LCLS-1 Cavity BPM Algorithm for Unlocked Digitizer Clock

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Introduction

Fig. 1 shows a typical cavity BPM. Transversal beam displacement excites the dipole mode in a "position" cavity. The monopole mode in a "reference" cavity provides a reference signal for amplitude (beam-charge) and phase.

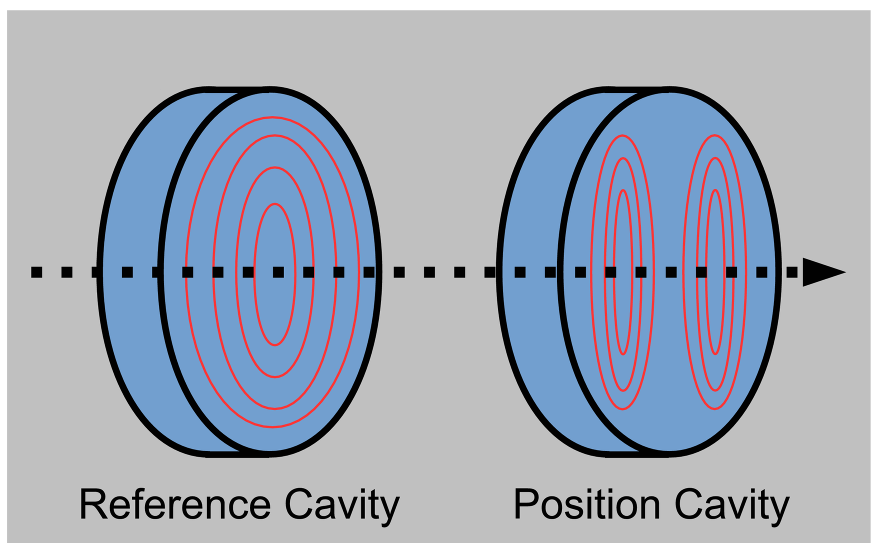

Fig. 1: Cavity BPM

Synchronous detection is used to determine the position ("*Re{pos_phasor/ref_phasor}*"):

- Suppression of quadrature signal caused by slanted trajectory or bunch.
- Better SNR for beam close to center.
- "Sign" of position comes for free.

The detector uses the phase of the reference cavity to establish a "time-scale".

Fig. 2 shows a typical receiver. RF signals are down-mixed and digitized. Since phase information is critical the position- and reference channels must use the same LO and ADC clock (only one axis of x/y shown).

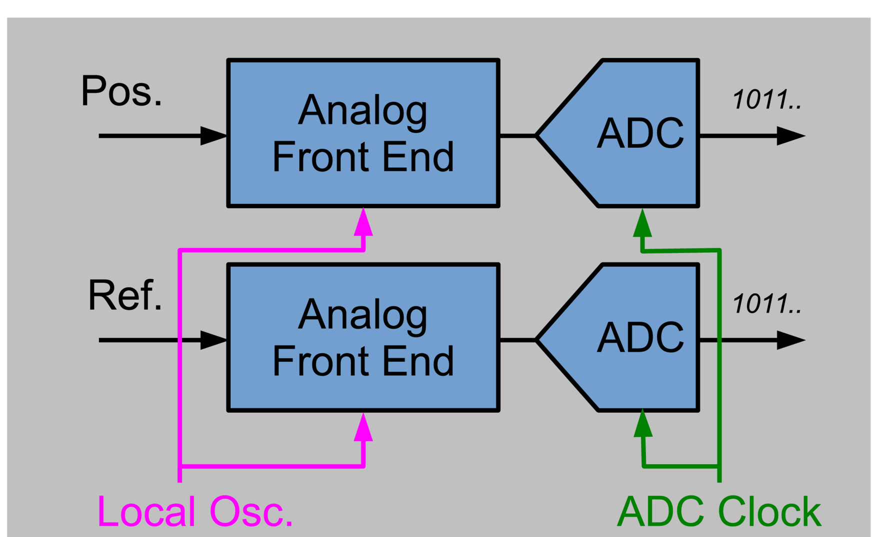

Fig. 2: BPM Receiver

If the ADC clock is not locked/synchronized to the LLRF (beam) and the reference and position cavities are not tuned exactly to the same frequency then phase errors are introduced (since the sampling time T is not known):

$$\Phi_{Ref} = \omega_{Ref} T + \varphi_{Ref} \qquad \Phi_{Pos} - \Phi_{Ref} = \varphi_{Pos} - \varphi_{Ref} + (\omega_{Pos} - \omega_{Ref}) T$$
$$\Phi_{Pos} = \omega_{Pos} T + \varphi_{Pos}$$

