Beam Phase Cavity

Note: FS is Full Scale, fS is femtosecond, F is Fahrenheit - context supercedes preceding definitions.

Purpose

The beam phase cavity will be used to measure the timing of the beam compared to the RF phase. The beam timing is dominated by the timing of the laser onto the cathode of the RF gun. The results of the measurement will be used to correct timing of the laser, which is expected to drift outside LCLS tolerances.

Specification

The specifications for the beam timing measurement are as follows.

Short term (2 second) timing jitter: 100fS rms
Long term (4 day) timing jitter: ±1pS
Data available at 120Hz
Control interface will be EPICS running on RTEMS

SNR

The ADC (LTC2208) has a SNR of about 76dB, which is the dominating noise source in the system. The SNR of 76dB has been measured in on a demo board in the lab.

The noise floor of the RF signal from the cavity is about –174dBm/Hz.
The noise floor in the reference system, LO, is predicted to be < -143dBc/Hz at 2830.5MHz. At 13dBm this is –130dBm/Hz. The LO noise floor is 44dB higher than the cavity signal noise floor and thus dominates the RF signal noise levels.

A 4MHz IF bandpass filter will give a SNR of 77dB on a signal with a noise floor of –143dBc/Hz. By use of a 4MHz IF bandpass filter the noise level from the signal will be about the same as the ADC noise level. The filter will reduce the rise time of the beam induced cavity signal to the order of 80nS.

ADC Clock Jitter

The ADC clock allowable jitter is calculated from:

$$SNR = -20Log(2\pi \times 25.5MHz \times T_{jitter})$$

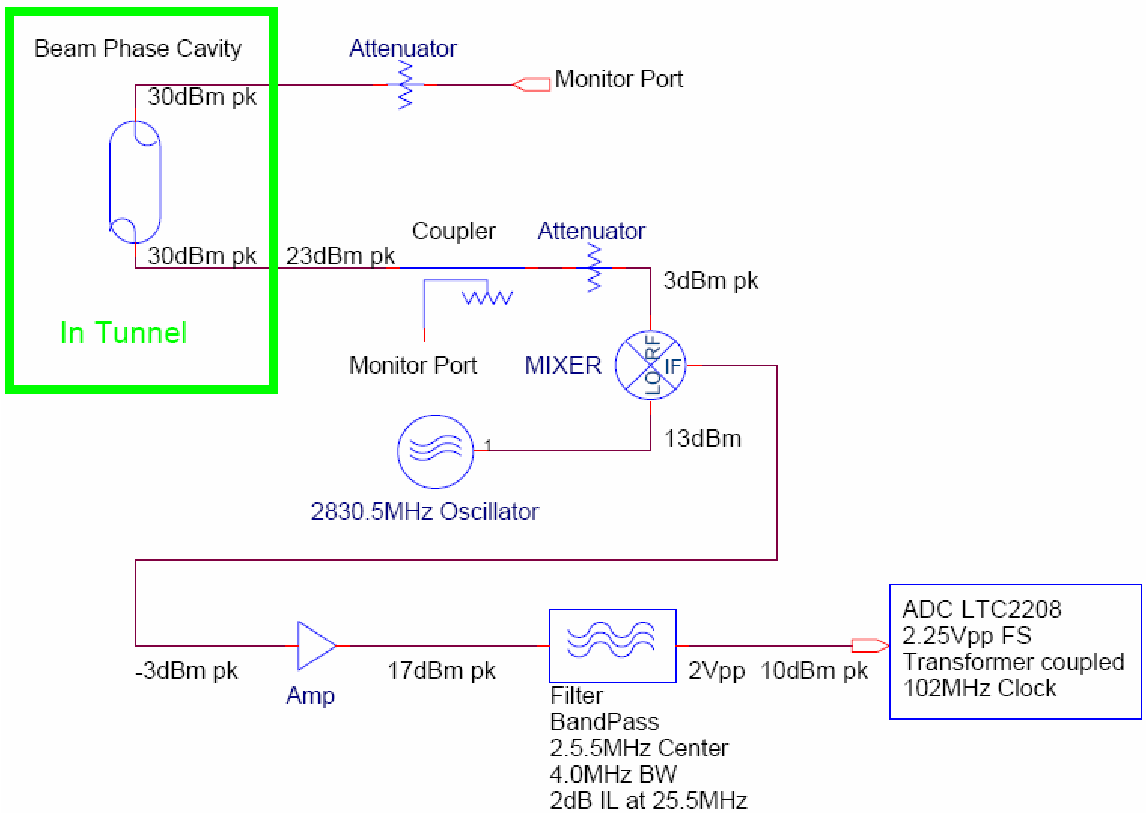
From this equation1pS rms clock jitter gives a SNR of 76dB. This amount of clock jitter will double the noise level at the input to the ADC. The 102MHz clock jitter is expected to be on the order of 100fS rms jitter. This corresponds to a SNR of 96dB. The clock jitter will not add significantly to the noise levels.

