The Development and Testing of a Signal Processing Algorithm to Improve OMEGA Beam Timing

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1. Abstract:

60-beam OMEGA coincidence timing at target chamber center (TCC) is achieved by adjusting individual beamline path lengths until ~1-μJ, 1053-nm, 1-ns laser pulses propagated along each beamline arrive simultaneously at TCC. The final turning mirrors before the target chamber are coated for high reflectivity at 351 nm. Unfortunately, at 1053 nm, this creates a second delayed pulse from the back surface of the mirror. If the wedge angle of the mirror is small, then both the timing pulse and the delayed pulse reach the detector and oscilloscope. The detector records the sum of these pulses, resulting in a distorted timing signal. Distorted timing signals that were created using an offline test setup introduced 60-ps shifts in timing measurements when using the oscilloscope's built-in analysis routines. A new signal-processing algorithm has been developed that recovers the timing pulse from the distorted pulse shape. Using this algorithm, the recovered timing pulses introduced only a 6-ps timing shift, not 60 ps.

2. Introduction:

OMEGA is a 60-beam laser system capable of imploding ~1-mm-diameter thin-wall spherical fuel pellets pressurized with isotopes of hydrogen gas. The 60 laser beams must arrive coincident at the fuel pellet to produce the pressure and temperature necessary to form helium from the hydrogen by a process known as thermonuclear fusion. Fusion is exothermic, releasing energy in the form of energetic free neutrons. OMEGA utilizes a beam timing system in advance of a 60-beam fusion experiment capable of verifying that all 60 beams will arrive simultaneously at the fuel pellet within ±20 ps. The beam timing system propagates a low-energy, 1-ns, 1053-nm, laser pulse at 5 Hz down each of the 60 beamlines, one beamline at a time. Before propagating down a beamline, a sample of the pulse is sent to a reference photodiode, which connects directly to an oscilloscope and is used as a baseline timing reference. Each beamline's path length varies in distance, which causes the pulse to arrive at the target at different times.

Figure 1 shows a schematic of the OMEGA Laser. The beam timing system positions a photodiode at the center of the target chamber; this is where all 60 beams will ultimately converge. The timing difference of a certain beamline can be calculated from the time the pulse reaches the reference photodiode to the time it arrives at the measurement photodiode. Using this, the timing differences of all 60 beamlines can be compared. For example, a pulse on beamline 1 may take 120 ns to arrive at the target, but a pulse on beamline 2 could take 121 ns if beamline 2 was longer in distance. In beam timing, the PLAS (Path Length Adjustment System) individually tests each beamline and shifts the distance of mirrors to adjust the path length of each beamline so that all of OMEGA's 60 beamlines will be co-timed at the target chamber center.

