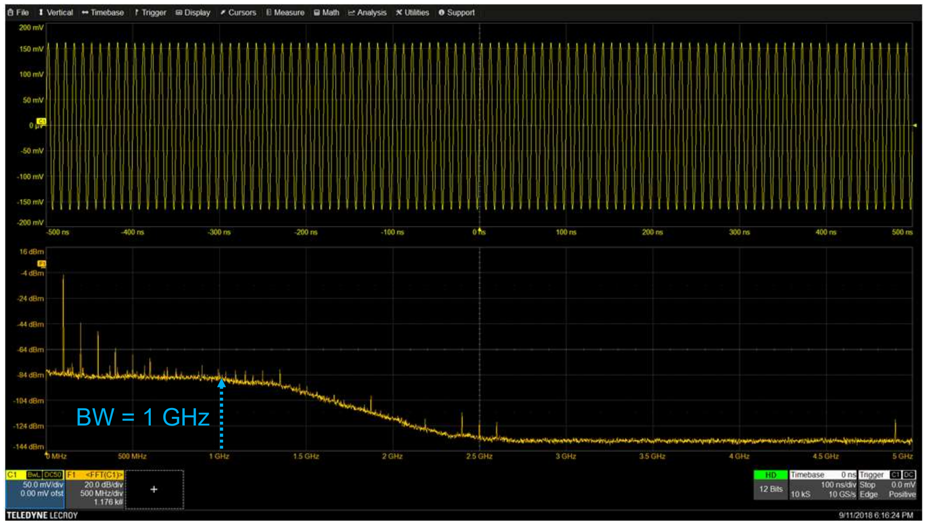
Bandwidth of the scope's amplifier	Frequency where response is – 3 dB down from pass band value

Effect of oscilloscope bandwidth on FFT

- The oscilloscope bandwidth is defined as the point where its response has reduced by 3 dB relative to DC
- Here, we have applied a 1 GHz bandwidth limit, and the roll-off beyond this point is clear



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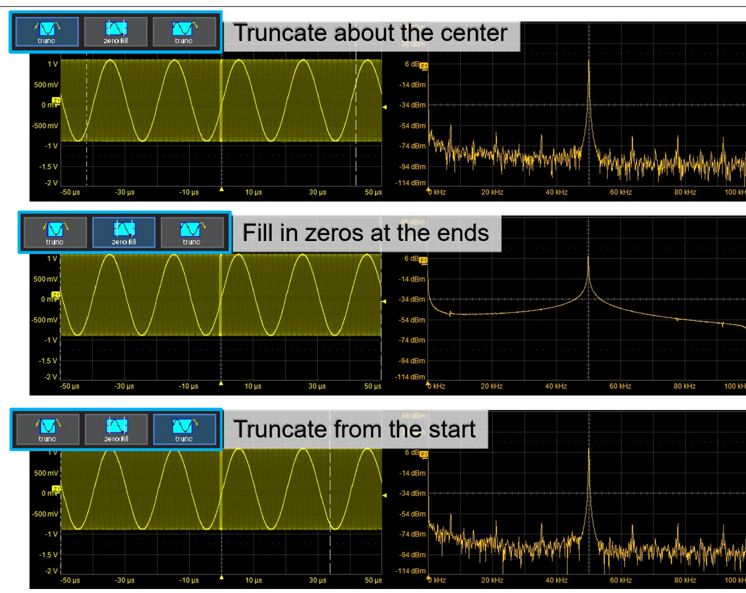
What to do with the extra data points?

- An FFT uses 2^n points - this means we need to take the number of points in the scope acquisition and truncate/expand to a power of 2
- Without a compelling reason otherwise, use truncate about the center of the acquisition window (not the trigger point)



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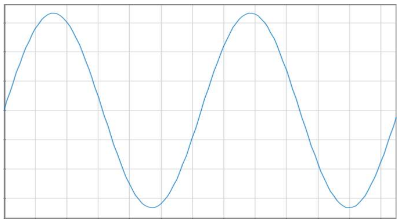
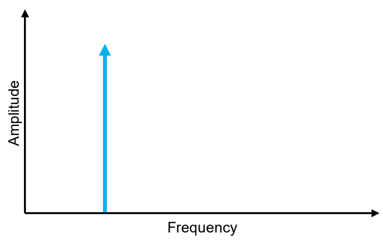
Periodicity in FFT acquisitions

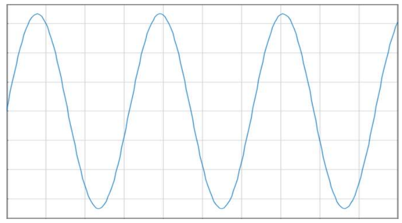
A sine wave periodic within the acquisition window



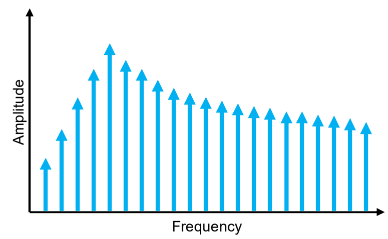
An integer number of periods gives an ideal FFT:



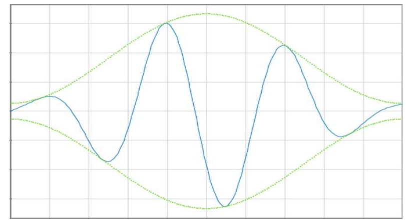
A sine wave not periodic within the acquisition window



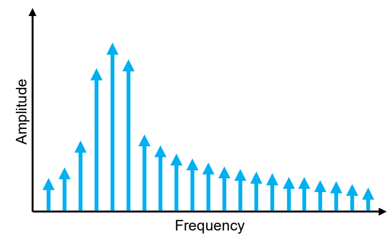
A non-integer number of periods causes spectral leakage in the FFT



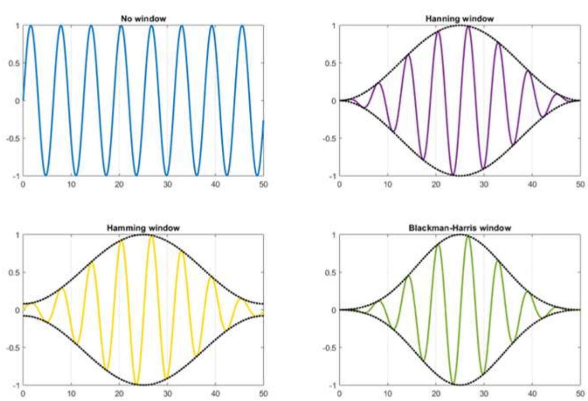
Multiplying by a window function makes the signal continuous at the ends