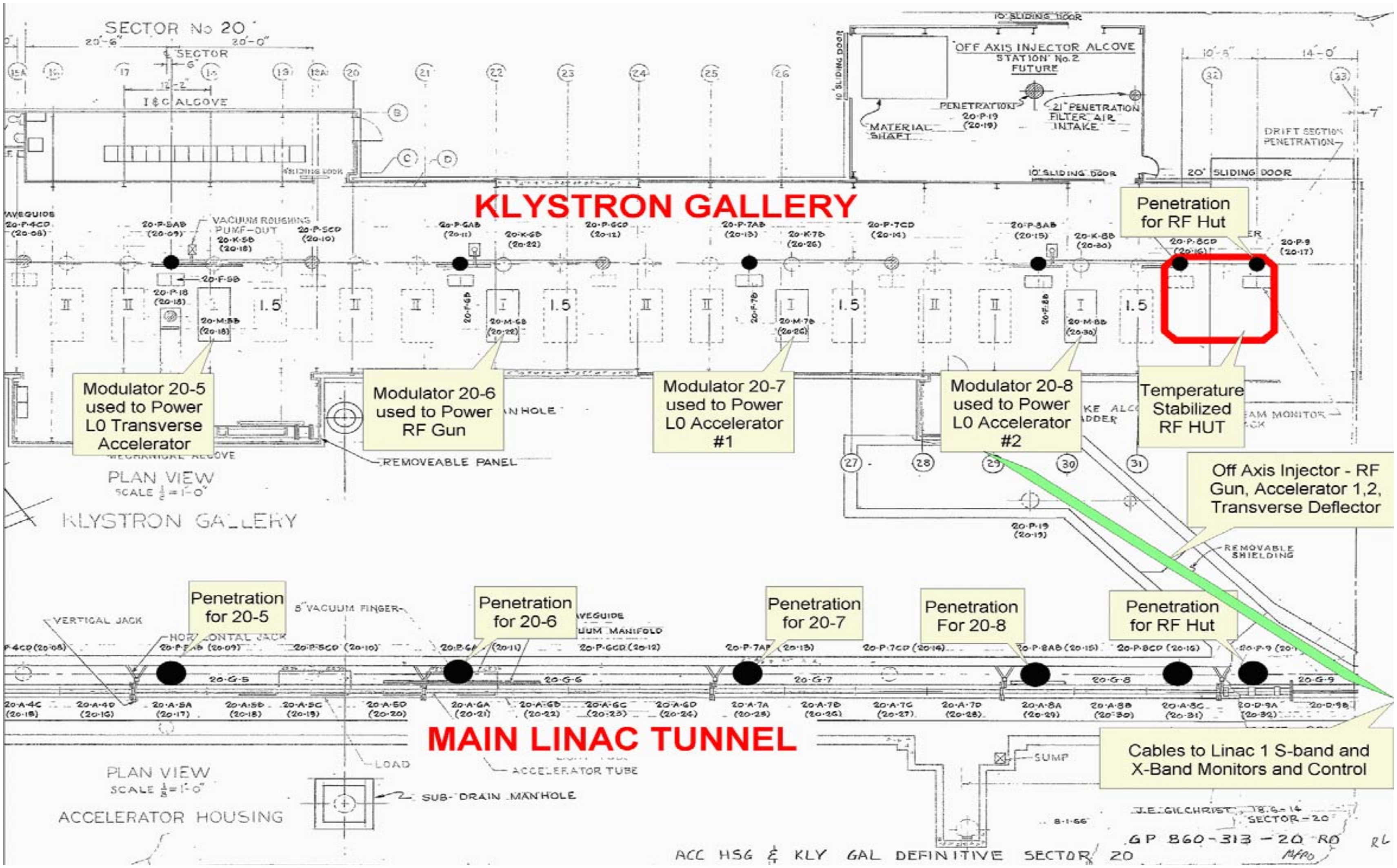
Temperature Drifts

Temperature Coefficient of the cavity is 28kHz/˚F (50kHz/˚C). The specified water temperature stability is ±0.1˚F. The frequency change for this temperature variation is ±2.8kHz. A 2.8kHz frequency shift will cause a phase change of 1 degree in 1uS.

Phase Stable 1/2 inch superflex Heliax cable will be used from the electronics to the cavity. The cable is 80 feet in length and runs from the temperature stabilized RF Hut, down a penetration, through a shield wall, and to the cavity in the injector tunnel. The temperature coefficient of the cable is listed as –1 to +3ppm/˚F. For this analysis a temperature coefficient of 4ppm/˚F is used. The cable will be run with water stabilized lines for most of the run. The specification for the water temperature is ±0.1˚F. About 10% of the cable might be exposed to temperatures in the RF Hut and injector area of ±1˚F. Eighty feet of cable is 1e6 degrees S-band and a ±0.1˚F temperature variation will cause a ±0.4˚ phase change, or ±400fS. If the cables near the connectors are not stabilized well this number could easily double to ±800fS.

