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The LTS Timing Analysis program: User's manual and description of the methods of analysis

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The LTS Timing Analysis program: User's manual and description of the methods of analysis

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Abstract

The LTS Timing Analysis program described in this report uses signals from the Tempest Lasers, Pulse Forming Lines, and Laser Spark Detectors to carry out calculations to quantify and monitor the performance of the the *Z*-Accelerator's laser triggered SF_6 switches. The program analyzes *Z*-shots beginning with Z2457, when Laser Spark Detector data became available for all lines.

Acknowledgment

The software described in this report was written by Dr. Darrell Armstrong in Org. 1682 during 2012–2013 and was developed with the guidance and help of Dr. Jens Schwarz, also in Org. 1682, who was the Person in Charge of LTS during part of the same time period.

Contents

Appendix

1 Introduction

LTS Timing Analysis uses signals from the Tempest Lasers, Pulse Forming Lines (PFLs), and Laser Spark Detectors (LSDs) to carry out calculations to quantify and monitor the performance of the the *Z*-Accelerator's laser triggered SF_6 switches.[1] The program analyzes *Z*-shots beginning with Z2457, when LSD data became available for all lines.

LTS Timing Analysis generates three different reports that are briefly described below. Complete details of their contents can be found in Appx. A.2. The names for these report files are:

Shot_*n*.csv Complete analysis results for a single *Z*-shot, where *n* is the shot number, using a comma-separated values format that can be read by Excel.

LTS_Report_Z*n*.pdf A PDF file that contains quantities that characterize switch data that are derived from the results in Shot_*n*.csv. The data are presented graphically and numerically. The derived quantities include the accuracy of laser timing, the trigger section runtime, the entire switch runtime, and the PFL deviation. The numerical values include the average, standard deviation, and the latest and earliest times for each derived quantity.

LTS_Report_Data_*n*_*m*.csv A continuously updated file where *n*, *m* denote the earliest and latest *Z*-shots contained in the report. This file contains the same numerical results presented in the PDF report but maintains them as a record sorted in ascending *Z*-shot order to help identify trends in switch behavior.

Analysis of each *Z*-shot requires reading 108 binary files of length 125 kB each from a remote server that maintains an archive of *Z* data files. Read-time depends on network speed and can be considerably longer than the time required to carry out the calculations, so the program offers the option of storing data locally in a special binary format to achieve short read times during subsequent re-analysis. Locally stored data for one *Z*-shot occupies approximately 13.5 MB of disk space. In addition to the binary data, two files with .csv formats that contain Tempest Laser reference times and PFL switch closure times are also read from the remote server. These values are also stored in the local binary file so that re-analysis can be run without access to the server.

1.1 How to Use This Manual

This manual is best used when the main graphical user interface (GUI) for LTS Timing Analysis is available on your computer's desktop.[2] This way you can test the action of the menu items,

[1] Sections 2–4 assume familiarity with the basic physical layout of the *Z*-Accelerator and to a lesser extent with its operation. These sections also assume familiarity with the Tempest Laser, PFL, and LSD signals generated during a *Z*-shot, and with their signatures that indicate events such as switch closure. For introduction to these signals, their characteristics, and how they are analyzed, consider reading Sec. 6 first, and then read the remainder of the manual.

[2] The actual manual for LTS Timing Analysis, without all the SAND report front matter, is available in two-column format from the author; darmstr@sandia.gov

buttons, and the shot selection slider found on the main GUI while the manual guides you through their use. You'll also be able to open the various popup forms accessed from the main GUI while their functions are described, and you can follow along with the example analyses presented in Sec. 4.

This manual follows a convention that titles on the main GUI, buttons, popup forms, and graphics windows are presented in the text as they appear on your monitor, with first letters capitalized. Words that describe analysis results or conditions such as Nominal, Late, or Bussed Out will also have first letters capitalized. Titles or labels that require emphasis when they appear in the text will be placed within double quotes.

Navigation Blue text and numbers provide active links to figures and sections within the manual using standard Adobe Reader shortcuts. Left click the mouse to go to a new location, then use Alt + left-arrow to return. If you've been been to a new location and returned, you can go there again using Alt + right-arrow.

1.2 Getting Started

LTS Timing Analysis uses a set of directories on the local machine for storing report files and data. These directories must be selected by the user, so the first time you run the code it will ask you to select or create these directories. Actually, it won't ask, it will insist you do this. Thereafter LTS Timing Analysis should run without too much user intervention. Depending on which report files are written to disk, analysis will consist of selecting a Z-shot and clicking the "Run LTS Timing Analysis" button. While those two steps will suffice most of the time, occasional intervention will be required to accommodate anomalies in the data, or in the data files themselves. For the most part LTS Timing Analysis tries to carry out its tasks in an automated manner so you'll receive notification from popup dialog messages only if intervention is required, or if there is a possibility the analysis will be compromised.

2 The Main Graphical User Interface

Figure. 1 shows the main graphical user interface with the title LTS Timing Analysis. This GUI contains File, Edit, Export, and Help menus, four boxed subsections with titles that are self explanatory, and three separate buttons for additional analysis options.

2.1 Subsections

Status Displays the current Status and the Last Shot Analyzed. In Fig. 1 Status indicates that the analysis was successfully completed for *Z*-shot 2519 and File Write Complete indicates the report files were written to disk.

Data Source and Shot Selection This section of the GUI contains controls that include:

- Radio buttons to select the Remote server or Local disk as the data source
- On and Off radio buttons under Auto Save LTS Data for storing individual *Z*-shots to a local disk for later use.
- A button for View Local Data Files that opens a native Windows interface to view LTS data files available on a local drive. These are binary files for use only by the LTS Timing Analysis program.
- A slider labeled Select Shot for Analysis. The list of *Z*-shots available on the server is updated during program startup.

Single-Shot Analysis Clicking the button labeled Run LTS Timing Analysis loads remote or local data files, carries out the analysis and generates selected report files for a single *Z*-shot. If the user has selected to write the file LTS_Report_Z*n*.pdf to disk, execution halts until a decision is made for editing the input fields for this report by clicking the Edit or Skip Edit buttons. Any open report files are automatically closed before the new files are written to disk.

Plots for Single-Shot Analysis This section offers five options for viewing the results of the analysis, including the various signals and the parameters used during the analysis. The signals and over-plots of the analysis parameters, such as linear fits to rising edges and locations of important maxima and minima, can be saved in a variety of graphical formats, including postscript and PDF. Use of these plotting options and the features they contain will be described in greater detail in Sec. 3.

Multi-Shot Analysis This analysis option reads multiple binary files from the local hard drive that were previously stored during single-shot analysis. This option sequentially plots results for individual lines and *Z*-shots to observe trends in switch behavior over time.

Interactive Analysis Clicking the button labeled Interactive Analysis opens a popup form to select data for a specific *Z*-shot and line, and for a selected time range, so the user can interactively adjust the results for any line where the automated analysis might have failed. Section 4.2 provides an example of using Interactive Analysis.

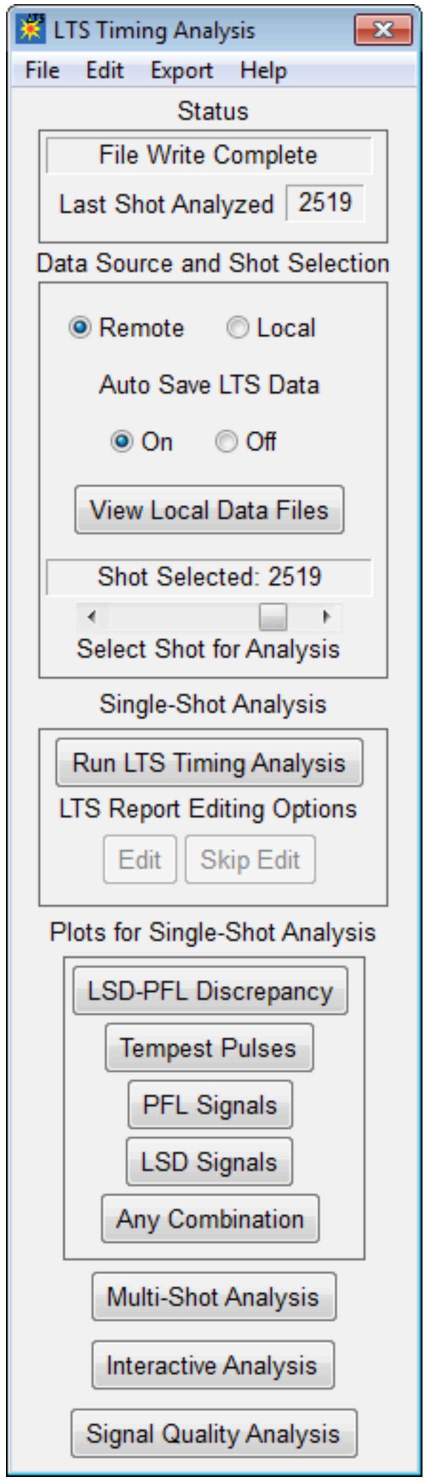

Figure 1. The main GUI for LTS Timing Analysis.

Signal Quality Analysis Clicking the button labeled Signal Quality Analysis opens a popup form to generate plots of signal quality versus shot number for LSDs, PFLs, or Tempest laser pulses, where the condition is loosely analogous to the conventional signal-to-noise ratio but is derived from spectral analysis of the signals. This tool is useful for tracking the condition of the signals for the 36 lines as a function of time.

2.2 File Menu

Select Report File to Open Opens a native Windows interface in a directory that's selected by the user (see Directory for Reports, below) where the LTS_Report_Data_*n*_*m*.csv report files are stored. The Shot_*n*.csv and LTS_Report_Z*n*.pdf files are stored in subdirectories labeled by their respective *Z*-shot numbers.

Last Open Report File Directly accesses the last open report file without using the Windows interface.

Report File Options Opens the form in Fig. 2 for selecting which reports are written to disk by LTS Timing Analysis.

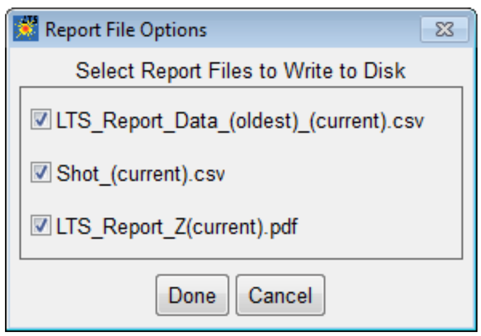

Figure 2. The form for selecting report files written to disk.

Directory for Reports Opens a native Windows interface for creating and/or selecting a directory for saving the report files. After selecting a new directory a popup dialog box asks the user if they want to copy files from an existing directory to the new directory. The old directory and existing files are not deleted during this process.

Directory for LTS Data Files Opens a native Windows interface for creating and/or selecting a directory for saving LTS binary data on a local drive. After selecting a new directory a popup dialog box asks the user if they want to copy files from an existing directory to the new directory. The old directory and existing files are not deleted during this process.

Quit Quits LTS Timing Analysis. Similar to all Windows programs, left-clicking [x] on the title bar also quits the program, while right-clicking anywhere in in the title bar opens a menu with a Close option. Note that clicking [x] or the title bar works *only* for the main GUI, native Windows interfaces, and certain graphics windows, but not for most other popup forms where [x] and the title bar are insensitive.

2.3 Edit Menu

Time Delays Opens the form in Fig. 3 for setting time delays for the Tempest Lasers, PFLs, and LSDs. For the Tempest Lasers and PFLs the delays are changed by entering new values in the fields where the current values appear. For the LSDs, where each delay can be set separately, use the scroll button to access each line. After shot Z2457, when data for all LSDs became available, all LSD delays have been set to zero by the data acquisition system, however the ability to set each line individually was retained in this program. Note that you must hit the Enter key to accept each new value. When accepted, the new number is right justified in its cell.

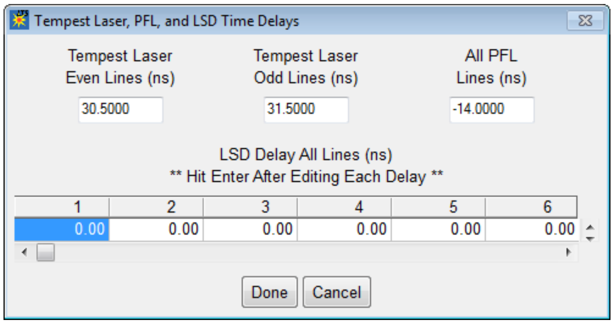

Figure 3. The form for editing Tempest, PFL, and LSD time delays.

Time Range for Analysis Opens the form in Fig. 4 with the title Analysis Start and End Times, where the Start- and End-Times are set using the droplists labeled Select New Start Time and Select New End Time. The nominal time range for analysis is 100 ns before, and 240 ns after the Tempest laser pulse for each switch. For most *Z*-shots this time range will allow an accurate analysis, however it can be changed if necessary. For example, to produce a plot of one of the signals over a smaller time range using one of the built-in plotting utilities one could reduce the total time to some extent. Or in the event of a very early pre-fire the Start Time can be increased up to 200 ns. Note that the time range selected here does not apply to the time range for Interactive Analysis as described in Sec. 3.5.

Calculation Parameters Opens the form in Fig. 5 with the title Calculation Parameters. With the exception of the Analysis Start- and End-Times described above, this form allows the user to set essentially every adjustable parameter used during the analysis. Most of these parameters will rarely require adjustment but for certain *Z*-shots, or perhaps for a series of *Z*-shots where some lines produce less than ideal signals, these parameters will require small changes. For example, the entries for “LSD derivative first local minimum window” might

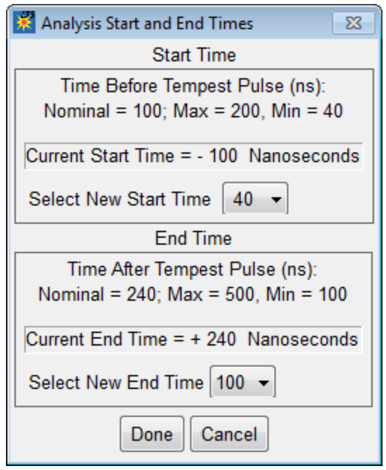

Figure 4. Popup form for changing the time range for analysis relative to the Tempest Laser pulse.

need to be changed if some lines have unusually long switch run-times. During run-time the program will open dialog messages to warn you if it detects a failure during the analysis so you can adjust the calculation parameters as necessary. Some of the popup dialogs offer suggestions while others only warn of potential problems.

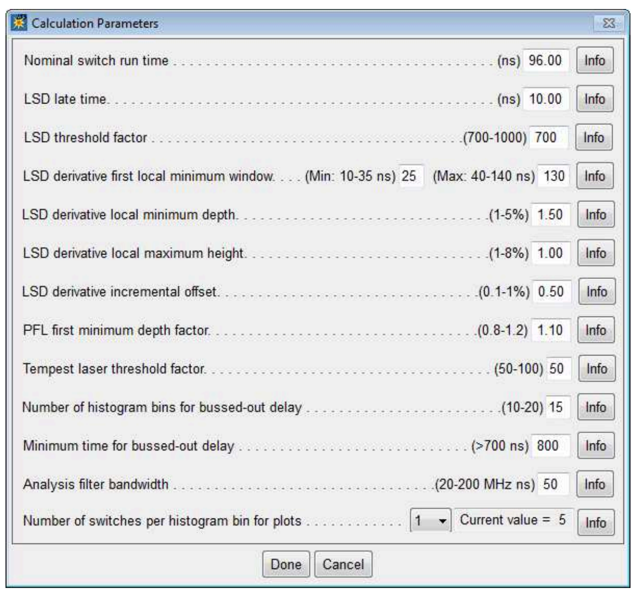

Figure 5. Popup form for changing the adjustable Calculation Parameters used during the analysis.

Clicking an Info button on this form provides a detailed description of its associated parameter, and for most parameters the description also includes a graphical illustration of its effects using actual *Z* data. For example, the Info button for "LSD threshold factor" opens the form in Fig. 5 that contains text that explains this parameter, and shows a plot of the LSD threshold relative to a typical LSD signal.