Sampling with an unsynchronized ADC introduces an "apparent" time-shift (Fig. 3):

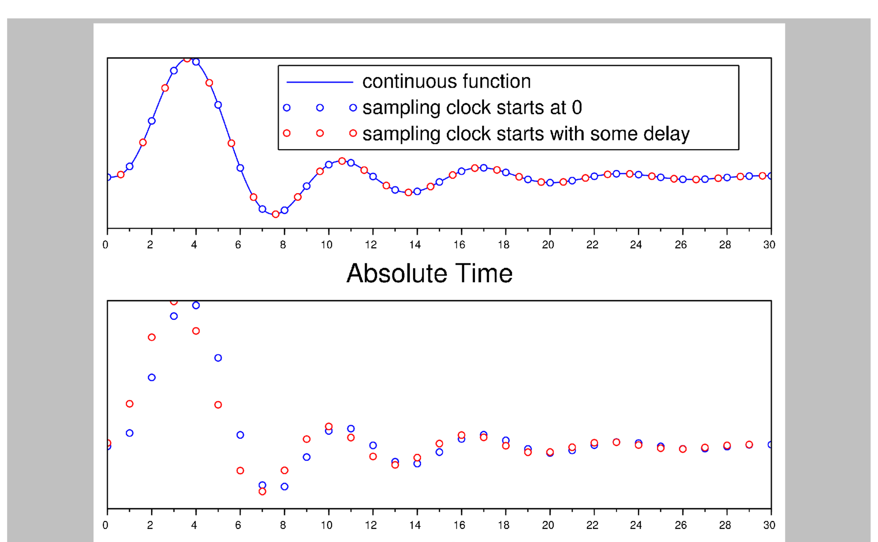

Fig. 3: Unsynchronized ADC

TOA Estimation

The Problem

In order to eliminate the phase error we need to estimate the "Time of Arrival" (TOA).

The idea is as follows:

- We use a known "test" or "template" function (blue dots in Fig. 3).
- We have a measured set of samples (red dots in Fig. 3).
- We want to estimate by how much we have to shift the red set in time to match the blue one.
- Tricky: *the time-shift is not an integer number of samples.*

Approach to Solution

How can we describe our problem?

→ look at the *correlation* between template (x_i) and measured data (s_i):

$$R(\tau) = \Sigma x_i s_i(\tau) \rightarrow \max$$

Clearly, at the correct time-shift, this correlation must exhibit a maximum – but its computation requires the data set to be shifted potentially by a fractional sample interval τ.

Such a shift can be performed easily in the frequency-domain (F{}: Fourier-transform):

$$\begin{aligned} Y(\omega) &= F\{\ y(t)\ \} \\ y(t-t_o) &= F^{(-1)}\{\ Y(\omega)\ e^{(-j\omega t_o)}\ \} \end{aligned}$$

The correlation *R* can also be expressed in the frequency domain:

$$\begin{aligned} R(\tau) &= F^{(-1)}\{\ X(\omega)\ S(\omega)\, e^{-j\omega\tau}\ \} \\ &= F^{(-1)}\{\ |X(\omega)||S(\omega)|\ e^{j(\Psi(\omega)-\omega\tau)}\ \} \end{aligned}$$

and the extremum is found by taking the derivative to τ and setting to zero:

$$\frac{\partial R(\tau)}{\partial \tau} = F^{(-1)}\{\ |X(\omega)||S(\omega)|\ (-j\omega)\ e^{j(\Psi(\omega)-\omega\tau)}\ \} \stackrel{!}{=} 0$$

The LHS is a non-linear function of τ (since τ appears in the exponent). However, close to the optimum – where R has a maximum – we can assume the phase difference $\Psi(\omega) - \omega\tau$ to be small.

Note: *we do not assume that τ itself is small*; *only that $\omega\tau$ tracks Ψ reasonably well!*

Under this assumption we can linearize

$$\frac{\partial R(\tau)}{\partial \tau} \approx F^{(-1)}\{\ |X(\omega)||S(\omega)|\ (-j\omega)(j\ (\Psi(\omega)-\omega\tau))\ \}$$

(only the odd part of the exponential is relevant) and solve for the unknown τ

$$\tau \approx \frac{F^{(-1)}\{\ |X(\omega)||S(\omega)|\ \omega\ \Psi(\omega)\}}{F^{(-1)}\{\ |X(\omega)||S(\omega)|\ \omega^2\}}$$

(The full algorithm is a little bit more complex due to an unknown phase contribution from an unlocked LO.)

