Measurement Techniques for Data Recording and High Temperature Measurement

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Abstract

The Defense Threat Reduction Agency (DTRA) performs a wide variety of High Explosive (HE) blast events, supporting the War Fighter, Weapons of Mass Destruction (WMD) mitigation, characterization, international anti-terrorism mitigation, force protection, and agent defeat. United States Government agencies rely on these tests to gather useful data in the field and for laboratory use. The paper presented here addresses: (1) instrumentation design and, (2) high temperature data acquisition.

The Instrumentation design includes cable planning and layout, sensor selection (pressure, thermal response, acceleration, velocity, displacement, strain, and force), sensor calibration and fielding, data acquisition, long range transmission and storage of data signals, and high speed optical data. DTRA has also internally developed two fast response high temperature measurement systems that can sustain a harsh environment of up to 500 psi, and both with the capability of measuring temperatures in excess of 3000 Kelvin with a response time of 300 MicroSec. The first system is a Near Infra Red (NIR) ratio pyrometry four color system which is completely self contained (detectors, conditioning electronics in same unit), and the second system is also a NIR low cost ratio pyrometry system that uses an expendable front end mounting configuration that secures fiber optic cables (each of which are assigned a specific narrowband IR center wavelength) in a specific measurement location. These fiber optic cables convey the infrared data produced by the fireball or other thermal event to a separate array of physically protected NIR photo detectors whose data signals are then conditioned, recorded and, processed to provide fireball or other thermal event temperatures.

Introduction

There are two primary themes to be presented in this paper. The first theme is an overview of the Data Acquisition System (DAS) that the DTRA instrumentation branch employs for all of its events to include signal conditioning (amplification, sensor excitation, bridge completion circuitry, shunt calibration, electronic filtering) and digital recorder functions (analog to digital conversion and storing data). The second theme is the recent accomplishments of the DTRA instrumentation branch to measure fast response, high temperature events.

The data acquisition system consists of equipment for measuring blast phenomena; equipment for acquiring, amplifying, and storing data; and equipment for transmitting and archiving data.

The instrumentation branch of DTRA, in order to meet the mission requirement of acquiring fast response high temperature data to support agency events, applied the principles of ratio

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14. ABSTRACT

The Defense Threat Reduction Agency (DTRA) performs a wide variety of High Explosive (HE) blast events, supporting the War Fighter, Weapons of Mass Destruction (WMD) mitigation, characterization, international anti-terrorism mitigation, force protection, and agent defeat. United States Government agencies rely on these tests to gather useful data in the field and for laboratory use. The paper presented here addresses: (1) instrumentation design and, (2) high temperature data acquisition. The Instrumentation design includes cable planning and layout, sensor selection (pressure, thermal response, acceleration, velocity, displacement, strain, and force), sensor calibration and fielding, data acquisition, long range transmission and storage of data signals, and high speed optical data. DTRA has also internally developed two fast response high temperature measurement systems that can sustain a harsh environment of up to 500 psi, and both with the capability of measuring temperatures in excess of 3000 Kelvin with a response time of 300 MicroSec. The first system is a Near Infra Red (NIR) ratio pyrometry four color system which is completely self contained (detectors, conditioning electronics in same unit), and the second system is also a NIR low cost ratio pyrometry system that uses an expendable front end mounting configuration that secures fiber optic cables (each of which are assigned a specific narrowband IR center wavelength) in a specific measurement location. These fiber optic cables convey the infrared data produced by the fireball or other thermal event to a separate array of physically protected NIR photo detectors whose data signals are then conditioned, recorded and, processed to provide fireball or other thermal event temperatures.

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pyrometry theory, and developed two distinct custom designed ratio pyrometry sensor designs each with a response time of 300 µSec, a temperature range from 600 Centigrade (873 Kelvin) to greater than 3000 Centigrade, (3273 Kelvin) and each with a durability to be able to acquire the full duration event of the fireball (100mSec or greater). In addition, to supplement the data acquired from ratio pyrometry measurements, conventional thermocouples are used concurrently to acquire the long duration temperature environments associated with an event. Thermocouples are also employed to provide an environmental temperature profile of the event as well. Thermocouples have a (50 mSec) rise time and the pyrometers have a rise time of 300µSec rise time.

Two designs of a ratio pyrometry sensor were produced.

This first pyrometer design is a completely self contained unit that has both the photo detectors and conditioning electronics, and Thermoelectric Cooling (TEC) configured in a commonly used gage mount canister that can be placed at the measurement point of interest provided a location exists to accommodate it and that was close enough to acquire data to the measurement point of interest.

This first design is a Near Infra Red (NIR) sensor using four NIR band pass filters. These four photo detectors and their NIR filters were configured on a customized COTS quad PbS (Lead Sulfide) detector unit and, along with the supporting conditioning electronics this entire configuration is mounted on a circuit board secured in a gage canister commonly used by DTRA. This sensor and protection design can sustain a blast (not fragmentation) environment up to 500 psi as its detection port uses a sapphire window to shield it from the direct blast effects. Its four output signals are then conveyed to the DAS system for recording at the Instrumentation Van (I-VAN), typically stationed 1000 ft. away or greater.

As an improvement to this first sensor design, a second pyrometer system was developed employing a low cost fiber optic configuration which physically separates the blast from the vulnerable conditioning components (photo detectors and conditioning electronics) by using two (or more depending on the number of photo detectors used) jacketed fiber optic cables whose lengths range from 50 to 100 ft. to convey the Infra Red (IR) energy to the photo detectors and signal conditioning components. This 50 ft. minimum range was selected as the protective distance to physically separate the front end fiber detection section from the photo detectors which are contained in a blast protected environment. This fiber design compared to the four color IR offers an increased flexibility to take measurements at any location within the blast environment while only exposing a low cost front end mounting system to secure the sensing end of the fiber optic cables within the fireball, and if this front end is destroyed it will only have a minimal cost impact, as it is easily replaceable and inexpensive.