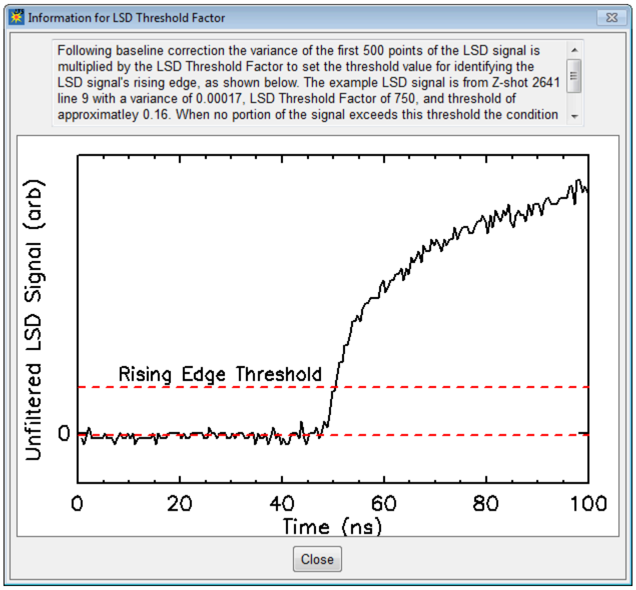

Figure 6. Popup form that shows Info for the Calculation Parameter called "LSD threshold factor."

Plot Colors Opens the form on the left of Fig. 7 with the title Select Colors which in turn opens the form on the right for color selection. This Edit Menu item allows the user to select any color scheme they want for on-screen plots using the preset colors in the Select a Color form, or they can select the Default Colors by clicking the White Background or Black Background buttons. Figure 7 shows these two forms when the user is changing the color for Axes and Text. Note that plot colors cannot be changed for Interactive Analysis or for the Info plots for the Calculation Parameters.

2.4 Export Menu

Export ASCII Data Exports Tempest Laser, PFL, and LSD data in two-column .csv format for all lines, where the first column is time and the second column the signal data. For more details about these files see Sec. 5.2.

Delete Exported ASCII Files All of the ASCII files written to a local hard drive from the Export menu can be deleted in one convenient operation.

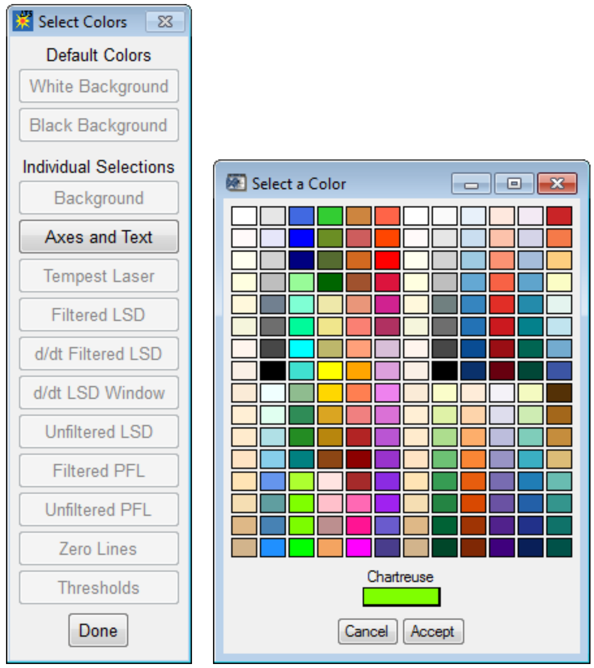

Figure 7. Popup forms labeled "Select Colors" and "Select a Color" for changing the color scheme for on-screen plots.

2.5 Help Menu

Open LTS Timing Analysis Manual Provides a link to this manual. Because LTS Timing Analysis is largely self-explanatory for knowledgable users, there is no index- or contents-searchable help application.

About LTS Timing Analysis Opens a dialog message with author contact information.

Code Documentation for LTS Timing Analysis Opens an HTML file with an index of all of the files that comprise LTS Timing Analysis, including the source code. The documentation was prepared using IDLdoc 3.5.1.

3 Additional Details of LTS Timing Analysis

This section provides details about various features of LTS Timing Analysis that you'll likely encounter. In addition, while most features in the main GUI are self explanatory, several of them require a more complete description. And finally, various conditions occur during run time, such as trapping of errors that would otherwise crash the code, or an invalid file path, or a server that's unavailable, and several of these open popup dialog messages, so we describe some of them below.

3.1 Dialog Messages and Warnings

The first time you run LTS Timing Analysis a dialog message might appear that tells you the output directory is invalid. This can occur because the initialization file it reads during startup was generated on another machine, or the directory was deleted, so the output directory must be updated to match your local directory structure. If you see the dialog in Fig. 8 click OK and either select or create a directory from the native Windows interface.

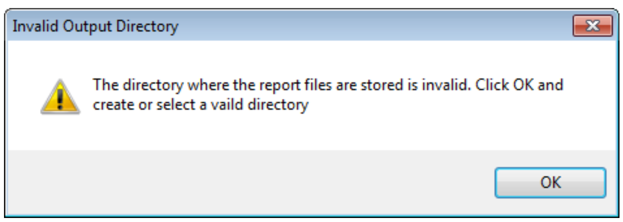

Figure 8. Popup dialog message informing the user of an invalid output directory.

If you try to ignore the message in Fig. 8 it will appear again until you choose a directory. You can skip this process altogether by using File:Directory for Reports to choose or create a directory before the first attempt to run the code and save any reports. There is also a popup dialog for Invalid Local Data File Directory, and the process is the same, and again it can be avoided using File:Directory for LTS Data Files the first time you start the program.

There are several other popup dialog messages you might occasionally see, with the most common probably being the one in Fig. 9 warning of an LSD analysis failure. Of the three signals analyzed, Tempest, PFL, and LSD, those generated by the LSDs are the most difficult to analyze correctly, so the purpose of this dialog is to inform you there is a problem. Sometimes analysis is improved by adjusting one of the Calculation Parameters shown in Fig. 5, but other times you'll have to correct the problem interactively, as described in Sec. 3.5. Another somewhat common dialog message is the one in Fig. 10 warning that some of the data files have shorter than normal lengths and may be unusable. Many times the code can resurrect short data files to obtain a complete analysis, but sometimes data in these files is discarded. The process of dealing with file-read errors is described in Sec. 5.1.

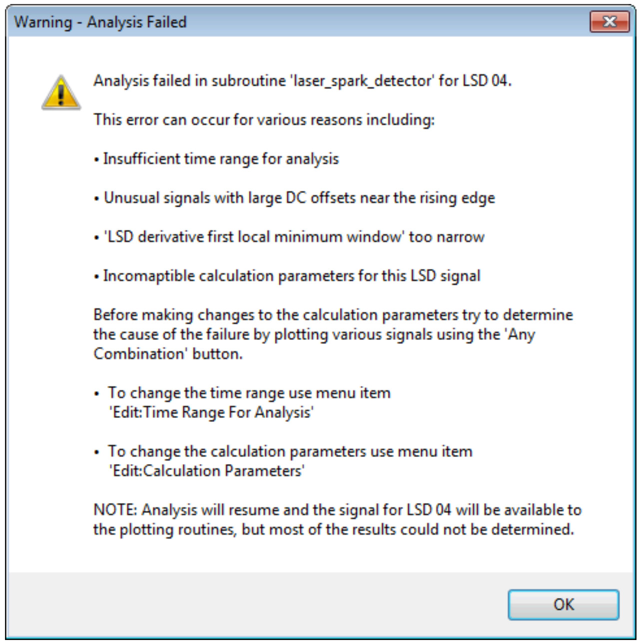

Figure 9. Popup dialog message informing the user of a failure in the analysis of LSD 04.

3.2 Edit and Skip Edit Buttons

Prior to clicking the Run LTS Timing Analysis button, the two buttons labeled Edit and Skip Edit will be in an insensitive state, and they will remain that way unless the box for LTS_Report_Z*n*.pdf in the Report File Options form is checked as shown in Fig. 2. Before the report LTS_Report_Z*n*.pdf is written the user has the opportunity to fill the input fields in the popup form titled Names and Executive Summary shown in Fig. 11. Text entered into these fields is then imported into the report. If the Done button on this form is clicked and the fields are blank the report will receive blank input. If the Cancel button is clicked the contents of the fields is ignored, blank or text, and the last available text is used when the file is written. Note that clicking the Skip Edit button on the main form also results in the use of the last available text.

3.3 Plots for Single-Shot Analysis

This section of the main GUI allows the user to view the three different signals used for LTS analysis: The Tempest Laser pulses, the PFL signals, the LSD signals, and the analysis parameters that include linear fits to rising edges, baseline zero-crossings from these fits, and minima and maxima in these signals that indicate switch closure. The signals can be viewed individually or in various combinations. There is also a bar plot accessed from the LSD-PFL Discrepancy button that shows the differences in LSD and PFL switch closure times that is useful for identifying lines

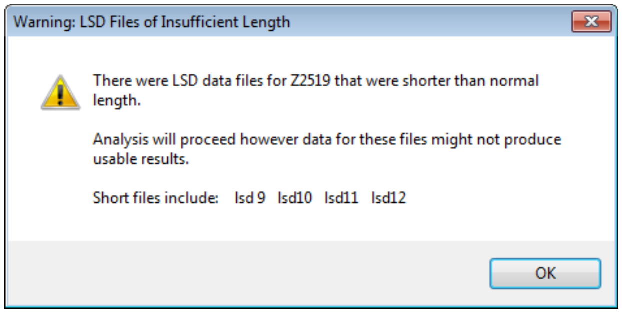

Figure 10. Popup dialog message informing the user that several of the LSD files read from the server had shorter than normal lengths. This is just one example of several possible file-read errors that the code can trap, with most of them producing a different dialog message, and each specific error resulting in different action by the code. See Sec. 5.1 for more details.

where the discrepancy is large, the analysis failed, or the line was Bussed Out.[3] Titles on the plots include the *Z*-shot and information about the condition of the switch or the signal, such as Nominal, Early, or Bussed Out, and also indicate the time for the baseline zero-crossing of a rising edge, or information about the time for switch closure. The titles also give the status of the data file with values of Good, Short, or Bad. The purpose of these plots is to provide diagnostic tools for graphically viewing the analysis results. They are useful for understanding why the analysis might have failed for a particular line, or why the LSD-PFL Discrepancy is large. All signals in these plots are normalized, and they are time corrected according to the the time delays shown in Fig. 3.

The plots appear in convenient resizeable graphics windows, however the fonts and other characteristics of these plots were selected for speed and on-screen versatility and not for best appearance. The plots are therefore unsuitable for inclusion in slide presentations or publications and should not be captured directly from the screen. For high quality output the graphics windows include a File Menu that offers a range of plotting options, including postscript and encapsulated postscript formats, PDF, and the raster formats BMP, GIF, JPEG, PNG, and TIFF. To generate postscript and PDF outputs requires installation of the open source application Ghostscript, and very high quality raster formats are available by installing another popular open source application, ImageMagick.[4] The default location for all files written from the graphics windows' File menu is the Directory for Reports, and not the sub-directory for a specific shot number, however the interface for saving files allows choice of any location.

Use of the five buttons under Plots for Single-Shot Analysis is largely self explanatory, however examples of their use are given in Sec. 4. More complete details of the analysis for each type

[3]To understand the numerical value of this discrepancy see Sec. 6.6 and Sec. 6.7 for definitions of switch closure time used by LTS Timing Analysis. Note that the PFL-derived closure time used by LTS Timing Analysis is the time at a minimum, whereas previous methods such as those described in Ref. [1] use the 50% point that precedes this minimum.

[4]Executable files for installation of Ghostscript and ImageMagick are included with installation package for LTS Timing Analysis.

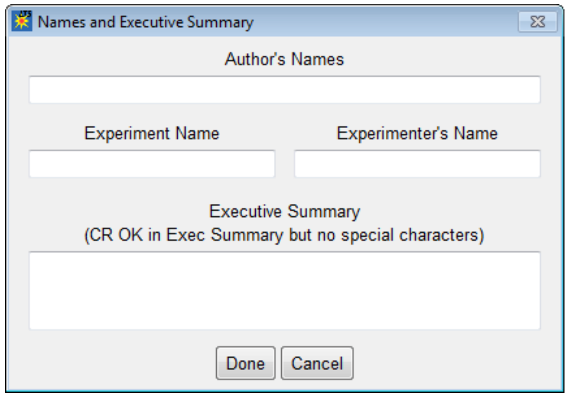

Figure 11. Popup form for entering Author Names, Experiment Name, Experimenter Names, and Executive Summary for LTS_Report_Z*n*.pdf. Carriage returns can be used in the Executive Summary so that all entered text is visible without using left-right arrow keys. The allowed name lengths are approximately equal to the fields on the form, while the executive summary will accept 480 characters. None of the fields on this form limit the number of characters entered.

of signal, and what the various conditions mean, are given in Sec. 6. The complexity of the popup forms ranges from simple, such as LSD-PFL Discrepancy, to somewhat busy, such as Any Combination which is shown in Fig. 12.

All popup forms in Plots for Single-Shot Analysis include a Cancel button, and any form that can open more than one window also has a button for Close *name* Windows, where *name* is Tempest, PFL, etc. Clicking the Cancel button closes the form and all windows opened by that form, while clicking Close *name* Windows closes only the graphics windows but leaves the popup form on the desktop. Although having multiple buttons introduces redundancy, the Close *name* Window button offers the convenience of cleaning up your monitor when there are too many open graphics windows without closing the forms.

Finally, the Run LTS Timing Analysis button on the main form can be clicked repeatedly without closing any graphics windows or their respective popup forms. When the analysis is run for the current *Z*-shot, or for a different *Z*-shot, all analyzed data are immediately available to all open forms and graphics windows. To re-display the results requires clicking a button or interacting with a slider. Buttons with titles such as All Signals in One Window retain an open window after re-analysis of the current *Z*-shot but will open a new window following analysis of a different *Z*-shot. Clicking or moving a slider button will open a new window if none are open, otherwise sliders only update existing windows.

The list below provides a brief description of the on-screen graphics for each button under Plots for Single-Shot Analysis.

LSD-PFL Discrepancy Plots the difference in LSD and PFL switch closure times determined from the analysis. The results are plotted in the form of a color-coded bar chart with the

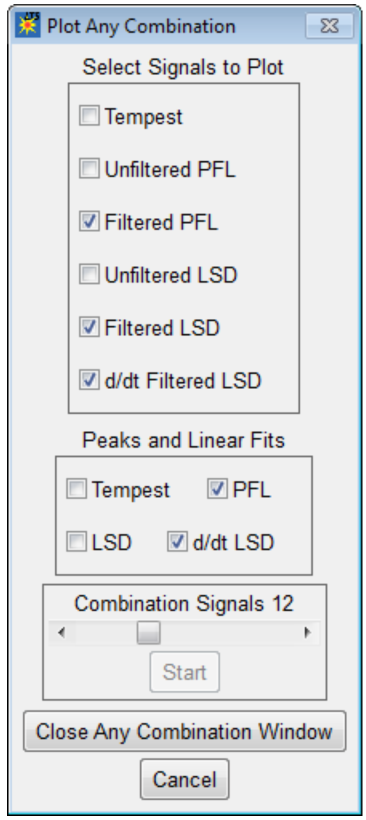

Figure 12. Popup form for selecting Any Combination of signals to plot, including their related analysis results.

order of subtraction either LSD−PFL or PFL−LSD. The popup form has only a Cancel button so the popup form and graphics window always close together.

Tempest Pulses Plots the Tempest Laser pulses with the options All Pulses in One Window, Pulse Times in One Window, or each pulse selected individually using a line selection slider labeled Tempest Laser 01–36. The individual plots show the peak of the pulse, 50% point on the rising edge, and the linear fit to the rising edge with the zero-crossing time for the linear fit displayed in the plot title.

PFL Signals Plots the PFL signals with the options All Signals in One Window or each signal selected individually using a line selection slider labeled PFL Signal 01–36. Check boxes select filtered or unfiltered signals either individually or together. The individual plots display a vertical line to identify the minimum associated with switch closure. A dashed line indicates the line was bussed out so in that case identification of this minimum may be erroneous. The switch closure time is displayed in the plot title.

LSD Signals Plots the LSD signals with the options All Signals in One Window or each signal selected individually using a line selection slider labeled LSD Signal 01–36. Check boxes offer the following options: Unfiltered LSD, Filtered LSD, d/dt Filtered LSD, Zero Line, LSD Threshold, LSD Threshold Time, and Analysis Window. Any or all of the boxes can be checked. The individual plots can become quite busy because analysis results are also plotted. For example, Filtered LSD also plots the fit to the LSD rising edge, while d/dt Filtered LSD plots the fit to the rising edge of the derivative's first big peak, a vertical line through the maximum of this peak, and a vertical line through one of the derivative's secondary maxima, which indicates switch closure. The LSD signal's zero crossing time and the derivative's witch closure time are displayed in the plot title.