System Diagram

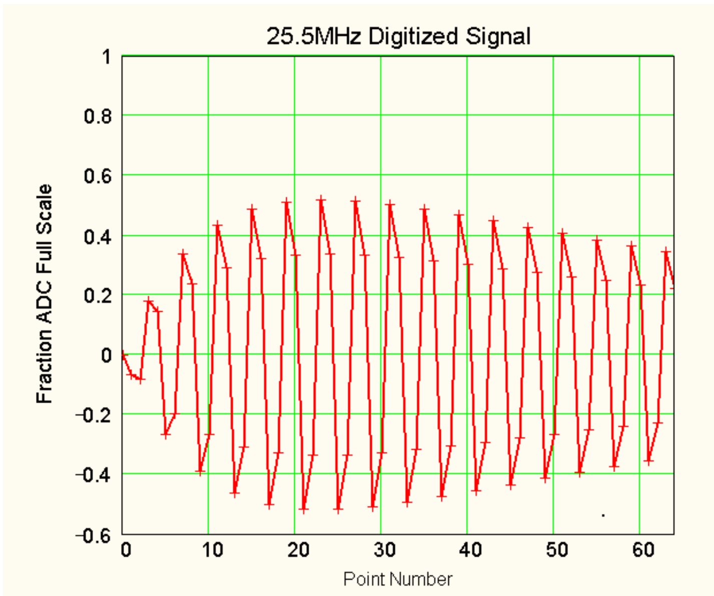




RF HUT with respect to LCLS Injector

Digital Data Processing

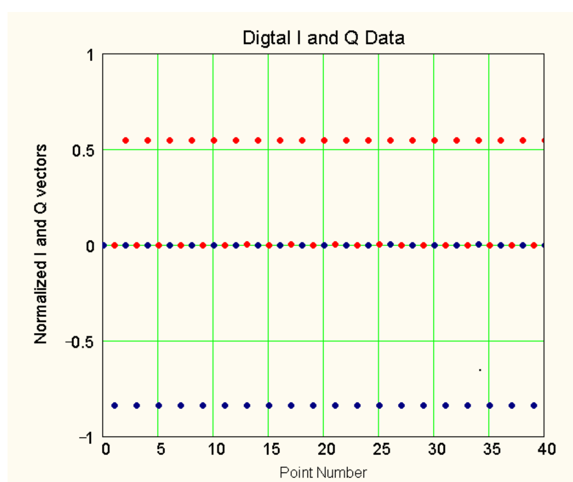
The 25.5MHz signal will be digitized at 102MHz. The 4MHz bandwidth filter before the ADC will dominate the rise time and the cavity Q will dominate the fall time of the signal. The below plot is an example of the digitized waveform.



The signal will then be digitally down converted and normalized by division of the measured/calculated function. The normalization vector will be