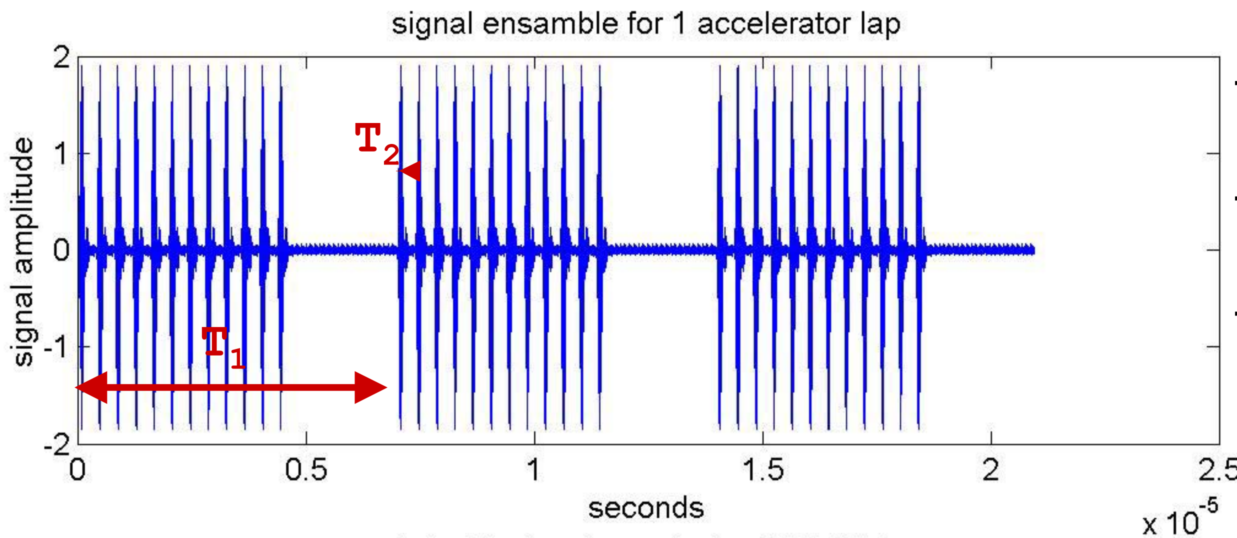
BPM test signal Spectrum analysis

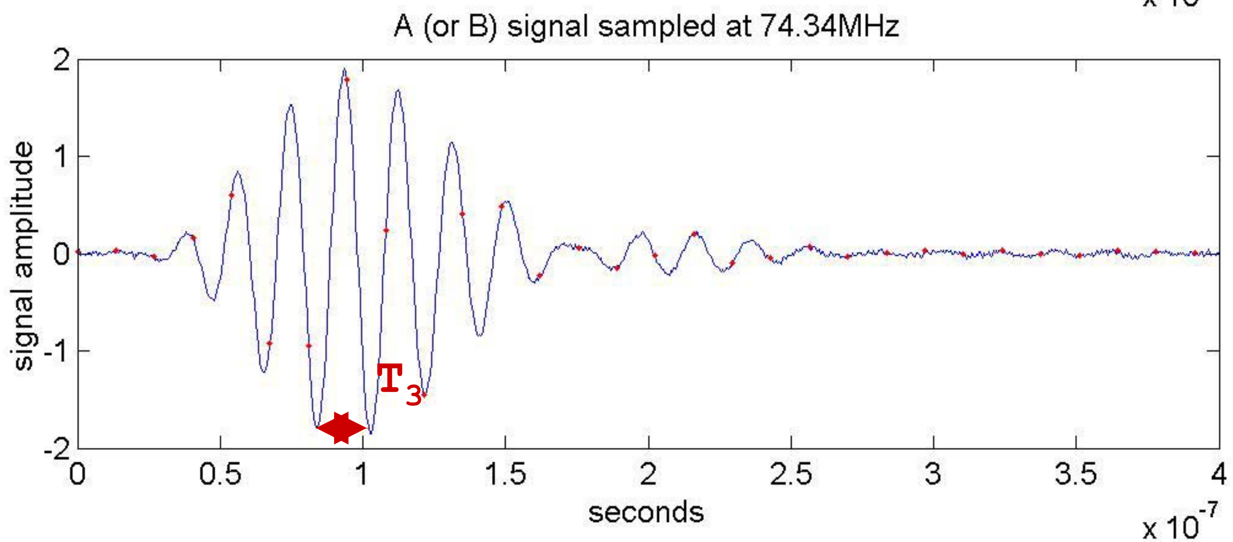
BPM project

Gustavo's test signal

- No RF buckets = 1113.
- RF frequency = 53.104 MHz.
- 1 lap period = 20.958 μs.
- Starting from Jim Steimel's A and B sampled at 2GHz a closed-orbit load of 36 bunches in 3 batches of 12 bunches separated by abort gaps is generated. i.e. 41917 samples.
- This signal is resampled at a freq. close to 7/5 of 53.104MHz.
