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Modelling of Echo Amplitude Fidelity for Transducer Bandwidth and TFM Pixel Resolution

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Outline

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Motivation 1 – Temporal Sampling

- Temporal and Amplitude sampling needs to be sufficient to reconstruct the waveform so that echo amplitude and time-of-flight can be estimated to the required level of accuracy

- Temporal sampling has typically been done at around 20 samples per cycle (20x Fc)

  - The large number of A-scans in each Full Matrix Capture (FMC) frame means transferring data at 20x Fc can be the limiting parameter for the frame acquisition rate

  - Optimizing temporal sampling can remove this constraint

Motivation 2 – Spatial Sampling

- Similar considerations about echo amplitude fidelity are required for B-scan images, which determine the minimum pixel pitch
- For Total Focusing Method (TFM) imaging, the ASME V standard requires the maximum amplitude measurement error to be <2dB
- For smooth images the pixel pitch has typically been between 10 and 20 pixels per cycle
  - The heavy processing load to generate each pixel in the TFM image is a strong incentive to reduce the sampling resolution as much as possible, so as to increase the image reconstruction rate
  - This must not violate the 2dB amplitude fidelity criterion in ASME V

Temporal Sampling Rates

- Investigated by many: Edmund Whittaker (1915); Harry Nyquist (1928); Vladimir Kotelnikov (1933); Claude Shannon (1948), etc. This work resulted in the criterion:
  - Temporal Sampling rate > 2x maximum frequency in signal

- Shannon's modified case for band-limited signals (1949)
  - Temporal Sampling rate > 2x bandwidth of signal

- Practical systems don't have a hard cut-off frequency
  - Fractional bandwidth is usually specified at the -6dB points
  - Better to use -20dB cut-offs to minimise aliasing
  - For Gaussian spectra, -20dB width is ~1.85x the -6dB width
  - → Temporal Sampling rate ≥ 4x Fractional Bandwidth

1D Model for Parametric Analysis

- Model was developed using LabVIEW® (National Instruments)

- Test signal is Gaussian-windowed sine wave sampled at 1GS/s, with control over:
  - Amplitude & Phase of sine (RF) component
  - Offset of Gaussian window
  - Standard deviation of Gaussian window
  - Noise can be added (but is not considered here)

- Reference (RF) for comparison uses typical instrument values:
  - 50MHz sampling at 12bits

- Echo amplitude measurement approaches are compared with the Test signal amplitude, over variations in:
  - Test Signal Phase (0 to 360°)
  - Gaussian window Offset (-180° to 180°)
  - Test Signal's -6dB Fractional Bandwidth (Gaussian window Standard Deviation)

Rectification Approaches

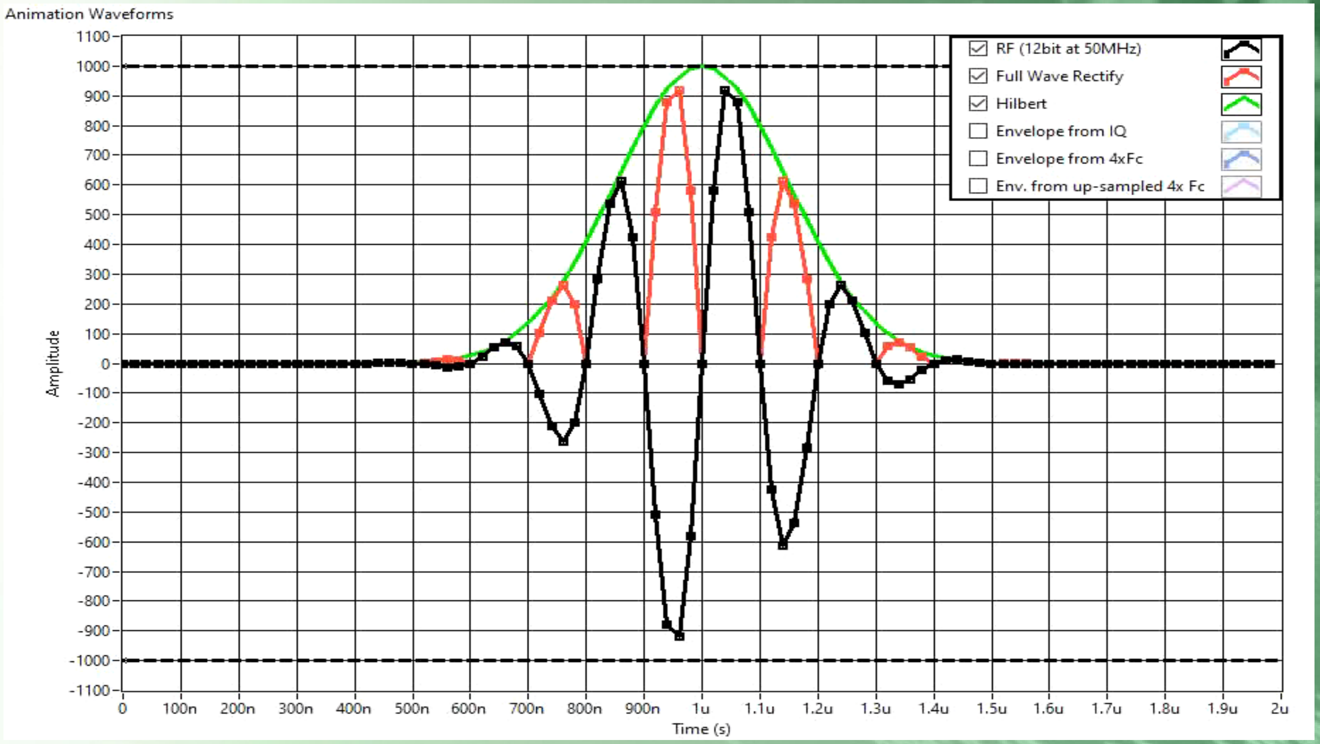
Sample Rate = 50MHz at 12bits
Signal at 5MHz with 50% Fractional Bandwidth