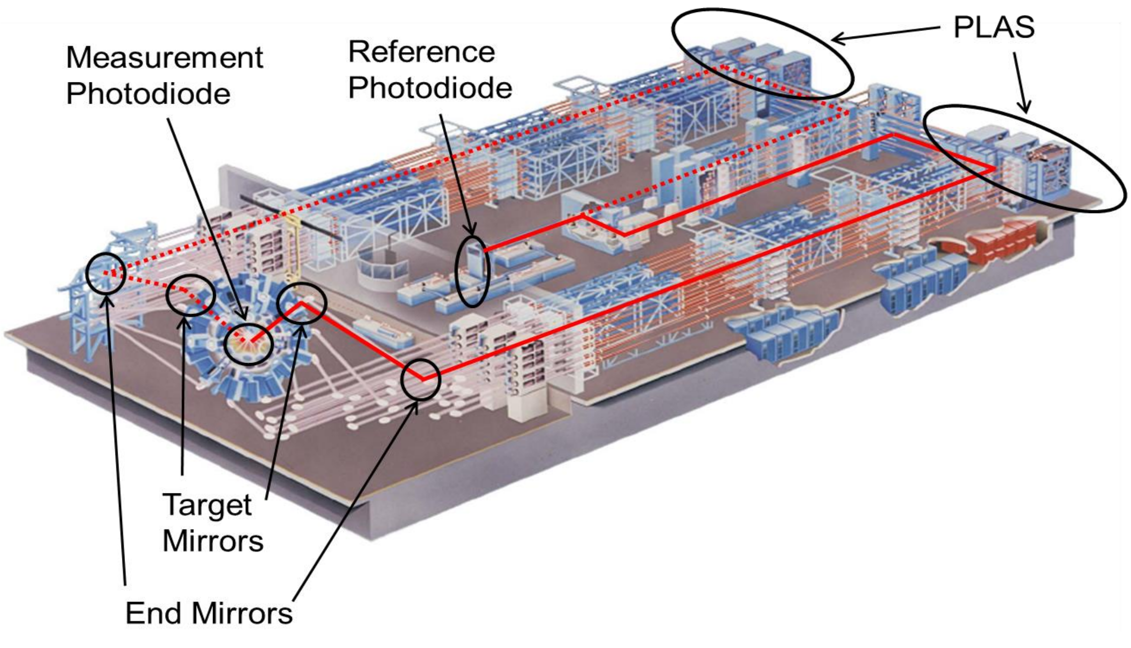

Figure 1: Diagram of beam timing on the OMEGA Laser – Shown are two separate beamlines, which travel different paths but center on the same target. In OMEGA, there are 60 beamlines. The beam timing system utilizes the PLAS (Path Length Adjustment System) to ensure all 60 beamlines are co-timed. This project investigates potential timing errors caused by back surface reflections from the final two turning mirrors, the end and target mirrors.

For a majority of beamlines, adjusting the path length with the PLAS reduces timing errors to as low as 10 ps [1]. However, timing errors as large as 30 ps still exist on some beamlines even after PLAS adjustments. One possible source of error is due to the fact that a 1053-nm laser is used during beam timing while a 351-nm laser is used in an actual shot. 1053-nm laser timing pulses can be propagated at 5 Hz with micro-Joule energy. This is not possible at 351 nm; therefore beam timing is performed at 1053 nm.

The target mirrors and end mirrors are coated for high reflectivity at 351 nm (at greater than 99% reflectivity); however, they transmit at 1053 nm, creating a delayed signal from the back surface [2]. As a result, four timing pulses are generated from a single timing pulse for each beamline at the turning mirrors [3]. Only the pulse that reflects off the front surfaces of both mirrors is the correct timing pulse. The other three are delayed pulses created from back surface reflections. For some beamlines, the wedge angle in one or both of the mirrors is small enough to allow this back surface reflection signal to reach the detector, creating a distorted pulse shape at the detector (figure 2).

The PLAS adjusts each beamline path length based on oscilloscope measurements. For beamlines whose back surface reflections do not overlap the original timing pulse, the oscilloscope measurement is correct. However, when they do, the composite pulse shape creates a distorted signal, giving an inaccurate measurement. This poses a problem for beam timing since the PLAS adjusts the path length based on inaccurate data. In this project, a post-processing algorithm is used to recover the original timing pulse from the distorted composite pulse so that more accurate timing measurements can be obtained.