calculated during calibration. The values of the normalization vector will be such that when multiplied by the I and Q vectors, all I values will be equal and all Q values will be equal. The equation below will be used in down conversion and normalization. The resultant I and Q vectors are shown below.

$$I_N := \cos\left[\frac{N\cdot(2\pi)}{4}\right]\cdot\frac{\text{Signal}_N}{\text{Normalization}_N}$$

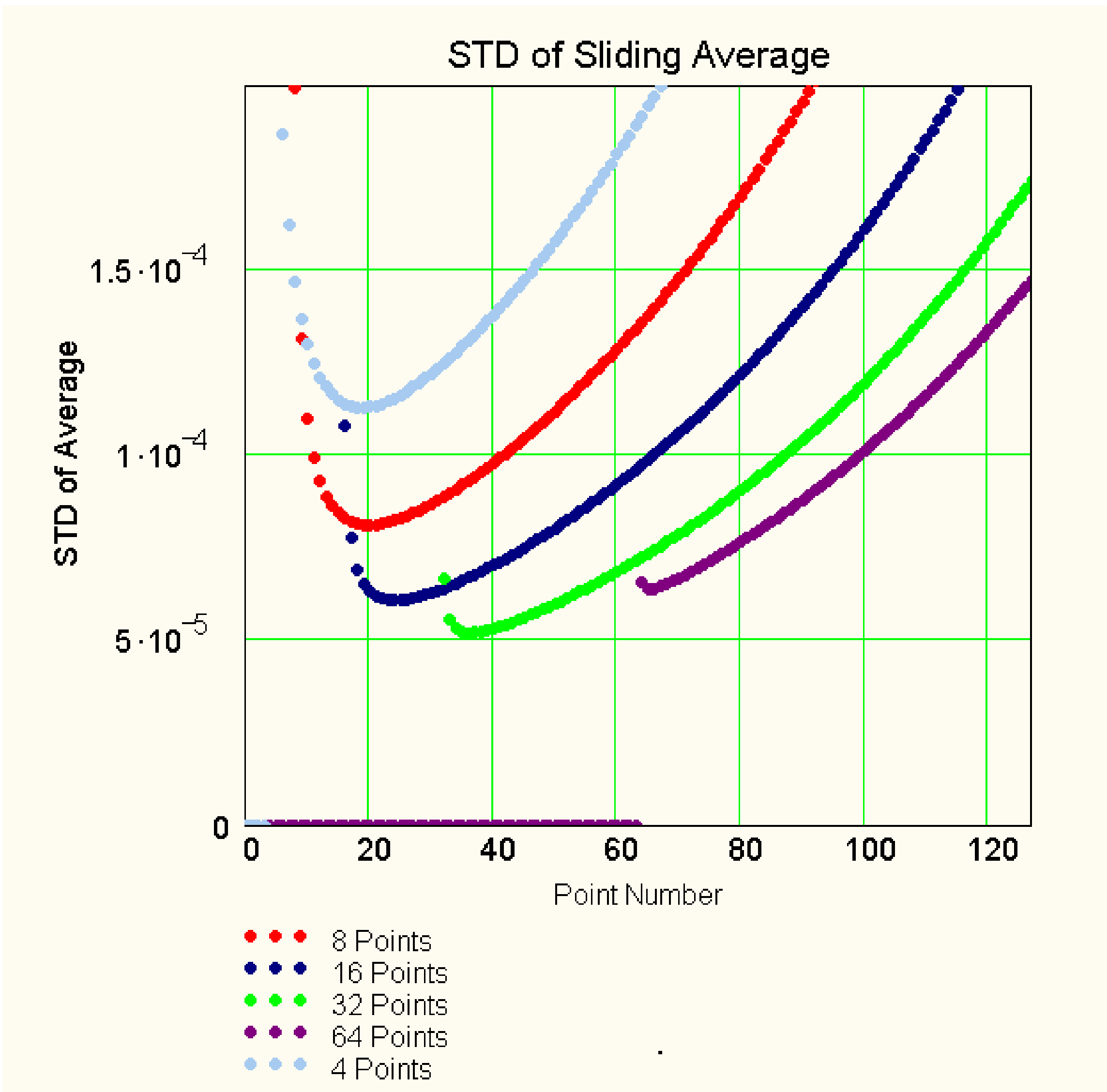
$$Q_N := \sin\left[\frac{N\cdot(2\pi)}{4}\right]\cdot\frac{\text{Signal}_N}{\text{Normalization}_N}$$



