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The addition of inexpensive high-speed oscilloscopes has enabled higher Te Thomson scattering measurements on the SSPX spheromak. Along with signal correlation techniques, the scopes allow new analyses based on the shape of the scattered laser pulse to discriminate against fluctuating background plasma light that often make gated-integrator measurements unreliable. A 1.4 J Nd:YAG laser at 1064 nm is the scattering source. Spatial locations are coupled by viewing optics and fibers to 4-wavelength-channel filter polychrometers. Ratios between the channels determine Te while summations of the channels determine density. Typically, the channel that provides scattered signal at higher Te is contaminated by fluctuating background light. Individual channels are correlated with either a modeled representation of the laser pulse or a noise-free stray light signal to extract channel amplitudes.

I. Introduction

Thomson scattering is difficult in general due to the low scattering cross-section of electrons in plasma. A large laser energy and very efficient light collection is usually required along with a spectrometer of sufficient sensitivity and spectral resolution to determine the scattered spectrum. It is also possible, in general, to evaluate deterministically the noise levels and uncertainties in the measurement system hardware to come up with a total uncertainty in the measurement. For instance, one keeps very careful track of the sensitivity and noise of the optical detection system electronics and the uncertainty in the spectral pass-band of the spectrometer. One can also handle photon statistics of the collected Thomson-scattered light in a regular way. However, background plasma light cannot be determined a priori and is always a concern.

A typical system might use a gated integrator to sample several spectral channels during the laser pulse. The number of optical channels and the spectral width of each channel must be evaluated very carefully when designing the system to provide enough scattered laser light in each channel and sufficient wavelength resolution to determine the scattered spectrum. The spectral width also determines the background plasma light in each channel. One can gate the signals to provide measurements before, during, and after the laser pulse to subtract out background light. It is also common to use a differential amplifier and delay line to subtract off the background light to increase measurement dynamic range. These schemes assume the background light is not varying much during the laser pulse and measurement time. In many experiments however (including our own), the background light is large and varying on a time-scale similar to the laser pulse. Thus, the fluctuating background light represents the largest uncertainty in the measurement. Under these circumstances, gated integrators are not reliable and one is forced to sample the signals temporally with a fast oscilloscope or transient recorder. This provides a recording of the scattered laser light riding on the background plasma light. One obtains an immediate visual sense of the signal-to-noise ratio (SNR) on each of the spectral channels, and standard signal processing techniques provide a quantitative measure of SNR. This provides a reliable measure of uncertainty.

II. System description

The SSPX Thomson Scattering System[1] consists of a 1.4 Joule pulsed Nd:YAG laser mounted on an enclosed table in an enclosed room located on the first floor of the experimental building. This room is insulated and temperature controlled at 20 C for thermal stability of the optical components. A series of beam tubes and mirrors transport the beam up to the SSPX vessel on the second floor. The entrance and exit beam tubes mounted on the SSPX vessel are baffled to reduce stay light. A beam dump is positioned at the far end of the exit tube where a remote TV camera monitors alignment. A visible HeNe laser is used for alignment. Ten locations along a radius are imaged onto ten optical fibers by collection optics. These fibers transport the light to polychrometer boxes on the ground floor in the enclosed room. The polychrometers are commercially produced by General Atomics[2] and are configured with spectral filters to split the incoming light into four wavelength ranges (See Figure 1). The first wavelength range is the laser wavelength and is used for calibrating the system. The other three ranges are selected to provide temperature measurements from 2 to 2000 eV. The overall sensitivity of the system is designed to measure a minimum density of 5×10^{18} m^{-3}. The polychrometers have passages for water flow and are kept at 16 C with a water chiller unit. Temperature control of the polychrometers is important because the units use avalanche photodiodes (APDs) for light detection and these devices are temperature sensitive.