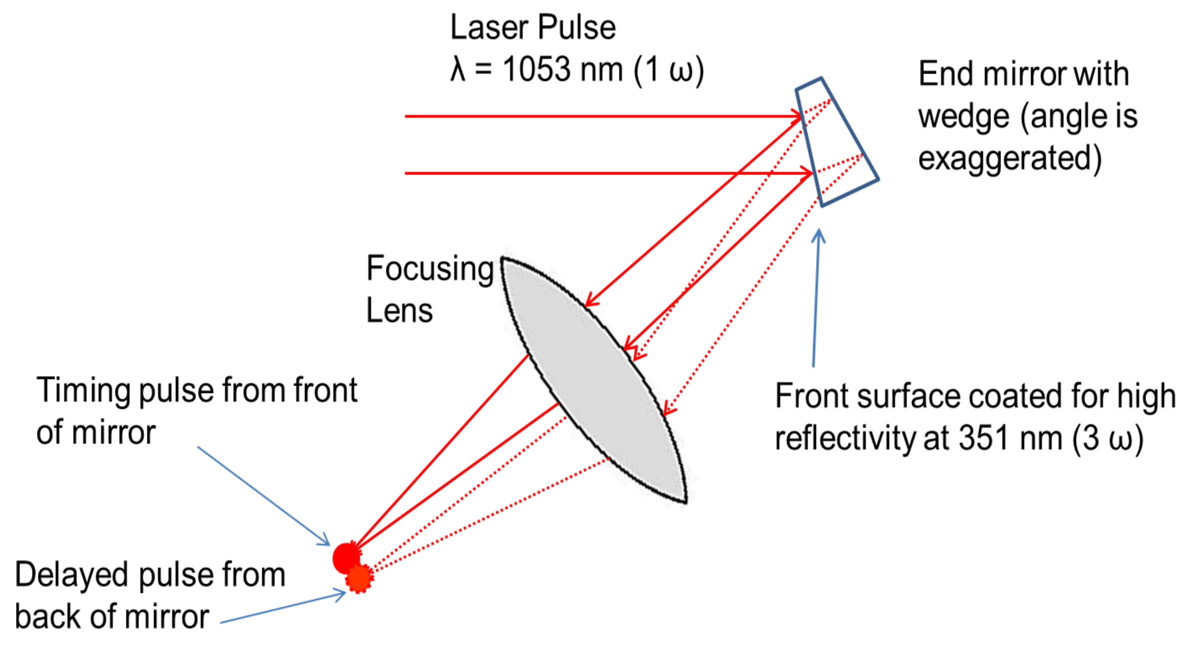

Figure 2: Diagram of Back Surface Reflection from Turning Mirror – A portion of a 1053-nm laser pulse transmits through a mirror coated for high reflectivity at 351 nm, creating a back surface reflection and a second spot when focused to the detector at TCC. The distance between the two spots varies based on the wedge angle of the mirror. When the spots overlap, they create a distorted signal at the detector. In the diagram, only one mirror is shown. In OMEGA, there are two mirrors, creating four spots.

3. Experimental Setup:

An optical setup was built to duplicate conditions seen on OMEGA's beam timing system (figure 3). The system begins with a 1053-nm fiber-delivered laser pulse, which connects to a 10/90 splitter so that 10% of the laser is sent into a photodiode that connects directly to an oscilloscope on channel 1. This represents the reference signal on OMEGA. The other 90% of the laser travels through a 50/50 splitter and the resulting two pulses are injected into the optical setup. The timing pulse (highlighted in blue) takes a shorter path to the fiber while the delayed pulse (highlighted in red) travels a longer distance to reach the fiber. In OMEGA, the final turning mirrors have a thickness of 5 cm. Therefore, the light would take approximately 0.25 ns to travel through one