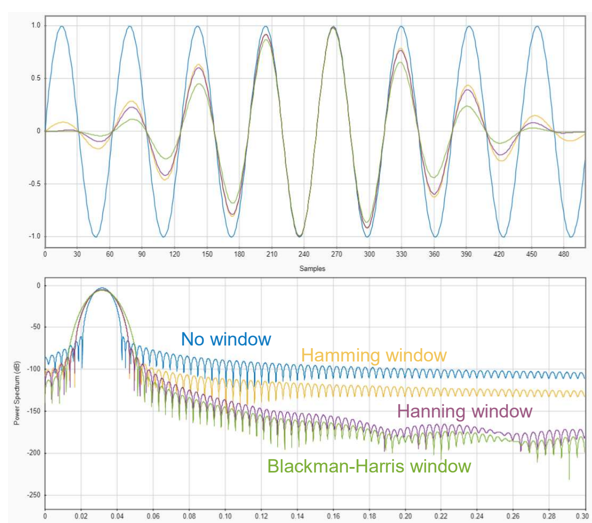


Applying a window minimizes the spectral leakage effect

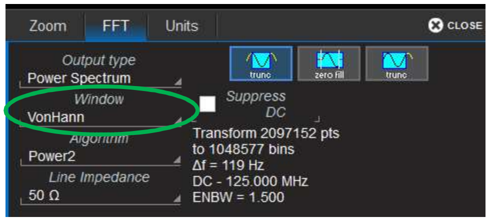


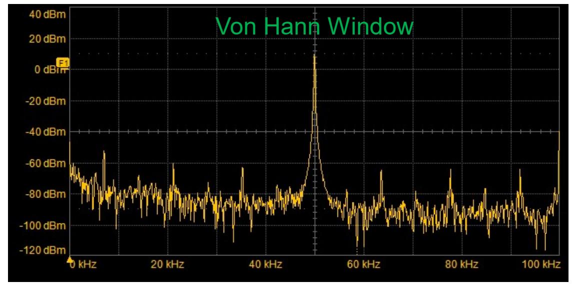
Which windowing function to use?

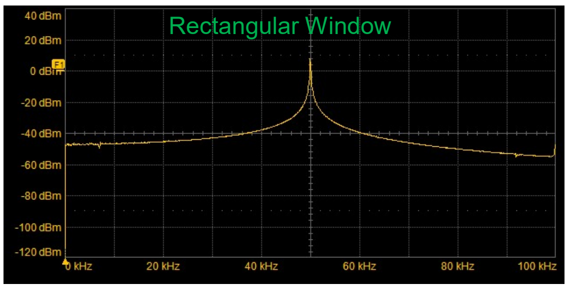


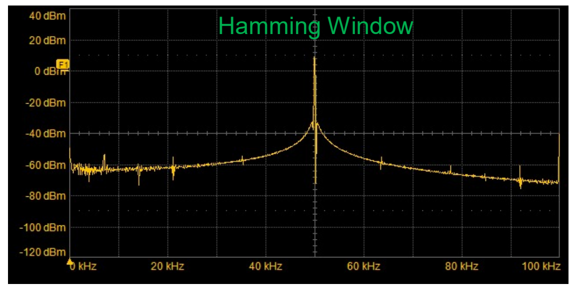


Practical effect of different window types









The Vertical Scale

- FFT default units are dBm: a power with 1 mWatt as the base.
- Power is what the voltage would generate in a 50 Ohm resistor

$$\text{Power[Watts]} = \frac{V_{rms}^2}{50} \qquad \text{Power[mWatts]} = \frac{V_{rms}^2[V]}{50} \times 1000$$

$$\text{Power[dBm]} = 10 \times \log\left(V_{rms}^2[V] \times 20\right) = 10 \times \log(20) + 10 \times \log\left(V_{rms}^2[V]\right)$$

$$\text{Power[dBm]} = 13\text{dBm} + 20 \times \log\left(V_{rms}[V]\right)$$

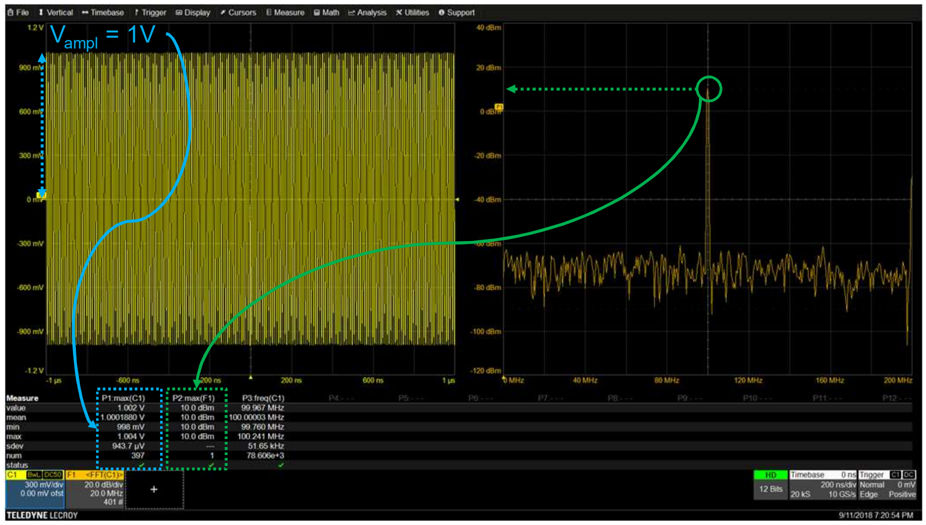
- It is the power in each frequency bin
- How do we interpret the voltage amplitude?

$$\text{Power[dBm]} = 13\text{dBm} + 20 \times \log\left(V_{rms}[V]\right) \qquad V_{rms}[V] = \frac{1}{\sqrt{2}} V_{amplitude}[V]$$

$$\text{Power[dBm]} = 13\text{dBm} + -3 + 20 \times \log\left(V_{amplitude}[V]\right) = 10\text{dBm} + 20 \times \log\left(V_{amplitude}[V]\right)$$

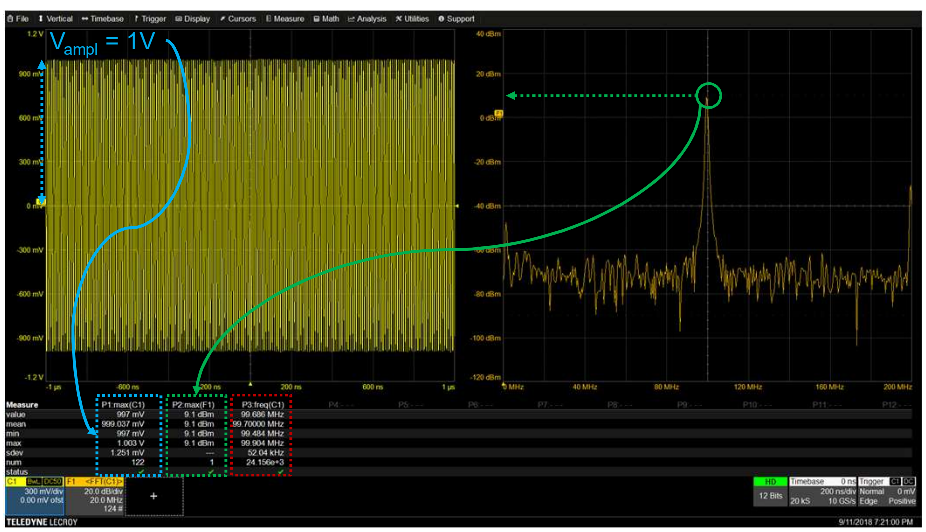
Vertical scale example: sine wave with 1V peak amplitude