- The difference between my sampling freq and 7/5 of 53.104MHz was 0.39%.
- This error shifts the spectrum centered at 53.104MHz by 207.7KHz.
- The "recicler" filter BW is ~10KHz, so it was very sensitive to this error.

Spectrum analysis





T_1=6.99μs => f_1=143KHz

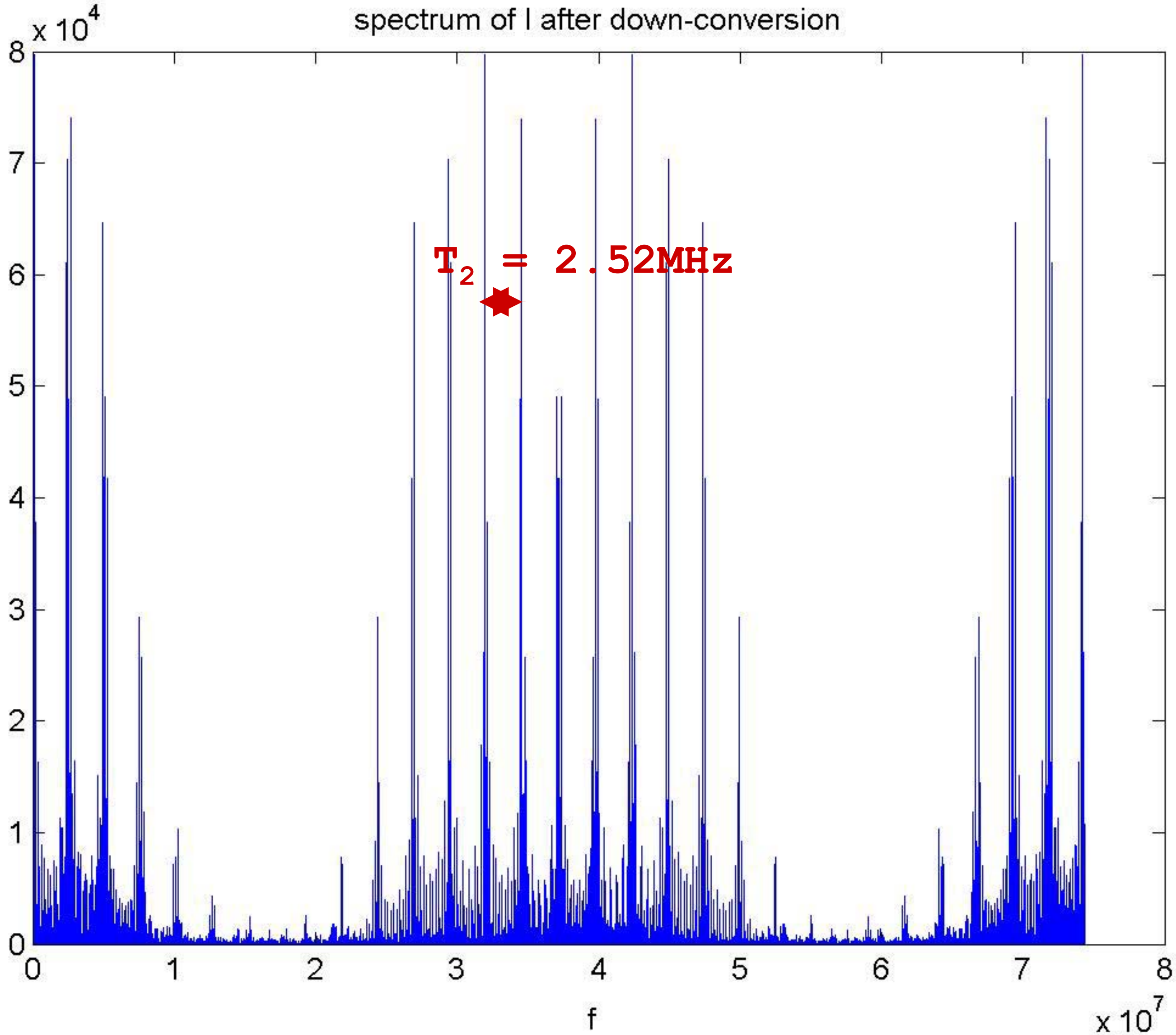
T_2=396ns => f_2=2.52MHz

T_3=18.9ns => f_3=53.1MHz

The 53MHz signal is not periodic f_3 represents its 1st harmonic.