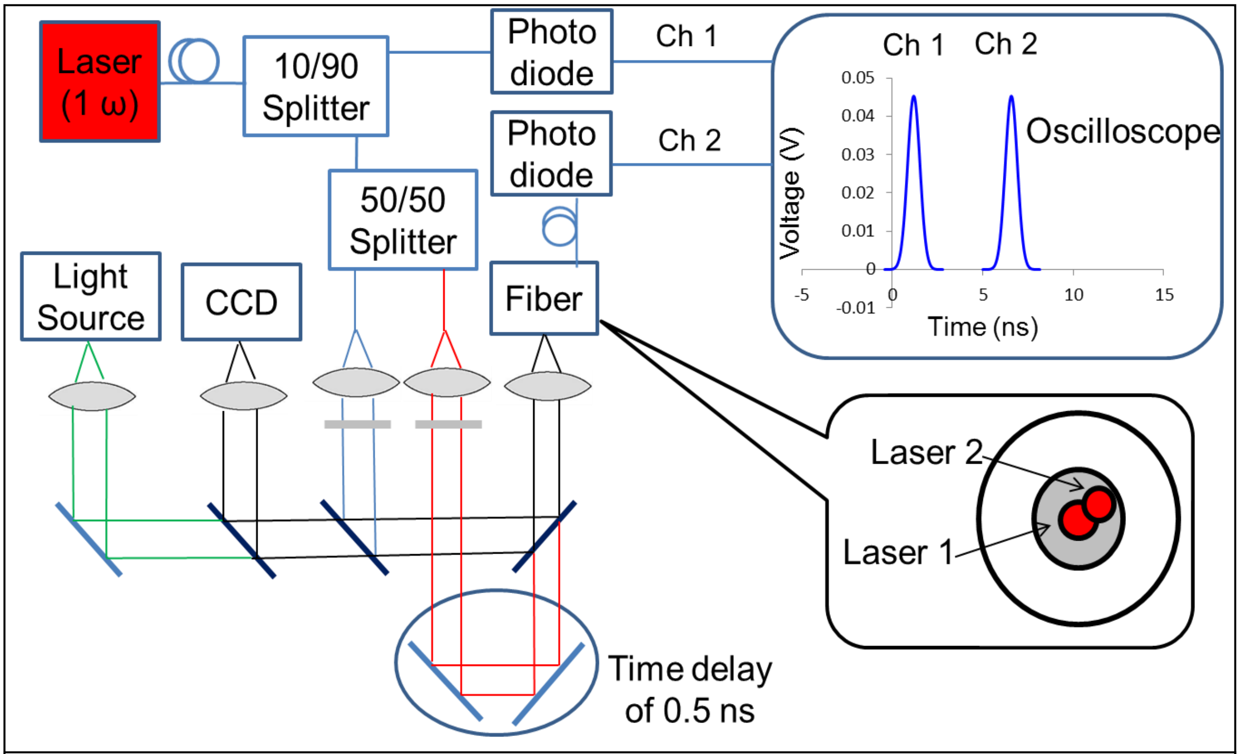

Figure 3: Diagram of Offline Laser System – Diagonal black lines represent beam splitters, while diagonal blue lines represent mirrors. The path lengths of different laser pulses are colored for clarity. The diagram of the fiber shows two laser pulses, one with a time delay, being injected into the fiber core, which can be seen on the oscilloscope.

mirror when striking it at a roughly 45° angle with a speed of 2.0 x 10^8 m/s (3.0x10^8 m/s speed of light divided by 1.5 index of refraction in glass). Hence, it takes about 0.5 ns for the light to travel through both the end mirror and the target mirror. In the