There are two output channels from the light detection electronics: pulsed (or AC), and DC. The pulsed output uses a 100 nsec delay line in one leg of a differential amplifier to subtract off the DC background light signal and provide the scattered photon signal. This produces a bipolar signal with a positive pulse from the delay line following 100 ns after the initial negative pulse. The DC output produces a unipolar negative signal from the laser pulse and provides a continuous measurement of the DC plasma light background level. The DC output can be also amplified up to 10 times more than the AC channel to allow calibration with available calibration sources

The pulsed signals from each of the four spectral channels are recorded on fast oscilloscopes (Tektronix[3] Model 2014, 4 channels, 100 MHz bandwidth, 1 GHz sampling) as well as being integrated by gated-integrator modules (Phillips Scientific[4] Model 7166). The DC signals are only gate-integrated. Ideally, an integral of the pulsed signal from either the scope or the gated integrator provides a measure of the total laser-scattered photons collected in each spectral channel, and the DC signals measured by the gated integrators provide a measure of the background light. However different kinds of noise can interfere with the measurement and can affect the two measurement methods differently.

III. Measurement uncertainties

In addition to systematic errors, which we do not discuss in this paper, there are three sources of random uncertainty: photon statistics; noise in the electronics; and background plasma light. The first two are dominant in lower density regimes since the scattered signal is proportional to electron density. These two noise sources can also be evaluated quantitatively (photon statistics) and measured (electronics noise) to give a minimum detectable density for a given laser power. The third noise source, plasma light, is much more troublesome, particularly a fluctuating background signal. Large DC plasma light signals can exceed the linear range of the detection electronics causing compression (i.e.

reduction) of the measured signal. Fluctuating background light can change the baseline of gated integrator signals or provide a false peak during the integration time. Combining time-resolved scope signals with measurement of the DC background level provides a means of evaluating this type of measurement interference.

IV. Determination of channel counts and variance with gated integrators.

Both gated integrators and scopes are used in the measurement. The gated integrator counts, C_{nx}, (n = spectral channel 1-4; x=a,d for AC or DC) are obtained by subtracting the measured counts in each channel nx for a shot, by counts from each respective channel for a shot with no plasma or laser light. These no plasma or laser light shots are called background shots and are taken regularly. Three standard deviations are applicable: photon deviation, $\square_p$; electronic noise $\square_e$; and background plasma light, $\square_b$. Photon count deviation for each channel is the square root of the photon counts scaled by the sensitivity, $\square_{p,nx} = S_{nx}\ \square_{ph,nx}^{\ 1/2}$ where $N_{ph,nx} = C_{nx}/S_{nx}$ and S_{nx} is the sensitivity in counts per photon for the channel. Typical numbers are C_{nx} = 50 counts, S_{nx} = 0.01 counts/photon, giving $N_{p,nx}$ = 5000, and $\square_{p,nx}$ = 1. In all cases of interest to us, the photon statistic noise is negligible. Electronic noise is determined by direct calculation of the channel standard deviation for many successive measurements during calibration of the system. Typical values are $\square_{e,nx}$ = 5 counts. Plasma light deviation however, varies widely and is highly dependent on plasma conditions of density, temperature, and impurity level. For one of our standard shot conditions, the background deviation can be as high as $\square_{b,nx}$ = 50, completely dominating the uncertainty. This provided the main motivation to implement the fast transient measurement.

V. Determination of channel counts and variance with fast scopes.

In Thomson scattering, each spectral channel will have a portion of the signal due to scattered photons, which should have the same shape as the laser pulse (perhaps modified somewhat by amplifier characteristics) and noise. The shape of the scattered photon signals should be identical between channels, but the amplitude will vary due to the spread in scatted spectrum that is a function of the electron temperature. Total counts summed for all channels should be a function of the electron density.

With the fast scopes, we perform a least-squares fit between each of the three noisy scattered-light channels and a model waveform of the expected amplifier response to the scattered laser pulse. The model waveform can be taken from several sources. One possibility we use regularly is the low-noise laser channel of the polychrometer being analyzed. The laser channel has significant stray light, which can be a problem if one wants to perform a Rayleigh-scattering calibration for density, but is also fortuitous in this case because it is a very large, clean signal. Additionally, one can average this signal over many shots to average out the random noise and produce an even lower noise model signal that includes all the artifacts of the amplifier (like small amounts of ringing), in other words a very good ideal representation of the amplifier response to the scattered laser light pulse.