The fiber optic pyrometer sensor for this improved design also operates in the near infra red (NIR) spectrum utilizing anywhere from two to four NIR band pass filters selected with the same criteria (at slightly different center frequencies to accommodate cost effective COTS availability) as that of the first design. Two to four (Low OH; 700-2400 µM, Multi-Mode, Step Indexed) fibers are used to convey the IR energy to the InGaAs (Indium Gallium Arsenide) photo detectors which are designed to detect in the near infra red spectrum (0.7 to 2.2 µM).

Data Acquisition

There are three primary components of the data acquisition system (DAS) consist of the transducers, the Signal Conditioning Amplifier (SCA), and the digital data recorder (or RRS; Real Time Recording system developed by the DTRA instrumentation branch). Figure 1 is a diagram of the Data Acquisition Process. Figures 2 is of the four color IR event used as an example for this presentation, and figure 3 shows the data acquisition components used to acquire for the four color IR data.

Signal Conditioning Amplifier – Amplifies low-level signals and isolates and filters (within the frequency domain) them for more accurate measurements.

Digital Recorder – Performs analog to digital signal conversion and stores the information for display and analysis via computer.

Signal Conditioning

The electrical signals generated by transducers must be optimized for the input range of the digital recorder through the signal conditioning amplifier which performs the following:

Amplification – The most common conditioning is amplification. Low level signals are amplified to increase the digital recording resolution (signal resolution) and reduce noise (improve the signal-to-noise-ratio). For the highest possible accuracy, the signal should be amplified so the maximum voltage range of the conditioned signal equals the maximum input range of the recorder Analog-to-Digital converter (ADC). Unless otherwise indicated amplification refers to voltage amplification.

Excitation – Signal conditioning generates an excitation source (power) for some transducers. Strain transducers, pressure, and accelerometers require external voltage or current excitation for operation. A constant voltage or constant current excitation is available.

Bridge Balancing and Completion – Typical signal conditioners provide a compensation circuit to eliminate the residual imbalance of the transducer and connected cable plant. bridge completion is required when using single or two arm resistive transducers.

Shunt Calibration – Shunt calibration is a method used to calibrate a DAS channel. It is used for setting up amplifier/recorder gains and also for data reduction/engineering unit conversion. Shunt calibration is performed by applying a known resistance across one leg of the Wheatstone bridge circuit of a piezo-resistive transducer to create a deviation from the quiescent gage output as though it were actually sustaining the maximum predicted value of the event phenomenon, thereby simulating an output from the transducer.

Bandwidth Selection – Bandwidth is the useable frequency range of a given measurement. The bandwidth is depended on the type of measurement employed. For example, for a high-explosives test, the pressure measurements require a bandwidth of no more than 50 KHz, while the accelerometers and strain measurement typically require 5 KHz and 2 KHz, respectively. If a greater bandwidth capability is required as the case for the pyrometer signal bandwidth, there is also the option to configure the Signal Conditioning Amplifier (SCA) without one of the internal filter selections available (I.e. 2, 5, 10, or 50 KHz; 6 Pole Bessel filter) and use the internal default filter range of the amplifier which is 100K Hz @ -3dB cutoff frequency.

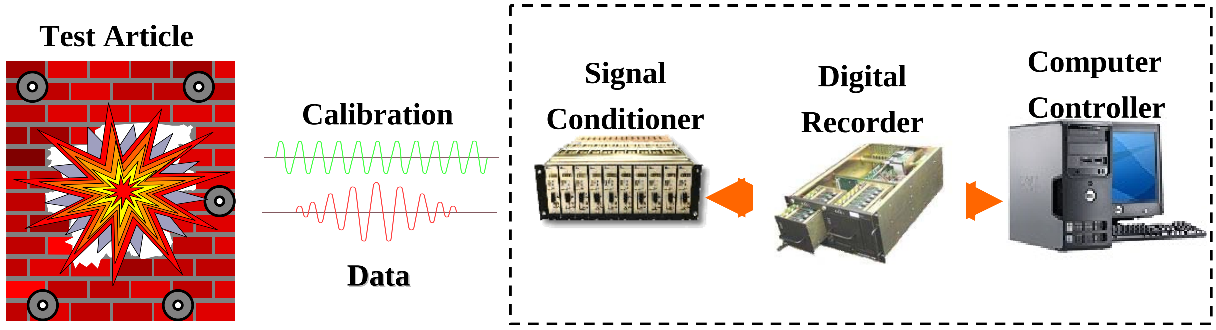

Fig 1, diagram of the data acquisition process.

Figure 2, four color IR unit with protective gage canister.

