UNDERSTANDING NATIONAL IGNITION FACILITY EXPERIMENTAL RESULTS: TARGET DIAGNOSTIC AUTOMATED ANALYSIS

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Abstract

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is the most energetic laser system in the world. During a NIF laser shot, a 20-ns ultraviolet laser pulse is split into 192 separate beams, amplified, and directed to a millimeter-sized target at the center of a 10-m target chamber. To achieve the goals of studying energy science, basic science, and national security, the NIF laser shot performance is being optimized around key metrics such as implosion shape and fuel mix. These metrics are accurately quantified after each laser shot using automated signal and image processing routines to analyse raw data from over 50 specialized diagnostics that measure x-ray, optical and nuclear phenomena. The analysis is comprised of both routine instrument correction and specialized corrections including series of inverse problems, timing analysis, and/or specialized processing customized to each diagnostic. This paper will review the framework for general diagnostic analysis with a focus on the areas of calibration and operational support. Specific examples will be provided that demonstrate the complexity of maintaining calibration and supporting these algorithms in a state-of-the-art laser research facility.

INTRODUCTION

The NIF, a 192-beam pulsed laser system for studying matter at extreme densities and pressures, was completed in May 2009 and is producing experimental data and results [1]. Currently the data is collected with over 50 specialized diagnostic instruments that measure optical, x-ray, and nuclear phenomena. These diagnostics have been designed to provide redundant and independent measurements of fundamental physical quantities. [2] Interpreting the data from these diagnostics is key to fulfilling NIF's goals and to demonstrating ignition of deuterium and tritium fuel in a laboratory setting. These important data, collected after each NIF laser shot, are inherently and uniquely distorted by the customized hardware. The distortions must be carefully removed from the data, without increasing the noise or decreasing the bandwidth or dynamic range [3]. Further analysis is needed to reconstruct the fundamental physical quantities, often requiring combining corrected information from several instruments (Fig. 1).

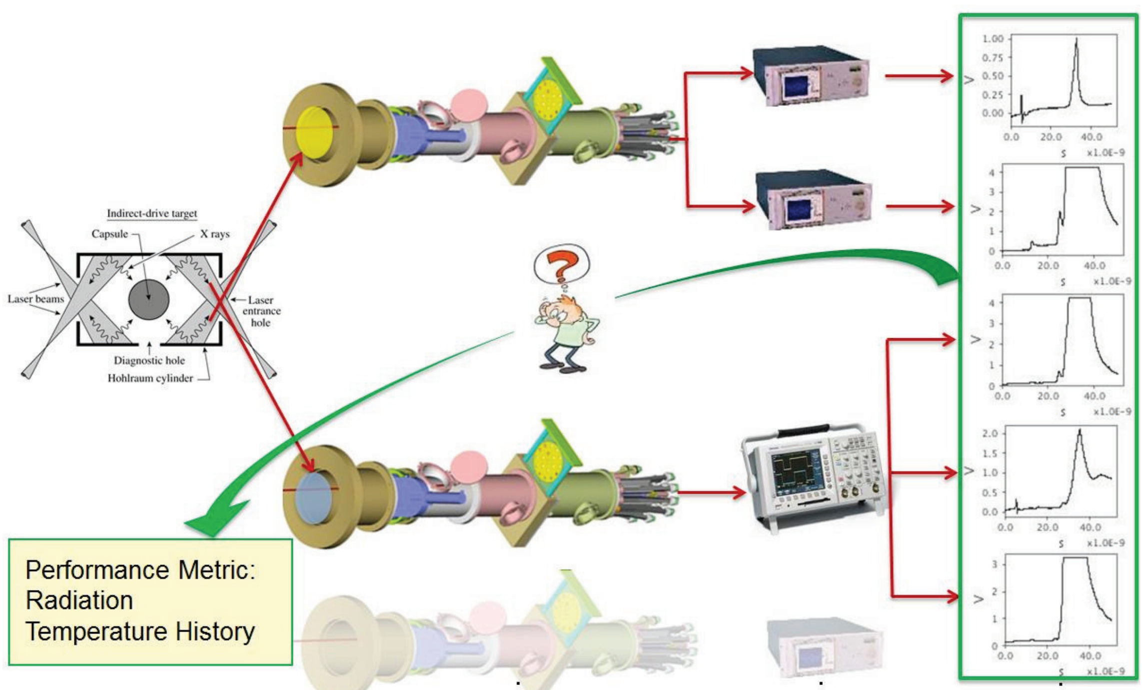

Figure 1: General example of target diagnostic data, automated analysis, and the NIF performance metrics.