The least squares fit for amplitude, offset, and slope to the model waveform gives the lowest-error fit of the amplitudes for each channel. These fitted amplitudes are multiplied by the integral of the very clean model waveform, converted to counts (to compare with the gated integrators) and input to the fitting routine. The least squares fit is very sensitive to any time shift between signals, which is one reason to use the laser channel as the model signal since all four spectral signals are digitized on a single 4-channel scope and therefore simultaneously triggered. Care must be exercised to keep all system delays and cable lengths equivalent to ensure simultaneous sampling given the typically fast sampling rate of 1 nsec per sample. If, however, an unavoidable shift does exist between waveforms and the model signal, one can use the cross-correlation as discussed in the next section to time-align waveforms prior to least squares fitting. Three standard deviations are again applicable: photon deviation, σ_p; electronic noise σ_e; and background plasma light, σ_b, however, the following correlation method does not distinguish between electronic noise and background light fluctuations, so really just two deviations are used: photon deviation, σ_p (still typically negligible), and fluctuation noise, σ_f, which combines the electronic noise and background plasma light interference.

VI. A cross-correlation method to determine Signal to Noise Ratio

A standard correlation detection method from statistical communications theory[5] is applied to determine SNR. This method depends on having two signals, nominally identical with the exception of uncorrelated noise. Also allowed is a noisy signal and a noiseless model signal. An interesting point is that, with proper normalization, the method is insensitive to amplitude changes between the signals, only the shape of the signals is important. The method requires that noise must be Gaussian and un-correlated. One must be careful here to be sure that measurements show that the noise in each spectral channel is uncorrelated.

The cross-correlation function *Rxy(t)* of two signals *x(t)* and *y(t)*:

$$R_{xy}(t) = x(t) \otimes y(t) = \int_{-\infty}^{\infty} x(\tau)\, y(t-\tau)\, d\tau$$

can be normalized to

$$\rho = \frac{s_1 \quad s_2 - \langle s_1 \rangle \langle s_2 \rangle}{\sigma_1 \sigma_2} \qquad \begin{aligned} s_1 &= a_1 s + a_1 n_1 \\ s_2 &= a_2 s + a_2 n_2 \end{aligned}$$

with each signal composed of a true signal and uncorrelated noise and the brackets < > denoting time averaging of the signal, and σ_n the standard deviations. If the two signals are aligned in time, the maximum of ρ can be given by:

$$\rho_m = \frac{\langle s_1 s_2 \rangle - \langle s_1 \rangle \langle s_2 \rangle}{\sqrt{\left[\langle s_1^2 \rangle - \langle s_1 \rangle^2\right]\left[\langle s_2^2 \rangle - \langle s_2 \rangle^2\right]}}.$$

For equal noise energies, such as successive waveforms of a repetitive measurement where the noise in each waveform is fairly constant, i.e. $n_1=n_2=n$,

$\rho_m = \frac{a_1 s_1}{a_1 s_1 + n}$ and the SNR is given by $\frac{s_{(energy)}}{n_{(energy)}} = \frac{\rho_m}{1 - \rho_m}$. Note that we usually want the SNR in terms of signal voltage, so we use $\frac{s_{(volts)}}{n_{(volts)}} = \sqrt{\frac{\rho_m}{1 - \rho_m}}$

When one signal is noiseless, $n_1=0$ and $n_2=n$, the maximum of the cross-correlation function is $\rho_m = \frac{s}{\sqrt{s(s+n)}}$ and the signal to noise is

$$\frac{s_{(energy)}}{n_{energy}} = \frac{\rho_m^2}{1 - \rho_m^2} \qquad \text{or} \qquad \frac{s_{(volts)}}{n_{(volts)}} = \sqrt{\frac{\rho_m^2}{1 - \rho_m^2}}.$$

The method is insensitive to the amplitude of the signals, only the shape and phase are important. In practice, one normally computes the correlation function from a canned routine and finds the maximum of the function. As commonly used in radar applications, the peak of the correlation function will also occur at the time lag needed to align the two signals and it is necessary to align the two signals before performing any kind of amplitude fitting between the signals.