- V_{ampl} = 1V
- P = 10 dBm
- Power (dBm) = 20*log10(V_{ampl}) + 10 dBm
- This simplification works **only** when the signal is narrowband (fits in one FFT bin)
  - Here the bin size is 500 kHz, and the input frequency is 100 MHz



Vertical scale example: sine wave with 1V peak amplitude

- Change the input signal's frequency so that it spreads across several bins, and the relationship becomes more complex
- Here the input frequency is 99.7 MHz, not an integer multiple of 500 kHz – so its power is spread between 2 bins



Vertical scale: three special cases

- A flat, white noise spectrum V_{rms}

$$\text{Power[dBm]} = 13\text{dBm} + 20 \times \log\left(V_{rms}[V]\right)$$

- A DC component: V_{DC} = V_{rms}

$$\text{Power[dBm]} = 13\text{dBm} + 20 \times \log\left(V_{rms}[V]\right) = 13\text{dBm} + 20 \times \log\left(V_{DC}[V]\right)$$

- A sine wave component:

$$V_{rms}[V] = \frac{1}{\sqrt{2}} V_{amplitude}[V]$$

$$\text{Power[dBm]} = 13\text{dBm} + 20 \times \log\left(V_{rms}[V]\right) = 13\text{dBm} + 20 \times \log\left(V_{amplitude}[V]\right) - \frac{20}{2}\log(2)$$

$$\text{Power[dBm]} = 10\text{dBm} + 20 \times \log\left(V_{amplitude}[V]\right)$$

Other Vertical Scales on the Spectrum Analyzer Option

dBV: reference level is 1 V

$$\text{dBV} = 10 \times \log\left(\frac{V^2}{1\,V^2}\right) = 20 \times \log\left(V[\text{Volts}]\right)$$

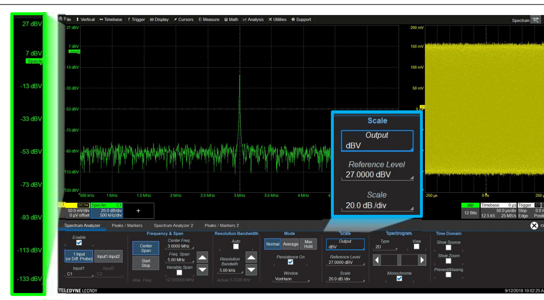
1 V = 0 dBV

dBmV: reference level is 1 mV

$$\text{dBmV} = 10 \times \log\left(\frac{V^2}{1\,\text{mV}^2}\right) = 20 \times \log\left(V[\text{mVolts}]\right)$$

1 V = 60 dBmV

Note: when using a voltage (not power) scale, ALWAYS use the factor of 20

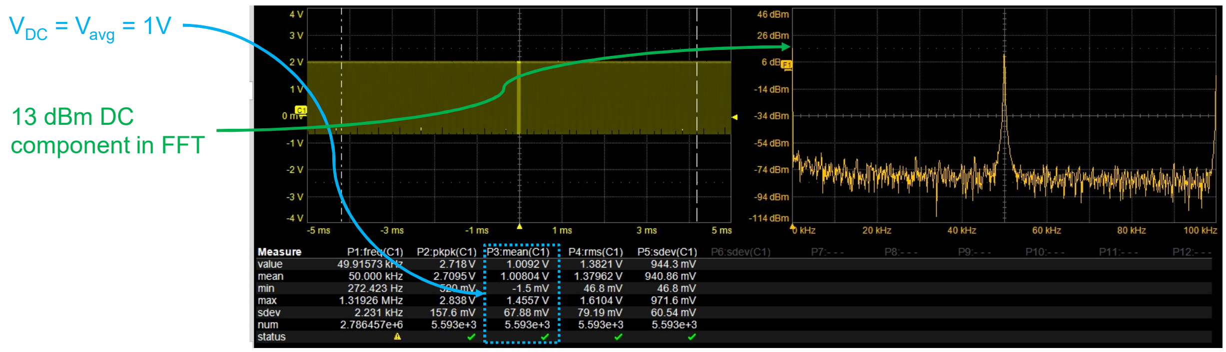


Special Case: The DC Value as 0th harmonic

The RMS value of a DC component ***is*** the DC component

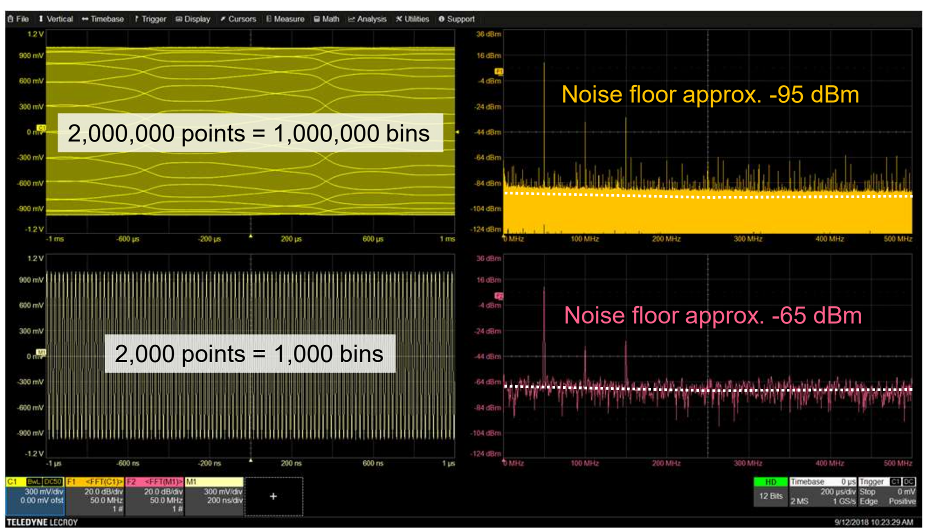
$$\mathrm{Power[dBm]} = 13\mathrm{dBm} + 20 \times \log\left(V_{average}[V]\right)$$