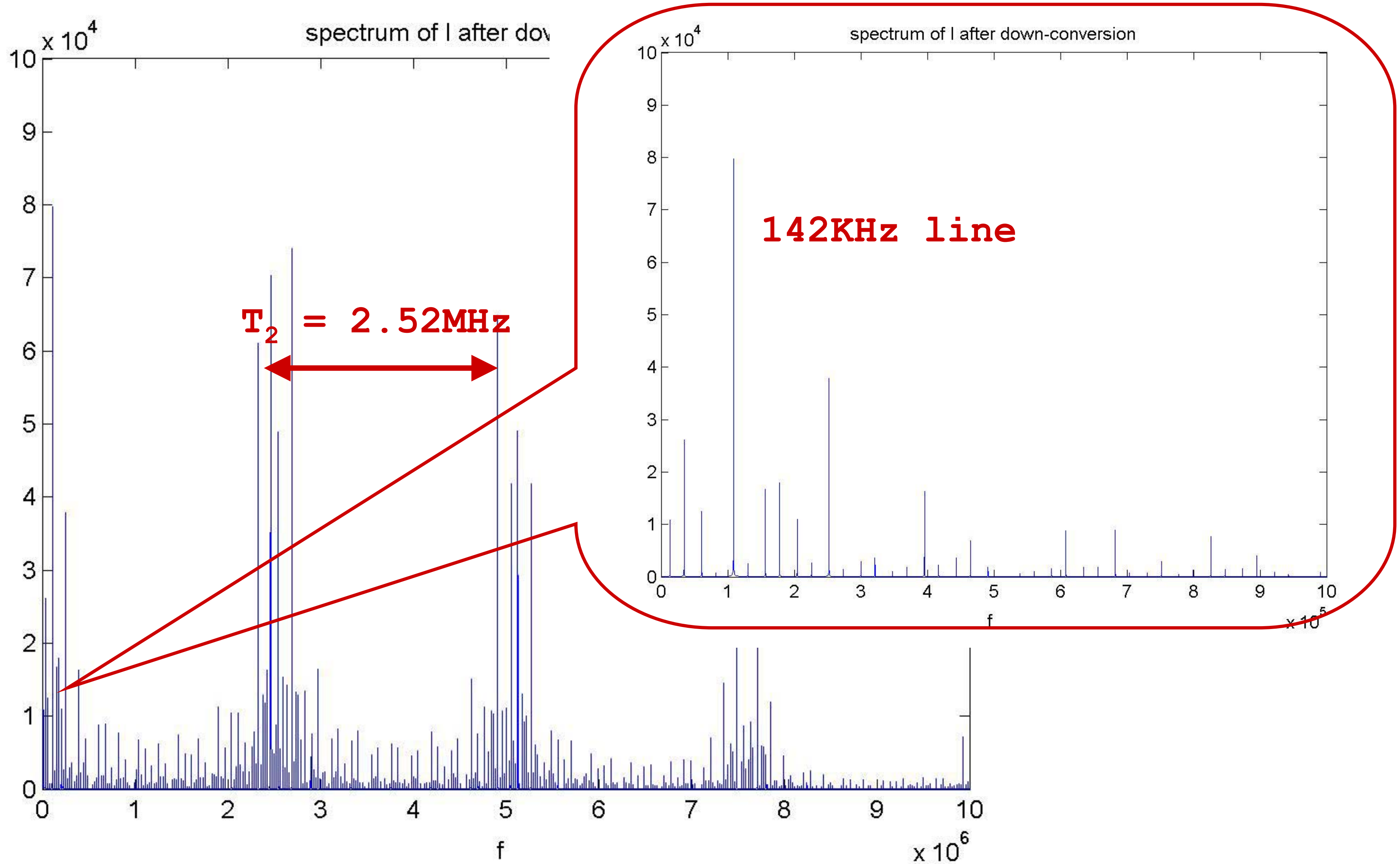
Sampling frequency
fs = 74.3MHz

Spectrum analysis

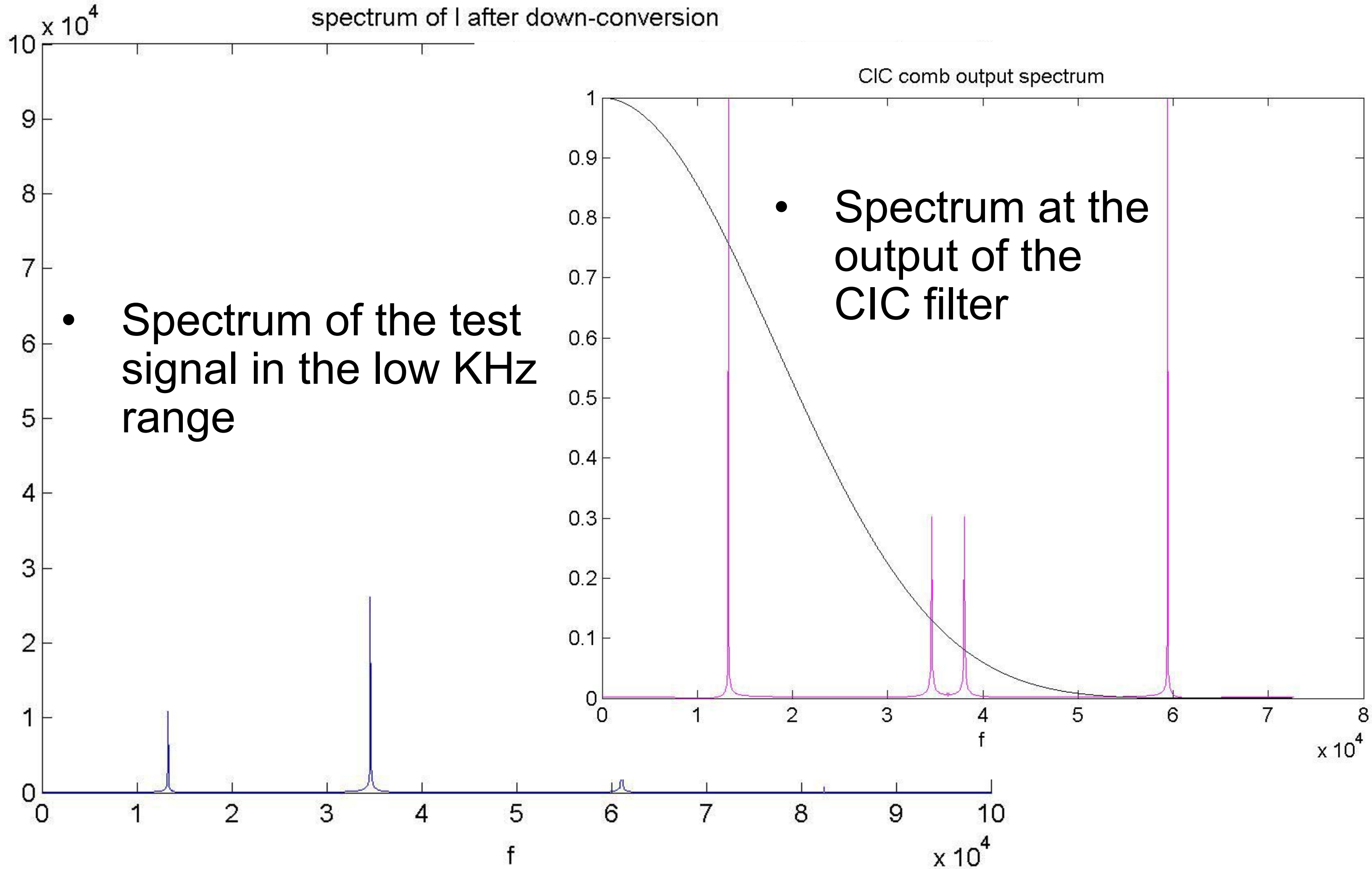


The spectrum of the input (sampled) signal is centered at 53MHz. After down-conversion a portion is sent to baseband.
Most of the spectrum density concentrates around 2.52MHz lines.