VII. Signal to noise calculation

In our implementation we use the c_correlate function from IDL[6] defined as:

$$\rho_{xy}(L) = \frac{\sum_{k=0}^{N-L-1} \left(x_{k+L} - \bar{x}\right)\left(y_k - \bar{y}\right)}{\sqrt{\left[\sum_{k=0}^{N-1} \left(x_k - \bar{x}\right)^2\right]\left[\sum_{k=0}^{N-1} \left(y_k - \bar{y}\right)^2\right]}} \quad For \;\; L < 0$$

and

$$\rho_{xy}(L) = \frac{\sum_{k=0}^{N-L-1} \left(x_k - \bar{x}\right)\left(y_{k+L} - \bar{y}\right)}{\sqrt{\left[\sum_{k=0}^{N-1} \left(x_k - \bar{x}\right)^2\right]\left[\sum_{k=0}^{N-1} \left(y_k - \bar{y}\right)^2\right]}} \quad For \;\; L \geq 0$$

where k is the index, L is the time lag, and the overbar represents the signal mean. This version of the correlation coefficient is normalized to be equal to 1 when the signals are perfectly correlated. The model signal is derived by averaging the laser channel of polychrometer #1 (which is observing the outer edge of the plasma) over a range of shots near the desired shot number. These model signals are stored in a database and called up as needed. The model signal is cross-correlated with each of the four signals from each the ten polychrometers. An example of the signals for polychrometer #7 is shown in Fig. 2. The left side traces show the model signal on top with the four spectral channels below. The right side traces are the cross-correlation function for each of the left hand traces. The top of these is a cross-correlation of the model signal with itself, producing an auto-correlation. Since the model signal is largely noise-free, we use $\frac{s_{(volts)}}{n_{(volts)}} = \sqrt{\frac{\rho_m^2}{1 - \rho_m^2}}$ to calculate the SNR from the maximum in the correlation function. Calculated SNR is printed on the related plot. The time lag for aligning the signals prior to amplitude fitting is calculated from the difference in peak times between the cross-correlations of the signals and the autocorrelation of the model.

VIII. Signal Fitting and integration

The IDL routine regress.pro is used after signal alignment to return the coefficients to the fit: $s_i = a_i s_0 + b_i$ with s_0 the model signal, and a_i the amplitude, b_i the offset, and s_i the signal for the ith spectral channel. The clean model signal, s_0 is integrated over the first pulse only to determine the total charge collected and multiplied by the calibration of counts/charge for the gated integrators to get a direct comparison in counts. Counts for each spectral channel is calculated by multiplying the model integral counts by the amplitudes determined from the signal fitting. The standard deviation for each channel is calculated by dividing the counts in each channel by the respective SNR. The final result is counts and standard deviation of counts for each of the spectral channels. These are the desired inputs to the fitting routine used for calculating temperature and density.

It is this signal-fitting step, where the offset is separated from the amplitude, that provides the method's advantage. The baseline of the fourth channel (which contributes importantly to the Te calculation at higher Te) is often shifted by plasma light causing erroneous gated-integrator measurements. This new method provides a reliable fourth channel contribution with measured uncertainty even when the baseline is shifting.

IX. Temperature calculation

We use a model of Thomson scattering[7] (Sheffield) that includes the laser power, scattering angle, polarization, light collection volume, collection efficiency, and models of the rest of the hardware to calculate the photons in each spectral channel for a given density and temperature. T_e is calculated by fitting the three shorter wavelength channel counts (channels 2-4) to the scattering model using the spectral response of the polychrometer (spectral response is the counts in each channel for a given temperature and density). Each channel of each polychrometer is calibrated for sensitivity and spectral width. When coupled with the scattering physics and viewing geometry, each polychrometer has a unique spectral response. The curvefit.pro routine from IDL is used to perform the fitting with (Gaussian) weighting of each channel count set to its respective $1/(\text{standard deviation})^2$.