A signal with a 1 V average value will have 13 dBm f = 0 amplitude



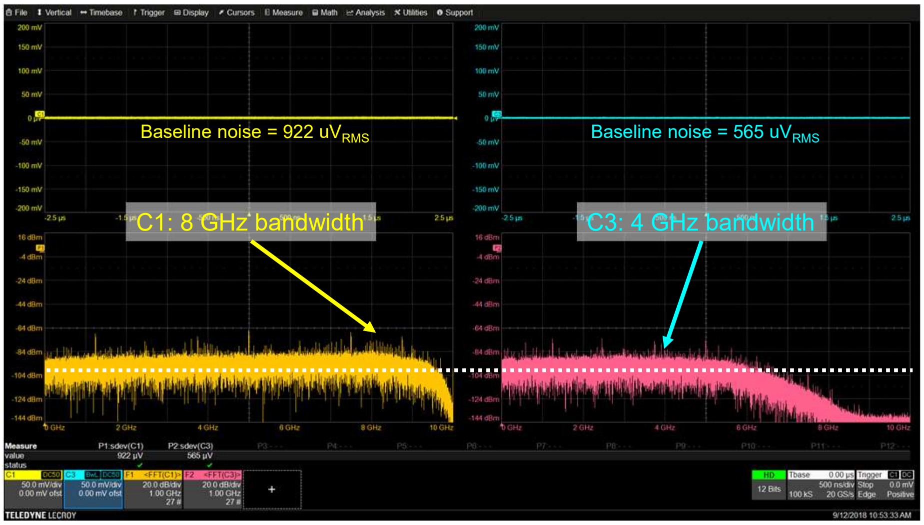
Reducing noise: FFT noise floor vs number of bins

- In frequency domain: Total power = Pbin x Nbins
- To reduce noise floor, increase number of bins
- For lowest noise floor, use the largest feasible number of samples



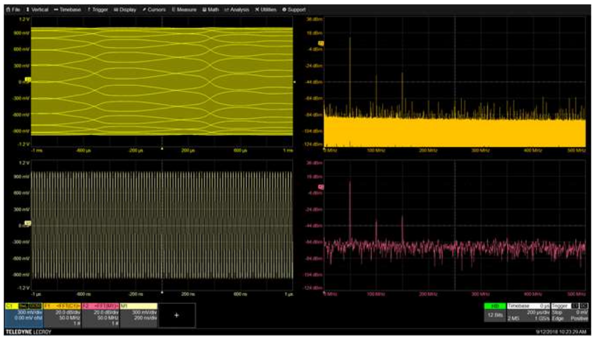
Reducing noise: scope bandwidth

- Reducing scope bandwidth:
  - **Will** reduce baseline noise in the time domain
  - **Will not** reduce the spectral power density of the noise floor



Reducing noise

- Reduce noise floor with lower RMS noise source
  - If digitizing noise, use greater bit resolution (12 bit oscilloscope)
  - If digitizing noise, use higher sensitivity scale, and offset
  - Use lower noise amplifier



- **Recommended general process:**
  - **Use highest sample rate at highest frequency range**
  - **Adjust acquisition time to increase number of samples and reduce noise floor**
  - **For fixed spectral noise density, more bins → smaller dBm noise level**

Spectral Analysis Package

Automate and Simplify FFT Calculation and Display

- Select time base, sec/div
- Select start, stop frequency
- Sample rate automatically selected as highest available
- Can adjust number of points by time base
- Vertical scale can be set to dBmV
- Everything is automatic
- Markers identify peaks

Example 1

Low-cost sine wave generator

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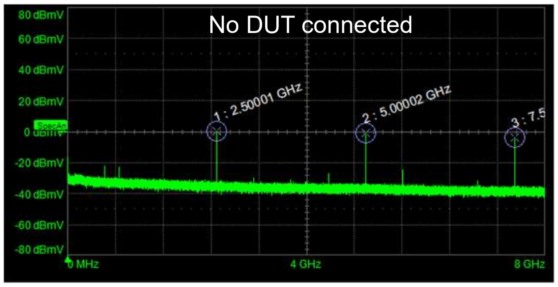
Example: a Sine Wave Generator

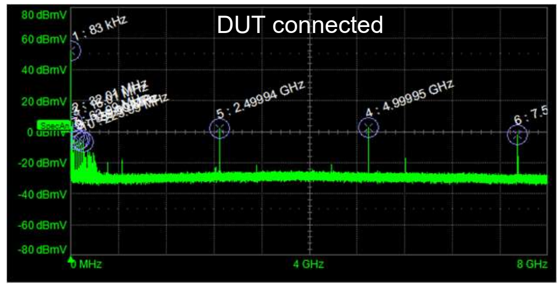
- What do we expect to see?
  - Sample rate compared to repeat frequency
  - Total number of samples
  - Acquisition window
  - Frequency range
  - Signal within voltage window-not saturating

Measured Response

- Note 1st harmonic = 52 dBmV
  - = 0.4 V amplitude sine wave
- But large 2nd harmonic: 6 dBm
  - = 2 mV amplitude
- Large higher order amplitudes
  - Even 1 MHz is approx. 0.8 mV
- The output signal is heavily distorted
  - How do we find the root cause?

Step 1: Examine entire frequency span and background



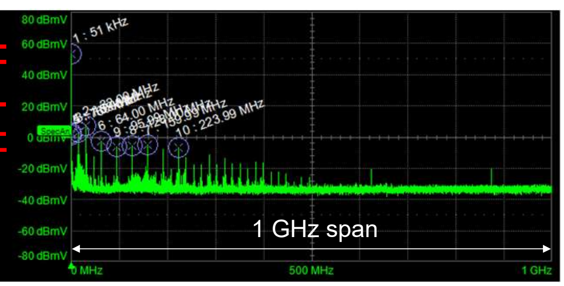


- Measure spectrum with input gnd to get system background
  - Base line noise floor ~ - 30 dBmV ~ 0.03 mV amplitude
- Measure signal
  - All the noise is < 1 GHz

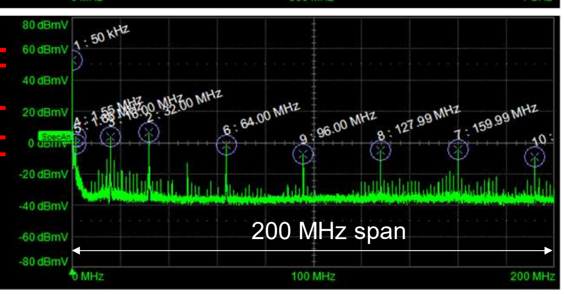
Step 2: Change span to view frequency band of interest

- Peaks are multiples of 16 MHz clock
- Shows up even when amplitude is zero
- 6 dBmV ~ 2 mV amplitude

Peaks	Frequency	Amplitude
1	51 kHz	53.212 dBmV
2	32.004 MHz	6.9590 dBmV
3	16.002 MHz	2.8686 dBmV
4	1.587 MHz	2.4360 dBmV
5	760 kHz	1.4063 dBmV
6	63.997 MHz	-2.626 dBmV
7	159.991 MHz	-5.400 dBmV
8	127.997 MHz	-5.569 dBmV
9	95.987 MHz	-6.593 dBmV
10	223.986 MHz	-7.271 dBmV