- RF: full sample rate
    - Max amplitude error when samples equi-spaced around peak
    - Error depends on samples/cycle

- Full Wave Rectification
    - ABS(RF)
    - Same amplitude errors as RF

- Envelope (Hilbert)
    - $\sqrt{RF^2 + (Hilb(RF))^2}$
    - Amplitude error depends on bandwidth

Signal phase variation: 360° in 2° steps

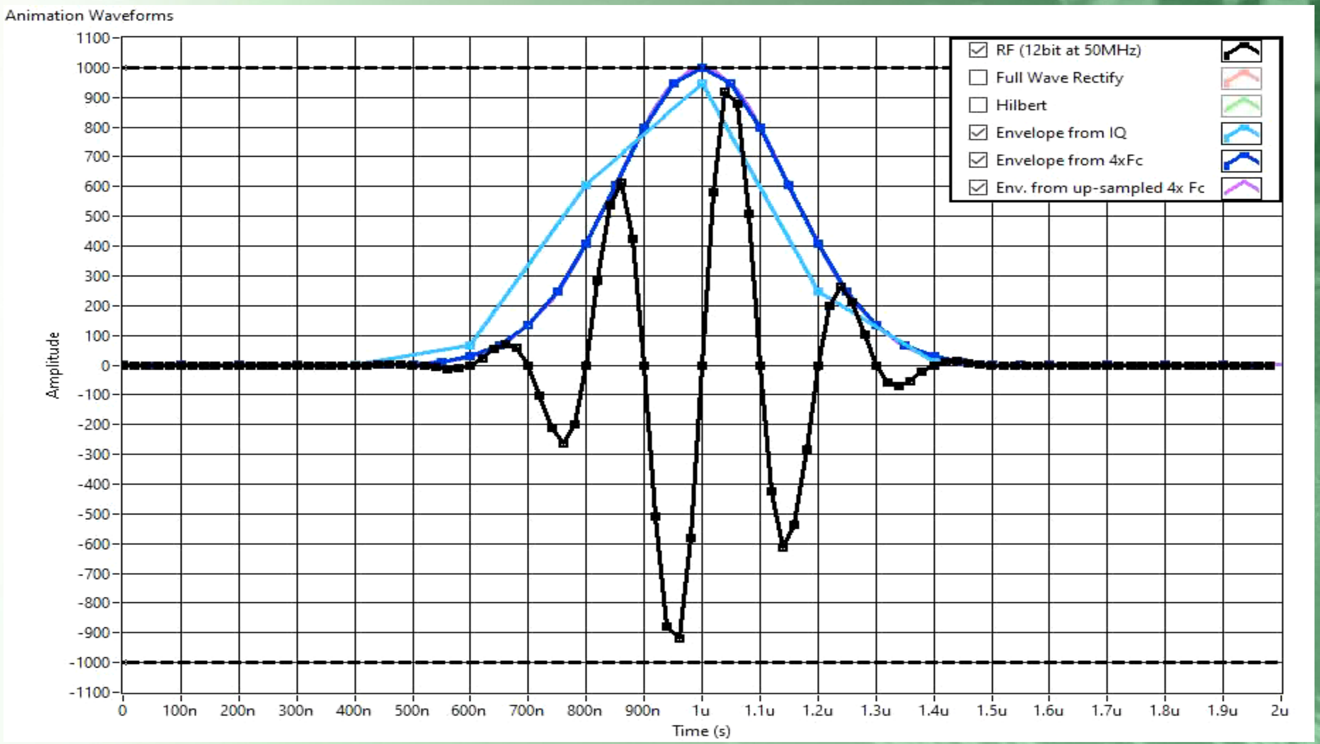


Rectification Approaches

Sample Rate = 50MHz at 12bits
Signal at 5MHz with 50% Fractional Bandwidth

- RF: full sample rate
- Quadrature Sampling
  - Amplitude errors vary with signal phase
- Sample at 4x Fcentre
  - $\sqrt{4Fc^2 + (Hilb(4Fc))^2}$
  - Amplitude errors less affected by phase
- Up-sampled from 4x Fc
  - 4xFc up-sampled (50MHz) & envelope as for Hilbert
  - Errors similar to original