X. Error bar calculation

Error bars are calculated by first determining the T_e and n_e deviations resulting from adding and subtracting the respective standard deviation to each of the three applicable counts followed by refitting the model. Six separate deviations in T_e and n_e are thus produced. Deviations that result in T_e going up are quadrature summed to produce an upper T_e error bar. Deviations that result in lowering T_e are quadrature summed to produce a lower Te error bar. Density error bars are handled the same way.

XI. Effects of window width and time alignment.

The calculated SNR is based on the total noise and signal energy in the measured window. One can reduce the window about the pulse (See Fig. 3) and directly remove much of the noise energy outside the window while leaving the desired signal intact. This is equivalent to reducing the bandwidth of the measurement by removing some lower frequency components in a FFT power spectrum. A narrow window has higher SNR, but is more sensitive to time shifts (Fig. 4a). A wide window can find correlations over a wider range, but the SNR is lower. The optimum is always dependent on the specifics of the problem at hand. For our case, narrowing the time window increases SNR up to a point (Fig. 4b). Eventually the window starts collapsing on the laser signal and SNR decreases. The effect on T_e, and the error in T_e is also shown as the window gets very narrow. It is clear that it is better to err on the side of using a slightly larger window since the error falls off much more gradually on that side.

XII. Conclusions

We have added fast scopes for time-resolution of the scattered laser signals on the SSPX Thomson scattering system. This has enabled measurements of T_e in the presence of background plasma light that made gated integrator measurement unreliable. It has also allowed the random errors associated with background plasma light and electronic noise to be quantified, providing more reliable error estimates. We have also presented some important considerations when using correlation techniques.

XIII. Acknowledgement

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References

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[7] J. Sheffield, Plasma Scattering of Electromagnetic Radiation (Academic Press, New York, 1975).

Figures.

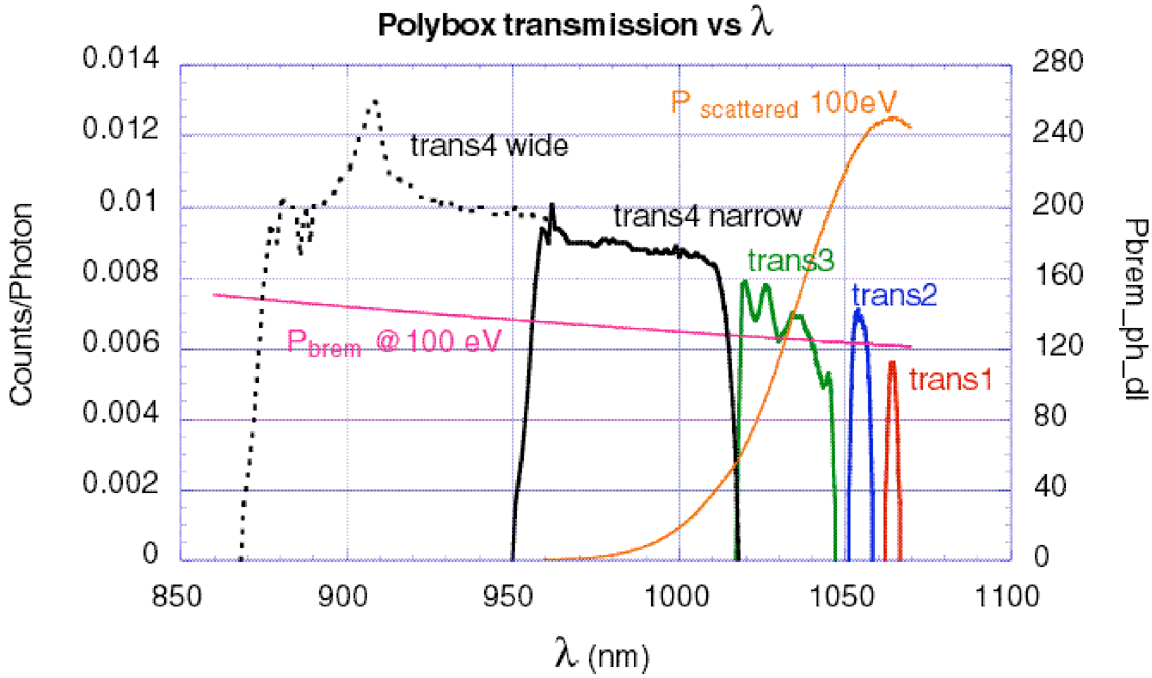

Figure 1 Typical spectral response of polychrometer channels along with scattered and bremsstrahlung spectrum at 100 eV.