Any Combination Plots Tempest Laser pulses, PFL signals, and LSD signals in any combination using a line selection slider for lines 01–36. One group of check boxes labeled Select Signals to Plot includes Tempest, Unfiltered PFL, Filtered PFL, Unfiltered LSD, Filtered LSD, and d/dt Filtered LSD, and a second group of check boxes labeled Peaks and Linear Fits will overplot the respective parameters for each signal when selected. The popup form for Any Combination was shown in Fig. 12. The lower time axis for the plot is absolute and an upper time axis displays the time relative to the Tempest pulse. Unlike other single-shot plots, Any Combination auto-scales the length of its time axes, a necessity for displaying all of the signals. For example, a Bussed Out line might require > 1000 ns. The Any Combination plot can become very busy but can also display the most complete visual information about an individual line for any given Z-shot. It may be useful to expand the graphics window for Any Combination to full-screen on multi-monitor systems. The plot title displays the conditions for the Tempest Laser, LSD and PFL signals but no times associated with the analysis.

3.4 Multi-Shot Analysis and Plots

The Multi-Shot Analysis button opens the popup form in Fig. 13 that allows the user to analyze and plot results for a series of Z-shots. The operation of this form is different from the single-shot forms as it requires that binary data from previously analyzed Z-shots be available on the local hard drive. The default location for data is the one selected from File:Directory for LTS Data Files, however data can be loaded from any location. The overall architecture of the LTS Timing Analysis code was optimized for single-shot analysis, so multi-shot analysis is comparatively inefficient. For example, any of the single-shot on-screen plots will update as fast as you can click your left mouse button on the arrows of their line selection sliders, whereas changing the shot- or line-number on the multi-shot analysis form results in an on-screen update delay of about two seconds – and even longer with popup dialogs warning of an analysis failure. In addition, selecting a new line or shot produces a new graphics window so you can quickly clutter up your desktop with many open windows. Nonetheless, multi-shot analysis does allow the user to view the behavior of the same line for a series of Z-shots so it can be a useful diagnostic tool.

3.5 Interactive Analysis

The Interactive Analysis button opens the popup form shown in Fig. 14. Interactive Analysis provides a tool for obtaining results when the automated analysis fails. If failures occur they usually involve no more than a few signals that possess anomalous features, and more likely than not the popup dialog in Fig. 9 appeared to indicate a failure during LSD analysis. Although results such as LSD or PFL switch closure times might not be available, the signals for any line that produces a failure can still be viewed using the on-screen plotting routines. For example, the bar plot for LSD-PFL Discrepancy might indicate large closure-time differences for lines where failures occurred, and subsequent viewing of the signals for that line using the Any Combination plot will usually reveal the problem.

The form for Interactive Analysis is similar to the popup forms for LSD Signals or Any Combination, but with one important exception: The user can select the time range for viewing signals independent of the time range used for analysis. The allowed time ranges are 0–999 ns before and after the temporal reference point, which in this case is the Tempest Laser reference time read from the server instead of the default reference, which is the peak of the actual Tempest pulse derived from analysis. Generally the nominal time range of -100 ns to $+240$ ns works well for Interactive Analysis, however longer time ranges can be used if necessary. Sometimes a very early pre-fire or a very late switch closure time, or even an error in data acquisition, can be revealed using a longer than usual time range.

After the failed line and time range are selected, clicking the Plot Signals for Analysis button on the popup form opens an additional form with the title Z*n*:Signals for Interactive Analysis, where *n* is the shot number. This form is shown in Fig. A.1 in Appx. A.1 because it takes up almost an entire page, and Sec. 4.2 provides examples of how to correct for a failed analysis using this form. The top of the form includes instructions for its use, which amounts to positioning a cursor over a feature in a signal, left clicking the mouse, and then selecting the appropriate measurement at the bottom of the form by left clicking in its check box. Fields for Time and Amplitude located above the plot show the position of the cursor. If correcting an analysis failure also results in a change in the Tempest, LSD, or PFL Condition for any of the signals, the appropriate Condition can be reset as well by clicking its radio button. Note that the check boxes at the bottom of this form don't acquire the familiar check mark ✓, but instead subtly change color while the left mouse button is depressed. When interactive measurements for a given signals are complete, clicking the Done with Interactive Analysis button closes this form. The new measurements are immediately available for any on-screen plots however you must click the Update Reports button to update the results in any report files that were previously written to disk for the current *Z*-shot.

3.6 Signal Quality Analysis

For many types of measurements the signal-to-noise ratio is defined as $\text{SNR} = P_{\text{signal}}/P_{\text{noise}}$, where P is the average power measured within the same system bandwidth for both the signal and the noise. However for the single-shot PFL and LSD signals that are essentially transient in nature

– not because they decay quickly, but because all useful information is derived from a short time period – the traditional SNR derived from average power can be problematic to apply. Although rigorous treatments of SNR for this situation no doubt exist, an alternative derived from purely empirical considerations can be used instead, namely comparing the low frequency content of a signal to its higher frequency noise. For the signals analyzed by LTS Timing Analysis the following observations provide a non-rigorous definition of what we call the Signal Quality.

After inspecting many PFL and LSD signals it becomes obvious that the frequency spectrum for a high SNR signal tends to have a large near-DC spectral amplitude and smaller higher frequency spectral amplitude, while a noisier signal has the opposite characteristics and lower SNR. Consequently what we call the Signal Quality consists of the ratio of two frequency-integrated single-shot quantities: The integral of the central band of a signal's power spectrum divided by the integral of the wings of its power spectrum. For determining Signal Quality the time range for analysis and the width of the central spectral band are user-selected parameters, however the time range should almost always the same one used for timing analysis.

Defining Signal Quality this way provides a tool for monitoring the quality of the LSD and PFL signals over time, and to a lesser extent the quality of the Tempest Laser pulses as well. Signal Quality is displayed graphically using plots that show its mean value for all 36 lines for a series of *Z*-shots, along with error bars for standard deviation, and they include an over-plot of Signal Quality for the one user-selected line.

The popup form opened by clicking Signal Quality Analysis is shown in Fig. 15. At the top is a button labeled Select Data Files and Analyze that opens a native Windows interface to select binary files that were stored on a local hard drive, which is followed by analysis. A button labeled Reanalyze Selected Files repeats the analysis in case you change an analysis parameter, and the Status message updates progess. Boxes for Signal and Line for Plot, Start and End Times, Center Band FW, where FW denotes full-width, and a box for Plot Average Spectrum, fill out the remainder of the form. Plot Average Spectrum lets you view the average spectrum for all lines for a selected signal and *Z*-shot as an aid for selecting the center bandwidth.

Example plots of Signal Quality Analysis for LSD 10 and LSD 07 for shots Z2458–Z2485 are shown in Figs. 16 and 17, and plots of LSD signals 10 and 07 for shot Z2459 are shown in Figs. 18 and 19. In Figs. 16 and 17 we see that LSD 10 produces signals having a higher than average SNR, whereas LSD 07 produces signals with a substantially lower than average SNR. We also see that Z2473 produced LSD signals that are essentially pure noise, suggesting some type of data acquisition malfunction because further inspection reveals that the PFL signals and Tempest laser pulses for this shot have nominal noise characteristics. Figures 18 and 19 for LSD 10 and LSD 07 for Z2549 clearly show the difference indicated by the two signal quality plots, where the relative amplitude of the noise oscillations about their respective baselines is clearly obvious.

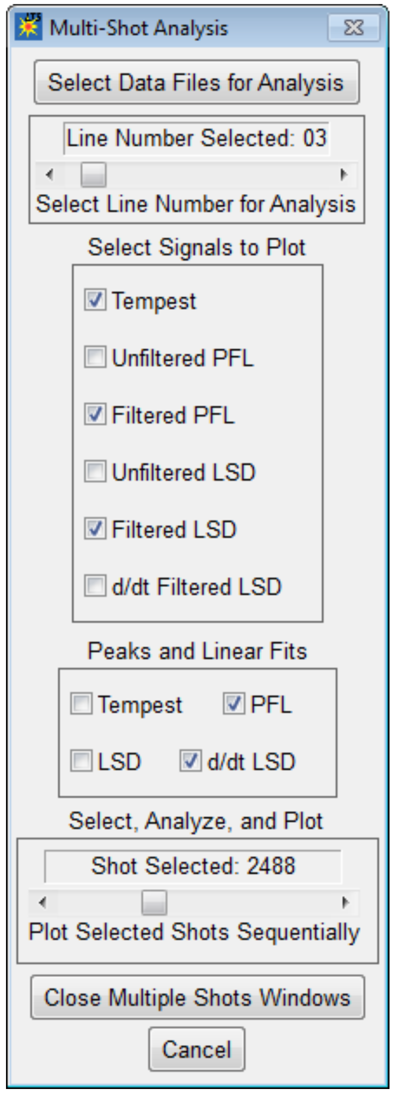

Figure 13. Popup form for Multi-Shot Analysis.

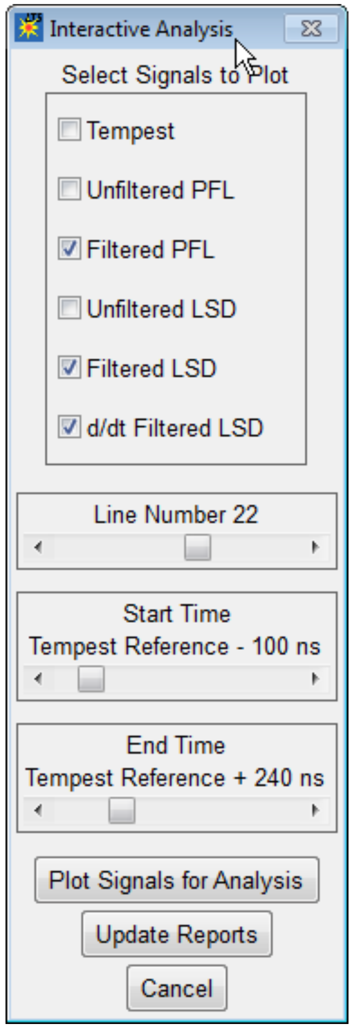

Figure 14. Popup form for selecting signals and display parameters for Interactive Analysis.

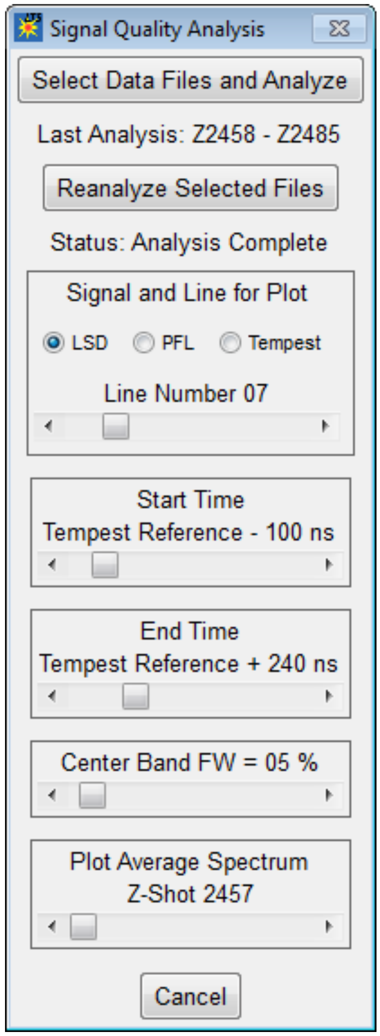

Figure 15. Popup form for selecting data files, analysis parameters, signal, and line number for Signal Quality Analysis.

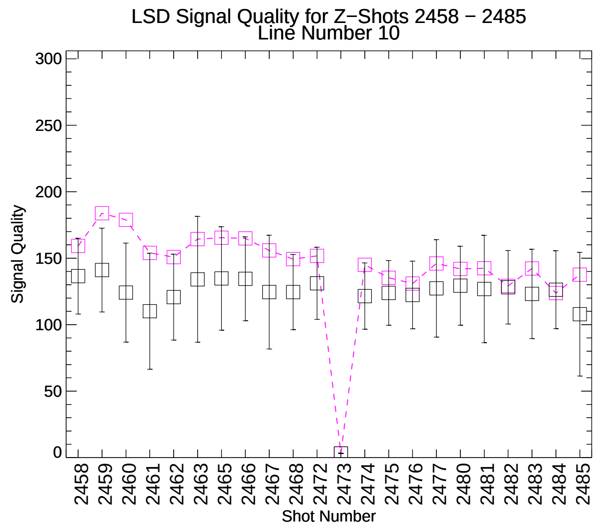

Figure 16. Example plot for Signal Quality Analysis for Z2458–Z2485 for LSD 10. The black boxes with error bars show the average and standard deviation for all lines for each *Z*-shot, and the purple boxes show the signal quality for a specific line. This plot shows LSD 10 generally produces high SNR signals.

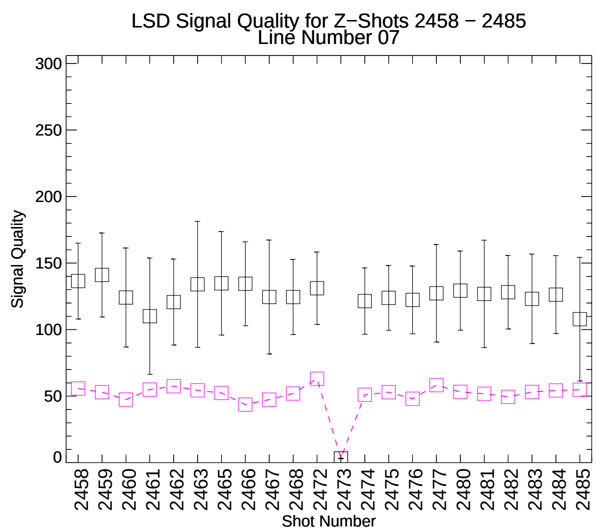

Figure 17. Example plot for Signal Quality Analysis for Z2458–Z2485 for LSD 07. The black boxes with error bars show the average and standard deviation for all lines for each *Z*-shot, and the purple boxes show the signal quality for a specific line. This plot shown LSD 07 generally produces low SNR signals.

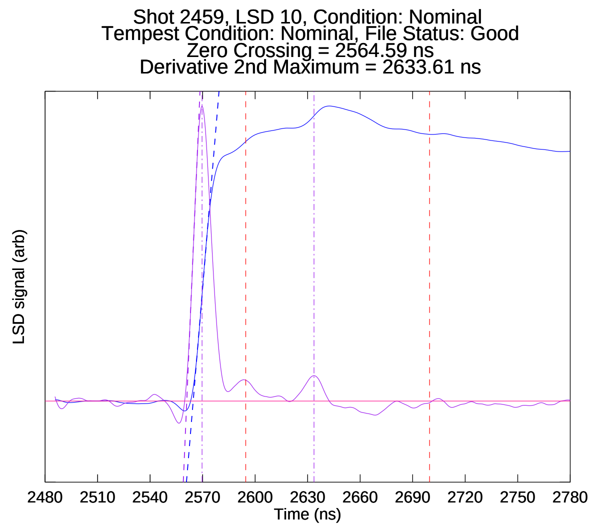

Figure 18. LSD 10 for Z2459. The relatively small noise-related fluctuations around the baseline for d/dt LSD indicate LSD 10 generates high SNR signals.

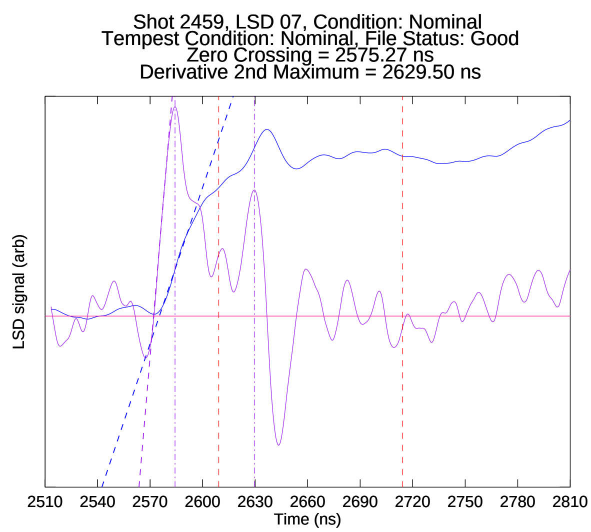

Figure 19. LSD 07 for Z2459. The relatively small noise-related fluctuations around the baseline for d/dt LSD indicate LSD 07 generates high SNR signals.