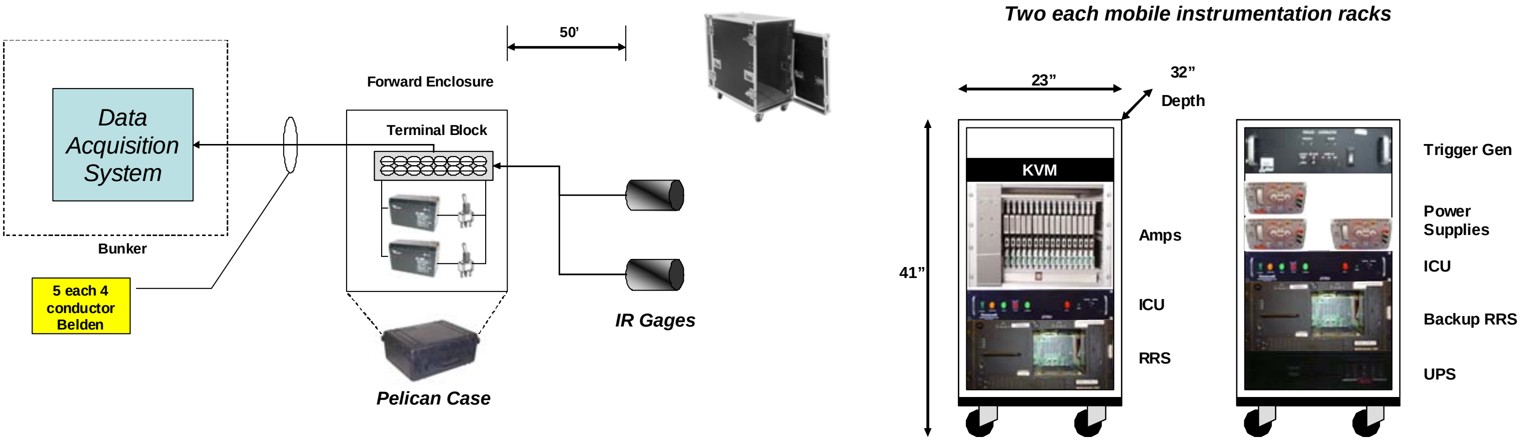

Figure 3, data acquisition components used in the four color IR event.

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Digital Recorder

The Digitizer currently in use was customized for DTRA using Commercially Off The Shelf Components (COTS) and is called the Real Time Recording system (RRS). It has been successfully fielded on all DTRA events since 1996. The RRS is completely self contained and provides a space savings of 80% and a power consumption improvement of 80% compared to the previous system. A single unit of the RRS consists of a 19” rack mount chassis that can accommodate up to four separate 32 channel ADC (Analog to Digital Converter) digitizer boards employing a Sigma-Delta sampling architecture at a fixed 1.0 MSample/Sec rate (1 μSec/pt) with an effective data capture bandwidth of 1.0 MHz, a main controller unit, and 4 Terabytes of memory capacity that enables to record for a duration of up to 4 hours at the sampling rate of 1.0 MSample/Sec for all 128 channels. If more than 128 data channels are required several RRS units can be tied together to support this increased data channel requirement.

High Temperature Measurement

The outline for the high temperature measurement will consist of: (I) general pyrometry theory, (II) selection of the NIR filter band pass wavelengths and performance Specifications of both the four color IR photo detector units (PbS) and the fiber optic pyrometry photo detector units (InGaAs), (III) calibration, (IV) the test events and fielding configurations, and (V) results and summary.

I Ratio Pyrometry theory

The ratio pyrometers are sensors which measure at a point directly in their field of view which is the standoff distance in front of their aperture at which they were calibrated (using a calibrated black body source). The section on calibration provides specific details.

The relevant variables and constants are shown in Table 1.

Variable/Constant	Description	Units
$h = 6.626 \times 10^{-34}$	Planck's constant	Joule Sec
$c = 3.0 \times 10^{8}$ (lower case)	Speed of light	Meters/Sec
$K = 1.38 \times 10^{-23}$	Boltzmann constant	Joule/Kelvin
T	Temperature	Kelvin (or Fahrenheit, Centigrade if indicated).
ϵ ($0 \leq \epsilon \leq 1$)	Emissivity (measure of how close IR emissions are to Black body radiator).	Dimensionless
C_1	Calibration Coefficient; Least Squares Straight Line Intercept value.	Dimensionless
C_2	Calibration Coefficient; Least Squares Straight Line Slope.	Kelvin
R	Correlation Coefficient; statistical measure of how well least squares straight line fit correlates to the data.	Dimensionless
λ	Wavelength	μM
P_λ	Intensity	Watts/M^3
V	Voltages	Volts
Ln		Natural Logarithm (Log_e)
$\gg$	$\Rightarrow$ Greater by factor of 10	

Table 1, list of variables and constants.

The ratio pyrometrty technique employs four separate NIR center wavelengths to create a set of six possible ratios which yield six temperature calculations. This was the technique used for the first design, the four color IR, as well as the second design which was the fiber optic pyromery system. The second design has the option to accommodate a minimum of two NIR center wavelengths which will provide only one ratio set from which a single temperature can be calculated, however this design can easily be expanded to use more than two ratios and this yields a greater selection of temperature calculations that can provide increased measurement accuracy. Generally, the more ratio combinations available, the better the accuracy of the temperature calculation. The temperature base is in Kelvin unless otherwise indicated.

Beginning with Planck's equations (1a, 1b), corresponding to a specific wavelength set (λ_1, λ_2), the calculation of temperature from a gray body process is derived. The gray body process assumes that the emissivities [ϵ] associated with the measurements while unknown are all assumed equal, and strictly less than 1 ($\epsilon < 1$).

For a black body process the same assumptions as that of a gray body would also apply except that all emissivities are identically 1 ($\epsilon \equiv 1$).

The theoretical calculation of the temperature is derived by the ratios of equation (1a) divided equation (1b) ($P_{\lambda_1}/P_{\lambda_2}$) with corresponding wavelengths (λ_1, λ_2). $V_{\lambda_1}, V_{\lambda_2}$ are the voltage outputs corresponding to the photo sensors for the wavelengths $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$ respectively. The photo sensors used for the initial four color IR are PbS based, and those used for the fiber design are InGaAs based.

The pyrometry ratio relation between the ratio of the actual voltages from the photo detectors to the ratio of the intensities for the specific wavelength is indicated in equation (1c). Since the ratios of the intensities ($P_{\lambda_1}/P_{\lambda_2}$) are proportional to the photo sensor output voltages ($V_{\lambda_1}/V_{\lambda_2}$) equation (1c), the emissivity's are eliminated from the theoretical temperature calculation as well as the uncertainty of the translation of the intensity of the measurement environment to voltage output of the photo detector, that is the ratio of the known measured output voltages are used in place of the ratios of the unknown intensities. For the specific case as to where the measurement of the photo detector is directly within the fireball, the translation to the voltage output of the photo detector with respect to the input intensity would be unity, however in a general environment this can not be assumed.