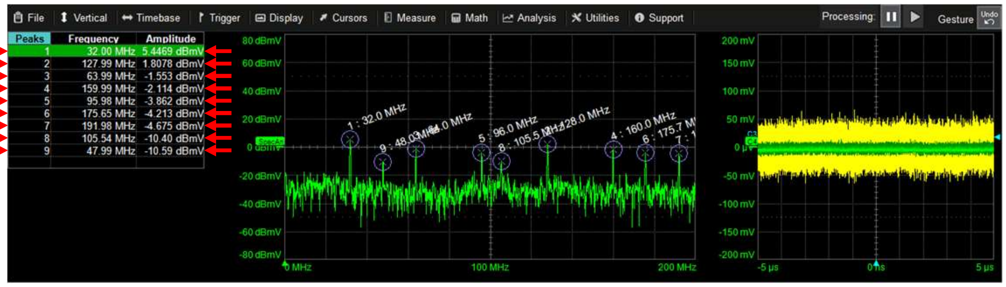
Peaks	Frequency	Amplitude
1	50 kHz	52.294 dBmV
2	31.997 MHz	6.1268 dBmV
3	15.999 MHz	3.5870 dBmV
4	1.551 MHz	3.3631 dBmV
5	1.650 MHz	-895 mdBmV
6	63.997 MHz	-1.796 dBmV
7	159.987 MHz	-4.893 dBmV
8	127.990 MHz	-5.473 dBmV
9	95.996 MHz	-7.804 dBmV
10	191.985 MHz	-9.394 dBmV



Step 3: Look at voltage rails on the board

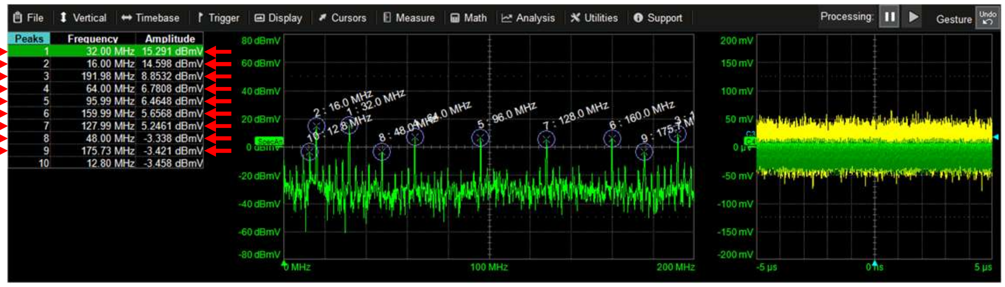
The input 9 V rail

- Lots of 16 MHz harmonics



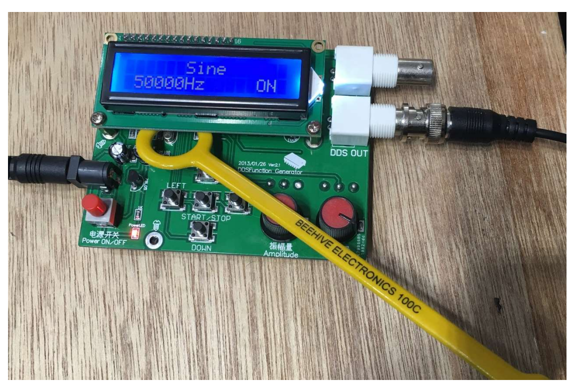
The 5 V linear rail

- Also lots of 16 MHz harmonics



Step 4: Look for the source of interference

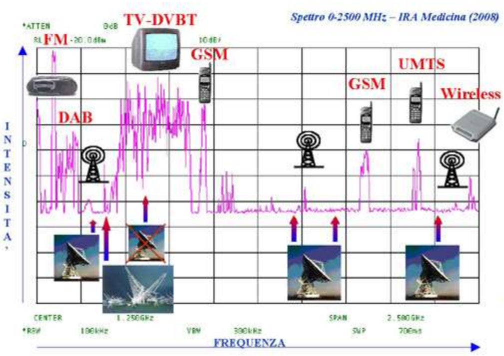
- "There are two kinds of designers: those who are designing antennas on purpose and those who are not doing it on purpose"
- Examples of pick up antennas
  - Near field probe



Looking for radiated noise from the microcontroller

RF pickup

- We live in a very bright RF background

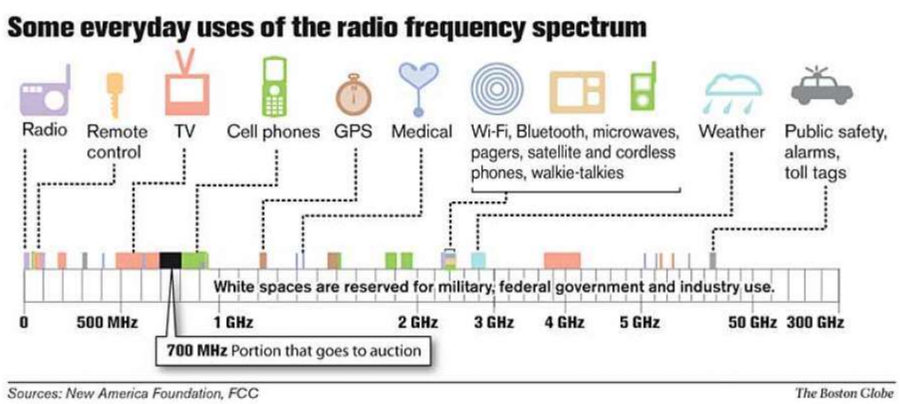


Frequencies and regulations

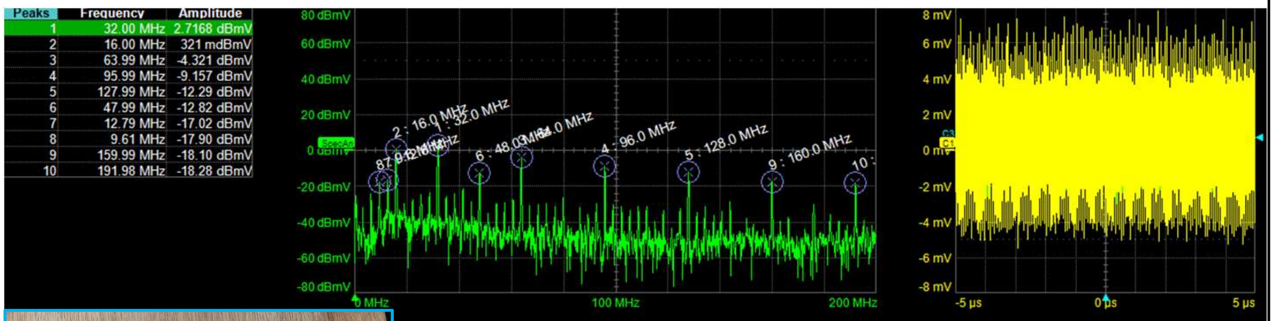
- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