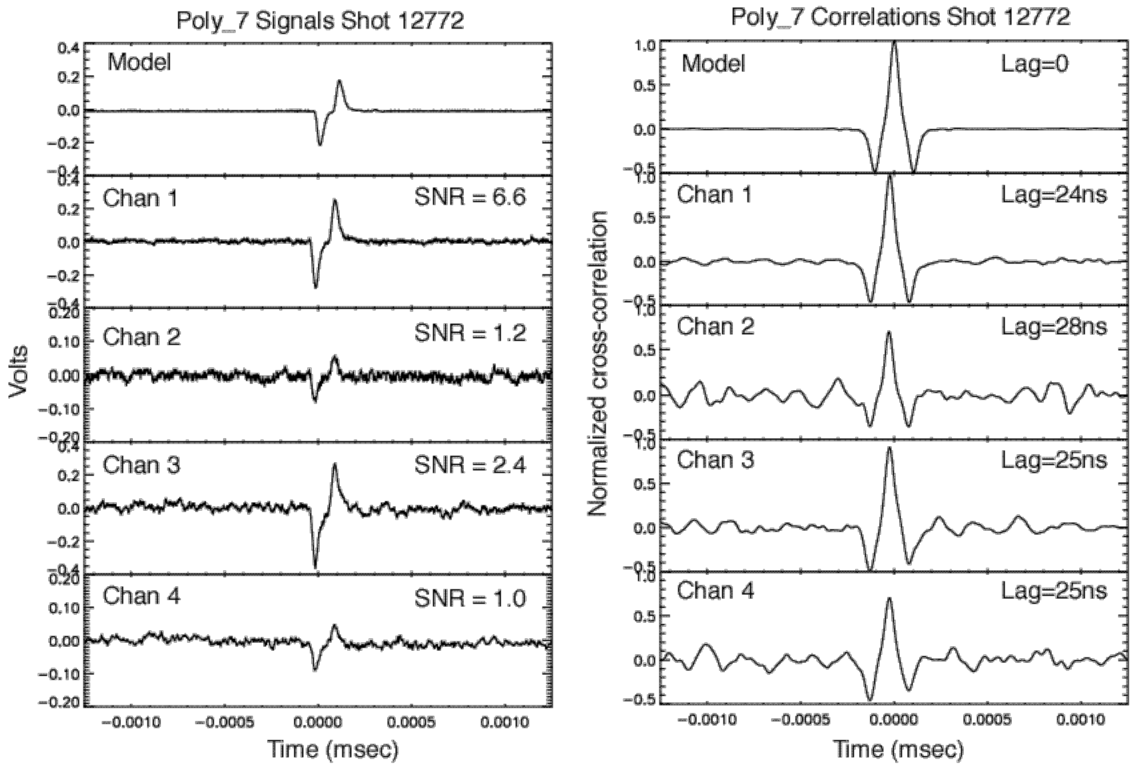

Figure.2 Thomson scattered laser light channels along with the cross-correlation to a model function. Top plot is model waveform(left) and auto-correlation(right). SNR is show for full window width.