4 Example Analyses: Z2500 and Z2485

LTS Timing Analysis is simple to use and produces accurate results for a high percentage of *Z*-shots without user intervention, however as we just discussed in Sec. 3.5, occasional deviations from nominal behavior for the LSD and PFL signals can result in failures. Because some amount of user intervention may be required for *Z*-shots where failures occur, this section illustrates that process using two examples: Analysis of Z2500, a shot that produced very well behaved signals and therefore requires no intervention, and analysis of Z2485, a shot with Bussed Out lines and several anomalous LSD signals that pose challenges for the automated analysis, and therefore does require intervention. Although the example analysis of Z2485 is useful for learning how to correct for failures, it by no means covers all possible examples of failures. In addition, Z2485 was selected because it produced failures that can be corrected with a high level of confidence, when in fact some *Z*-shots produce signals that result in a correction process that might be better described as guesswork. We begin with the simple case of Z2500.

4.1 Z2500: An Easy Example

For Z2500 the Calculation Parameters are identical to those in Fig. 5 and the analysis Start and End Times have the nominal values of -100 ns and $+240$ ns. If we uncheck all the boxes in File:Report File Options, set the radio button for Auto Save LTS Data to Off, and read locally stored binary data, clicking Run LTS Timing Analysis produces results in a little less than two seconds. There were no popup dialog boxes warning of failures, but to make sure the analysis was successful we check the results by opening the form for LSD-PFL Discrepancy, select the order of subtraction to be LSD Time $-$ PFL Time, and plot the results. From the bar chart shown in Fig. 20 we see the largest LSD-PFL discrepancy is about 10 ns, which indicates signals that are generally well behaved and easy to analyze.

To look a bit closer at the signals themselves we use the Any Combination button under Plots for Single-Shot Analysis with the following settings: In the box labeled "Select Signals to Plot" we check Filtered PFL, Filtered LSD, and d/dt Filtered LSD, and in the box labeled "Peaks and Linear Fits" we check PFL, LSD, and d/dt LSD. By sequentially plotting these signals using the slider we find late rising edges for the LSDs on lines 14, 16, 22, 27, 31, and 34, and one early LSD signal for line 26. Adding the Tempest pulse to the plots (but leaving its Peaks and Linear Fits box unchecked) we see that none of these timing discrepancies is large enough to compromise the analysis in any way. We also observe that the positions of the vertical lines through the peaks of d/dt LSD and minima of the PFL signals accurately locate the features for switch closure times for all lines. If we open the popup form for viewing Tempest Laser signals and click the Pulse Times in One Window button, the resulting plot shown in Fig. 21 displays the distribution of measured pulse times, including several clusters of pulses, but with all pulses occurring within about 55 ns. This shows there were no Bussed Out lines, in agreement with the bar plot in Fig. 20, where a Bussed Out line would be marked with a yellow bar. For the condition of the *Z*-Accelerator at the time of shot Z2500, this analysis is about as simple as it gets. If we now open File:Report File Options and select the check boxes for the report files we want, rerun the analysis, then edit the

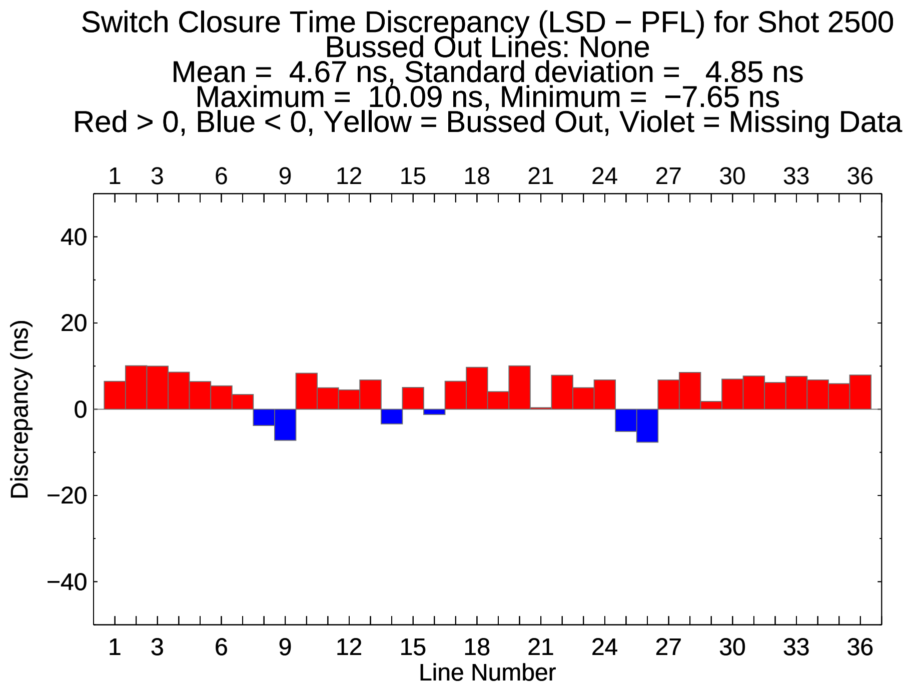

Figure 20. Plot of LSD−PFL discrepancy for Z2500. The length of the bars indicates the difference in switch closure time determined from the LSD and PFL signals. This plot is an example of an encapsulated postscript file generated using the File menu on the resizeable graphics windows as described in Sec. 3.3.

fields for LTS_Report_Z2500.pdf if needed, the entire process will probably be complete in less than one minute.

4.2 Z2485: Use of Interactive Analysis

We now turn our attention to Z2485, a shot with bussed out lines and several difficult-to-analyze LSD and PFL signals. When we run the analysis no popup dialog messages appear like the one in Fig. 9 warning of an LSD failure, however the LSD-PFL Discrepancy in Fig. 22 reveals line 22 has a discrepancy of about 90 ns. Although there was no outright failure during analysis, a 90 ns discrepancy indicates a problem, so to find it we use the Any Combination plot to display the PFL and d/dt LSD signals. For line 22 we see that the LSD algorithm located the switch closure time using a peak in d/dt LSD that is obviously wrong compared to switch closure determined from the PFL. To dig a little deeper we open LSD Signals under Plots for Single-Shot Analysis and check the boxes for Filtered LSD, d/dt Filtered LSD, Zero line, and Analysis Window. As seen in Fig. 23, there is a small peak in d/dt LSD for line 22 at about 3010 ns that precedes a minimum at about 3023 ns, and for most LSD derivatives the location of this minimum would indicate the

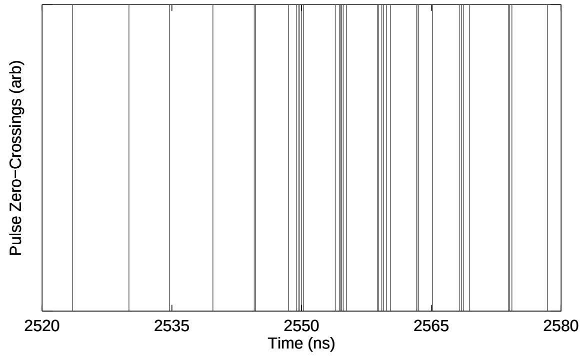

Figure 21. Measured Tempest Laser pulse times for Z2500.

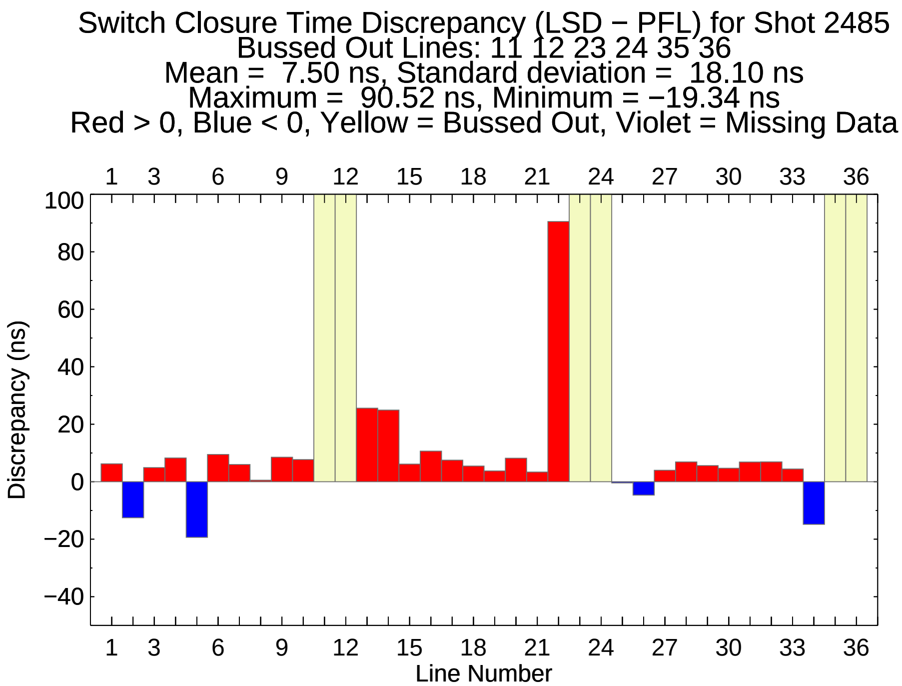

Figure 22. Plot of PFL-LSD discrepancy for Z2485. Line 22 has a discrepancy of about 90 ns, which indicates a potential error or failure in the analysis. See text for additional details.

zero-crossing used to find the switch closure time.[5] Because the peak and minimum fall within the LSD analysis window, this error suggests the LSD signal has an anomalous DC offset,[6] so we

[5]You can find the exact location of minima and maxima by reading the Time field in Interactive Analysis as described in Sec. 3.5.

[6]It does have a DC offset, otherwise this minimum would be deeper, i.e., more negative. The original baseline-corrected data are shown in the plot of the LSD so the effect of the Calculation Parameter “LSD Derivative incremental offset” is not apparent.

might obtain a more accurate result by setting “LSD derivative incremental offset” to its highest value of 1.0 instead of 0.5 as shown in Fig. 5. Unfortunately attempting to reduce the effect of the DC offset returns the same 90 ns discrepancy, so we take the next obvious step, which is reducing the maximum value of the “LSD derivative first local minimum window.” This excludes peaks in d/dt LSD for line 22 that are too late in time, but the correct peak isn’t identified until the window’s maximum is reduced from 130 ns to 70 ns. Unfortunately the short window won’t accommodate switches with long run times, such as the one for line 10, so in this situation we have no choice but to use Interactive Analysis to improve the results.

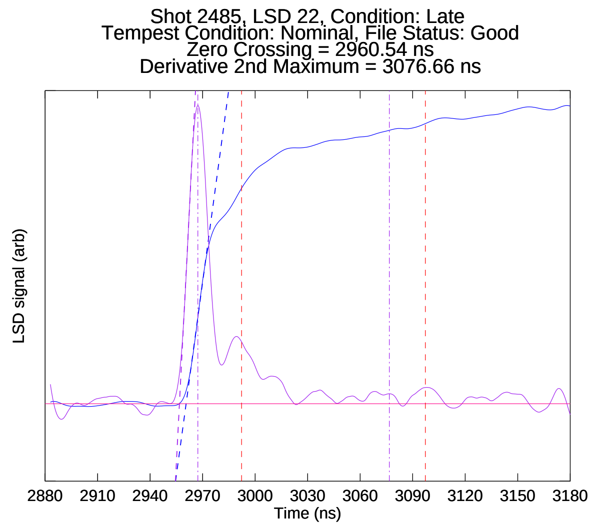

Figure 23. The LSD signal for Z2485, line 22, displaying Filtered LSD, d/dt Filtered LSD, Zero Line, and Analysis Window. The automated analysis correctly located the LSD’s rising edge and zero crossing, and the first big peak in d/dt-Filtered LSD, so the only correction required using Interactive Analysis is the secondary peak in d/dt Filtered LSD that indicates switch closure. The analysis window for d/dt LSD is indicated by the vertical dashed red lines.

Before opening Interactive Analysis we check Fig. 22 again and see lines 2, 5, 13, 14, and 34 also have large LSD-PFL Discrepancies so we check these lines using Any Combination plot. For lines 2 and 34 we find PFL signals that don’t display any obvious correct choice for the switch closure time, except perhaps minima that are quite late in time, so we’ll leave these results unchanged – unless you feel like guessing. For line 13 the LSD algorithm appears to have worked correctly, but for line 14 maybe not, so that leaves lines 5, 14 and 22 as the three requiring corrections.

To use Interactive Analysis we click that button on the main form, check the boxes on the Interactive Analysis popup form for Filtered PFL, Filtered LSD, and d/dt Filtered LSD and start by moving the Line Number slider to 22. The nominal Start and End Times of -100 ns and $+240$ ns are appropriate so we use the sliders to select these times then click the Plot Signals For Analysis button to open the form with the title “Z2485: Signals for Interactive Analysis” shown in Fig. A.1 in the Appendix. The bottom of this form contains three check boxes for LSD Results, but we might not need to update all of them, so we also open LSD Signals (it might already be open) to examine the results for line 22, which are shown in Fig. 23.[7] We see that the LSD Zero Crossing and the global maximum in d/dt Filtered LSD (the first peak for most LSD signals) were already correctly identified, so we need to update only the secondary peak in d/dt Filtered LSD that indicated switch closure. We do this by placing the black-cross cursor over the correct secondary peak, left click the mouse, then left click the check box labeled "d/dt switch closure" at the bottom of the form. We might be tempted to update the condition to "Nominal" by clicking that radio button under LSD Condition, but the LSD signal was actually late, so we leave it unchanged.[8] We can now click Done with Interactive Analysis to close the form. The Update Reports button on the Interactive Analysis popup form is now active, so we click that button to insert our hand-selected numerical results into any report files that were previously written to disk for Z2485.

To finish correcting the analysis we repeat the procedure above for lines 5 and 14, closing the form Z2485: Signals for Interactive Analysis after each correction, but we can wait until we are completely finished with all corrections before clicking the button for Update Reports. Our final corrected results for the LSD-PFL Discrepancy are shown in Fig. 24.

Use of Interactive Analysis for messy signals like those generated by Z2485 might seem a bit tedious, but it does allow the user to improve on the automated analysis when necessary. It's not a perfect process because analyzing switch timing using the PFL and LSD signals can be challenging.

[7] Every possible signal and all analysis results could have been presented in the plot for Interactive Analysis but it just becomes too crowded for practical use. It's easier to open a plot for a specific signal type if necessary.

[8] Include the Tempest pulse in Any Combination plot for line 22 to see the LSD delay is closer to 15–20 ns, but the Calculation Parameter "LSD late time" is set to 10 ns, so it's late.

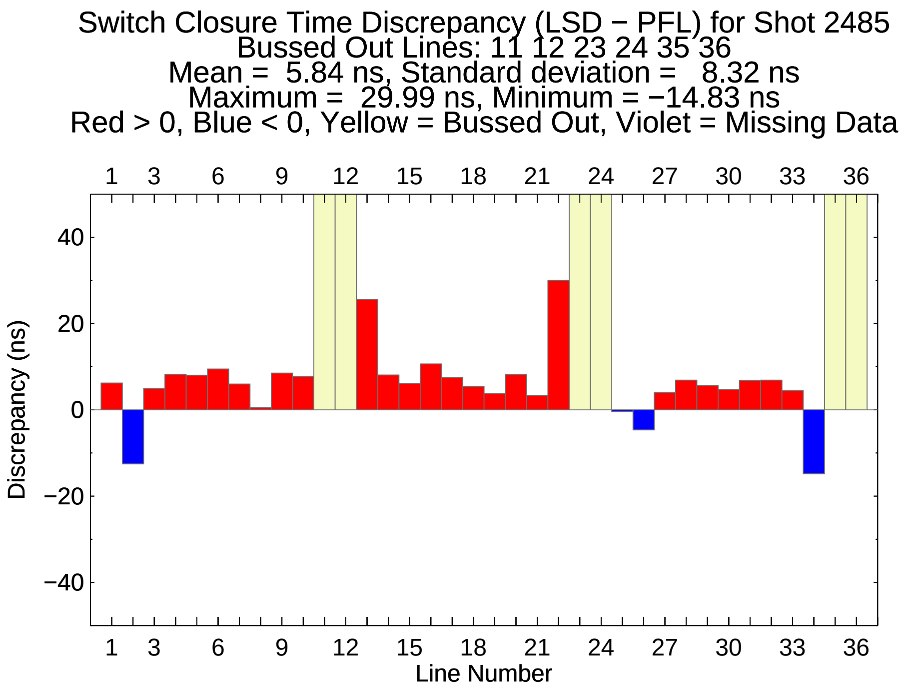

Figure 24. Plot of PFL-LSD discrepancy for Z2485 after making corrections using Interactive Analysis. We note that lines 2 and 34 have discrepancies $>$ 10 ns but as discussed in the text they arise from the PFL signals and we won't attempt to change these discrepancies. The convention for this bar plot sets the sign of the yellow bars indicating Bussed Out lines in the direction of largest discrepancy, which is positive in this case. Bussed Out bars are intentionally longer that the other bars.