offline setup, the path length of the second pulse is extended using two mirrors to achieve a delay of 0.5 ns and replicate conditions on OMEGA. A viewing system composed of a CCD camera and a light source is used to view the timing and delayed pulses so that the two pulses can be adjusted and placed precisely at the desired positions on the fiber core (figure 4). The fiber then connects to a photodiode, which reads on channel 2 of the oscilloscope.

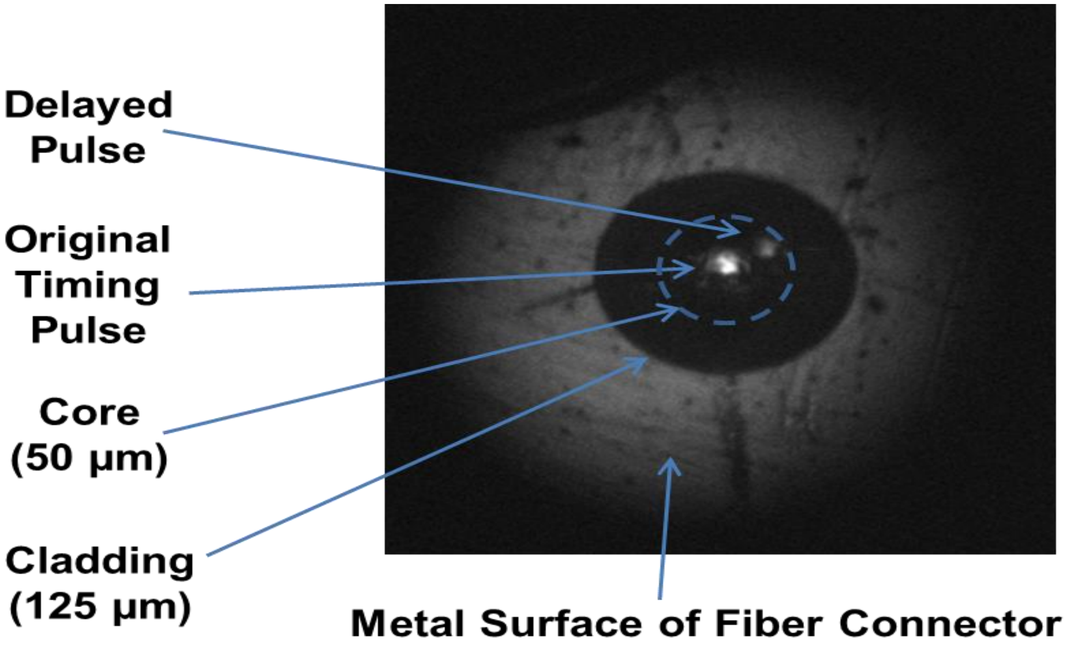

Figure 4: Image of Laser Pulses on Fiber from CCD Camera – An image taken from the offline setup shows the timing and delayed pulses injected into the fiber core.