Spectrum analysis



Spectrum analysis



- Spectrum of the test signal in the low KHz range
- Spectrum at the output of the CIC filter

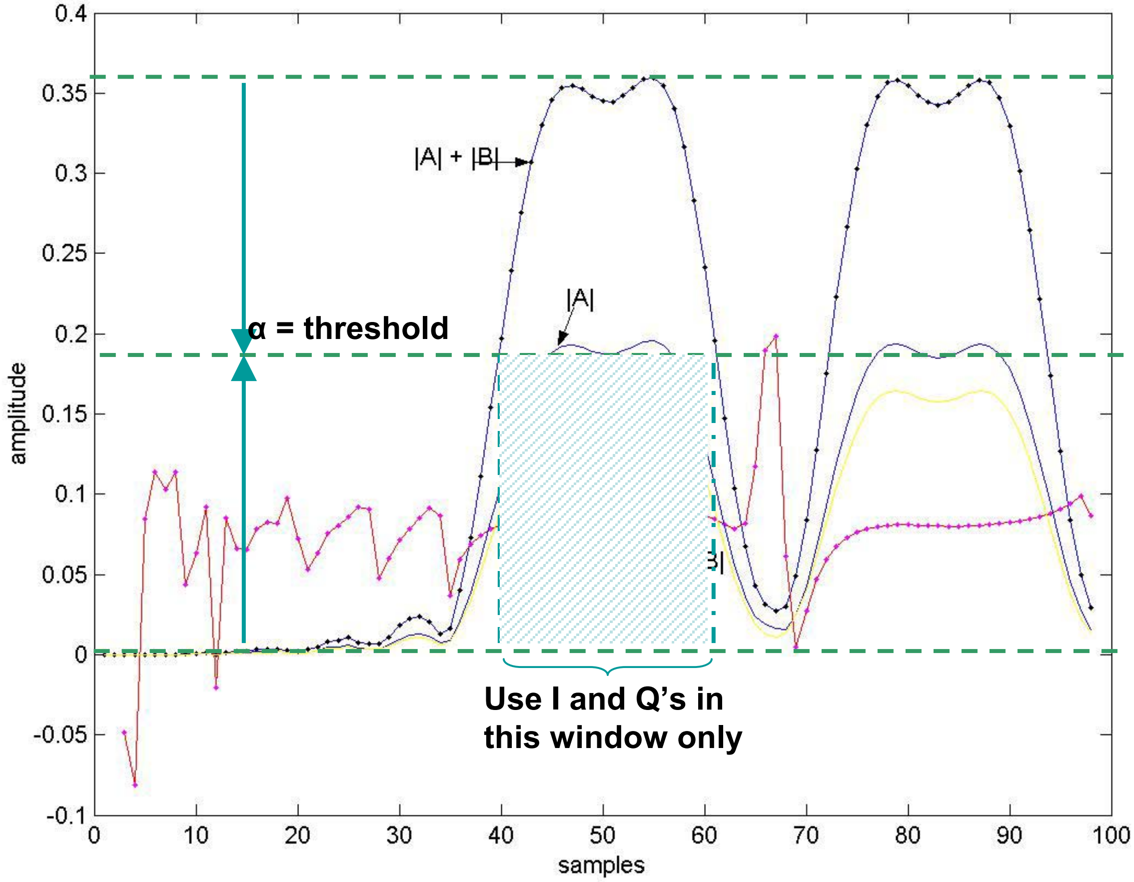
Specifications to implement the “batch envelope filter” in the Ecotek Stratix FPGA

BPM project

Signal to noise

- The matched filter is a linear filter widely used to recover deterministic signals embedded in white Gaussian noise (WGN) because it optimizes the S/N ratio.
  - $y(n) = x(n) * s(n)$, where $s(n)$ is the deterministic signal and $x(n)$ is the noisy signal. i.e. $x(n) = s(n) + w(n)$. ($w(n)$ is WGN).
  - $S/N = \varepsilon/\sigma^2$, where ε is the energy of the signal and σ^2 is the noise variance.
  - S/N increases with the number of “signal samples”.
  - The matched filter meets the Cramer-Rao lower bound.
- We can do better than the matched filter by choosing only “signal samples”. In a batch we have enough “signal samples” that can be detected applying a simple threshold cut.

Filtered signals



|A|-|B|/|A|+|B| is fairly constant for |A|+|B|>Threshold.

The example shows about 25 useful points per batch.

The samples are averaged to provide a single I and Q pair per batch.

Batch numbers are averaged again to improve estimate and lower the data bandwidth.