5 Data File Input and Output

LTS Timing Analysis reads binary data files from a remote server and it also offers options for writing specially formatted binary data, and .csv formatted ASCII data. This section describes how the code deals with occasional file read errors, and it also describes the formats for the optional binary and ascii data.

5.1 Input File Read Errors

The Z Accelerator's data acquisition system usually writes good binary data files for the Tempest Lasers, PFLs, and LSDs, but occasionally it writes files that are shorter than usual or are somehow corrupt and can't be read. Because any un-trapped file-read error during run time can result in a fatal crash, the code must trap all possible file-read errors and deal with them appropriately. The goal of handling file-read errors is to produce the most complete analysis possible. Consequently LTS Timing Analysis traps three different file read errors, warns the user with a dialog message, and takes actions for the errors as described below:

Files that are missing This is a highly unusual error but it will invalidate the analysis so the code issues a warning to the user and returns control to the main GUI. The user can then select another *Z*-shot for analysis or quit the program.

Files that are corrupt or too short If a file is present but can't be read, or is present but too short to contain useful data, the file reading subroutine uses the Tempest reftime and the nominal time increment for the type of data file to construct a suitable time array. It then generates data consisting of random noise. The time array and noise for that file allow analysis to proceed as usual because the analysis routines were written to accommodate the random noise without causing an error. The analysis routines issue "Conditions Flags" as described in Sec. 7 that alert the user to the incomplete analysis due to missing data. Some of the flags are shown in the titles of the on-screen plots, while all of them are recorded in the report file Shot_*n*.csv.

Files that are short but contain usable data If a file is present and short but might contain usable data, the file reading routine searches its contents for the Tempest reftime, and if present it constructs the remainder of the time array. It then concatenates the available data with random noise that has the appropriate baseline offset and amplitude to be characteristic of baseline noise for the specific file type. The actual process of resurrecting short data files requires delaying the Tempest reftime relative to the initial time in the file so that the analysis can proceed as usual. The time and data concatenation processes can therefore become a bit complicated but it can be worth the effort because an otherwise corrupt data file can be modified to yield usable results.

5.2 Binary and ASCII Output Files

The binary output files use a special format in the form of a structure variable that can be retrieved and processed only by LTS Timing Analysis. As mentioned in Sec. 1, storing and retrieving of these files is offered as a convenience to the user to reduce run time. For most *Z*-shots the analysis itself can be completed in less than two seconds, however reading the input files from the remote server can take a comparatively long time. Each locally stored binary file requires about 13.5 MB of disk space and contains all required input data for each *Z*-shot so that the code can be run without access to the server. If the user tries to access the server when it's unavailable, a dialog message will alert the user so they can use locally stored binary files, if available.

The ASCII files written by LTS Timing Analysis use a two-column .csv format for all lines, where the first column is time and the second column is the signal data. The file names are similar to those on the remote server; tmpst01.dat – tmpst36.dat, pfl01.dat – pfl36.dat, and lsd01.dat – lsd36.dat. These files contain purely raw data with no filtering, time correction, or baseline correction. The ASCII files are written to shot-numbered sub-directories below the directory for locally stored binary LTS data files. For each shot number there are 108 files and they occupy almost 45 MB of disk space. They are provided for use in spread sheets such as Excel but cannot be used by LTS Timing Analysis in any way.

6 Methods of Analysis

LTS Timing Analysis uses characteristic features of the Tempest Laser pulses, the PFL signals, and the LSD signals to analyze the performance the *Z*-Accelerator's laser triggered SF_6 switches. The code was written more from the perspective of signal analysis alone, and less from considerations of the physics of the switches themselves. This manual reflects that perspective and is therefore not intended to be a technical reference beyond describing the methods of analysis. For a better understanding of the actual operation of the switches please consult Ref. [1].

Although the diversity in quality of the signals encountered during the analysis can range from good to terrible, the various analysis algorithms are not overly complex and rely on a combination of filtering out unwanted noise and taking advantage of some specific features of each type of signal. Early in the analysis a small correction is applied to the baseline for all of the signals so we begin with a discussion of baseline correction.

6.1 Baseline Correction

All signals used in the analysis are recorded by digital oscilloscopes and all three signals contain DC offsets that are relatively small compared to their features of interest. Although baseline correction is a standard technique in signal analysis, removing the relatively small baseline for these signals results in only a small improvement in temporal accuracy of the results. Nonetheless, baseline correction adds essentially nothing to computational overhead so there is no reason to omit it from the analysis.

Baseline correction usually involves subtracting a mean value in an attempt to restore the baseline to zero, however for these signals an alternative to the mean offset is a better choice. When the signals are inspected closely fluctuations are seen at distinctly quantized values about a DC offset. Because round-up and round-down from digitization introduces errors relative to the actual analog values, these digitized signals possess what is commonly called quantization error or quantization distortion. When viewing a featureless portion of any of the signals the DC offset therefore appears as a median line that separates the positive- and negative-going quantized noise. As we'll show, this visual median doesn't necessarily correspond to the average value of the signal, but it does provide a meaningful measure of the offset. What this means for baseline correction is we might obtain a smaller residual DC offset by subtracting the median, rather than using the conventional method, which is subtracting the mean. In either case – subtracting the median or the mean – these quantities are calculated from the early portion of the oscilloscope record where there is no signal of interest. Examples of median-subtraction versus mean-subtraction for a 100 ns range of a Tempest Laser signal are shown in Figs. 25(a) and 25(b). Given the peak amplitude of the Tempest Laser's pulse is about 1.85 V for this particular signal, and the residual offset of the mean-subtracted baseline is < 5 mV, the difference between the two baseline correction methods is negligible, but nonetheless observable. All of the analysis routines use the median for baseline correction.

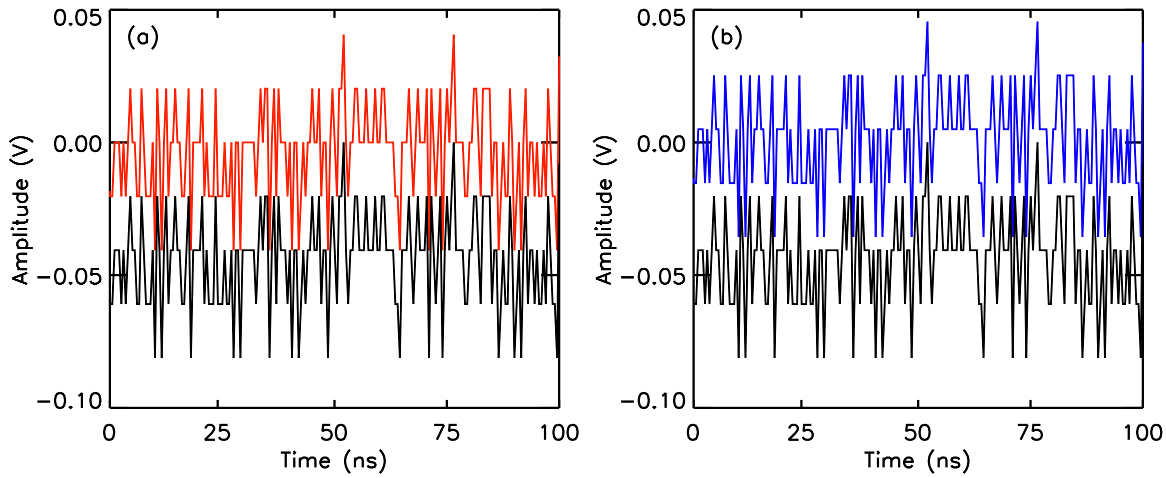

Figure 25. (a) Pulse-free section of Tempest Laser signal where the median was subtracted for baseline correction. Uncorrected signal (black) and baseline corrected signal (red). The residual baseline offset is approximately zero volts. (b) Same as (a) except the mean was subtracted for baseline correction. Uncorrected signal (black) and baseline corrected signal (blue). The residual baseline offset is less than 5 mV but clearly observable compared to the offset in (a). See text for additional details.

6.2 Filtering to Remove Noise

The relative amplitude of the noise in the three signals varies significantly, with the Tempest Laser pulses being large enough that noise can be neglected. For the PFL signals the noise in the time range near switch closure can be almost as large as the signal of interest, so filtering is mandatory. Fortunately the characteristic frequencies of the noise exceed the characteristic frequencies of the useful signal, so filtering results in high fidelity PFL signals. For the LSD signals the noise amplitude is comparatively small but these signals must be filtered because the first derivative of the LSD is used in the analysis, and for differentiation the signal must be temporally smooth. Fortunately the noise-frequencies in the LSD signals also exceed the frequency of the features of interest, so again we obtain a high fidelity signal.

For the PFL and LSD signals LTS timing analysis uses a fourth-order Butterworth filter, where the filter bandwidth is a user-selected value accessed through Edit:Calculation Parameters as shown in Fig. 5. The nominal value for the bandwidth is 50 MHz. To reduce computational overhead filtering is applied only over the user-selected time-range of interest, which is extracted from each signal during the analysis. The filtered PFL signals display substantial variations with changes in the filter bandwidth, however analysis of this signal is somewhat tolerant to a small amount of additional noise. The LSD signals on the other hand are quite susceptible to changes in the filter bandwidth because their derivatives play an important role in the analysis. Fortunately both PFL and LSD signals are filtered appropriately by the same filter bandwidth of 50 MHz. Given the greater susceptibility of the LSD's derivative to noise we suggest the user not adjust the filter bandwidth unless there is compelling reason to do so.

6.3 Linear Fit to a Rising Edge

Part of the analysis involves finding a linear fit to the rising edge of the Tempest Laser pulses, and to the rising edge of the LSD signals, and from these fits we obtain the zero-crossing times of their rising edges at the baseline. Although a similar linear fit technique is used for both signals, the two of them otherwise differ significantly.

An isolated, short duration disturbance such as a Q-switched laser pulse with a high SNR is easy to locate from its peak value. Its temporal characteristics are subsequently defined by the 10% and 90% points on its rising edge, 50% points, or other measure. However for signals that rise from a baseline and remain high we need a different approach, such as locating a single, initial, rising edge. This is done by finding the location where the signal exceeds a suitable threshold value, and then carrying out a linear fit to its rising edge to determine its location from its baseline zero-crossing point. For the LSD signals this process is more complicated that it sounds so the exact details are left to Sec. 6.7. Independent of signal type, Tempest or LSD, our approach for fitting the edge itself is very similar so we describe it briefly below.

The Tempest pulses have rising edges that are nearly linear from 20%–80% of peak value, so obtaining a good fit in their case is simple. Because the pulses are short relative to the reciprocal of the data acquisition sampling rate, we cubic-spline interpolate to increase the point density by a factor of five, but for only a short segment of the data record. The fit is initially carried out using all points between 20% and 80% and then optimized by decreasing this range until χ^2, the goodness of fit, falls below 0.005. This is sufficient to obtain a very accurate fit to the Tempest Laser's rising edge. The amplitude of Tempest Laser pulses is large relative to baseline noise, so as mentioned previously, filtering these signals is unnecessary.

Although identifying the rising edges for a LSD signal is a bit more complex, once located the linear fitting process is similar. As before a subset of the signal is extracted from the full-length data record, and because LSD signals contain significant noise, it is pre-smoothed slightly using boxcar averaging and then passed through the fourth-order Butterworth filter. Filtering can introduce steep-sloped artifacts near the endpoints of the extracted time-range, but they are easily identified and don't affect the analysis in any way. The LSD signal is then cubic-spline interpolated by a factor of 10 and the linear fit then begins by initially using points just above, and just below, the midpoint-amplitude of the rising edge. The number of points used in the fit is then increased by moving the higher point upward, and the lower point downward, while χ^2 remains below 0.002. This approach achieves a good fit to the edge, which in turn accurately locates the baseline zero-crossing point.

We also carry out a linear fit to the rising edge of the LSD signal's first derivative, and as before, complexities involved in locating this edge are left to Sec. 6.7. The method is otherwise identical to that used for the Tempest Laser pulses, except that the fitting process terminates with $\chi^2 \leq 0.015$, a higher value necessitated by some characteristics of the LSD's derivative.

6.4 Time Correction

The results of the analysis for all signals are recorded in the report file Shot_***n***.csv, where *n* is the shot number. Included in these results are time-corrected values (TC) and not-time-corrected values (NTC). Because time correction is a simple additive process it is not included in the discussion of methods of analysis.

6.5 Analysis of the Tempest Laser Pulses

The Tempest Laser pulses are analyzed primarily to provide a timing reference and to determine if a line is Bussed Out. In LTS Timing Analysis this timing reference establishes the Time Range for Analysis used in analyzing the PFL signals, and it is also compared to the Tempest Laser reftime that is read from the remote server.

The presence of a pulse for a Tempest Laser is determined by comparing the peak value in the entire data record to a threshold value. The threshold is determined from the product of the average of the entire data record multiplied by the Calculation Parameter called "Tempest laser threshold factor" as seen on the popup form in Fig. 5. Because the duration of a Tempest Laser pulse is very short compared to the duration of the data record, any influence on the average value from the pulse is ignored. If a pulse is present the Time Range for Analysis is set relative to the peak of the pulse using the Start- an End-Times selected in Edit:Time Range for Analysis. In the very rare case that a pulse is missing the Time Range for Analysis is determined using the same process but relative to the Tempest Laser reftime. For a missing pulse we don't complete the remainder of the analysis described below.

After a pulse is located and the time range is established, baseline correction is carried out as described in Sec. 6.1. Time and data arrays are then extracted from the full record. The time-array point density is increased by a factor of five and the data array is cubic-spline interpolated using the new time-points to acquire the interpolates. The increase in point density is required to successfully carry out a linear fit to the pulses' rising edges as described in Sec. 6.3. Following the linear fits and determination of the rising-edge zero-crossing times at the baseline, the 50% points on the rising edges are also identified.

The final step in analysis of the Tempest Laser pulses is identification of lines that are Bussed Out. Information for Bussed Out lines is also available in a file on the remote server, however the algorithm to locate them is fairly simple, so it will remain in the code for the foreseeable future. The approach involves placing the pulse zero-crossing times into a histogram containing 36 bins and looking for a contiguous block of empty bins, with its length defined by the Calculation Parameter called "Number of histogram bins for bussed-out delay." The length of time associated with the empty bins must exceed a threshold value for lines to qualify as bussed out, and that time is set by the Calculation Parameter called "Minimum time for bussed-out delay." These two Calculation Parameters are shown in the popup form in Fig. 5, where the nominal value for the number of empty bins is 15, and the minimum bussed-out delay is 700 ns. If for some reason the *Z*-Accelerator's parameters for Bussed-Out lines changes substantially these two parameters can be adjusted accordingly. Note that in the very rare case that a Tempest pulse is actually missing, the Tempest reftime is not used as a replacement for the zero-crossing time for the purpose of identifying Bussed Out lines.

6.6 Analysis of the PFL Signals

The only information extracted from the PFL signals is the switch closure time. In LTS Timing Analysis that time is associated with a minimum value as shown in Fig. 26, and not a 50% point, as was used previously in Ref. [1]. Raw PFL signals contain substantial noise, but after filtering they also exhibit fairly good reproducibility among the 36 different lines of the *Z*-Accelerator, consequently the signature for switch closure can be identified with reliability that probably exceeds 90%. Ideally we'd like 100% reliability but that's impossible using the PFL signals alone, but fortunately help is available from the LSD signals. In particular the first derivative of the LSDs contain an easily identified secondary peak that is usually adjacent to its global maximum, and this peak reliably correlates with the PFL's signature for switch closure. This secondary peak, and the deep minimum that is the PFL's signature for switch closure, are identified in Fig. 26 by vertical lines. We'll describe the characteristics of the LSD signal's derivative in more detail in Sec. 6.7, but first we'll continue with the methods used to determine switch closure times from PFLs.