4. Oscilloscope Measurements:

Using the oscilloscope's current built-in routines, data was taken for two configurations, one with the distorted pulse and one with just the timing pulse. The latter was done by blocking the delayed pulse (red beam in figure 3) with a dark object. In the first configuration, the oscilloscope measured a 3.11-ns timing shift between the reference pulse and the distorted pulse (figure 5a). In the second configuration, the oscilloscope measured a 3.05-ns timing shift between the reference pulse and the timing pulse (figure 5b). Therefore, the oscilloscope measurement was skewed by 60 ps when presented with a distorted pulse. The offline setup using the oscilloscope's built-in routines confirmed that the oscilloscope routines did not compensate for timing shifts caused by distorted pulses.

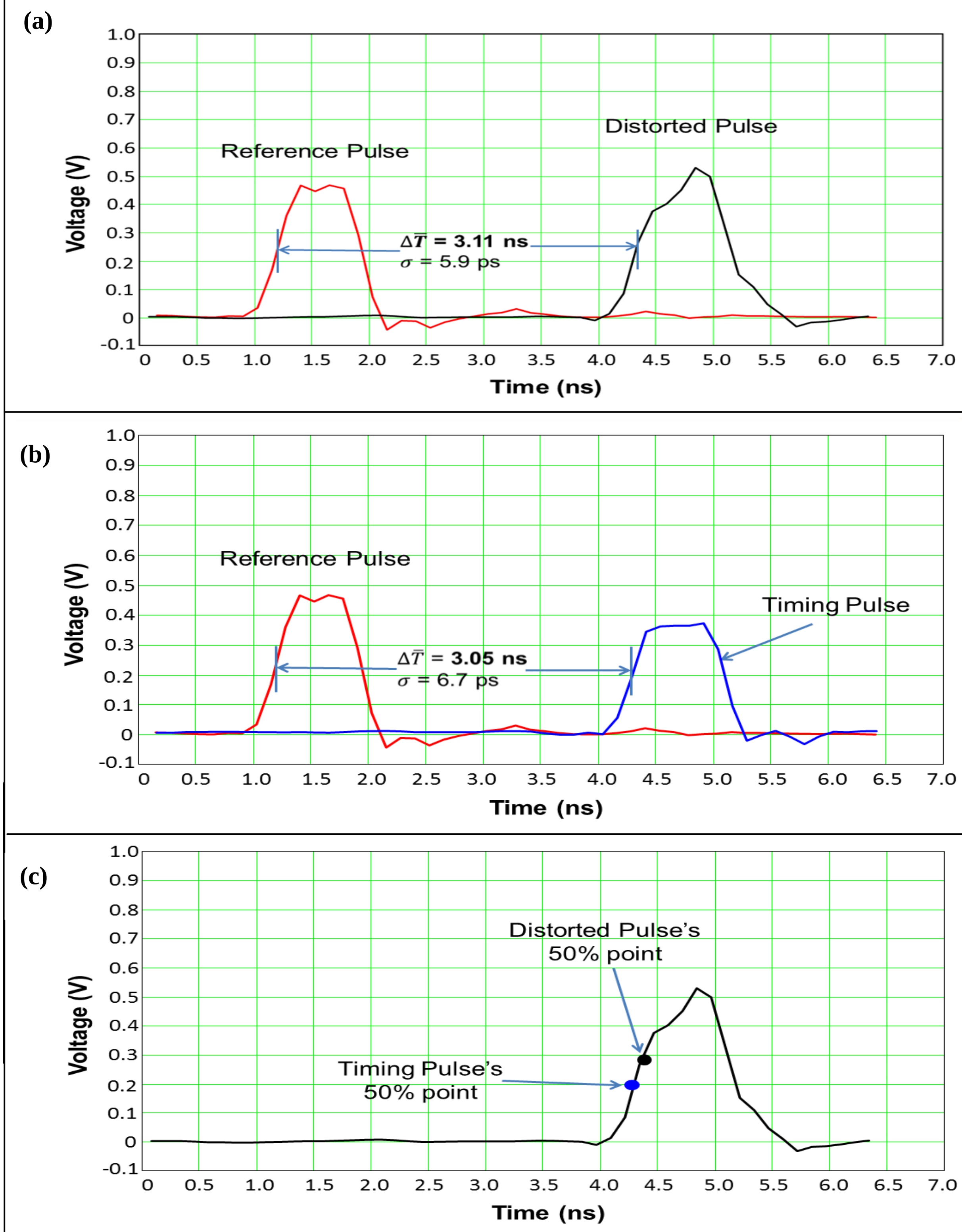

Figure 5: Oscilloscope Data Readings from Offline Optical Setup – The oscilloscope measured a 3.11-ns timing shift between the 50% points of the reference and distorted pulses (a) and a 3.05-ns timing shift between the reference and timing pulses (b). This discrepancy is caused by differences in the 50% points of the timing pulse and distorted pulse (c).

Current oscilloscope routines use a measurement technique called Full Width Half Max (FWHM), which finds the peaks of two pulses, goes down to their respective 50% points, and measures the difference in time between those 50% points (figure 5a). However, because the distorted pulse is the summation of the timing pulse and delayed pulse, its amplitude is larger and thus, its 50% point is higher than the 50% point of the timing pulse (figure 5c). This results in a timing shift in the oscilloscope measurement.

5. Algorithm:

A signal-processing algorithm was developed to correct for timing shifts caused by distorted pulses. The new signal-processing algorithm is designed to recover the timing pulse from the distorted pulse. An assumption made when creating the algorithm is that the reference and timing pulses are similar in shape. This is a valid assumption because both the reference and timing pulses originate from a single laser pulse. The algorithm takes two reference pulses and delays one in time to simulate the back surface reflection. It then scales the two pulses individually in amplitude, as the delayed pulse has lower intensity than the original timing pulse. Finally, the algorithm sums the two pulses to create a distorted pulse that is very similar in shape to the actual distorted pulse, as shown in figure 6.

A least-squares regression equation with a cubic spline interpolation served as the basis for the algorithm. The purpose of the least-squares regression equation is to fit the best curve along the oscilloscope's data points. The cubic spline interpolation first takes four consecutive data points and fits a cubic function through these points. It repeats this process on all possible sets of four consecutive data points. The two reference pulses are then placed on a time grid. The cubic spline interpolation combines the cubic functions and a least-squares regression equation is used to produce the best possible curve from the summation of the two reference pulses. The cubic spline is