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The NIF shot data analysis team has built algorithms to remove distortions and further process and quantify results from diagnostic data. After a shot, all diagnostic data are automatically transferred to an Oracle database which triggers the NIF shot data analysis engine. The engine gathers all necessary calibration data, runs the signal and image processing algorithms on a Linux cluster, and stores results back into the Oracle database where they can be viewed by scientists [4].

In our current phase of diagnostic analysis development at NIF there are four equally demanding areas that are required to provide accurate NIF performance metrics:

- Operational support updates for algorithms
- Design and maintenance of calibration data
- Quality assurance and integration testing
- Design and development of new analysis software for emerging diagnostics

In this paper we will review some of the recent work of the analysis team in operational support and maintaining calibration data.

ANALYSIS TO SUPPORT OPPERATIONS

Although automated analysis is written to be flexible and robust, it is also necessarily tailored to the diagnostic hardware and predicted experimental conditions. Therefore, when diagnostic raw data is different than expected due to the redesign of hardware, detector malfunction, atypical shot types, new noise sources, etc., the analysis team must enhance the algorithms accordingly.

Support Example: Gamma Reaction History Dither Correction

The Gamma Reaction History (GRH) diagnostic has four cells that each use a gas Cherenkov detector to sense gamma-rays in a specific energy range (Fig. 2). Each GRH cell uses a photo multiplier tube (PMT) and two Mach-Zehnder systems to transmit the signal down fiber optic cables and record the data with varying dynamic range on four oscilloscope channels [5]. The analysis consists of three main modules:

- Demodulating the amplitude modulated signal from the Mach-Zehnder hardware
- Stitching the multi-channel data into one seamless record [6]
- Deconvolving the frequency dependent system responses of the PMT and Cherenkov detectors and identifying the gamma bang time and burn width.

The GRH diagnostic and automated analysis was fully operational in 2011 and has been instrumental in providing fusion burn parameters such as fusion burn width and bang time. In May of 2013, the raw data showed unexpected differences between two of the Mach-Zehnder recordings of the same time samples. The peak of the data recorded by two oscilloscope channels showed significant discrepancies about five times the expected variability.

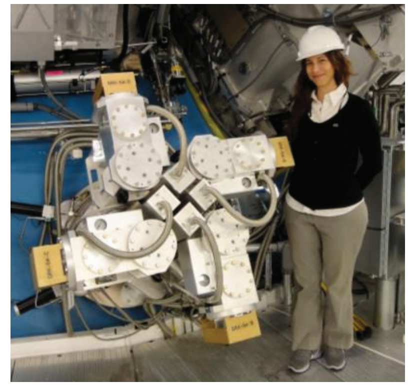

Figure 2: GRH diagnostic as installed in NIF

In investigating this operational issue with the diagnostic raw data, it was found that the hardware active control of the Mach-Zehnder bias point utilizes a dither signal that could affect the shot data by more than was anticipated. This dither is inherently unpredictable but was found to be able to change the gamma signal height by up to 10%. The solution was to use the recorded dither signal at shot time and incorporate that value into the demodulation correction equations [7]:

$$I_{out}(t) = \frac{I_{MaxIn}}{2}\left[1+\sin\left(\frac{\pi V_{pmt}(t)}{V^{\pi}_{pmt}} + \frac{\pi \Delta V_{bias}}{V^{\pi}_{bias}}\right)\right]$$

Where I_{MaxIn} and I_{out} represent the input and output laser intensities of the Mach-Zehnder, V_{pmt} is the voltage at the PMT, V^{π} is the the half-wave voltage, and V_{bias} is the bias controller voltage at shot time. Solving the above for the voltage entering the Mach-Zehnder and substituting measured variables when needed results in the following:

$$V_{pmt}(t) = \frac{V^{\pi}_{pmt}}{\pi}\left[\sin^{-1}\left(\frac{V_{dig} - V^{0}_{lightExt}}{abs(V^{0@Q-}_{Dig} - V^{0}_{lightExt})} + 1\right) - \sin^{-1}\left(\frac{V^{0shot}_{Dig} - V^{0}_{lightExt}}{abs(V^{0@Q-}_{Dig} - V^{0}_{lightExt})} + 1\right)\right]$$

Where V_{Dig} is the digitizer output, $V^{0}_{lightExt}$ is the voltage recorded when the MZ light is fully extinguished, V^{0shot}_{Dig} is the average digitizer recording before shot data, and $V^{0@Q-}_{Dig}$ is the measure of the dither signal. Using the above equation for the voltage at the PMT, the Mach-Zehnder signal can be correctly demodulated while accounting for the dither signal.