Signal phase variation: 360° in 2° steps

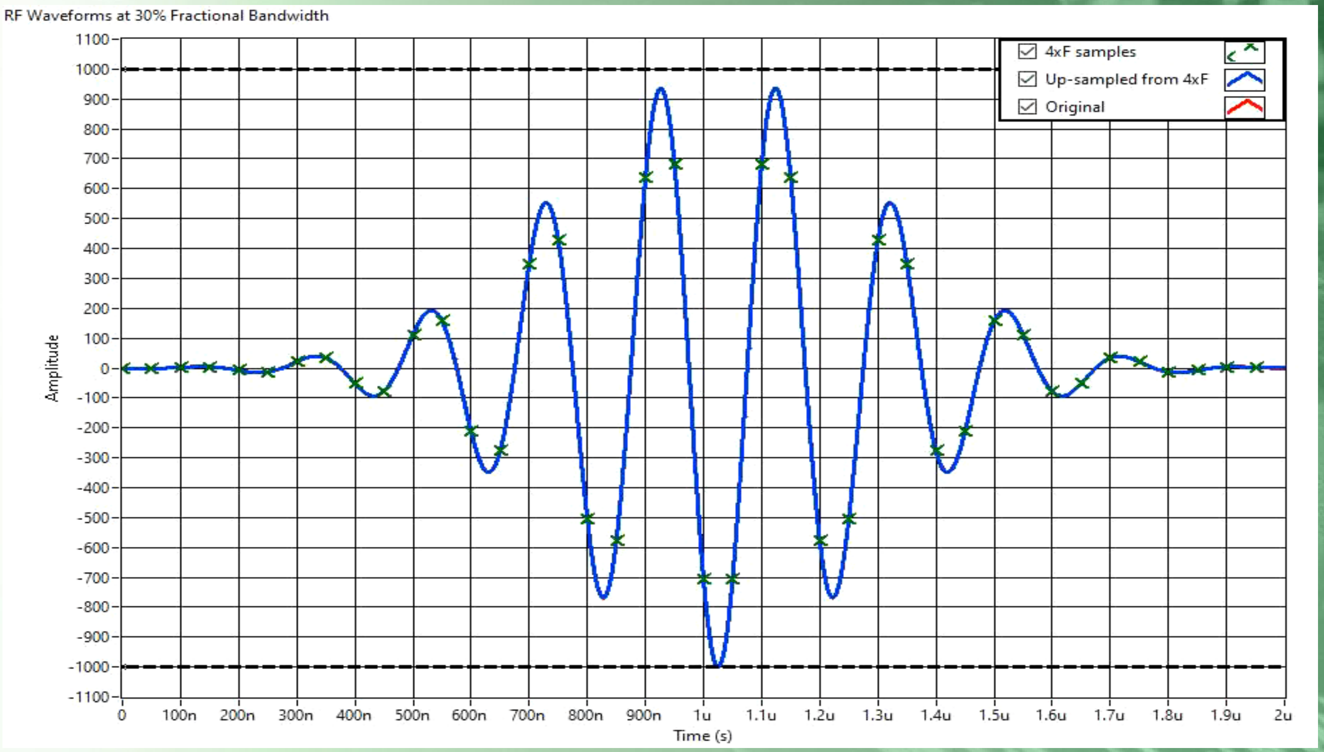


Effect of Bandwidth on RF

RF from 4xFc vs. Original as fractional bandwidth varies from 30% to 150%

Offset=45°, for worst case sampling around peak

- 4xFc samples
- Up-sampled from 4xFc
- Original RF waveform

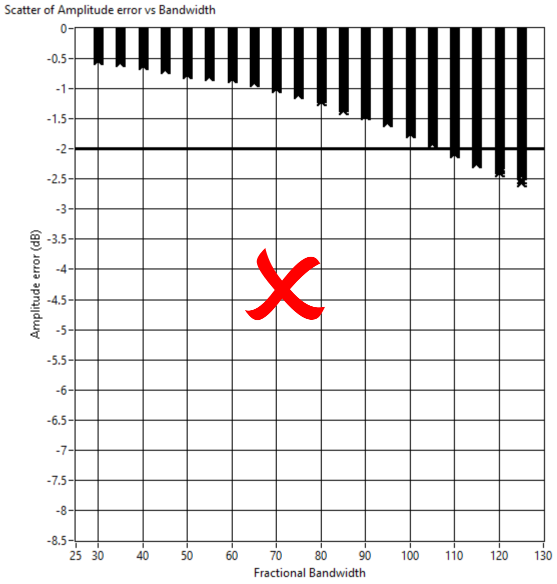


Parametric Analysis Results

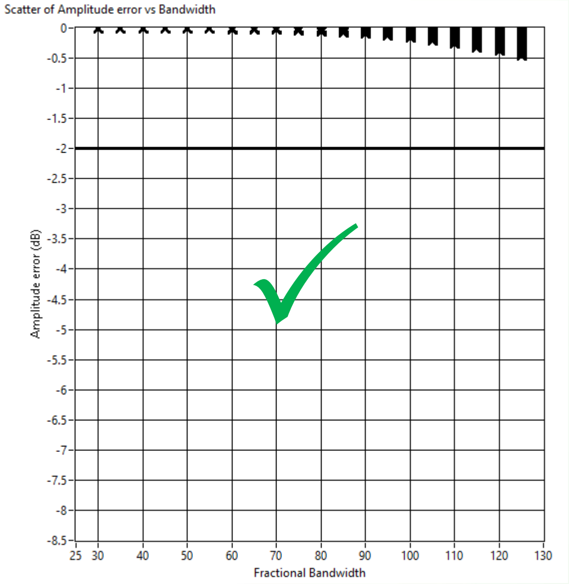
Max Amplitude error vs. Fractional Bandwidth

Sample Rate = 50MHz at 12bits
Signal at 5MHz
Phase & Offset varied in 5° steps

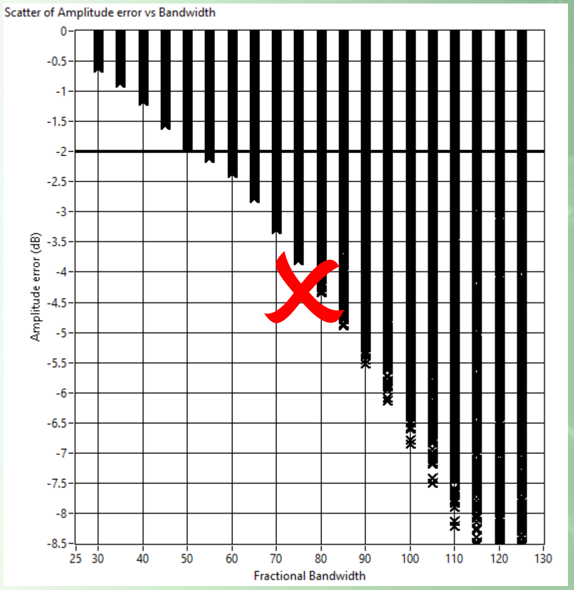
Full Wave Rect. (50MHz)



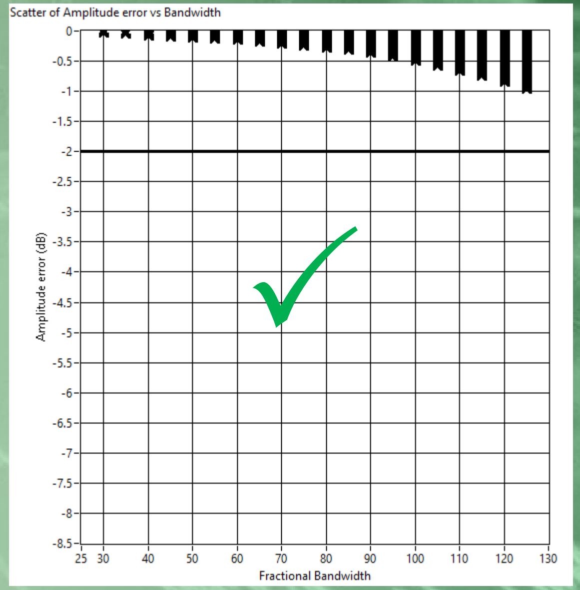
Envelope (Sampled 50MHz)



Envelope (Sampled IQ ≡ 10MSPS)



Envelope (Sampled 4x Fc = 20MHz)



1D Parametric Analysis Summary

- The Parametric Analysis has confirmed that the best echo amplitude estimate should be made by envelope detection
  - Maximum error of -0.173dB at Fractional Bandwidth of 100%
- The RF signal representation and envelope detection are best on the standard practice of over-sampling at 10x or 20x centre frequency.
- However, sampling at 4x transducer centre frequency is confirmed to achieve the necessary accuracy even at high bandwidth transducers
  - Maximum error of -0.284dB at Fractional Bandwidth of 100%
- Since 4x Fc sampling is able to represent the waveform to the required accuracy, it will be acceptable to sample the FMC data at this rate

Model extension for FMC+TFM

- 2D imaging model is an extension of the 1D model to analyse temporal sampling

- FMC data is created by simulating all the individual A-scans between each element pair for a point target
  - It uses the same Gaussian-windowed sine wave, sampled at 1GS/s, as for the 1D model
  - The round trip transit time, from transmit element to point reflector and back to receive element, is derived and used to interpolate the 1GS/s into the A-scan
  - An amplitude weighting, corresponding to element directivity, is possible
  - It is not used here so as to simplify the calculation of the amplitude error
  - Each A-scan is then sampled at the specified rates before inserting into the FMC matrix

- The TFM RF image around the position of the point target is created using the standard complex summation of contributions from all A-scans for each pixel