$$P_{\lambda_1} = \frac{2\pi\varepsilon hc^2}{\lambda_1^5\left[e^{\left(\frac{hc}{\lambda_1 KT}\right)} - 1\right]} \; ; \; P_{\lambda_2} = \frac{2\pi\varepsilon hc^2}{\lambda_2^5\left[e^{\left(\frac{hc}{\lambda_2 KT}\right)} - 1\right]}$$

Equation (1a, Planck's equation; λ_1)   Equation (1b, Planck's equation; λ_2)

$$\frac{P_{\lambda_1}}{P_{\lambda_2}} \propto \frac{V_{\lambda_1}}{V_{\lambda_2}}$$

Equation (1c, intensities proportional to output voltages of photo detectors)

Assume: $e^{\left(\frac{hc}{\lambda_1 KT}\right)} >> 1$; $e^{\left(\frac{hc}{\lambda_2 KT}\right)} >> 1$; and that emissivity's [ε] while unknown are the same for all wavelengths [λ_1, λ_2]. $V_{\lambda_1}, V_{\lambda_2}$ are the voltage outputs corresponding to the photo sensors for the wavelengths λ_1 and λ_2 respectively.

$$P_{\lambda_1} \approx \frac{2\pi\varepsilon hc^2}{\lambda_1^5\left[e^{\left(\frac{hc}{\lambda_1 KT}\right)}\right]}; \qquad P_{\lambda_2} \approx \frac{2\pi\varepsilon hc^2}{\lambda_2^5\left[e^{\left(\frac{hc}{\lambda_2 KT}\right)}\right]};$$

Equation (2a) Equation (2b)

$$\frac{P_{\lambda_1}}{P_{\lambda_2}} \approx \frac{e^{\left(\frac{hc}{\lambda_2 KT}\right)}}{e^{\left(\frac{hc}{\lambda_1 KT}\right)}}; \qquad \frac{V_{\lambda_1}}{V_{\lambda_2}} \approx \frac{e^{\left(\frac{hc}{\lambda_2 KT}\right)}}{e^{\left(\frac{hc}{\lambda_1 KT}\right)}}$$

Equation (3a) Equation (3b)

By combining equations 1c, and 3b, equation (4a) is derived indicating the relationship between $Ln\left[\frac{V_{\lambda_1}}{V_{\lambda_2}}\right]$ and $\frac{1}{T}$ as a straight line with the vertical axis $\left(Ln\left[\frac{V_{\lambda_2}}{V_{\lambda_1}}\right]\right)$ vs. the horizontal axis $\left(\frac{1}{T}\right)$.

Equation (4a) is the first order theoretical relationship showing the ratios of the voltage outputs of the Photo detectors ($V_{\lambda_1}/V_{\lambda_2}$) to the temperature, and equation (4b) is the equation relating the empirically derived 1st order coefficients (C_1 and C_2) from the calibration process used for the photo detector. The coefficients C_1 and C_2 are the intercept and slope respectively of the calibration curve (See figure 5b).

$$Ln\left[\frac{V_{\lambda_1}}{V_{\lambda_2}}\right] = 5Ln\left[\frac{\lambda_2}{\lambda_1}\right] + \left(\frac{1}{T}\right)\left[\left(\frac{hc}{K}\right)\left[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right]\right]$$

Equation (4a, Theoretical 1st order relation.)

$$Ln\left[\frac{V_{\lambda_1}}{V_{\lambda_2}}\right] = C_1 + C_2\left(\frac{1}{T}\right)$$

Equation (4b, empirical 1st order calibration.)

The 1st order straight line calibration data is used to provide a straight line slope and intercept value from the actual calibration of the photo detector as it is exposed to a known black body calibration source.

Solving for Temperature [T; Kelvin] from equations (4a and 4b) yield the following results:

$$T_{Theoretical} = \frac{\left(\left[\frac{hc}{K}\right]\left[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right]\right)}{Ln\left[\frac{V_{\lambda_1}}{V_{\lambda_2}}\right] - 5Ln\left[\frac{\lambda_2}{\lambda_1}\right]}; \qquad T_{Actual} = \frac{C_2}{\left(Ln\left[\frac{V_{\lambda_1}}{V_{\lambda_2}}\right] - C_1\right)}$$

Equation (5a, 1st order theoretical temperature) Equation (5b, actual temperature)

The theoretical definitions of C_1 and C_2 are:

$$C_{1_{Theoretical}} = 5Ln\left[\frac{\lambda_1}{\lambda_2}\right]; \qquad C_{2_{Theoretical}} = \left(\left[\frac{hc}{K}\right]\left[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right]\right)$$

Equation (5c, theoretical definition of the slope and intercept values)

Equation (5b) is the relation applied to derive the temperature from the actual voltage outputs of the photo detectors for both the four color IR and fiber optic pyrometry systems, and the corresponding 1st order calibration intercept and slope (C_1 and C_2; respectively) values for derived during the black body calibration of the photo detectors. Equation (5a) serves as a theoretical 1st order validation of the data to compare against the actual temperature calculation. Equations (5c) show the theoretical definitions of the slope and intercept values of the 1st order calculations.

II Selection of NIR (Near Infra Red) filter band pass wavelengths, fiber optic cable, and sensor performance specifications

Selections of NIR filter band pass wavelengths

The selection of the NIR center wavelengths used for the photo detectors for both pyrometry designs were selected with the following criteria: (1) a center wavelength to allow interference free pyrometry wavelengths revealing of the temperature of the combustion of the chemical species, (2) mitigation against dominant interfering species such as would be produced by CO, CO_2, and $H_2$0, and (3) cost effective COTS band pass filters to minimize the overall cost of the pyrometer. Table 2 shows the center wavelengths [µM] and the FWHM (Full Width Half Maximum) values associated with each band pass filter.