The majority of effort involved in developing this dither correction solution was in defining, storing and querying for the necessary data. First, the dither signal interface was modified so that automated extract transport and load software could reliably find the dither recording. Next new datasets were defined in the analysis calibration database to store the mapping connections between the

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channel of GRH data and the dither signal receiver. In addition, a second new dataset of calibration was needed to store dither correction scaling factors that are based on the Mach-Zehnder serial number. Finally the analysis engine was reprogrammed to access the new calibration and dither receiver power data so that all necessary data would be collected for use in automated analysis.

The results of this GRH operational support project changed the estimated gamma-ray peak height by up to 5% on future experiments and thereby had a significant effect on the estimated full with half max fusion burn widths, one of the key performance metrics for ignition.

Operational Support Accounts for One Third of Analysis Team Milestones

The target diagnostics analysis team had 45 major milestones in the past year that included projects to improve analysis, build new analysis for existing diagnostics, build new analysis for new diagnostics, and on-the-fly milestones to support all analysis currently in operations. The team supports 22 different target diagnostic systems, each with custom analysis algorithms. This year, 15 of the major milestones were completed in response to an operational issue and change in the raw diagnostic data. Many of these changes were directly due to diagnostic hardware or configuration changes. The analysis team is extremely adaptive and responsive to these issues and is therefore able to robustly provide critical NIF performance metrics that allow scientists to evaluate NIF experiments accurately.

CALIBRATION DATA FOR ANALYSIS

In order to analyse and correct for target diagnostic hardware, the automated analysis software needs access to every installed diagnostic part and calibration that affects the detected signal. On average this includes between 500 and 5000 calibration parameters per diagnostic. The analysis software queries NIF's Location Component and State (LoCoS) database which stores the part and serial numbers of target diagnostic hardware as well as provides dataset storage for associated calibrations [8]. The diagnostic team is faced with the challenge of designing the LoCoS calibration datasets, tools, and upload procedures so that this vital calibration data can be properly maintained by the diagnostic scientists and engineers and is available for accurate analysis.

Calibration Data Example: Dante Time Base Correction

One example of calibration data that is needed for automated analysis is the Dante time base calibration file.

The Dante diagnostic measures spectrally and temporally resolved x-ray flux. Dante results are vital to accurately characterize the drive for capsules implosion, hydrodynamic instability, material equations of state, astrophysics, and radiation transport experiments [9].

The Dante diagnostic is composed of 18 channels each configured with a different set of filters, x-ray mirrors, and x-ray diode detectors to optimize the x-ray spectrum coverage for particular experiments. The signal from each channel is then sent down long LMR-600 co-axial cables, through attenuators, jumper cables, and finally is recorded on high speed CRT-based oscilloscopes [10] (Fig 3). These oscilloscopes exhibit significant and nonlinear time base distortions that cause late time pulses to be offset from each other even by up to several hundred picoseconds when early time pulses are properly aligned.

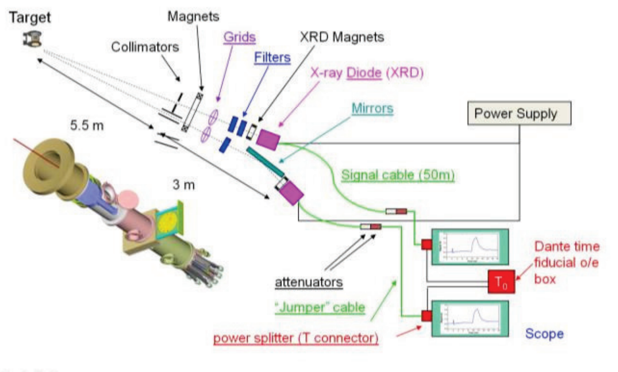

Figure 3: Dante single channel hardware diagram.