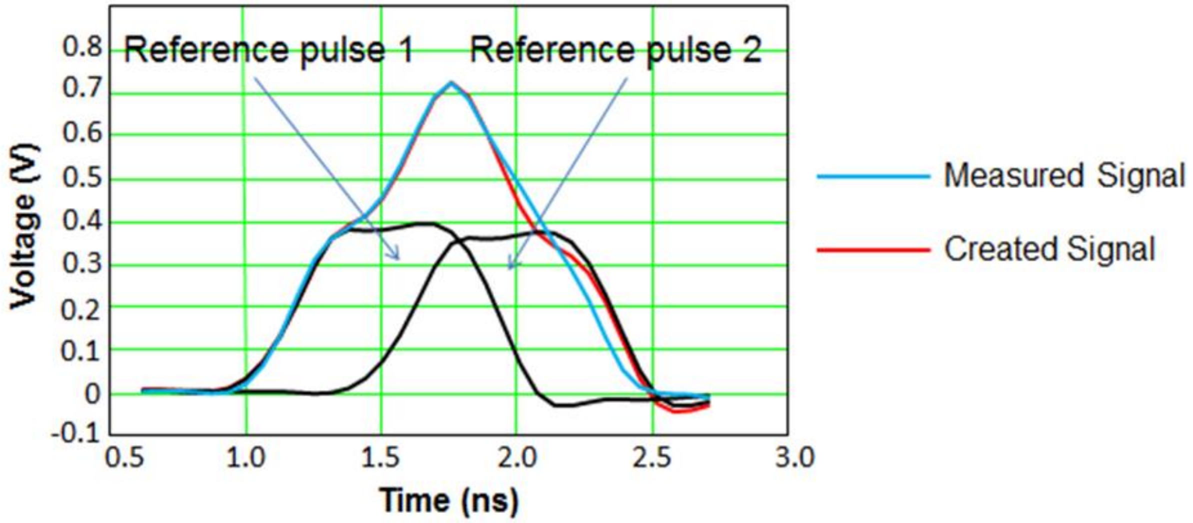

Figure 6: Mathcad Reconstruction of Distorted Pulse Shape – This graph shows two reference pulses, colored in black. One is measured on the oscilloscope and the other is copied and delayed in time, and both are individually scaled in amplitude. The new distorted signal, created from the summation of these two reference pulses, is in red, while the distorted pulse as seen in the offline setup is in blue. The two distorted pulses are nearly identical to each other.

needed because the oscilloscope's sampling rate is one data point every 125 picoseconds (8 GHz), but since the algorithm needs to measure timing shifts to the single picoseconds, data points must be interpolated. The algorithm minimizes the quantity σ, where

$$\sigma^2 = \sum_k \left[A \cdot Ref[t_k] + B \cdot Ref[t_k - \Delta t_1] - Dist[t_k + \Delta t_2]\right]^2$$

A and B are the amplitudes of the two reference pulses and t_k is the point k on the time grid of the first reference pulse. The algorithm sums over k, where t_k ranges from the beginning of the first reference pulse to the end of the second reference pulse. Δt_1 is the time delay of the second reference pulse with respect to the first, and Δt_2 is the time delay of the distorted pulse with respect to the first reference pulse, or the correct timing shift.

Results using the algorithm for a case in which the timing shift, Δt_2, was found to be 3.059 ns are shown in figure 7. Figure 7a shows the reference pulse and the newly created distorted pulse.

Blocking the delayed pulse so that only the timing pulse is injected, a 3.053-ns time difference was measured between the reference pulse and timing pulse (figure 7b). Therefore, the new algorithm only had a 6-ps timing shift when presented with a distorted pulse shape, an order of magnitude smaller than the 60 ps obtained above.