- Echo amplitude measurement approaches are compared with the Test signal amplitude, for specified pixel resolution (as pixels/wavelength), over variations in:
  - Gaussian window Offset (-180° to 180°)
  - Reflector Angle
  - Reflector Range
  - Test Signal's -6dB Fractional Bandwidth (Gaussian window Standard Deviation)

Clarification of Wavelength (λ) Terminology

For pulse-echo, in the time taken for 1 RF cycle, the location of the echo in the image moves by λ/2

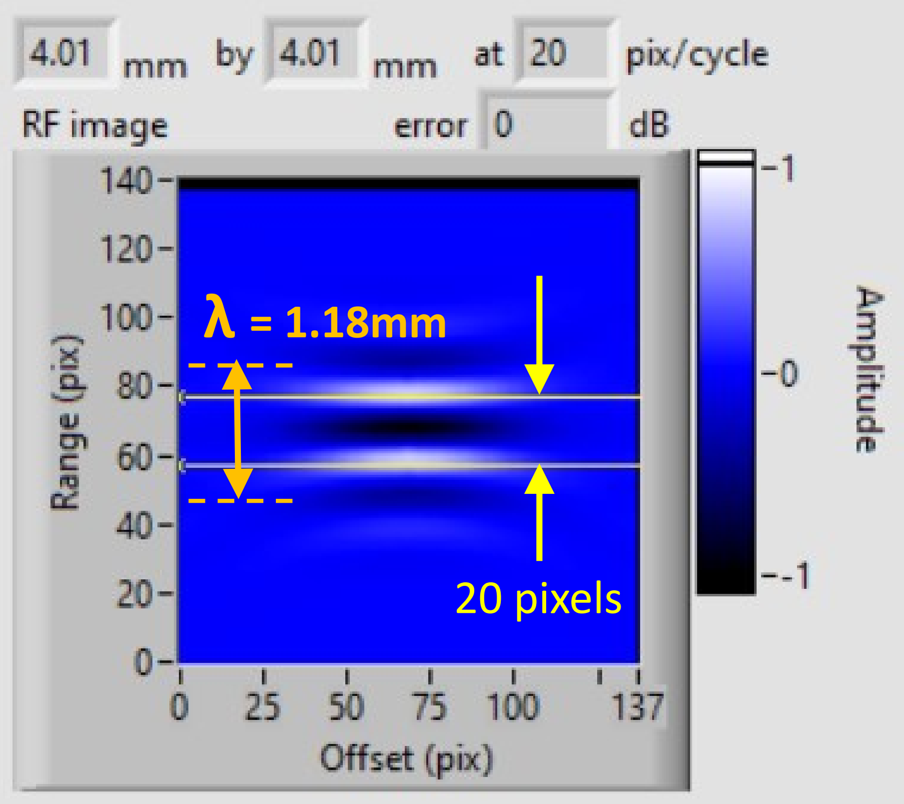
To avoid any confusion, the spatial pitch should always be defined in terms of the number of pixels/cycle rather than pixels/wavelength