The Dante time base calibration data is made up of an accurately measured and computed time base array for each Dante oscilloscope. The format for all calibration files is carefully configured in HDF 5 files so that automated software can robustly pull out the relevant information. The HDF 5 file formats for these array calibration data includes specific folder and data formats that are pre-arranged with the calibration facilities and scientists. After the time base calibration files are constructed, they must be uploaded into the LoCoS database and stored against a particular oscilloscope serial number and sweep speed. Once the data is uploaded and approved, it can be queried automatically by the analysis software. Currently there are 105 different time base correction files uploaded into the LoCoS database for different Dante oscilloscopes, sweep speeds, and effective date ranges.

Scale of Calibration Data for Analysis

Using Dante as an example we find that two Dante instruments, with18 detector lines each add up to over 500 effective calibrated elements that are queried for every analysis run. About a third of the 22 diagnostics that our team currently supports require a similar or greater number of calibrated parts. In addition, many of the calibrations need to be recalibrated on a regular basis to ensure that the hardware is performing as expected by the software. For the Dante example, the time base calibration files were found to be acceptably accurate for a three month period and then require recalibration. Accurately maintaining tens of thousands of calibration parameters within the LoCoS database requires suitable interfaces, teamwork, procedures, and tools.

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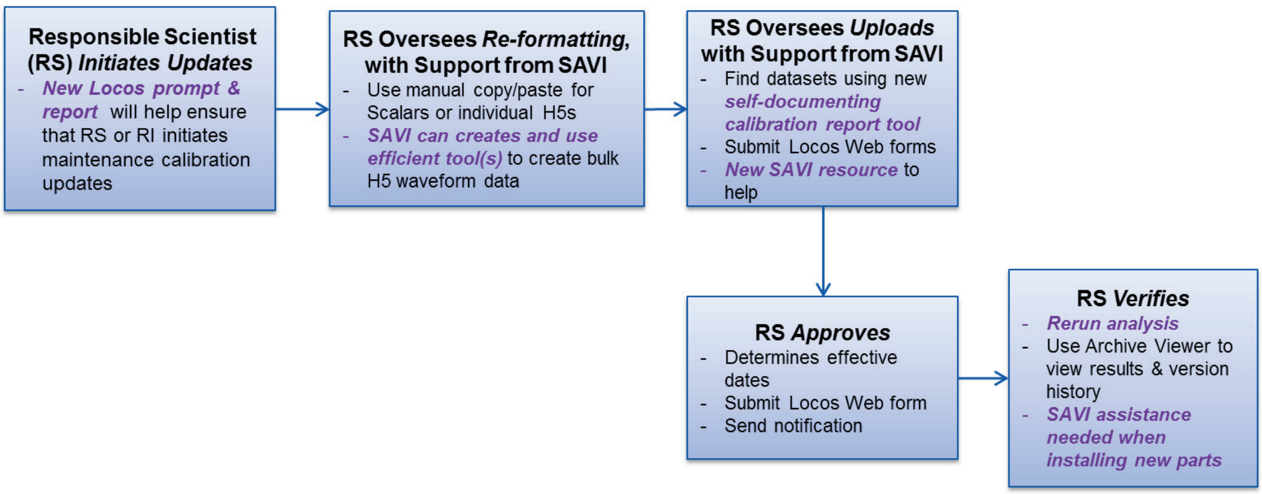

Figure 4: New calibration data maintenance procedure that involves the diagnostic Responsible Scientists (RS) and Shot Analysis and Visualization (SAVI) to accomplish the tasks of properly formatting through verifying the calibration.

Design of Calibration Procedure and Tools

We have proposed improving the calibration data maintenance by both designing a new procedure for calibrating and uploading data (Fig. 4) as well as offering scientists new tools for tracking their calibration data.

The new procedure highlights that the diagnostic Responsible Scientist will be involved in all types of the calibration needed for the automated analysis of their diagnostic and will able to initiate the re-uploading process whenever the calibration is updated. A new LoCoS tool has created expected recalibration dates within the database and both notifies scientists and allows them to browse their calibrations with upcoming expiration. The analysis team provides added resources for re-formatting and uploading data into the LoCoS database when needed and can help with bulk re-formatting. Developing a bulk upload LoCoS tool is being investigated. Finally the RS will approve and verify all calibration data that analysis will use for their diagnostic, ensuring that the analysis results after each NIF experimental run are accurate.

DISCUSSION

The automated analysis of the NIF target diagnostics provides timely, robust, and accurate estimates of key experimental metrics. With the current NIF shot schedule exploring new paths to ignition, the analysis team must be responsive in supporting new analysis for diagnostic and experimental changes while ensuring high quality calibration data of thousands of specific calibration parameters.

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