The Cosine and Sine functions are a vector of 1s, -1s, and 0s. The normalization vector is a vector of 16bit integers to multiply the signal by.

The beam phase will be calculated from two averaged values of I and Q measurements. The two values of I and Q will determine a slope and offset of the phase over a TBD time period. Errors in the measurement will be evaluated to determine the number of points to average.

Below is a plot of the standard deviation of a sliding average of the specified number of points along the normalized 25.5MHz signal sampled at 102MHz. The point number on the horizontal axis is the number of the point in the center of the integral. Integrating over several data points will increase the accuracy.



The bunch phase will be calculated from two points, which form the equation of a line, in the phase vs time domain. The below equation and plot were used to determine the two points to use and the number of points to average, where n91 is an index for point 1 and pnt2 was varied manually to minimize a point on the plot. The plot is for 8, 16, and 32 point averages. A filter delay of 120nS was also included in the equation. These numbers are expected to change slightly for the real data set. From the plot below, the minimum error is found with an average of 16 data points at point 18 and point 120. The value here is 1.1e-4.

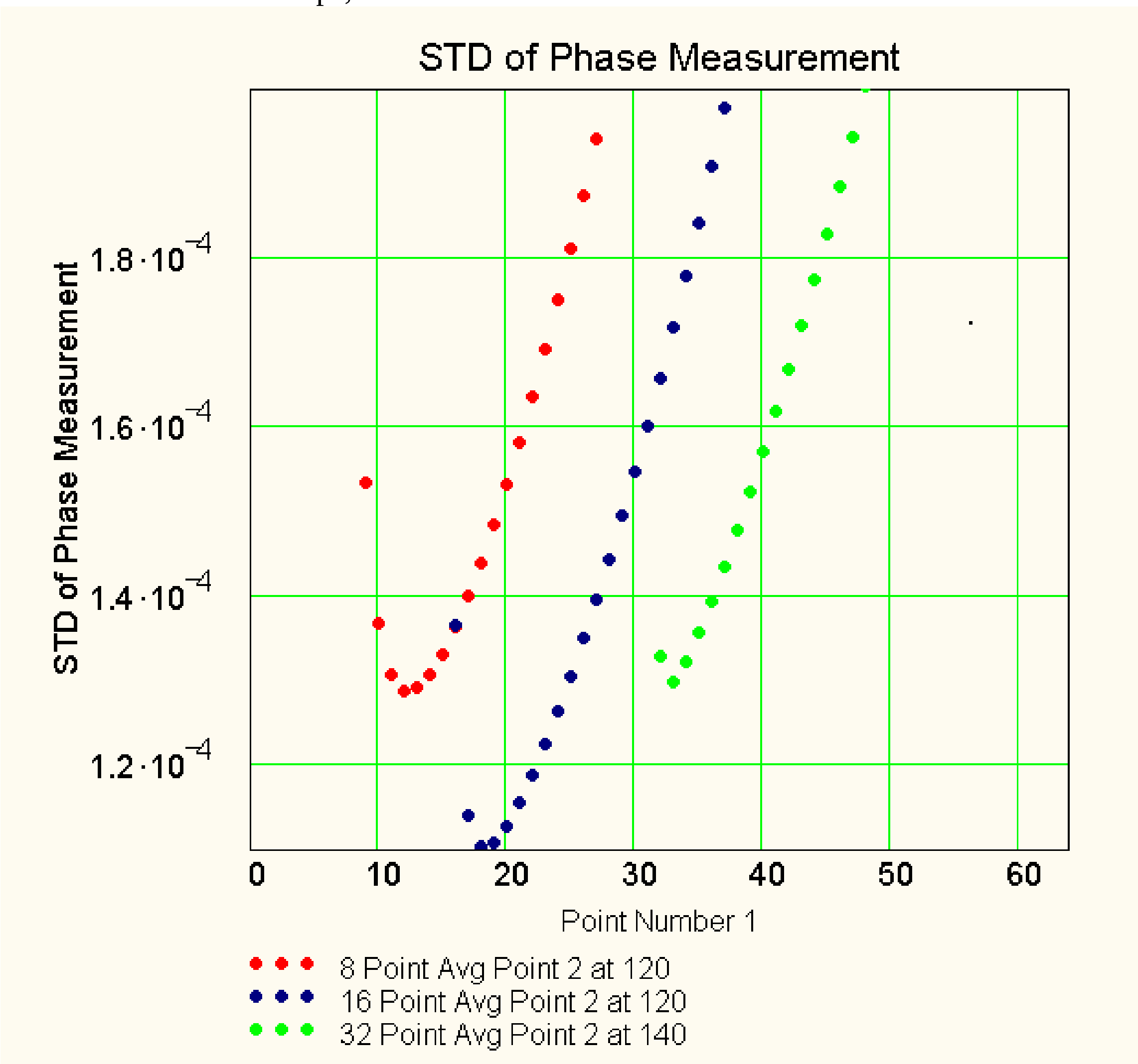
$$PhasErr8_{n91} := \sqrt{\left[\left[\sqrt{(STD8_{n91})^2 + (STD8_{pnt2})^2}\right]\cdot\left(\frac{n91 + FilterDelay}{n91 + FilterDelay - pnt2 + FilterDelay}\right)\right]^2 + (STD8_{n91})^2}$$

n91 is an index for point 1

FilterDelay is the delay for the filter, 12 points, 120nS

pnt2 is the index at point 2

The index is in 9.8nS steps, 102MHz.



Result sensitivities to changes in the data

The above analysis was done with changes to the frequency of the input signal, or cavity frequency, and phase of the signal, actual bunch timing changes, to determine the sensitivity of the result to input changes.

Sensitivity on phase vs cavity frequency is (0.0006˚)/(ppm freq change).
Looked at over ±10ppm
Sensitivity to beam phase change to caculated phase is 1:1 within STD of measurement.
Looked at over ±10˚

Summary of analysis

STD of measurement from the plot in the last section is 1.1×10^{-4} on a signal normalized to FS. The phase error would then be 0.006.3˚S, or 6.3fS rms.
If the noise levels at the ADC are four times, an SNR of 70dBc, phase error would then be **12.6fS rms**

Long term drifts due to temperature variations dominated by the cable can be as much as **±800fS**.

Comments

Due to the relatively low noise levels it is necessary to keep cables and electronics away from low impedance fields.