RF TFM image

4mm x 4mm TFM image of 45mm range 0° target at 20pix/cycle = 40pix/λ

- f = 5MHz at 50% bandwidth
- Velocity (v) = 5890m/s
- λ = v/f = 1.18mm

64 element 0.5mm pitch array



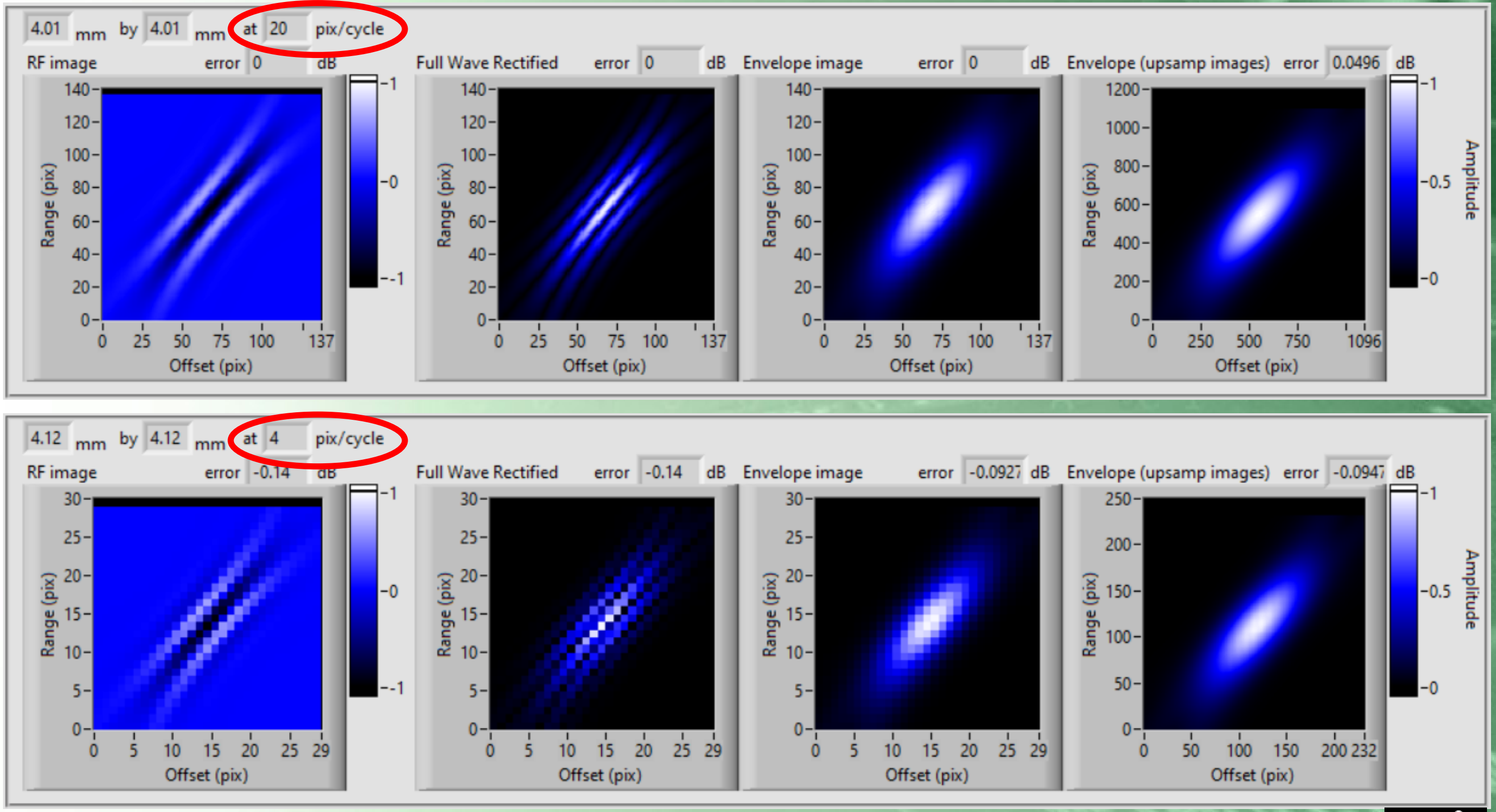
Rationale for spatial sampling

- Axial resolution is typically better than lateral resolution

- Column sampling through a 0° target is equivalent to the A-scan sampling already analysed so 4 pixels/cycle should give the same accurate rendition of the waveform

- 2D spatial up-sampling of the TFM RF image, before envelope detection, could give improved visual rendition without the processing time overhead of TFM generation at this resolution

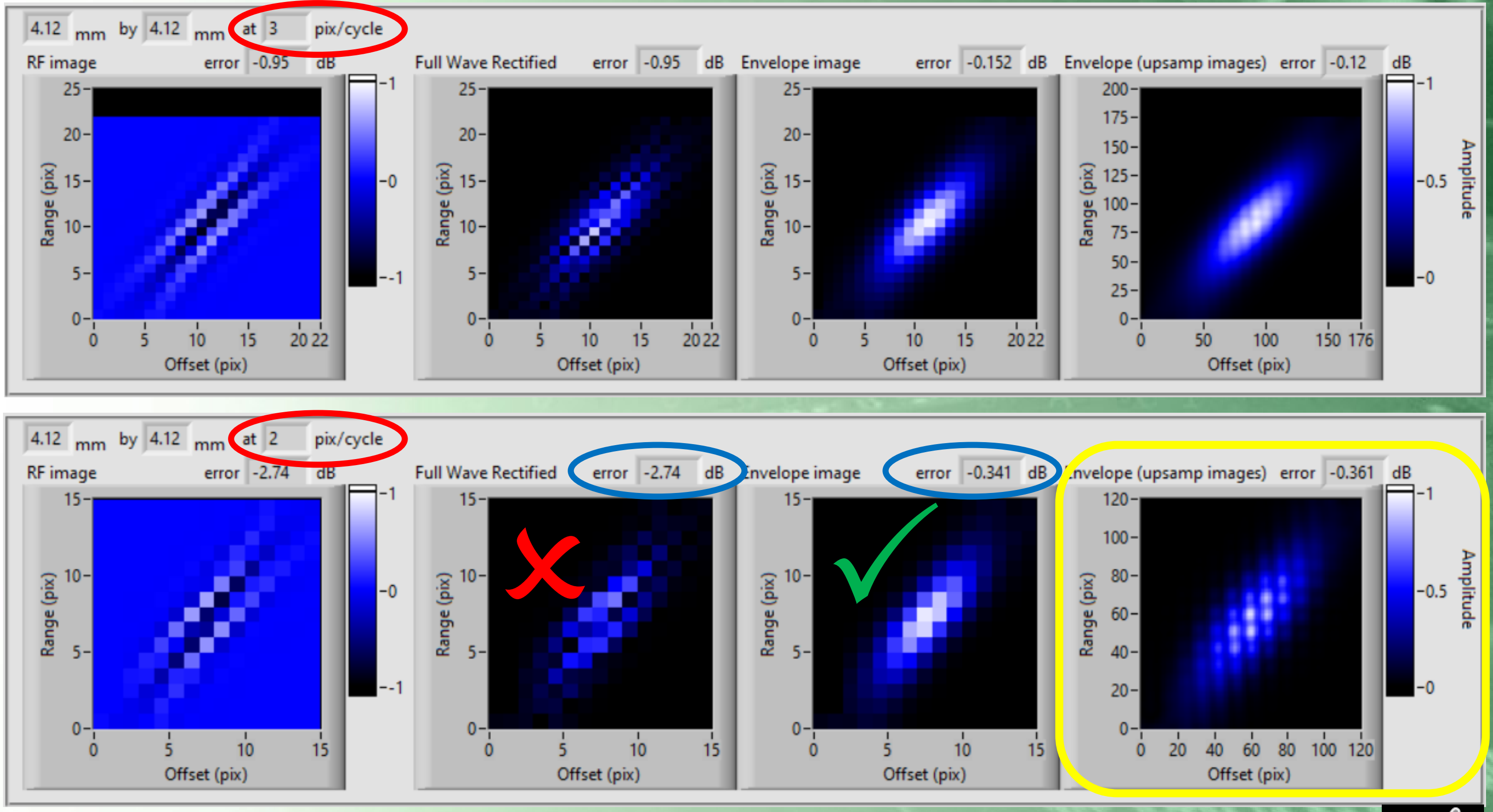
TFM images & amplitude errors for 75% bandwidth on 45mm range 50° target at 20 and 4 pixels/cycle