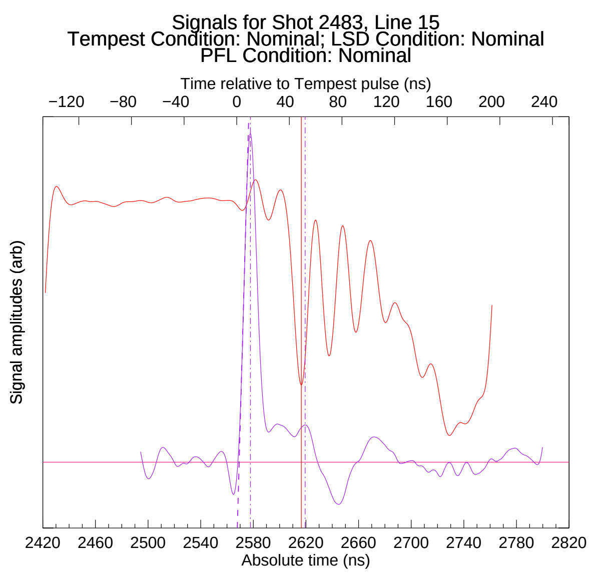

Figure 26. The vertical line through the first deep PFL minimum (red) coincides with a secondary peak in the the LSD's first derivative shown by the dot-dash vertical line near 2620 ns (purple). These two features are indicators of switch closure used in the analysis.

Extracting the switch closure time from the PFL signals begins by identifying a time-range of interest determined from the location of the corresponding Tempest Laser pulse. In the event of a failure in the Tempest Laser analysis, the Tempest "reftime," which is read from a file on the remote server, is used instead. Once this time is known, arrays for time and for the PFL signal are extracted from the full data record, relative to the Tempest time, where the arrays begin and end with the Start- an End-Times selected in Edit:Time Range for Analysis. Unlike the analyses for the Tempest Laser and LSD signals there is no identification of a peak value, or of a threshold value, that is used to identify the time range of interest.

A typical well-behaved PFL signal with an easily identified minimum that indicates switch closure is shown in Fig. 27. The upper plot is unfiltered, and the lower plot filtered with a bandwidth of 50 MHz. The higher frequency noise in unfiltered PFL signals makes them difficult to analyze however filtering removes the high frequency structure to reveal oscillations at a fairly constant frequency of around 20 ns, with well defined minima and maxima. Filtering can introduce steep-sloped artifacts for the data points at the ends of the Time Range for Analysis as seen in Fig. 27, but they are easily avoided and never identified as a spurious minimum or maximum.

Following filtering the time-array point density is increased by a factor of 10, and the PFL signal is cubic-spline interpolated with its interpolates corresponding to the points of the 10× density time array. The increased point density, and in particular the additional smoothness on a finer scale afforded by cubic-spline interpolation, is necessary for accurate location of maxima and minima as most extrema-locating algorithms work better with smooth, dense data sets.

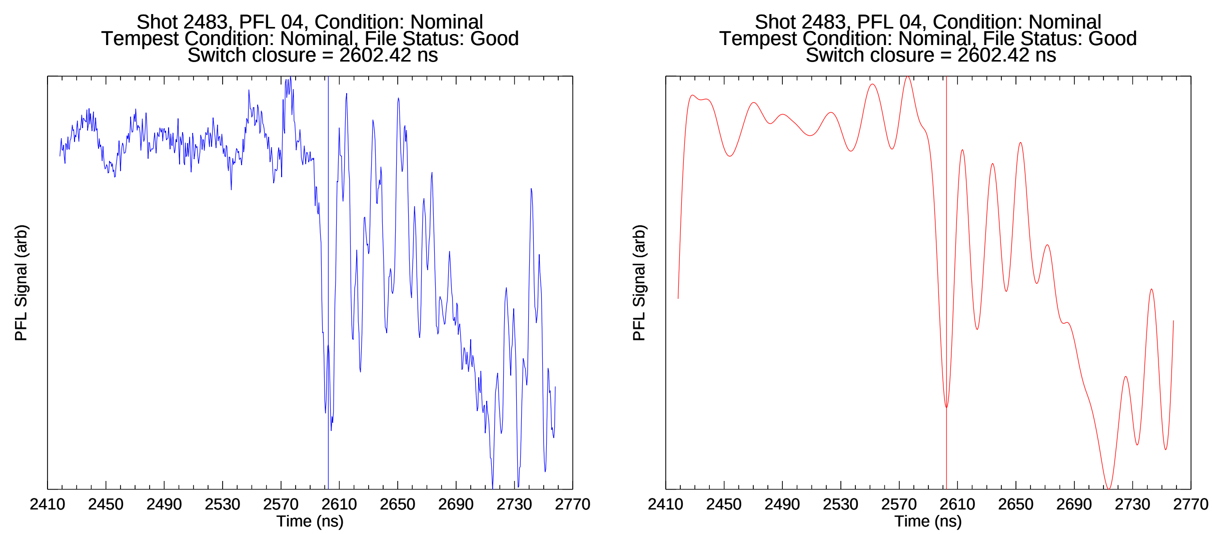

Figure 27. Unfiltered (upper, blue) and filtered (lower, red) PFL signals for Z2483, line 4. The vertical lines indicate the time for switch closure. This is an example of a well behaved PFL signal where the minimum that indicates switch closure is easily identified. Without filtering, the PFL signal can be difficult to analyze. A fourth-order Butterworth filter removes noise and retains the important features.

After observing many different filtered PFL signals we found we could apply two relatively simple tests to locate the deep minimum that identifies switch closure. This minimum follows a series of smaller-amplitude oscillations about the PFL's baseline, with one of those oscillations being the PFL “squiggle.”[9]

The first test uses a negative-valued threshold, where the threshold identifies the first deep minimum that is deeper than the average of all the minima in the time range used for analysis. The actual threshold value is the average minimum depth multiplied by a user-selected Calculation Parameter called the “PFL first minimum depth factor,” as shown in Fig. 5. The range of the factor is 0.8–1.2 with the nominal value being near 1. We note that the threshold test can fail if the time range is extended too far beyond the location of the Tempest Laser pulse because oscillations in the PFL signal continue downward, on average, beyond the nominal time range for analysis. Somewhat later in time the PFL signal contains large amplitude oscillations that are mostly positive going, so extending the time range to include any of these features would return the wrong threshold value. This is the main reason for the restriction on positive time range on the popup form in Fig. 4. Although this threshold test is simple, it locates the switch closure time with accuracy of about 90% for all PFL signals, as long as we exclude signals for lines that are Bussed Out. The PFL algorithm itself makes no distinction for lines that are Bussed Out because that condition is monitored and recorded elsewhere in the analysis.

The second condition that tends to indicate switch closure is the location of a minimum that precedes the largest difference between an adjacent minimum and maximum. This test is applied by first finding the maximum difference for all adjacent extrema within the time range for analysis, and then locating the closest minimum that occurs earlier in time. When we compare these two methods they agree for probably more than 90% of all PFL signals. Although this method for locating the switch closure time is also fairly reliable, and is monitored during analysis, the code reports only the position of the first large minimum indicated by the negative-valued threshold method.

Although PFL signals probably have the lowest SNR of the three signals used by the analysis, with proper filtering they are easy to analyze and their analysis is not prone to any errors that can interrupt program execution. Unfortunately associating switch closure with the first deep minimum in the PFL signal is not always correct. Sometimes the actual switch closure time occurs at a less-deep minimum that can precede or follow the first deep minimum, and fortunately this discrepancy can be identified by analyzing the LSD signals. This characteristic of PFL signals – more so than any other – is what limits the reliability of the PFL-derived switch closure time to about 90%.

6.7 Analysis of the LSD Signals

Analysis of the LSD signals provides two pieces of information. The baseline zero-crossing point derived from a linear fit to the LSD’s rising edge is associated with the trigger section close time, and a secondary peak in the time-derivative of the LSD is associated with the switch closure time, as we saw in Fig. 26. The additional identification of the switch closure time provided by the LSD’s derivative, combined with the equivalent signature from the PFLs, lets us infer the switch

[9] The PFL squiggle is associated with closure of the trigger section of the switch, as described in Ref. [1]. This code makes no attempt to locate the PFL squiggle and instead uses the baseline zero-crossing from a linear fit to the LSD’s rising edge for equivalent information.

closure time with close to 100% reliability.

Although the LSD signals provide valuable information about switch closure times, they can be much more difficult to analyze than signals for the PFLs. Due to various anomalies there is no "one size fits all" method for analyzing these signals, so the resulting algorithm to carry out this task is a bit complex. We'll describe it in detail here primarily for the purpose of documentation, but also because an informed user of LTS Timing Analysis will develop into a user that obtains results quickly and efficiently.

LSD Rising Edge

The starting point in the analysis is to locate the onset of the LSD signals. In the raw data that first edge is negative going, so for purely aesthetic considerations we invert the sign of the signal and look for a rising edge. Although we could attempt to use the Tempest time to establish the Time Range for Analysis, some subtleties in the LSD signals themselves, and the occasional pre-fire or late-fire, make that approach unreliable, so we use a threshold method instead. There are various ways to determine a suitable threshold value, but one that's fairly reliable is a threshold scaled against the baseline noise. To determine the threshold we calculate the variance of the first 500 data points, which are nominally featureless, and multiply the variance by the Calculation Parameter called the "LSD threshold factor" that is defined in the popup information form shown in Fig. 6, which is accessed through the popup form in Fig. 5. The LSD threshold factor can have values of 700–1000. We search for this threshold value on a rising edge, and once located, we record its corresponding position in time. The Start- and End-times for the Time Range for Analysis are set relative to this threshold time. Arrays for time and data are then extracted from the full data record, with the data array smoothed and filtered as described in Sec. 6.2, and then we take the time-derivative of the LSD signal. Because we need to locate the minima and maxima in the LSD and the LSD's derivative, we apply the same interpolation method used during PFL analysis to both of them. Because filtered and interpolated data arrays can contain semi-divergent features at their endpoints, the time and data arrays are truncated to eliminate these features.

If all LSD signals were created equal we could use the location of the LSD threshold on the rising edge as a starting point to carry out a linear fit, and then find the baseline zero crossing that corresponds to the trigger section close time. The LSD signal in Fig. 28 shows an example where this approach was successful. Unfortunately there are anomalies in the LSD rising edges that are usually associated with low SNR signals that complicate finding a good starting point for the linear fit, with Fig. 29 illustrating one example. For the signal in Fig. 29 we might be tempted to reduce the LSD threshold factor sufficiently to find the first linear portion of the rising edge, however doing so would likely result in errors for other signals. For this reason the form in Fig. 5 sets the lower limit of the LSD threshold factor to an appropriate value, which happens to be 700.

Since a threshold test alone can fail for the anomalous signal in Fig. 29, how do we find the correct point to initiate the linear fit? The answer lies in the LSD's derivative, where Fig. 30 shows how the first big peak in the derivative conveniently coincides with the midpoint of the correct part of the rising edge. For a LSD signal with a nominal SNR the first peak in the derivative is almost

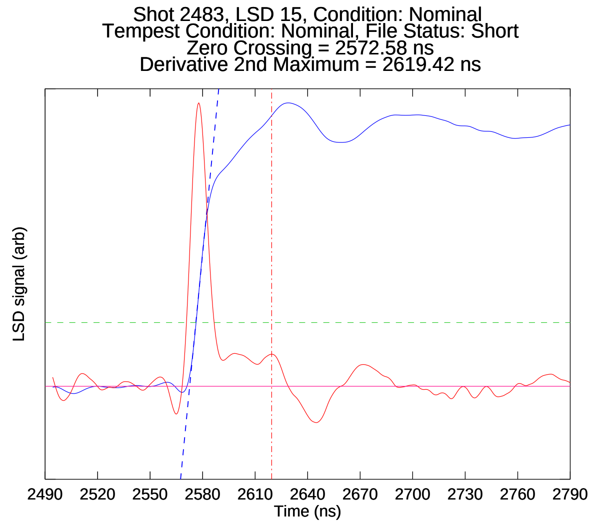

Figure 28. LSD signal (blue) with its rising edge intersected by the green threshold line at a location that can be used to initiate the linear fit. Note that this signal came from a short data file as described in Sec. 5.1, demonstrating that the extra effort in recovering data from an otherwise corrupt file was worth the effort. The derivative is shown in red with the dot-dash line indicating the switch closure time.

always its global maximum, and if this is true the starting point is easy to locate. However for the low SNR signal in Fig. 29 this is not the case, so we have to be very careful about choosing the correct peak in the derivative. An algorithm that accommodates both "good" and anomalous signals must take a comprehensive and step-wise approach, and we describe that algorithm below.

Examination of the LSD signals in Figs. 26, 28, 29, and 30 reveals a shallow and nominally negative-valued minimum located just before the LSD's rising edge, and Figs. 26 and 30 reveal a similar feature in the LSD's derivative. These features are universal, with the minimum in the LSD's derivative always preceding the minimum in the LSD, so we begin by finding the array index from an array of minima locations that identifies this shallow minimum. If the threshold time is wrong, as it is in Fig. 29, the initial test we use, which looks for the minimum lying closest to the threshold time, can identify a minimum whose value is positive and too large to be the correct minimum. This will occur for the LSD signal in Fig. 29, where the incorrect minimum occurs at about 2600 ns. To test for this possibility we make sure the value of the minimum is less than half the threshold value, and if it isn't, we reduce the minima-array index by one, check the new minimum value, and continue stepping down in minima-array indices until the minimum value is sufficiently small. If this condition cannot be satisfied before we reach the first index in the minima array, the analysis is considered a failure, and the dialog message in Fig. 9 will appear. If we can find the correct minimum in the LSD signal, we proceed to the next step, which involves finding the equivalent minimum in the LSD's derivative.

The test applied to the derivative is fairly simple and requires locating the last minimum in the

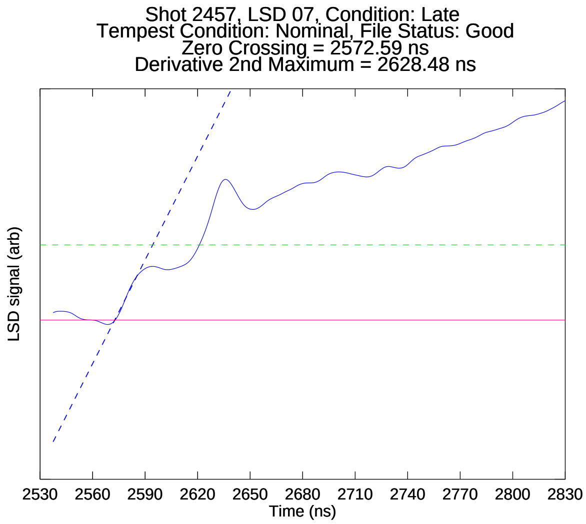

Figure 29. LSD signal with small amplitude and low SNR where the threshold line intersects the rising edge in the wrong location. The LSD analysis algorithm tests for this problem and correctly applies the linear fit to the rising edge, as shown.

LSD's derivative that just precedes the minimum we just located for the LSD signal. From the

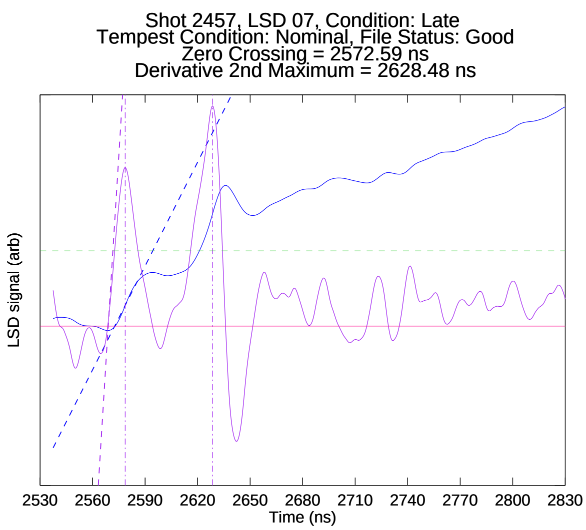

Figure 30. The small amplitude, noisy LSD signal in Fig. 29 including the derivative, which illustrates how the first large peak in the derivative is used to locate the correct starting point for initiating the linear fit. The derivative for this signal is also anomalous because the first peak is not the global maximum peak.

location of that minimum in the derivative, we move up in time to locate its next closest maximum because the vertical line that intersects that maximum also intersects the location on the LSD's rising edge where we want to begin the linear fit. This vertical line can be seen in Fig. 30. All these manipulations are necessary to accommodate the anomalous case where the first maximum in the LSD's derivative is not the global maximum, or equivalently, to accommodate low SNR LSD signals. Finally, the linear fit to the LSD's rising edge, and to the fit to the rising edge of LSD's derivative, are carried out as described in Sec. 6.3.