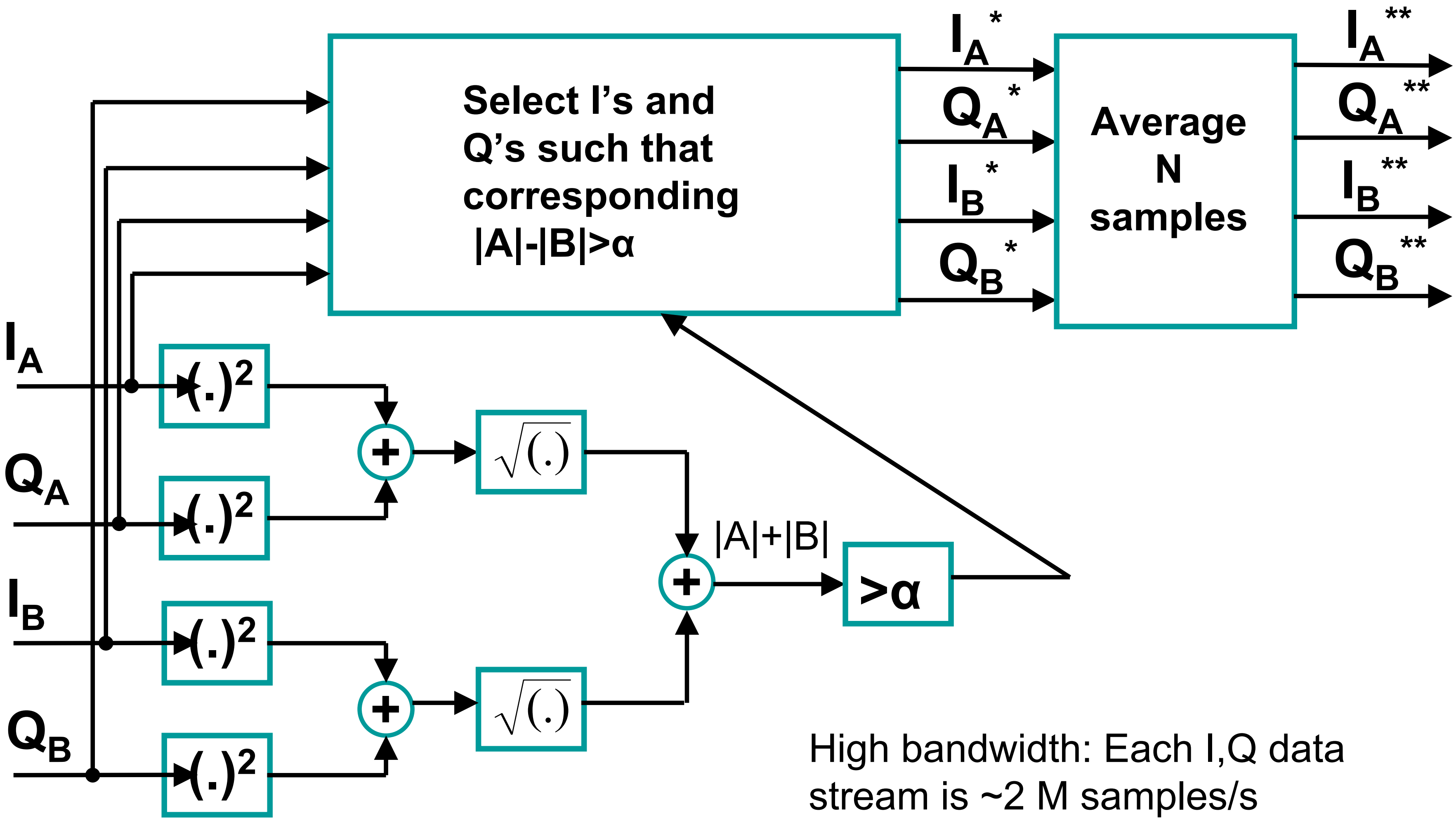
Task Description

- Implement the “batch envelope filter” in the Stratix FPGA that handles the I and Q data stream into the Ecotek’s FIFO.
- Write the Filter algorithm in VHDL code and simulate it on the PC using I and Q signals coming from Matlab simulations.
- Port the Filter VHDL to the Ecotek FPGA.
- Test and qualify the Filter using Jim Steimel’s setup.