Coarser spatial sampling

TFM images & amplitude errors for 75% bandwidth on 45mm range 50° target at 3 and 2 pixels/cycle

- ASME V criterion requires better than 2dB echo amplitude fidelity
- Coarser sampling can offer higher throughput rates whilst achieving amplitude fidelity
- Error for Full Wave Rectification is -2.74dB but still only -0.341dB for Envelope
- Up-sampling errors are similar but offer little benefit in improved rendition at coarser than 4 pixels/cycle



Parametric analysis: Error Amplitude vs. Processing

<u>Common parameters</u>

64 element 0.5mm pitch contact array

Velocity = 5890m/s

FMC data sampled at 50MHz 12bit

7mm x 7mm TFM reconstruction

<u>Varying parameters</u>

Bandwidths: 50%, 75% & 100%

Target Ranges: 30, 45 & 60mm

Target Angles: 0° to 80° in 5° steps

Echo phases: -180° to 180° in 5° steps

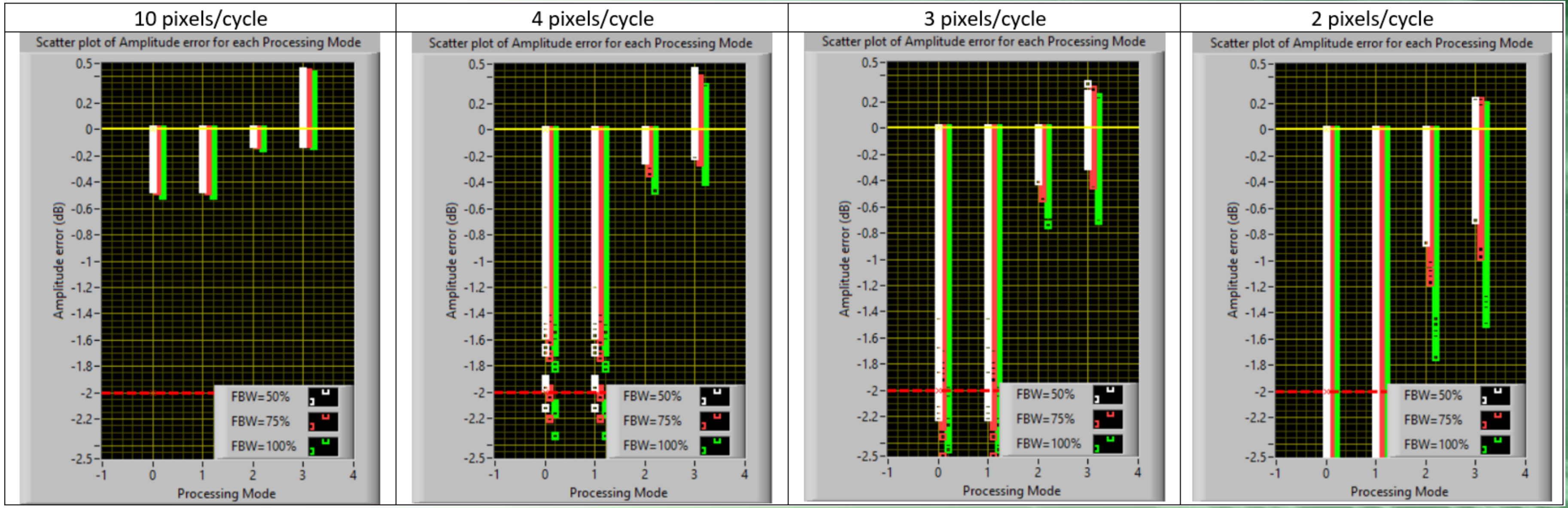
Processing Modes:

0 : RF display

1 : Full Wave Rectification

2 : Envelope (at ADC rate)

3 : Envelope on spatially up-sampled (8x) images



Parametric analysis: Error Amplitude vs. Angle & Range

<u>Common parameters</u>

64 element 0.5mm pitch contact array

Velocity = 5890m/s

FMC data sampled at 50MHz 12bit

7mm x 7mm TFM reconstruction

2 pixels/cycle

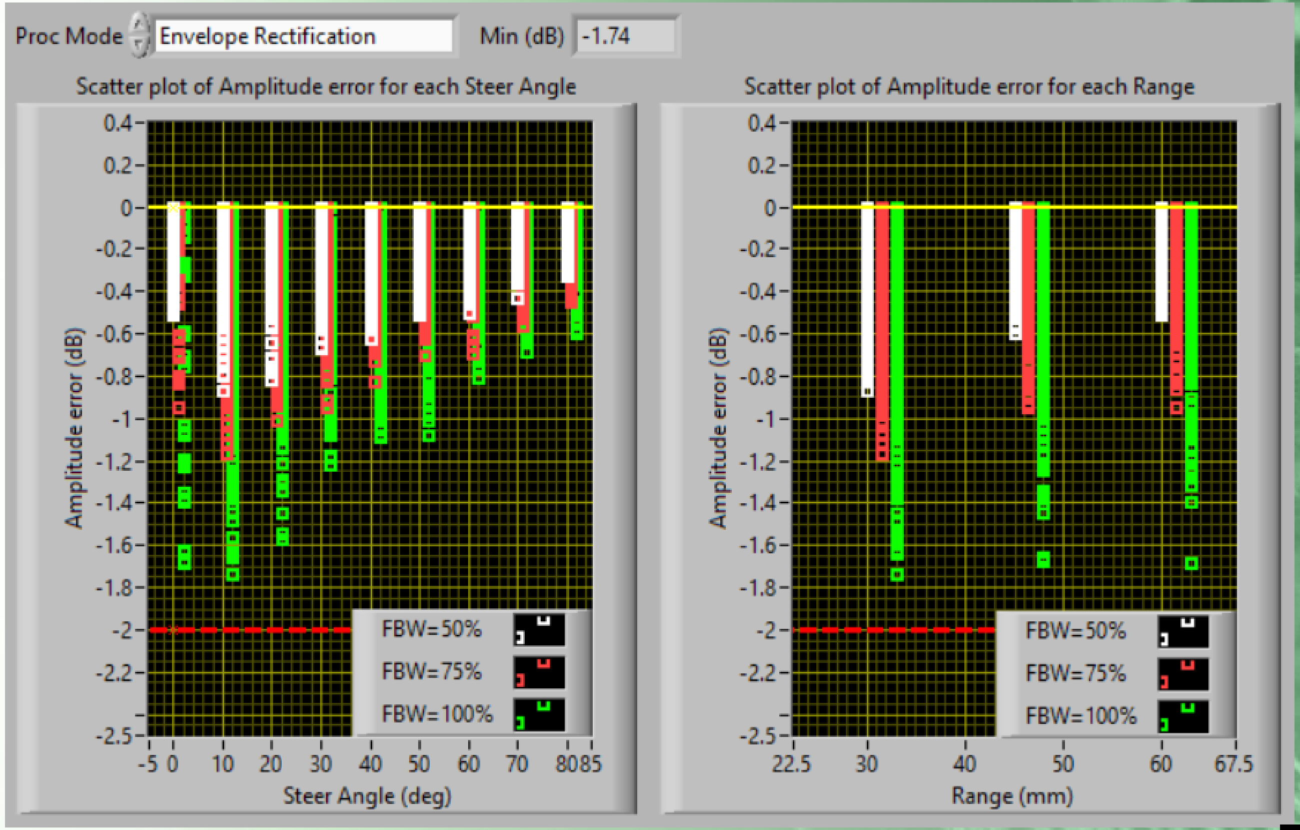
<u>Varying parameters</u>

Bandwidths: 50%, 75% & 100%

Target Ranges: 30, 45 & 60mm

Target Angles: 0° to 80° in 5° steps

Echo phases: -180° to 180° in 5° steps



Conclusions & Future Work

- Confirmed that temporal sampling of 4x Centre Frequency is accurate for bandwidths up to 100%
- Parametric analysis confirmed TFM spatial sampling of 4 pixels/cycle is accurate for same bandwidth range
- Coarser spatial sampling is possible whilst still achieving ASME V criterion (<2dB amplitude error)
- Coarse pixel sampling allows fast automated scanning with amplitude thresholding on TFM images
  - If the threshold is exceeded, a finer pitch reconstruction can be done on the same FMC data for detailed review

<u>Future Work</u>

- Confirm that temporal sampling at 4x bandwidth is still valid for coded excitations