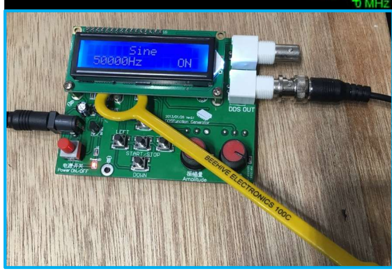
Examples	Europe	USA	Japan
Cellular phones	**GSM** 880-915, 925-960, 1710-1785, 1805-1880 **UMTS** 1920-1980, 2110-2170	**AMPS, TDMA, CDMA, GSM** 824-849, 869-894 **TDMA, CDMA, GSM, UMTS** 1850-1910, 1930-1990	**PDC, FOMA** 810-888, 893-958 **PDC** 1429-1453, 1477-1501 **FOMA** 1920-1980, 2110-2170
Cordless phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 245-380
Wireless LANs	**802.11b/g** 2412-2472	**802.11b/g** 2412-2462	**802.11b** 2412-2484 **802.11g** 2412-2472
Other RF systems	27, 128, 418, 433, 868	315, 915	426, 868

Range of Sources for RF Pick Up



Source of this problem:
Emissions coming from under the microcontroller

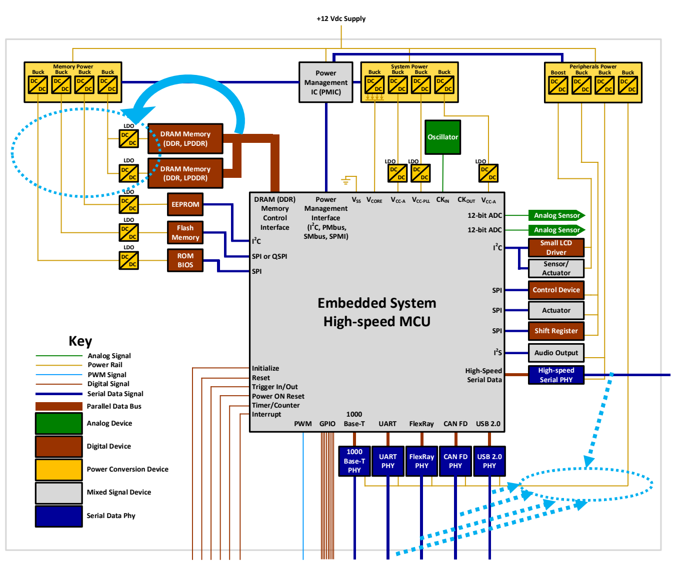




Likely root-cause is radiation from clock generation traces

Board/Interconnect Pollution

- From VRM
- From I/O
- From core
- From signals



Example 2
Oscillator board with a noisy power rail

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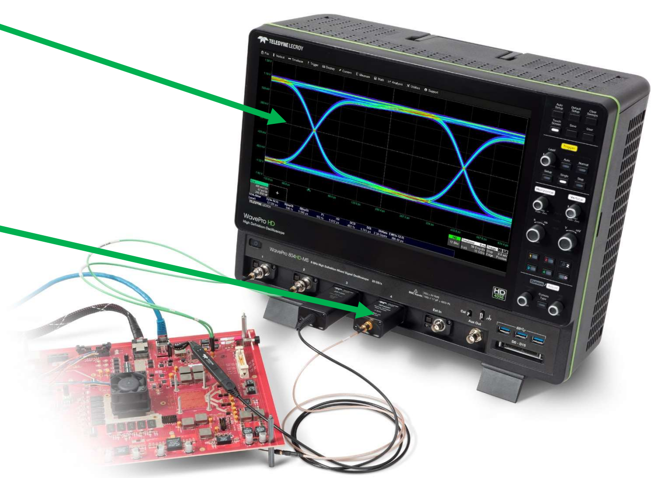
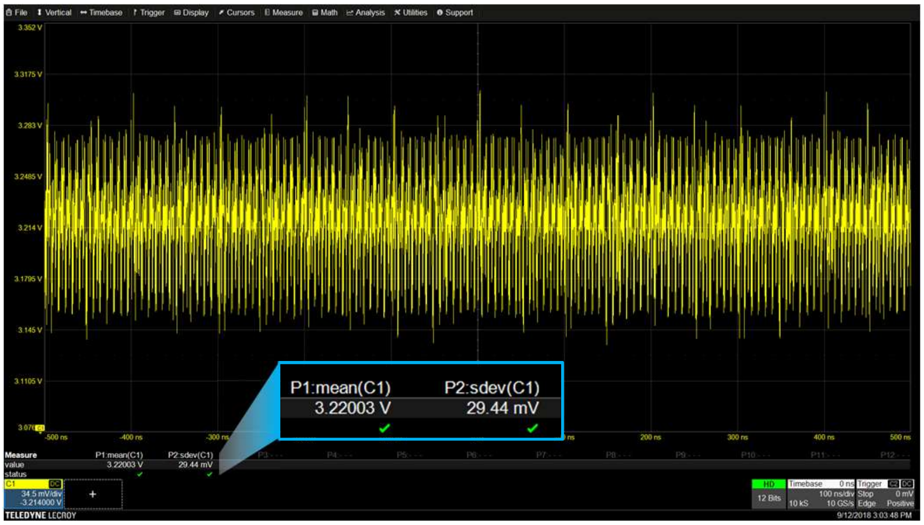
Example: Oscillator board

- WavePro 804HD oscilloscope
  - 8 GHz
  - 12 bits
- RP4030 voltage rail probe
  - 4 GHz bandwidth
  - 30V offset range to match rail voltage
  - Very low attenuation for extremely low noise



Example: Oscillator board

- Board has a ~3.3v power rail that's very noisy
- Some components on the rail are sensitive to high-frequency noise
- What is the root cause of the highest-frequency noise components?