Design	**NIR Filters**		**FWHM (nM)**	**Sapphire Window**
Four Color IR (PbS Detector)	CWL (µM)	$\lambda_1 = 1.230$	36	Diameter: 2.54 cm Thickness: 2.25 mm Transmittance:80% ($0.25 \le \lambda \le 8$ µM)
		$\lambda_2 = 1.590$	39	
		$\lambda_3 = 1.850$	48	
		$\lambda_4 = 2.200$	46	
Fiber Optic Pyrometry System (Nominally two colors but expanded to four colors.)	CWL (µM)	$\lambda_1 = 1.250$	10	Diameter: 3.8 cm Thickness: 3.17 mm Transmittance:80% ($0.25 \le \lambda \le 8$ µM)
		$\lambda_2 = 1.400$	12	
		$\lambda_3 = .1550$	12	
		$\lambda_4 = 1.650$	12	

Table 2, description of NIR filters.

Fiber optic cable selection

The photo detectors each have a dedicated fiber optic cable to convey the NIR energy from the blast to their front end aperture with the IR band pass filter. The cable lengths used were 17 Meters (51 ft.), and this length was selected as to allow sufficient distance to physically separate the photo detector from the front end sensing location, and minimize the cost and handling of the cable as it is a relatively expensive and difficult (easily breakable) to handle over long distances (> 100 Meters). Consideration was given to a design where a single (or two cable) system would service the four photo detectors using beam splitters, and this design would only require ½ or less cable than that required for the dedicated system to direct the optical signal to the four photo detectors. This beam splitter configuration while minimizing cable requirements and costs, would however introduce fragile optical components into the design, which could affect the overall reliability of the system. The design philosophy was to maintain as simple as possible a low cost design that has the greatest reliability, and easy to field.

The cables selected were a low OH Multimode, Stepped Indexed, High NA (Numerical Aperture) type of fiber whose spectral bandwidth is ranges from 0.4 to 2.2 μ M in the visible to near-IR transmission range. The cables used were terminated with “ST” type connectors which maintain the best orientation to the mounting fixture(s), and had durable jackets to protect them in a field environment. These specific cables are available as a custom COTS item.

The core diameter of the cable was 1000 μM and this diameter was selected to match the active photo detector aperture area which was a circular area of 80mm^2. A relatively high NA value of 0.48 was selected to encompass an effective working angle to acquire the IR energy from the blast ($\theta_{\text{Acceptance}} = 2\text{Sin}^{-1}(\text{NA}) = 57.4°$).

Performance Specifications:

Tables 3a and 3b summarize the performance specifications for the four color IR and fiber optic pyrometry system respectively.

Feature	Description	Numerical Quantity	Units
Rise Time	How long the detector takes to respond to a signal (10 to 90%).	300	μSec
IR Filters	Four Spectrogon™ Band-Pass Filters	λ_1: CWL 1230 BPHW 35.9 λ_2: CWL 1590 BPHW 39.3 λ_3: CWL 1850 BPHW 48.4 λ_4: CWL 2200 BPHW 46.0	Center Wave Length and Band Pass Half-Width given in nanometers.
Signal Output Coupling	AC coupling to capture transient data only. Does not capture static data to eliminate DC offsets.		
Output to High Impedance Interface	Feeds into Data Recorder (RRS).	$\geq 1.0^6\ \Omega$	Ohms
Sapphire Window	Protects IR sensor elements.	Diameter: 2.54 cm Thickness: 2.25 mm Transmittance: 80% ($0.15 \leq \lambda \leq 8$ μM)	Meters, Cm
Working Environment	Maximum designed working pressure.	500	psi
Custom Designed Unit	PbS photo diode and narrowband IR filters at sensing face. Provides biasing, amplification, thermo electric cooling (TEC) and line drivers.	Unit attached to 1,000 ft. of twisted pair cable with inner braided shield for data acquisition.	

Table 3a, four color IR performance specifications

Feature	**Description**	**Numerical Quantity**	**Units**
Rise Time	How long the detector takes to respond to a signal.	300 µSec	Microseconds
IR Filters	Four ThorLabs Band-Pass Filters.	λ_1 CWL 1230 BPHW 35.9 λ_2:CWL 1590 BPHW 39.3 λ_3:CWL 1850 BPHW 48.4 λ_4:CWL 2200 BPHW 46.0	Center Wave Length and Band Pass Half-Width given in nanometers
Signal Output Coupling	Direct Current (DC)		
Output Interface	Signal output to interface	5.0 V peak 50 Ω interface	Volts Ohms
Photo Detectors	Indium Gallium Arsenide detectors.	NIR Bandwidth: 1200-2600 nM Effective Aperture Area: 0.785 mm^2	nanometers mm^2
Fiber Optic Cable	Multimode Stepped Indexed Low OH cables.	NIR Bandwidth: 400-2200 nM Numerical Aperture: 0.48 Core Diameter: 1,000 µM	
Sapphire Window	Designed to protect IR sensor elements.	Diameter: 3.8 cm Thickness: 3.175 mm Transmittance: 80%	Centimeters Millimeters
Working Environment	Maximum designed working pressure.	500	psi
Cable Termination	Cable secured to sapphire window perpendicularly. Both ends of cable have "ST" type connectors.		

Table 3b, fiber optic pyrometry system

III Calibration

Both the four color IR and fiber optic pyromery gages perform point sensor measurements. The four color IR was designed to measure the thermal environment 13" in front of its aperture, and the fiber optic pyrometer measures 1.5" in front of its aperture (I.e. the location of the four fiber faces). Figure 4 shows the black body configuration for the four color IR. The calibration procedure is to align the aperture of the four color IR 13" in front of the black body calibrator aperture, and similarly do the same for the fiber optic pyrometer with a standoff distance of 1.5" to within its acceptance angle region (I.e. $\theta_{\text{Acceptance;}}$ figure 8) The fiber optic pyrometer calibration used a test fixture with a single fiber optic cable (Same cable type as that used for actual event with "ST" type connectors as well) that was 17 Meters in length, rather than the actual front end gage mount and its array of multiple cables that would be used in the actual event as this would be to cumbersome to utilize for the calibration procedure. Each photo detector with its specific NIR Band pass filter was calibrated in this fashion using this single cable configuration, and the process was repeated for all of the photo detectors.