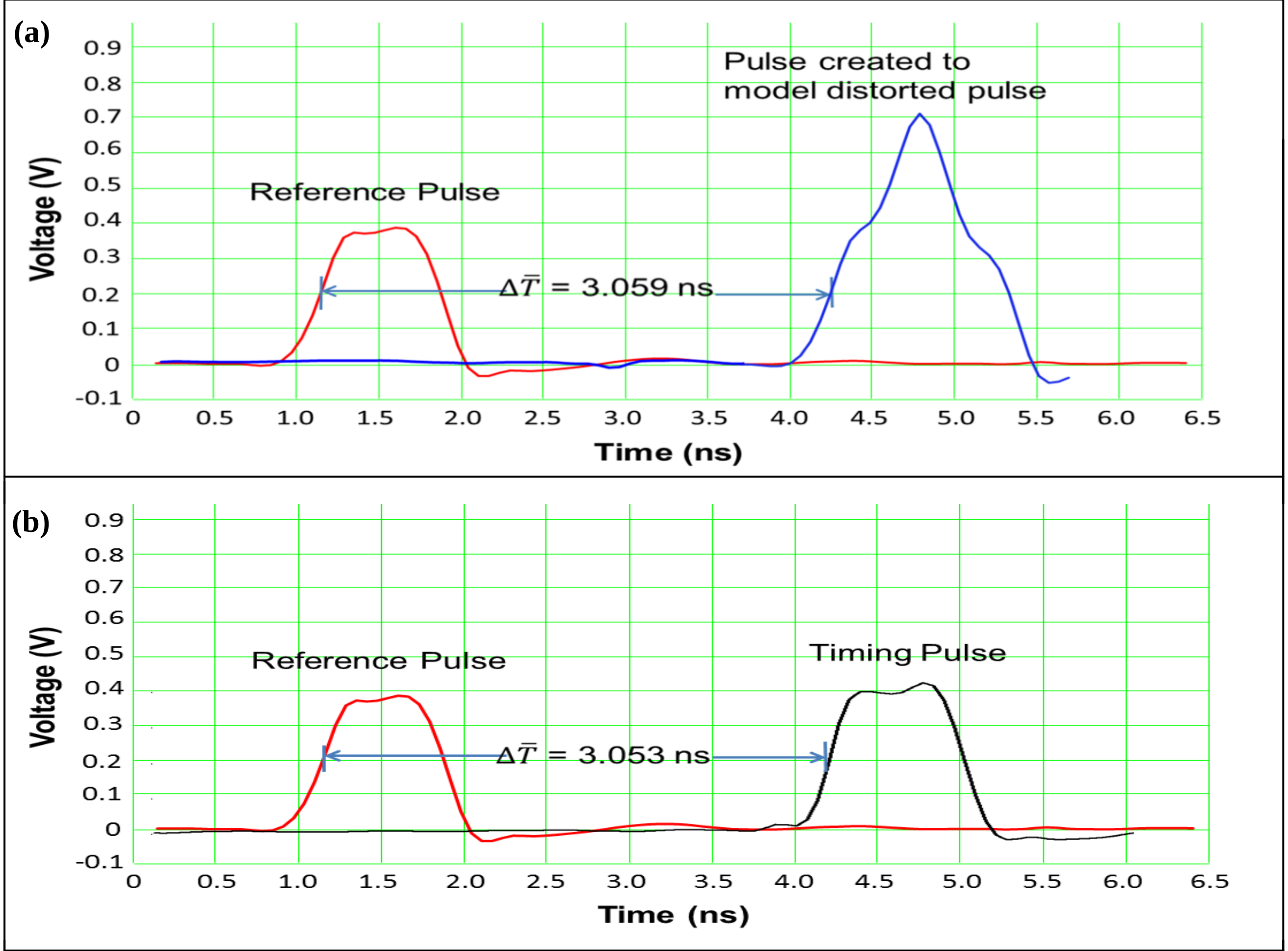

Figure 7: Results from the New Algorithm – (a) The algorithm calculated the timing shift from the reference pulse to the newly created distorted pulse to be 3.059 ns. The pulse created to model the distorted pulse is shown in blue. Its 50% point is shifted 3.059 ns from the 50% point of the reference pulse. (b) The actual timing shift from the reference pulse to the timing pulse was 3.053 ns. The new algorithm thus enabled the timing shift to be obtained to an accuracy of 6 ps.

6. Conclusion:

An offline setup has been built to test a new algorithm for the OMEGA laser timing system. Data obtained from the offline setup confirm that the oscilloscope's built-in measurement routine incorrectly predicts timing shifts by up to 60 ps when presented with distorted pulse shapes. A new signal processing routine recovers the correct timing offset from the distorted pulse shapes with only 6 ps of error. The offline setup used delayed pulses up to ten times larger in amplitude than the pulses from the back surfaces of the final turning mirrors to produce timing shifts that were large and unambiguous. However, since the signal processing algorithm places no restrictions on the amplitude of the distorting pulse, it can be used to predict the timing offset for any of the beamlines.

7. Future Work:

Results obtained using this algorithm show the algorithm’s effectiveness, but the algorithm was only used on two sets of data: one set with a delayed pulse the same amplitude as the timing pulse (figure 7), and another set with a delayed pulse half the amplitude of the timing pulse (figure 5). In the experiment, these two amplitudes were used simply so that there would be large timing shifts that could be clearly measured. However, it is believed that timing errors by distorted pulses on OMEGA rarely exceed 30 ps, so the real delayed pulse is much smaller than those simulated in the offline setup. There was an attempt to take data for the delayed pulse at one-twentieth the amplitude of the timing pulse, but due to laser instability and possible shortcomings in the optics, the reference pulse and timing pulse did not have the same shape and violated the necessary assumption. In the future, data should be taken with the amplitude of the delayed pulse small enough to see what timing errors can be expected for conditions on OMEGA.

The next step would be to implement the algorithm on OMEGA’s beamlines during beam timing. On August 2, 2013, a beam timing run was done and results from this run showed that beamline 61 had a distorted pulse shape very similar to distorted pulse shapes created in the offline optical setup. By implementing this algorithm on OMEGA’s next beam timing run, it can be verified if beamline 61 has been distorted by the delayed pulse and if its timing error can be reduced.

8. Acknowledgements:

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9. References:

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