Signal processing options

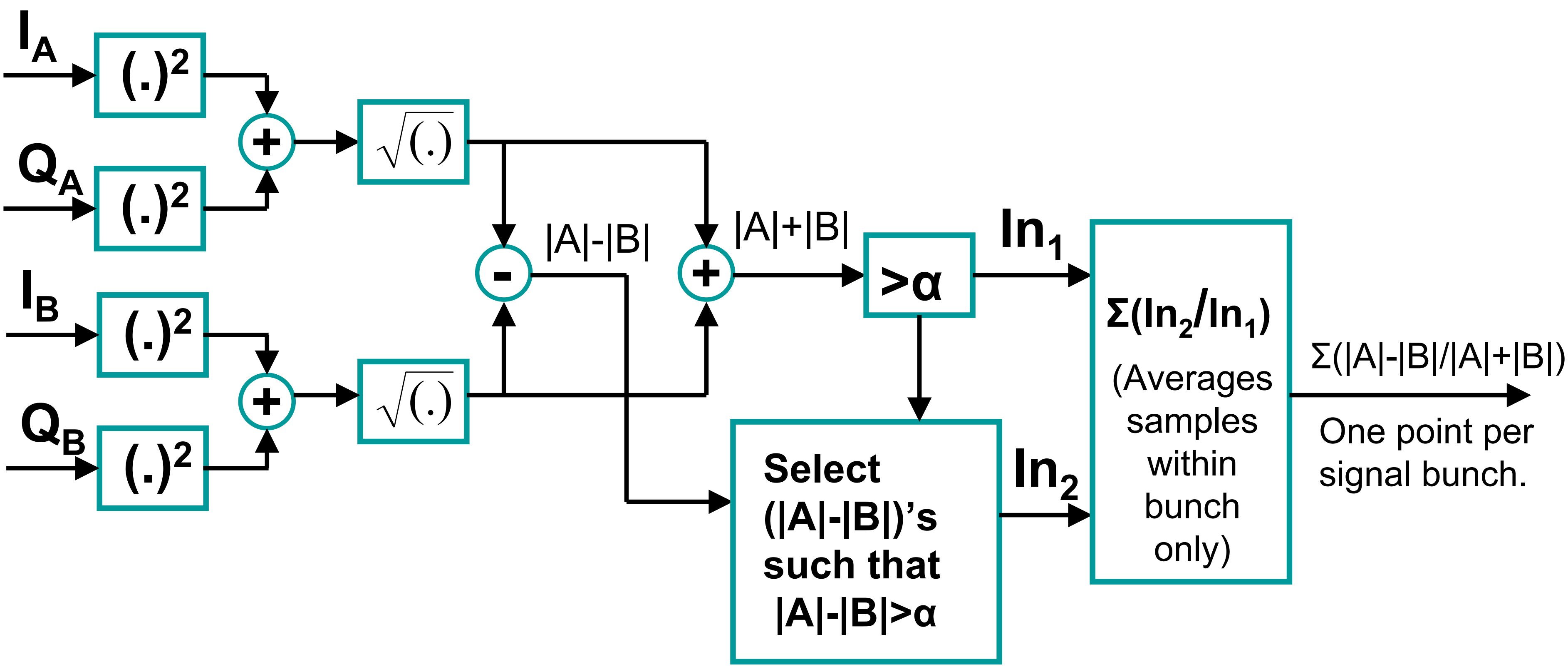
- The amount of signal processing done by the filter has alternatives:
  i. Select I and Q based on corresponding |A|+|B|>threshold but output “raw” I and Q to VME.
  ii. Select I and Q as above but output averaged I and Q’s to VME.
  iii. Select I and Q as above, compute |A|-|B|/|A|+|B| for each sample above threshold.
  iv. Select I and Q as above, compute |A|-|B|/|A|+|B| for each sample above threshold, sum up N number of points to eliminate betatron oscillations (N~32).
- How to determine the threshold?
  – The threshold can be fixed to a number above the noise level and below ½ the minimum |A|+|B| signal level expected.
  – It can be calculated from the signal level and set accordingly.

Filter Algorithm (Option i. and ii.)