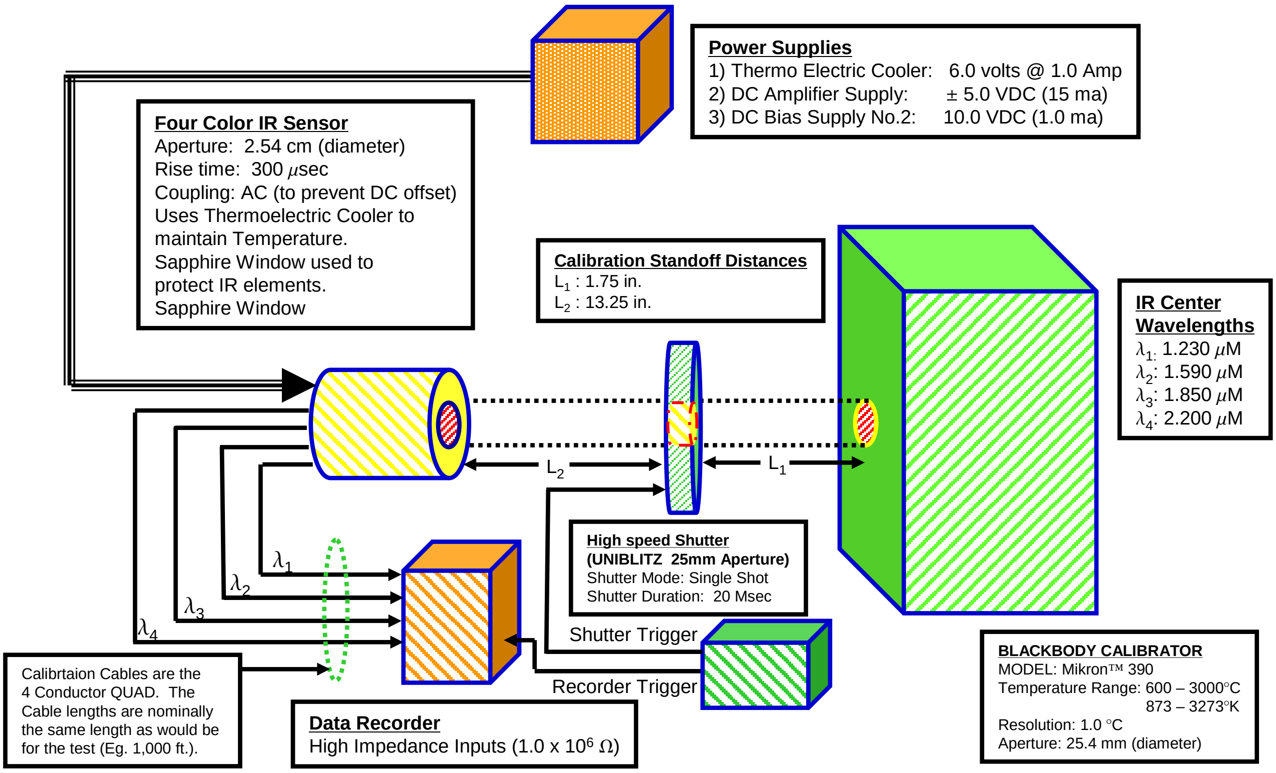
Prior to fielding sensors on an event, calibration against a black body source is a critical to establish the relationship between the input intensity from the black body source as it is conveyed to the photo detector aperture with the NIR band pass filters, and the output voltage of the photo detector. The black body source is a MIKRON™, Model 390 black body calibrator that has a working range of 600 to 3000 Centigrade (873 to 3273 Kelvin) with a resolution of 1 degree Centigrade, and a value of 0.998 emissivity (a near ideal performance value for an ideal black body emitter), and calibrated to NIST (National Institute of Standards and Technology) standards annually.

The input to the aperture of the photo detector from the black body calibration source is at a defined standoff distance (13"; four color IR and 1.5"; fiber optic pyrometry system) which is where the point measurement of the detection occurs (indicated in figure 4). The calibration system uses a precision shutter synchronized with the data recorder (RRS system) to record the change of transition voltage of the photo detector output with duration of 20 mScec to provide a clear transition window to define the ambient baseline output of the detector from the voltage produced from each temperature output of the black body calibrator. A range of 20 discrete temperature values (600 to 3000 Centigrade) from the black body calibrator are input to the aperture of the photo detector, and the corresponding output voltage produced at that temperature are recorded on both the digital recorder, and spreadsheet. These calibrations are performed for each photo detector with its specific NIR band pass filter. Figure 5a shows a typical output voltage to temperature response. In his example, it is of the four photo detectors used for the fiber optic pyrometry system, the character of the output response from the four color IR is similar. For each photo detector with a specific NIR band pass filter, the ratio of the output voltage vs. (1/Temperature [Kelvin]) is plotted. Table 4 shows the order of the voltage ratios of the four color IR, and fiber optic pyrometry system. As an example, figure 5b illustrates a plot of a ratio set Vs 1/T.

Specifically, the Ln[Ratios$\left[V_{\lambda_1}/V_{\lambda_2}\right]$] vs. [1/T] (where T is in Kelvin) is plotted for each ratio set used for the photo detectors as a function of the specific temperature produced by the black body calibrator. As an example, the data shown in figure 5b is the plot from a black body calibration procedure of the four color IR with a specific set of NIR center wavelengths (E.g. λ_3/λ_4). An analysis software package (KALEIDAGRAPH™) was used to process this calibration data and produce a least squares straight line fit with both aslope and intercept values and a correlation coefficient as to how well the line fit the points. A correlation coefficient of 0.9 or greater (1.0 is a perfect fit) is desirable. The intercept and slope values corresponding to the coefficients C_1 and C_2 (mentioned in equation (4b)) are the values applied in equation (5b) to yield the temperatures produced from a real event when applying the voltage produced from the photo detectors.