LSD Switch Closure Time

The final step in analyzing the LSD signals is to determine switch closure times from the their derivatives. In this process the fundamental feature we look for is the first negative-valued minimum that occurs just beyond the signature for switch closure, or equivalently, we look for the first zero-crossing following the derivative's first big peak, which is usually its global maximum. For the well behaved LSD signal in Fig. 28 this minimum occurs at about 2645 ns, and for this signal it's very easy to find. Once that minimum is located, the next adjacent maximum that occurs earlier in time, and that has a sufficiently large positive value, is the signature for switch closure. For the LSD derivative in Fig. 28 switch closure occurs at about 2620 ns.

Several of the Calculation Parameters in the popup form in Fig. 5 are involved in the search for the LSD switch closure time, including: "LSD derivative local minimum depth," which sets a threshold for the depth of the minimum beyond switch closure; "LSD derivative local maximum height," which sets a threshold for the height of the maximum that is the signature for switch closure; and "LSD derivative first local minimum window," which sets a time range where the minima and maxima that indicate switch closure can be located. When appropriate values are used for these Calculation Parameters, simple techniques for searching through the derivative's minima and maxima will return the switch closure time for the majority of LSD signals. Understanding the effects of the Calculation Parameters is important, so new users of LTS Timing Analysis should review the actions of the various Calculation Parameters by opening the form in Fig. 5 and then clicking their associated Info buttons to read their descriptions.

As before with the search for the LSD rising edge, anomalous features in the derivative can lead to errors while searching for the switch closure time. The code cannot trap all possible errors caused by these anomalies, but it does catch many of them, so we describe those that are successfully accounted for and the steps taken to recognize them.

Early zero crossing following the global maximum

Occasionally there is a spurious zero crossing leading into a negative-valued minimum that occurs too early in time. Sometimes the early minimum is a continuation of the falling edge of the first big peak in the derivative, which is nominally its global maximum. To prevent this feature from compromising the analysis we accept only those negative-valued minima that fall within the range of the user-selected Calculation Parameter "LSD derivative first local minimum window," which has a minimum time relative to the location of the derivative's first big peak of of 10–35 ns. Any minimum that occurs before the minimum time for the analysis window is ignored.

Negative-valued minimum with insufficient depth

Occasionally there is a very shallow negative minimum in the LSD derivative that falls within the nominal range of the "LSD derivative first local minimum window." This shallow minimum might precede the correct secondary peak that indicates switch closure and result in a spurious closure time. To prevent this type of anomaly from compromising the analysis we compare the depth of any candidate minimum relative to the normalized amplitude of the first big peak in the derivative. If a minimum is too shallow we continue looking for a deeper minimum. This minimum depth is controlled by the user-selected Calculation Parameter "LSD derivative local minimum depth."

Absence of a negative-valued minimum within the analysis window

Sometimes an otherwise nominal LSD derivative won't contain any negative-valued minima within the "LSD derivative first local minimum window." In other words, the derivative might possess an anomalous DC offset which prohibits successful completion of the analysis. To prevent this anomaly from compromising the analysis, the algorithm that searches for candidate minima repeats its search up to 10 times, and for each successive search it subtracts a DC offset whose size is determined from the Calculation Parameter called "LSD derivative incremental offset." If no qualifying minimum is found after 10 passes the analysis is considered a failure, and the dialog message in Fig. 9 will appear. Occasionally this failure is due to a cascade section run time that is longer than usual, and it can be eliminated by increasing the length of the analysis window. This is done through the popup form in Fig. 5 where the maximum time allowed for the window is 140 ns, relative to the first big peak in the derivative. Using the baseline adjustment technique described here with a longer than usual analysis window is of course not foolproof.

The derivative's first maximum not its global maximum

Usually the global maximum of the LSD derivative is also its first big peak, which coincides in time with the LSD's rising edge – but not always. If the first big peak in the derivative is not the global maximum, the code assigns the switch closure time to the global maximum, which is almost always the second big peak in the derivative. LSD derivatives with this characteristic are rare, however automatically assigning the switch closure time this way can obviously fail, but it doesn't fail very often. The LSD signals where this situation occurs tend to have a low SNR and are generally difficult to analyze using the search algorithms described above.

No maximum to indicate switch closure time

Sometimes the algorithm that searches for minima and maxima can't find a maximum in the first derivative between the negative-valued minimum and the first big peak. What we usually see in this case is a non-constant slope that is positive-going with decreasing time. Because the slope isn't constant the second derivative can display local maxima and minima at points where the magnitude of the slope changes. If maxima in the second derivative are present, we use the first one in the second derivative that just precedes the negative-valued minimum in the first derivative to identify the switch closure time. If this second derivative test fails then the analysis is considered to be a failure.

7 Condition Flags

During analysis the condition of each signal for each line is evaluated and flags are set accordingly. The flags include the condition of the data file and also conditions for the results of the analysis. There is some linkage between conditions for various signals because the time of the Tempest pulse for each line is used to determine if PFL and LSD signals occur at a time that is Nominal, Early, or Late. These time relationships are reported even when lines are Bussed Out, however the Bussed Out condition itself is recorded in report files, and also indicated several ways with the on-screen plots. The various condition flags are described below.

7.1 Condition Flags for Data Files

The conditions for data files were mentioned previously in Secs. 3.3. and 5.1. The three conditions reported for each of the 108 files that are read from the remote server are Good, Bad, and Short. The condition for a missing file is not reported because program execution halts when a missing file is encountered and the user must then select another shot for analysis, or quit the program. As described in Sec. 5.1 a file flagged as Short might undergo a somewhat complex repair process, but the flags don't indicate this – short is short regardless. The condition flags are reported in the report file Shot_***n***.csv and they are also saved in the locally stored binary files.

7.2 Tempest Laser Condition Flags

The condition flags for the Tempest Laser pulses are No Pulse, Nominal, and Bussed Out, with No Pulse being very rare. In the case of a No Pulse condition the Tempest reftime that is read from the remote server is used instead of the time derived from the actual pulse. This is done because the Tempest time is passed to the PFL analysis routine to establish the time range for analysis, as described in Sec. 6.6. Substituting the reftime prevents a data acquisition error, or a bad photodiode that detects the laser pulse, from compromising the analysis.

For the Tempest Lasers the No Pulse condition sets all numerical values determined from analysis to IEEE floating point NaN (Not a Number). The NaN values are ignored by plotting routines, but when present, will cause many of the quantities derived from the full analysis of the Tempest, PFL, and LSD signals to also be set to NaN. These quantities are saved in the report files so the effects of a NaN will be obvious. See Appx. A.2 for a description of the derived quantities.

7.3 PFL Condition Flags

The condition flags for the PFL signals are Early, Nominal, and Exceeds NSRT, where NSRT denotes the user-selected Calculation Parameter "Nominal switch runtime" in the popup form in Fig. 5. The PFL analysis routine takes no special action for Bussed Out lines, and the PFL condition flags themselves have no effect on completion of the PFL analysis. Consequently spurious PFL results are deduced from tests like the LSD-PFL Discrepancy described in Sec. 3.3, the Bussed Out flag for the Tempest Lasers, or in the case of a Bad data file that contains random noise, from a data file flag.

There are also two alternative conditions for the PFLs that are stored as variables in the code, which are Time Error Warning and Nominal, but they are not reported to the user. They result from the second method of finding the switch closure time from the PFL signals that was described in Sec. 6.6. These conditions are artifacts but were retained as programming diagnostic tools.

7.4 LSD Condition Flags

The condition flags for the LSD signals are No Rising Edge, Early, Late, Nominal, or Analysis Failed, where Late refers to the user-selected Calculation Parameter "LSD late time" in the popup form in Fig. 5. For analysis of the LSDs the conditions of Early, Late, and Nominal have no outcome on the analysis, and as before for the PFLs, a Bussed Out condition will still result in an attempt to carry out the analysis.

The conditions of No Rising Edge and Analysis Failed have similar outcomes, with almost all numerical values derived from the analysis being set to IEEE NaN – but with one exception. For No Rising Edge the Tempest reftime is used to define the time range for analysis and this information is retained. For Analysis Failed the information for the time range for analysis is retained, and because an actual analysis was attempted, the temporal locations of the "LSD derivative first local minimum window" are also retained. This is done because subsequent plotting of the LSD derivative with the local minimum window can sometimes reveal the reason for a failure. Otherwise, a failed analysis and the presence of IEEE NaN will result in many derived quantities that appear in the report files also being set to NaN.

References

[1] K. Lechien, J. E. Potter, M. E. Savage, J. R. Woodworth, T. G. Avila, J. P. Corley, S. D. Ploor, J. J. Seamen, "The PFL Squiggle: An Independent Monitor of Trigger and Cascade Section Runtimes," Sandia National Laboratories, Albuquerque, NM, **SAND2009-6158C**, 2009.

Appendix

A.1 Form for Interactive Analysis

The popup form with the tool for carrying out Interactive Analysis is shown below.

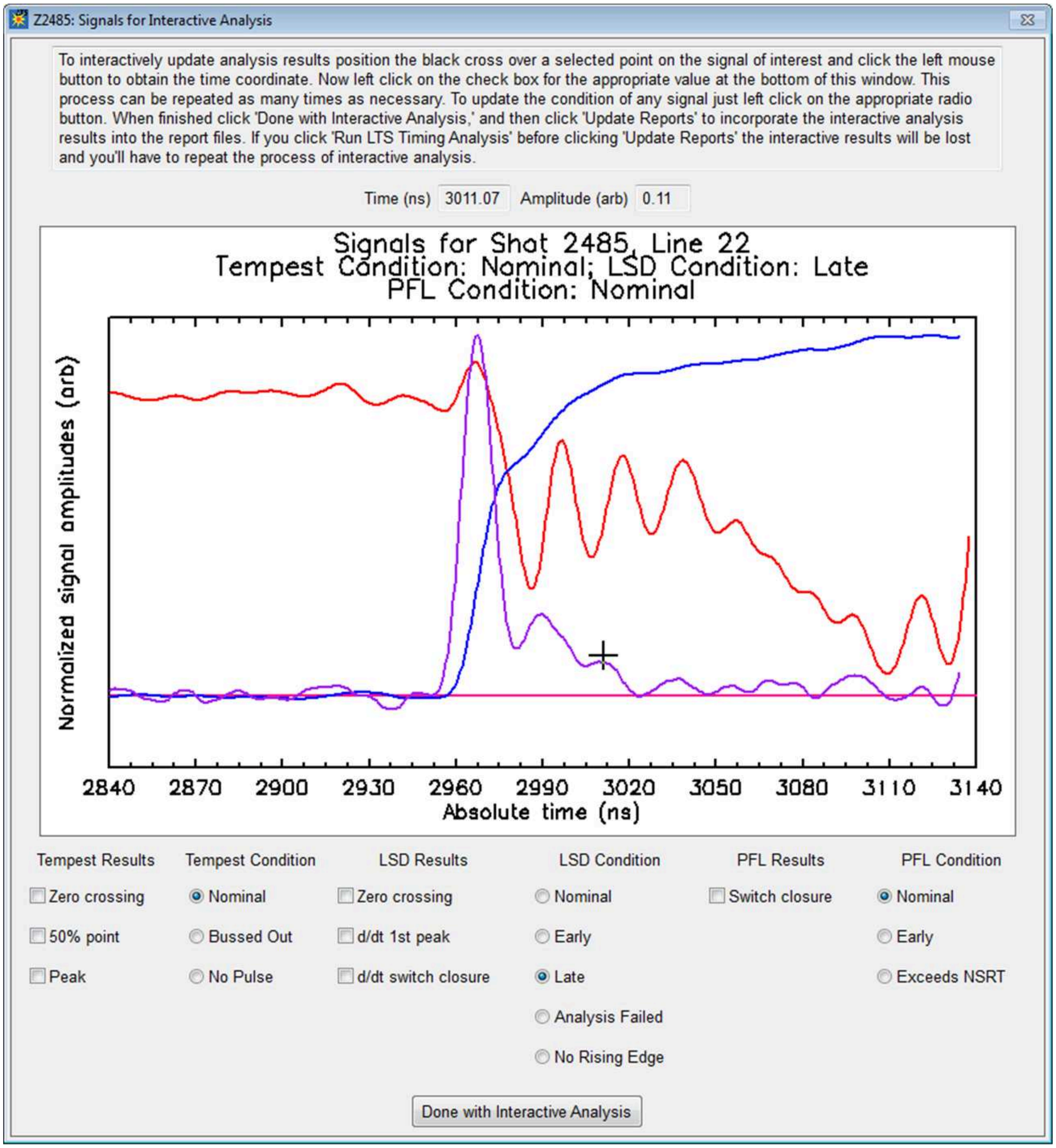

Figure A.1. Tool for Interactive Analysis. The black cross cursor shows the location of the peak that indicates switch closure.

A.2 Contents of the Report Files

The report files contain various quantities derived from the analysis results that characterize the performance of the laser triggered switches. Two of the reports have .csv formats with headers that define their contents. The report in .pdf format contains numerical data and graphics.

A.2.1 Shot_*n*.csv

This report file contains information for a single *Z*-shot. The numbered columns in this report correspond to the definitions below, with TC and NTC denoting time-corrected and not-time-corrected, RT and ZC denoting run time and zero-crossing, and closetime the PFL close time read from remote server. The comment below the numbered list warns the user that some columns will contain NaNs when there are Bussed Out lines.

Column numbering and column definitions:

(0) Switch No.
(1) Tempest condition
(2) Tempest file status
(3) LSD condition
(4) LSD file status
(5) PFL condition
(6) PFL file status
(7) Tempest deviation 50% = pulse 50% time NTC - tempest ref time
(8) Tempest deviation ZC = pulse rising edge ZC NTC - tempest ref time
(9) Tempest ZC NTC
(10) Tempest ZC TC
(11) LSD ZC TC
(12) LSD 1st deriv 2nd peak TC
(13) PFL closure NTC
(14) PFL closure TC
(15) PFL closure NTC - Tempest ZC NTC - NSRT
(16) PFL deviation = PFL closure NTC - closetime - NSRT
(17) Trigger RT = LSD ZC TC - Tempest ZC TC
(18) Cascade RT (LSD) = LSD 1st deriv 2nd peak TC - LSD ZC TC
(19) Cascade RT (PFL) = PFL closure TC - LSD ZC TC
(20) Cascade RT discrepancy = cascade RT (LSD) - cascade RT (PFL)
(21) Cascade RT reported = (cascade RT (LSD) + cascade RT (PFL))/2
(22) Total switch RT (LSD) = trigger RT + cascade RT (LSD only)
(23) Total switch RT (PFL) = trigger RT + cascade RT (PFL only)
(24) Total switch RT (ave LSD PFL) = trigger RT + cascade RT (avereage of LSD and PFL)

Header comments:

Note: This file contains derived quantities based on the raw results from the analysis

This means bussed out lines usually result in NaNs being written into (8), (9) and (14)-(21), but not always.

A.2.2 LTS_Report_Data_*n*_*m*.csv

This report file contains information for a a series of *Z*-shots and it is continuously updated for each new *Z*-shot analysis. The file is arranged in order of increasing *Z*-shot where each row contains the information for one shot. The abbreviations and definitions for this file are given in its header which is shown below.

Abbreviations and corresponding definitions from A.2.1	*Column titles*
ALT: Accuracy of Laser Timing, Col. (7)	Shot
TSR: Trigger Section Runtime, Col. (17)	Shot Date
ESRD: Entire Switch Runtime, Col. (22)	ALT Ave
PFLD: PFL Deviation, Col. (16)	ALT SDEV
SDEV: Standard Deviation	ALT Early
	ALT Late
	TSR Ave
	TSR SDEV
	TSR Early
	TSR Late
	ESR Ave
	ESR SDEV
	ESR Early
	ESR Late
	PFLD Ave
	PFLD SDEV
	PFLD Early
	PFLD Late

Header comments:

Note: IEEE NaNs in the analysis results indicate missing data or a bussed-out lines and should not appear in the table below.

All NaNs are ingnored for the purpose of determining the calculated values in this file.