Results

Figure 4 shows the measured signal out of a LCLS reference cavity for two beam pulses. The effect of the unlocked clock is obvious.

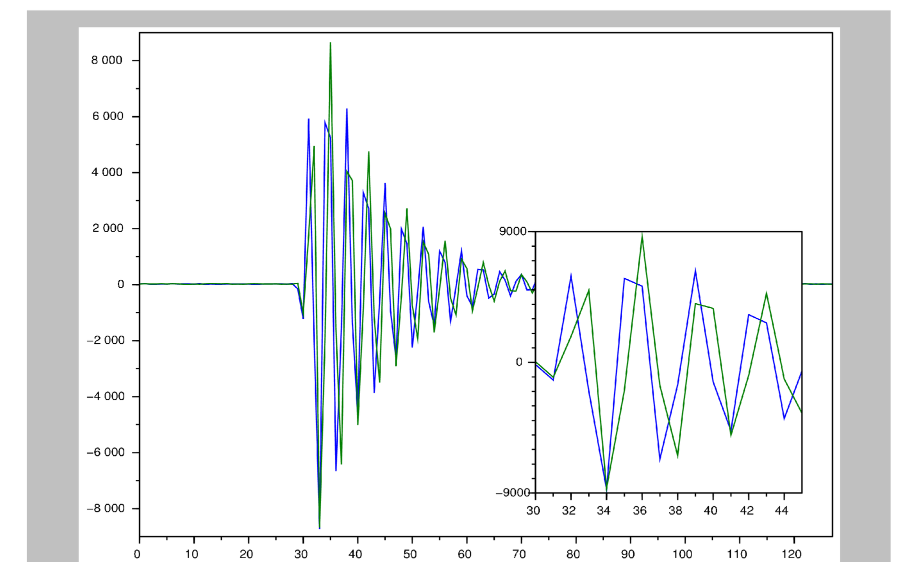

Fig. 4: Uncorrected Signals

The zoomed area shows more detail. It can be seen that the time-difference is not a multiple of an integer sampling interval.

The TOA estimation was then applied to the signals and they were time-aligned to the test function (using a FFT) – see Fig. 5. (The amplitude was also normalized for this plot.)

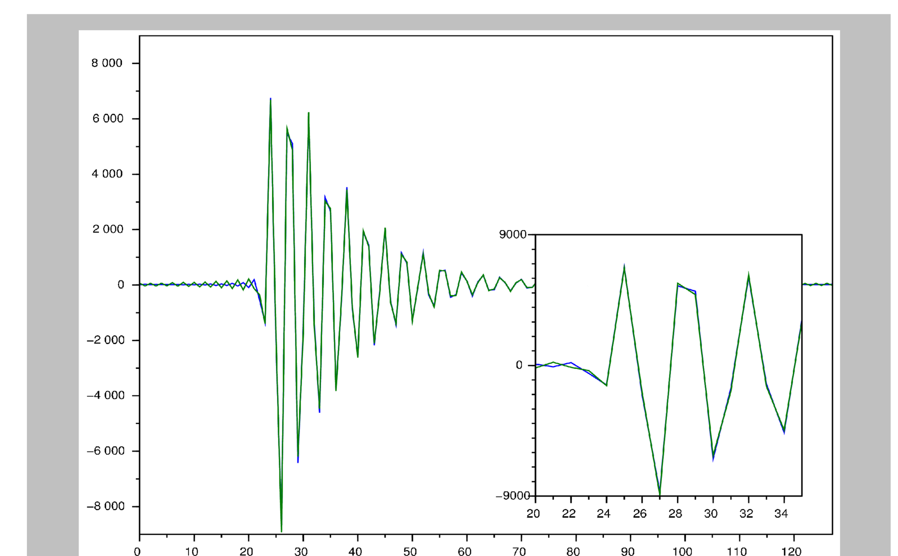

Fig. 5: Time-aligned Signals

Implementation Note

The estimation is computed on-line at the LCLS beam-rate of 120Hz using a CPU with SIMD co-processor under a real-time OS to calculate FFTs and perform other operations.

Conclusion

The proposed algorithm is able to estimate the timing errors introduced by an unlocked ADC. This reduces costs for a clock distribution and does not require careful tuning of the cavities.

The method could also be useful for other applications.

Acknowledgment

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