Design	Ratio Set	Specific Band pass Ratios @ CWL
Four Color IR	1	1.230/1.590
	2	1.230/1.850
	3	1.230/2.200
	4	1.590/1.850
	5	1.590/2.200
	6	1.830/2.200
Ratio Pyrometry System (4 Filter Band pass selections)	1	1.250/1.400
	2	1.250/1.550
	3	1.250/1.650
	4	1.400/1.550
	5	1.400/1.650
	6	1.550/1.650

Table 4, band pass ratios.



Power Supplies
1) Thermo Electric Cooler: 6.0 volts @ 1.0 Amp
2) DC Amplifier Supply: ± 5.0 VDC (15 ma)
3) DC Bias Supply No.2: 10.0 VDC (1.0 ma)

Four Color IR Sensor
Aperture: 2.54 cm (diameter)
Rise time: 300 μsec
Coupling: AC (to prevent DC offset)
Uses Thermoelectric Cooler to maintain Temperature.
Sapphire Window used to protect IR elements.
Sapphire Window

Calibration Standoff Distances
L_1 : 1.75 in.
L_2 : 13.25 in.

IR Center Wavelengths
λ_1: 1.230 μM
λ_2: 1.590 μM
λ_3: 1.850 μM
λ_4: 2.200 μM

High speed Shutter
(UNIBLITZ 25mm Aperture)
Shutter Mode: Single Shot
Shutter Duration: 20 Msec

Calibrtaion Cables are the 4 Conductor QUAD. The Cable lengths are nominally the same length as would be for the test (Eg. 1,000 ft.).

Data Recorder
High Impedance Inputs (1.0 x 10^6 Ω)

BLACKBODY CALIBRATOR
MODEL: Mikron™ 390
Temperature Range: 600 – 3000°C
873 – 3273°K
Resolution: 1.0 °C
Aperture: 25.4 mm (diameter)

Figure 4, calibration configuration for four color IR.

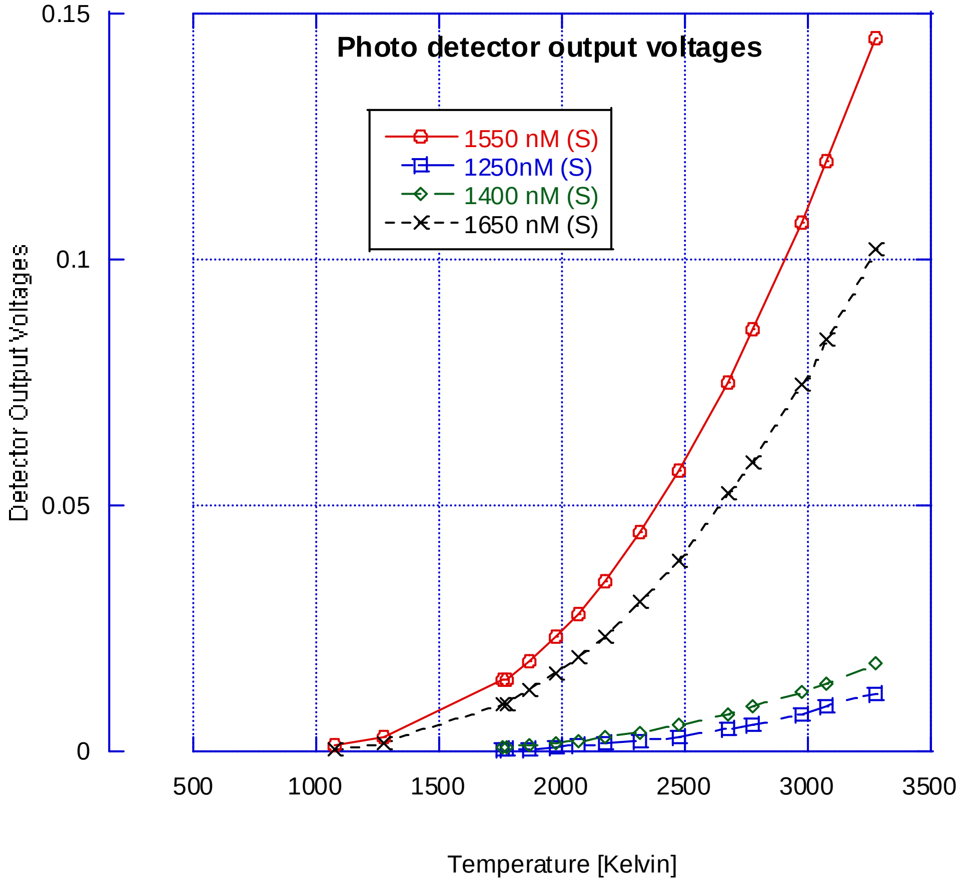


Figure 5a, example from fiber optic pyrometer system of photo detector output voltages for each photo detector with a specific NIR band pass filter using the black body calibrator source.