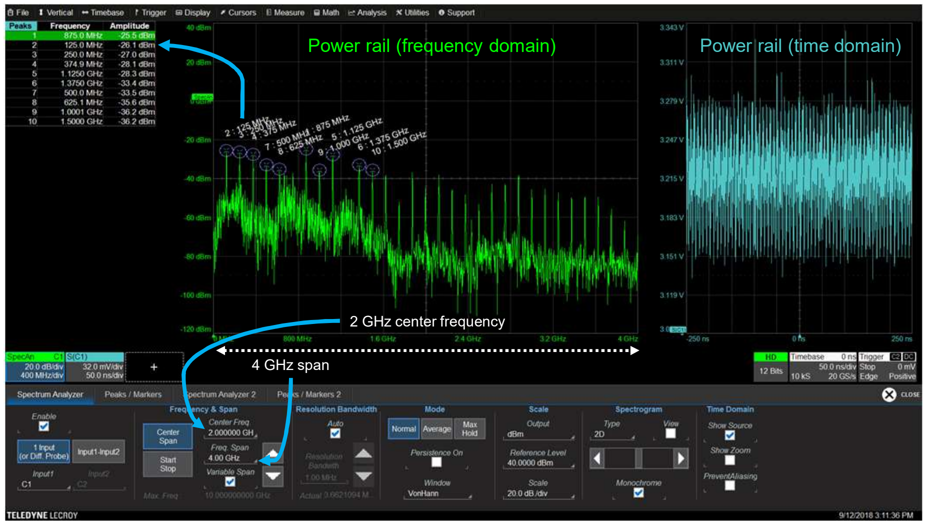


Possible noise sources

- The board also has two clock sources:
  - 10 MHz
  - 125 MHz

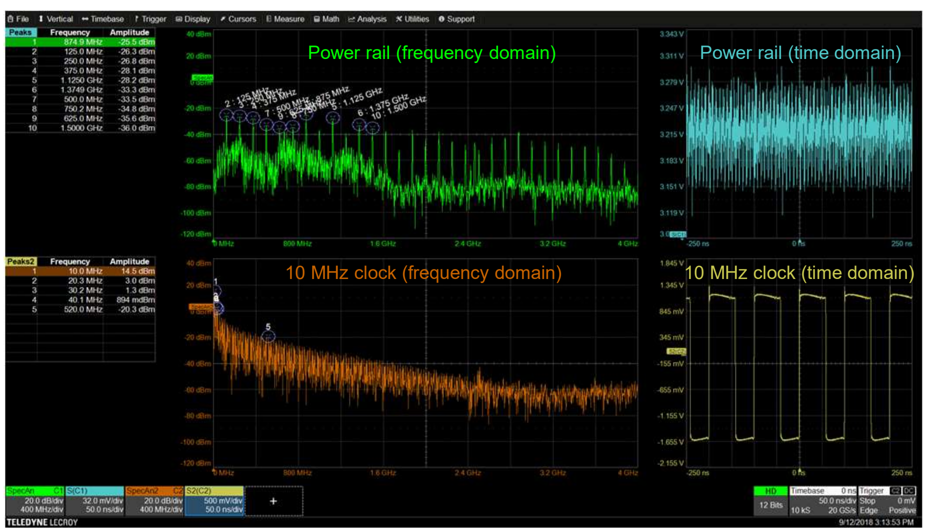
Use the Spectrum Analyzer option

- Allows visualization in the frequency domain
- Easily set:
  - Span
  - Center
  - Resolution bandwidth (FFT bin size)
- Automatic markers



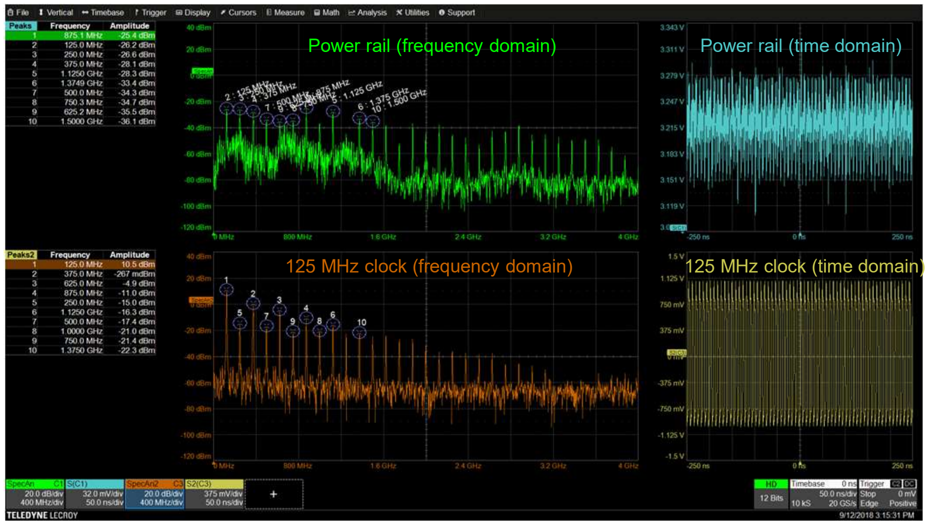
Compare the rail spectrum with the 10 MHz clock

- Use the dual spectrum analyzer feature
- Most of the 10 MHz clock's spectral energy exists below ~200 MHz



Compare the rail spectrum with the 125 MHz clock

- Use the dual spectrum analyzer feature
- The 125 MHz clock has very high-frequency spectral components that match with the “problem frequencies” seen on the power rail



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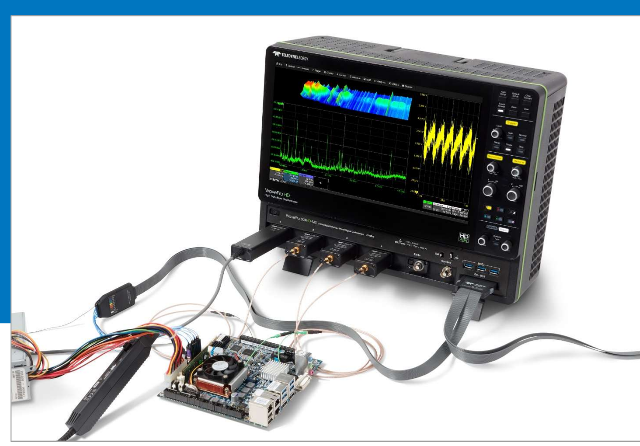
Questions?



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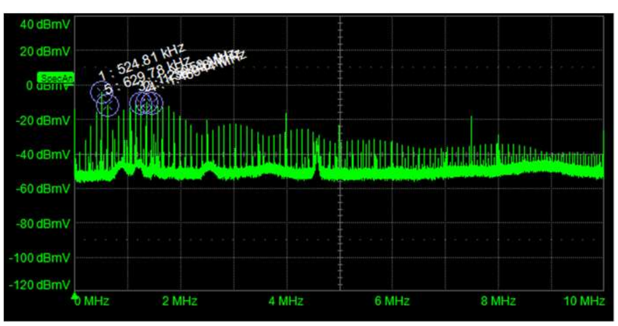
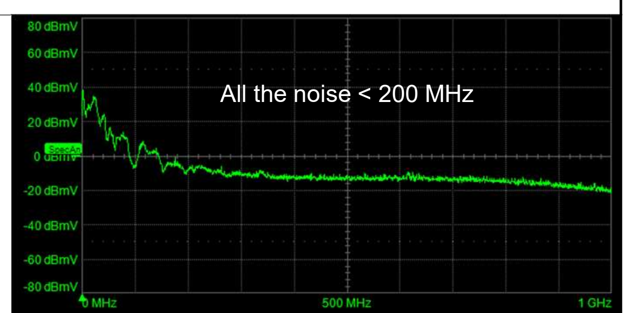
Some more short examples