A.2.3 LTS_Report_*Zn*.pdf

This report file begins with a title page that is shown in Fig. A.2 that contains information entered through the popup form in Fig. 11. The next four pages contain graphical and numerical results that correspond to the abbreviations and definitions in Appxs. A.2.1 and A.2.2. These pages are shown in Figs. A.3–A.6 with the titles: “Accuracy of Laser Timing,” column (7); “Trigger Section Runtime,” column (17); “Entire Switch Runtime,” column (22); and “PFL Deviation,” column (16). For the histogram plots in this report the Calculation Parameter “Number of switches per histogram bin for plots” at the bottom of the popup form in Fig. 5 controls the bin width, with the available widths being 1, 2, 5, and 10.

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Z Facility LTS Report

Report prepared by: Author

Z2526 Shot Date: 06/27/2013

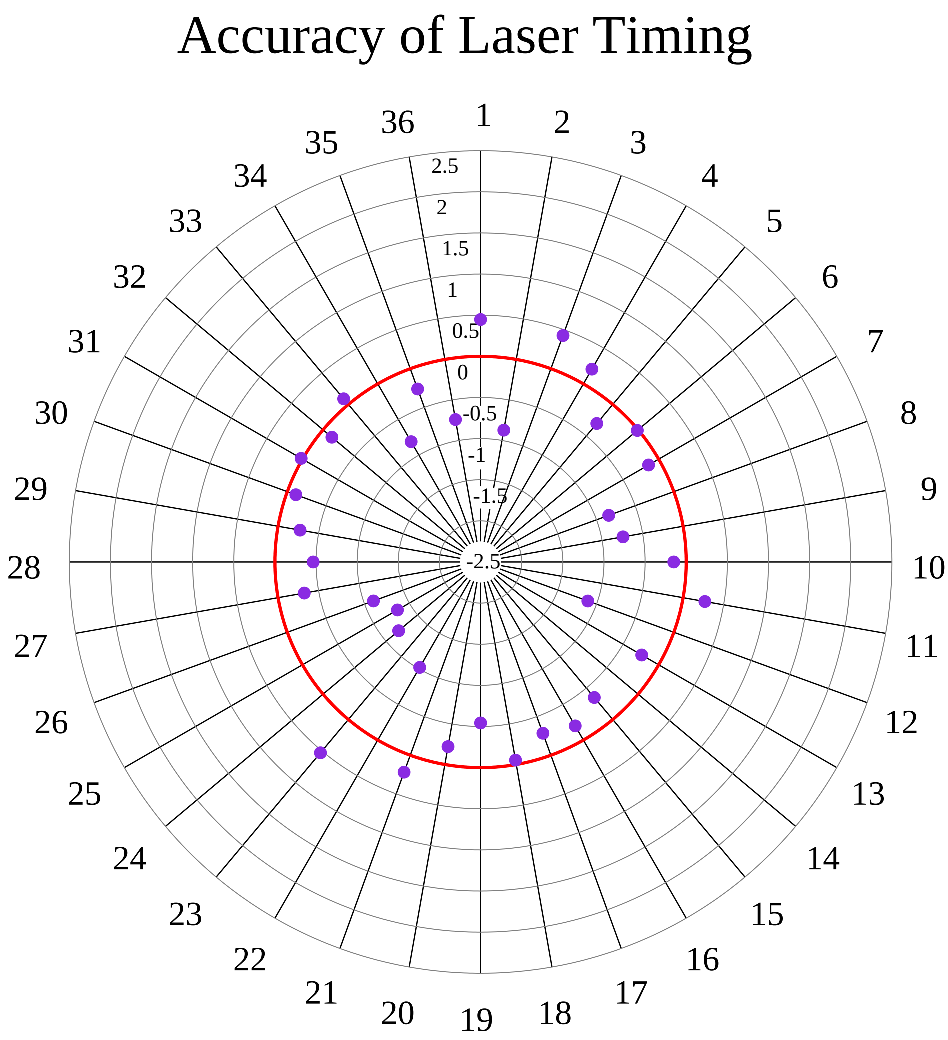
Experiment Name: Z2526

Experimenter: Tom Ao

Executive Summary:

XRTS, hardware set A0258D

Figure A.2. Page 1 of example report: LTS_Report_Z**2526**.pdf



This plot shows the timing error of each of the 36 lasers on the downline shot. Missing data points indicate off-scale values.

Average Timing Error:	-0.333 ns
Standard Deviation:	0.491 ns
Earliest Line:	-1.333 ns
Latest Line:	0.528 ns

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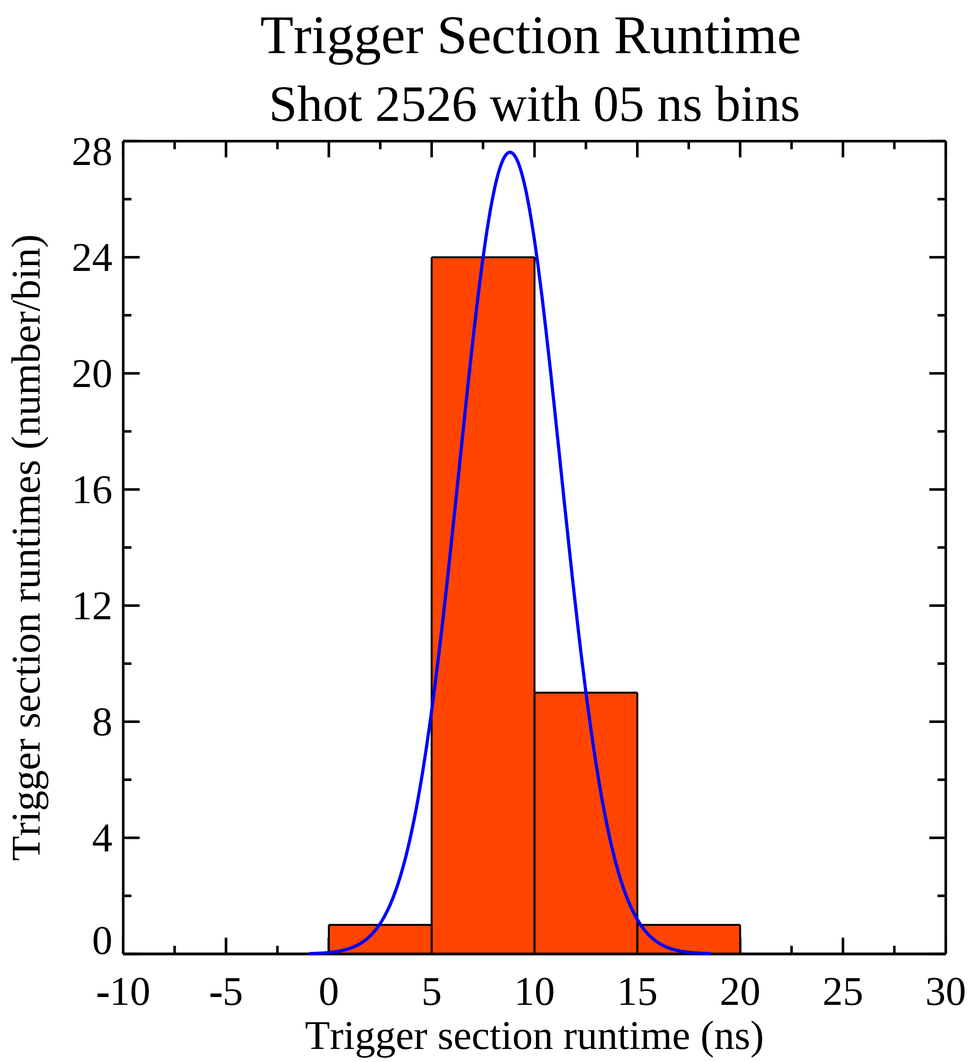
Figure A.3. Page 2 of example report: LTS_Report_Z**2526**.pdf



This plot is a histogram of the trigger section runtimes
All bussed out lines are omitted from the analysis.

Average Timing Error:	8.879 ns
Standard Deviation:	2.674 ns
Earliest Line:	0.350 ns
Latest Line:	16.693 ns

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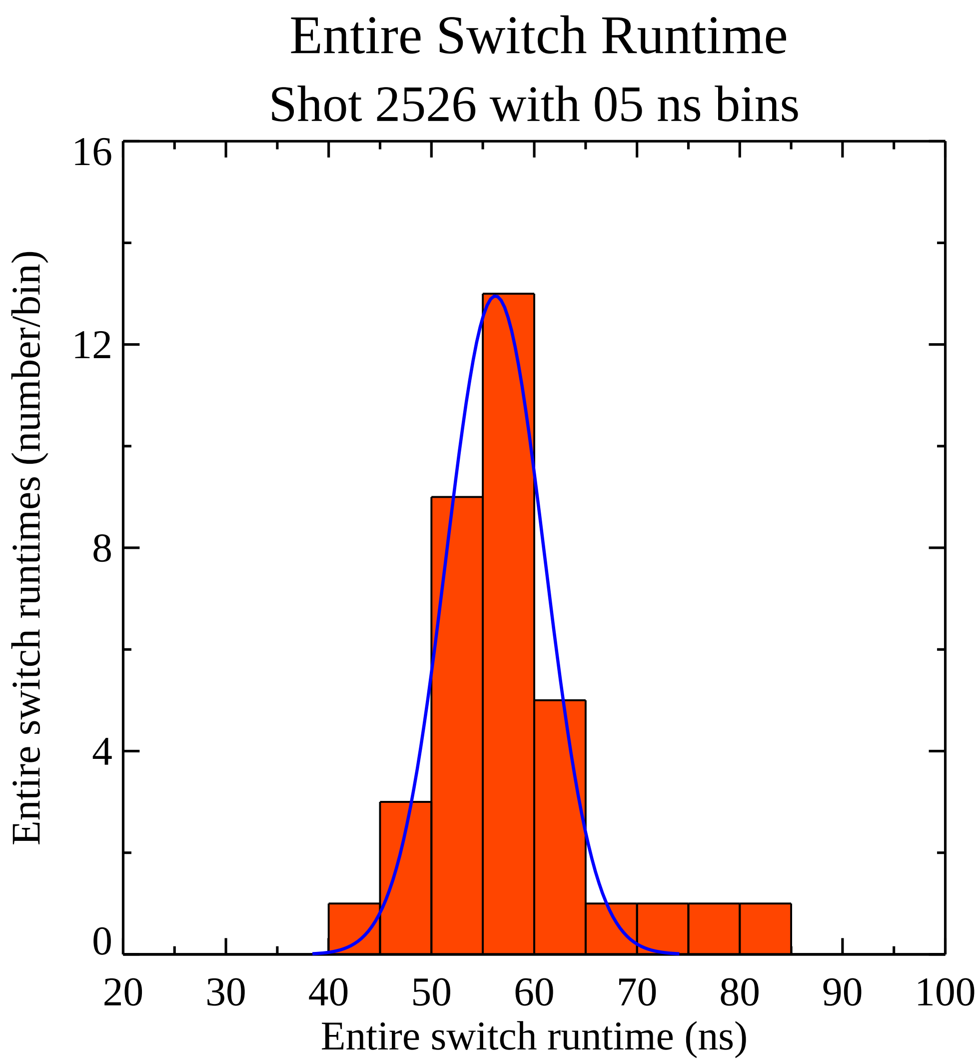
Figure A.4. Page 3 of example report: LTS_Report_Z**2526**.pdf



This plot is a histogram of the entire switch runtimes
All bussed out lines are omitted from the analysis.

Average Timing Error:	57.673 ns
Standard Deviation:	8.019 ns
Earliest Line:	42.060 ns
Latest Line:	84.999 ns

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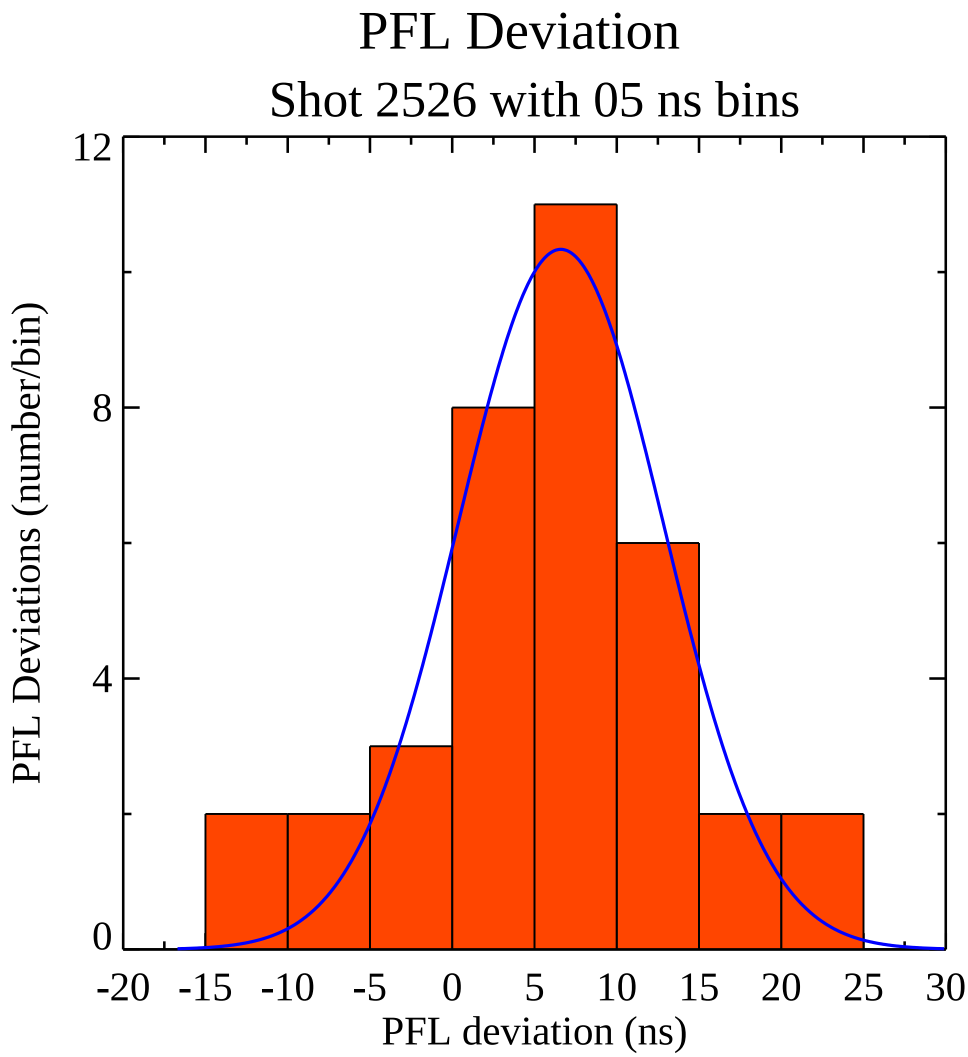
Figure A.5. Page 4 of example report: LTS_Report_Z**2526**.pdf



This plot is a histogram of the PFL deviation from the desired machine timing average. All bussed out lines are omitted from the analysis.

Average Timing Error:	5.908 ns
Standard Deviation:	7.733 ns
Earliest Line:	-10.534 ns
Latest Line:	22.164 ns

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Figure A.6. Page 5 of example report: LTS_Report_Z**2526**.pdf

A.3 Programming Notes

LTS Timing Analysis was written in the IDL language by Dr. Darrell Armstrong in Org. 1682 during 2012–2013. The code and its algorithms were developed with the assistance of Dr. Jens Schwarz who was the Person in Charge of LTS during part of the same time period.

The main GUI and most popup forms, and all analysis algorithms, were written by Dr. Armstrong, however the code makes substantial use IDL freeware available from archives, and code available from the IDL consultant David Fanning. For full implementation LTS Timing Analysis also requires the open source applications Ghostscript and ImageMagick.

LTS Timing Analysis makes use of a few objects but is not an object oriented code. It does however pass all data among event handlers using pointers (as they are defined in IDL – not as they are defined in the language C) and therefore it does not contains any common blocks. The GUI definition module and most event handlers are contained in one file with total length of about 6000 lines, and there are 26 subroutines and functions in separate files. The code is fairly robust and is extensively commented so that any competent IDL programmer should be able maintain the code without difficulty. LTS Timing Analysis has no known memory leaks and will usually require no more than 50 Mbyte of dynamic memory unless a very large number of *Z*-shots are processed using Multi-Shot Analysis or Signal Quality Analysis.

Documentation for LTS Timing Analysis was generated using IDLdoc 3.5.1 using the rst document format. The documentation is in HTML format and includes the source codes. The index for the HTML documentation is accessed through the Help menu.

DISTRIBUTION:

1	MS	0899	Technical Library, 9536 (electronic copy)
1	MS	1191	John Porter, 1682 (electronic copy)
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