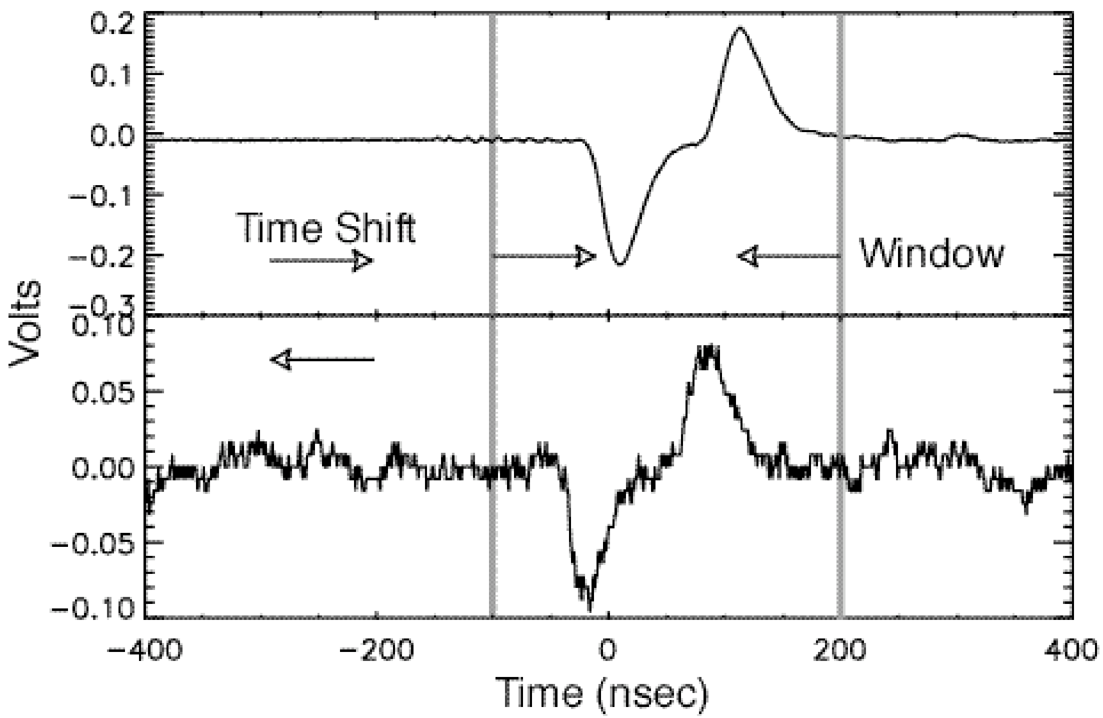

Figure 3. Important operations are time shifts and windowing.

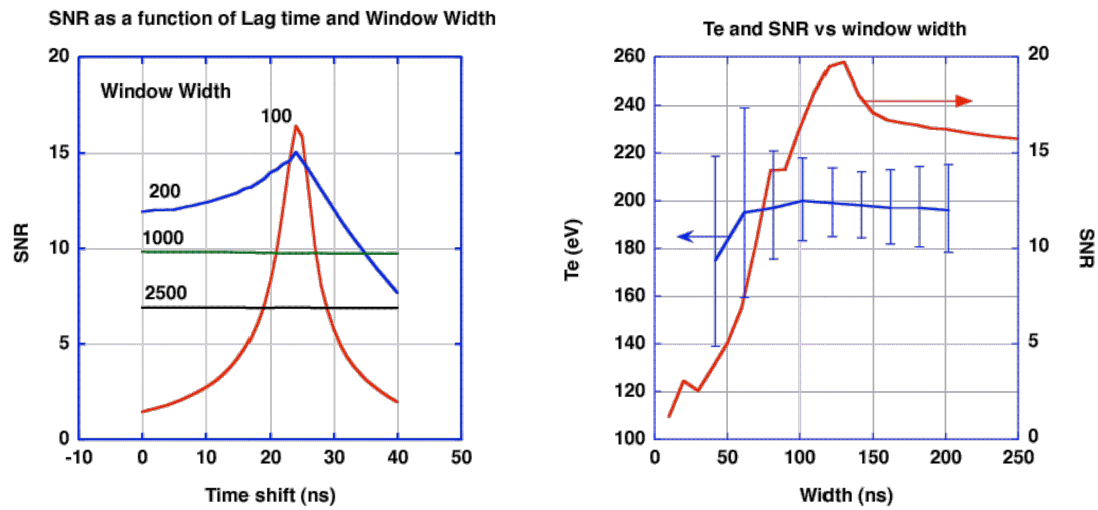

Figure 4. a) Effect of time shifting and window width on SNR. b.)Effect of windowing at fixed time shift on SNR, T_e, and the error in T_e.