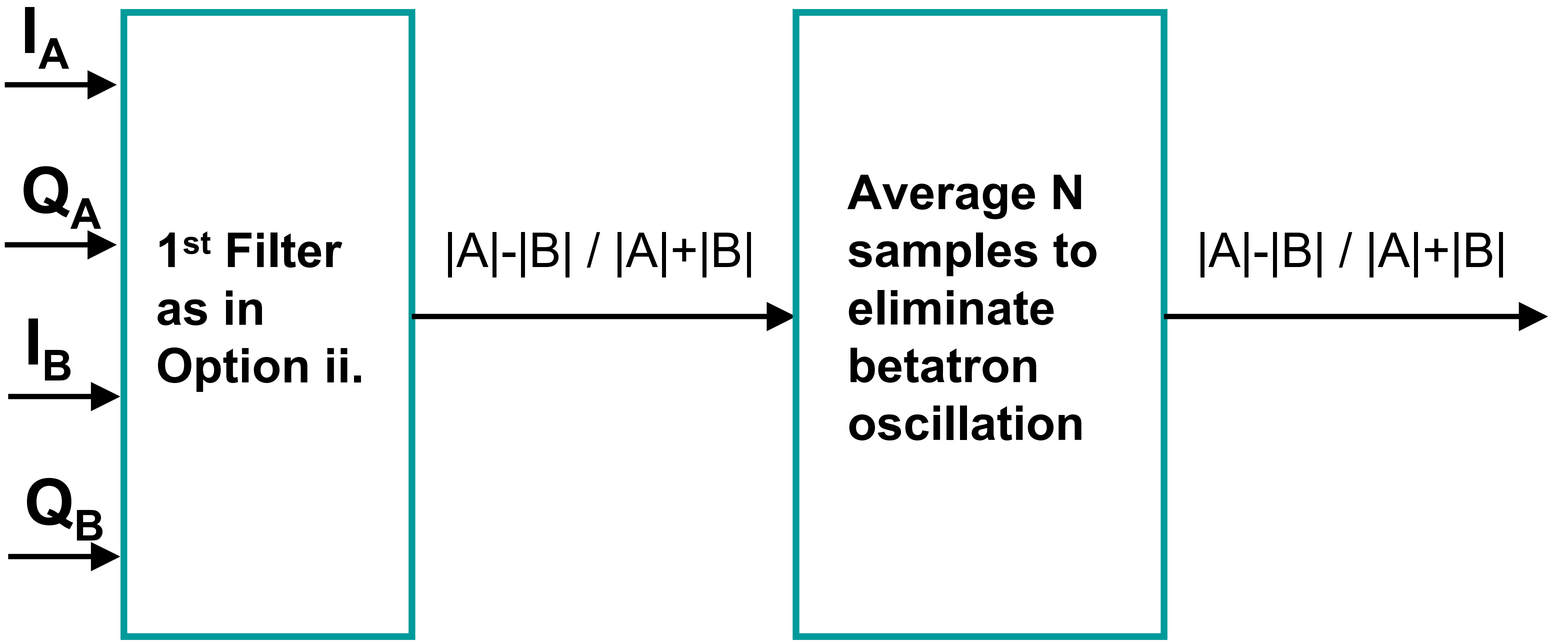
High bandwidth: Each I,Q data stream is ~2 M samples/s

Filter Algorithm (Option iii.)



Moderate bandwidth: 145 K samples/s

Filter Algorithm (Option iv.)



Low bandwidth: 4.5 K samples/s

Position estimation

Let $s_I(n) = I(n) + w(n) \quad and \quad s_Q(n) = Q(n) + w(n)$ If the noise is WGN ~ N(0,σ²),

the likelihood estimation function of **I** is: $L(I,\hat{I}) = \frac{1}{\left(2\pi\sigma\right)^{N/2}} \exp\left[\frac{1}{2\sigma^2}\sum_{n=0}^{N-1}\left(x(n)-\hat{I}(n)\right)^2\right]$

Similarly for Q.

However, the position estimation is nonlinear with respect to I and Q.

$$P = \frac{|\hat{A}|-|\hat{B}|}{|\hat{A}|+|\hat{B}|} = \frac{\sqrt{\hat{I}_A^2+\hat{Q}_A^2}-\sqrt{\hat{I}_B^2+\hat{Q}_B^2}}{\sqrt{\hat{I}_A^2+\hat{Q}_A^2}+\sqrt{\hat{I}_B^2+\hat{Q}_B^2}}$$

It is better to run sums over I and Q before calculating P.

The filters color the noise. Not WGN any more.

How to set the threshold

- The threshold can be fixed to a number above the noise level and below ½ the minimum |A|+|B| signal level expected.
- It can be calculated from the signal level and set accordingly.