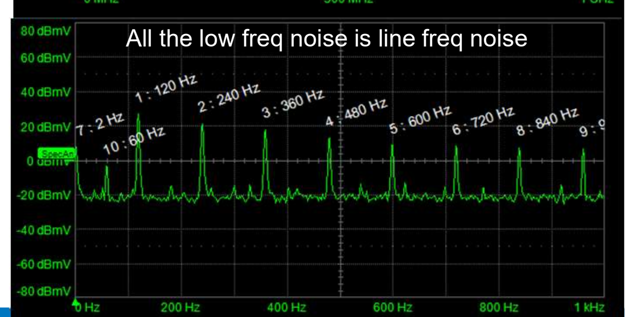
9 V wall Wart

- 1 A load

Another SMPS

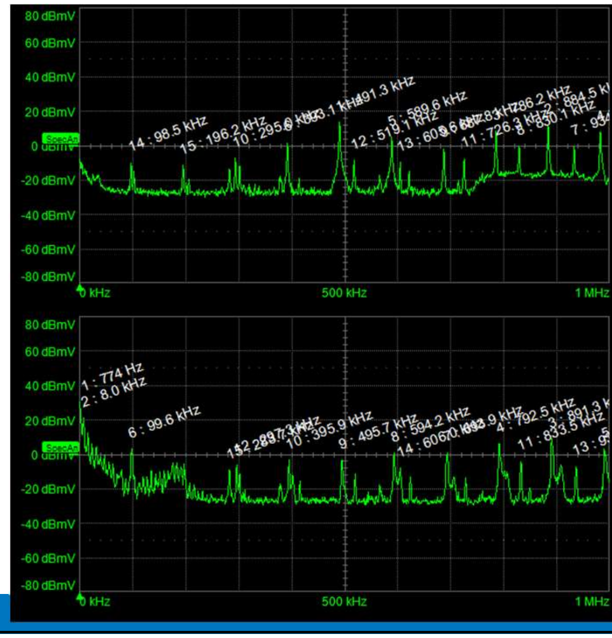






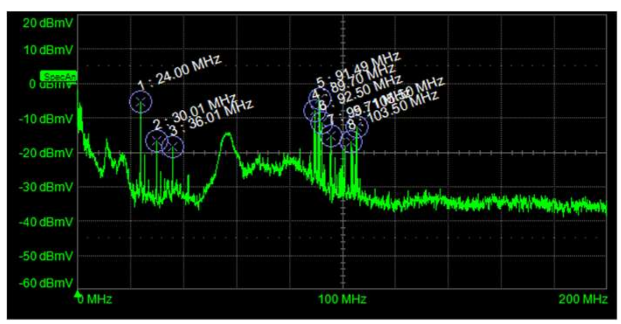
9 V wall wart, < 1 MHz range

- Lots of 100 kHz harmonics
- Peak amplitude ~ 20 dBmV = 10 mV amplitude, out of 9 V, 0.1%
- After 1 A load, all the excess noise is at low freq- 60 Hz multiples
  - Peak of 30 dBmV, 30 mV out of 9 V.
- So what: weakness in this design is poor DC rectification of 60 Hz- need more capacitor filtering on DC input side



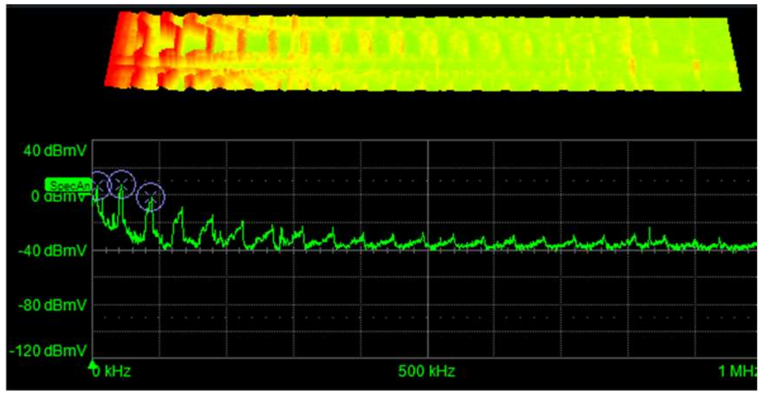
USB source

- 0.5 A load
- All the noise < 200 MHz
- Near 24 MHz
  - ~ -3 dBmV which is 0.7 mV amplitude
- Looks like 6 MHz 1st harmonic with 4th, 5th and 6th harmonics showing up



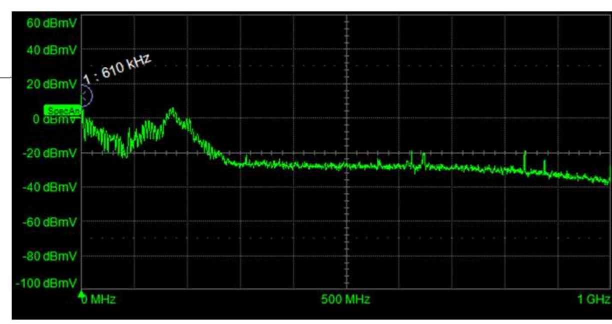
Note: switching frequency sometimes changes with supply load

- 5 v SMPS
- ~ 50 kHz switching frequency
- Amplitude ~ 1 mV

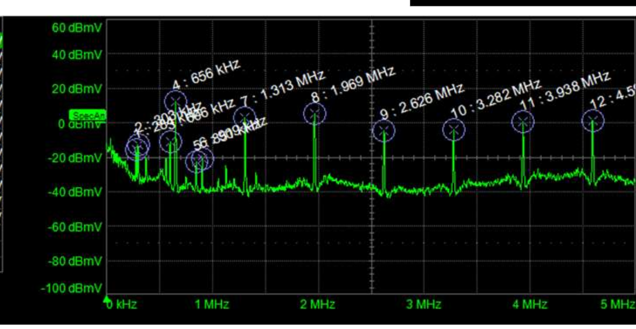


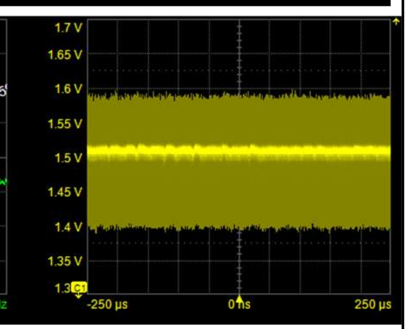
1.8 V Vdd Rail

- no load
- Lots of switching noise at 650 kHz
- All noise < 200 MHz



Peaks	Frequency	Amplitude
1	283.6 kHz	-15.87 dBmV
2	303.0 kHz	-12.76 dBmV
3	605.7 kHz	-11.01 dBmV
4	656.4 kHz	11.763 dBmV
5	850.7 kHz	-22.96 dBmV
6	909.0 kHz	-20.99 dBmV
7	1.3128 MHz	2.5269 dBmV
8	1.9692 MHz	5.1735 dBmV
9	2.6256 MHz	-5.087 dBmV
10	3.2820 MHz	-4.351 dBmV
11	3.9384 MHz	210 mdBmV
12	4.5948 MHz	750 mdBmV





9 V Battery

- Noise floor is about – 40 dBmV = 10 uV amplitude noise, out of 9 V DC
- Some peaks at 875 kHz, 1.325 GHz,   probably rf pick up