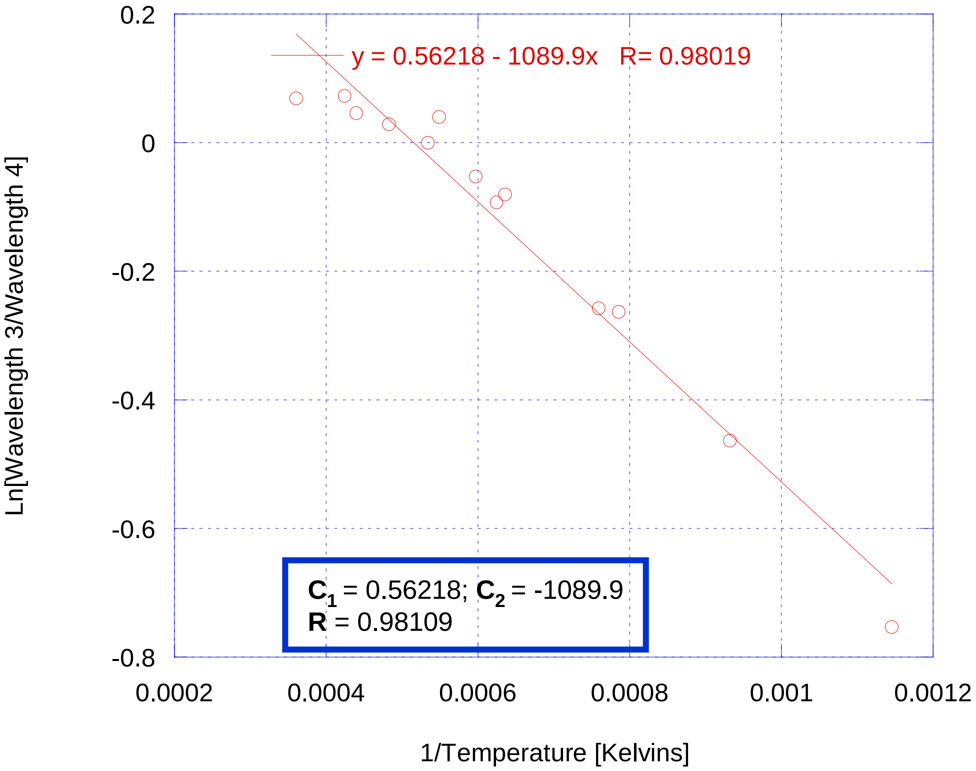


Figure 5b, example from four color IR of a least squares straight line calibration curve with intercept (C_1), slope (C_2), and correlation coefficient (R) using the black body calibrator source.

IV Test events and Fielding Configuration

Two separate test events fielded by DTRA that Highlight the performance of both the four color IR and fiber optic pyrometry system are presented.

The event fielded for the four color IR consisted of two separate tests each with two four color IR sensors fielded. One sensor was placed 28 Meters, and the other was placed 41 meters from ground zero. Each test used the same type of charge. Figure 6a shows the general physical fielding layout, and figure 6b shows the actual fireball with the sensor locations engulfed by the fireball.

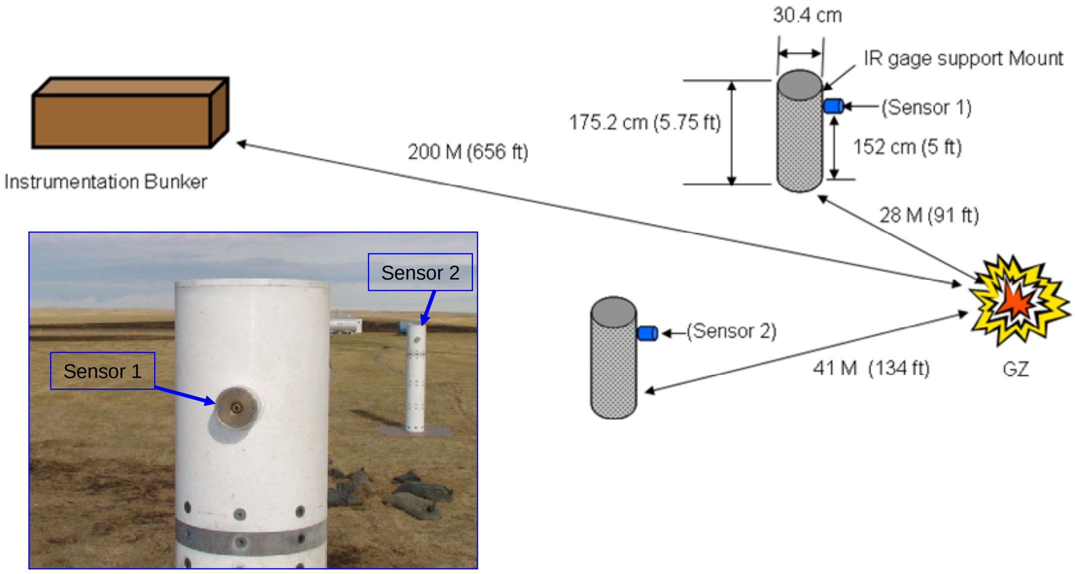


Figure 6a, general fielding layout for four color IR event.

Figure 6b, fireball of actual event with four color IR gages fielded.

The event fielded for the fiber optic pyrometry system was the first event for this newly developed sensor and it acquired accurate data from within an enclosed area. Figures 7a, 7b show the front end mounting plate design used to secure the optical fibers within the test structure at the measurement point, and figure 7c shows the configuration of the structure in which the test was conducted. There was also one type K thermocouple (2500 Fahrenheit, 1644 Kelvin) fielded to acquire the overall environmental temperature within the test structure. This thermocouple has a much slower rise time (50 mSec) as compared to the rise time of the pyrometers (300 µSec).

Figure 7a, actual fiber optic front end interface secured on metal mounting plate in ceiling of structure.

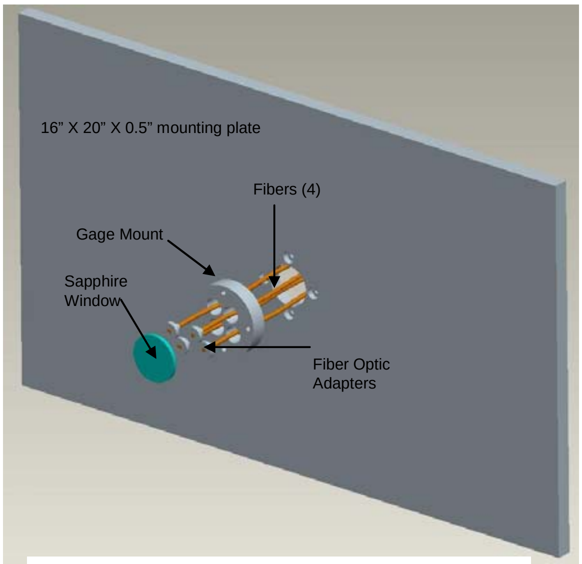


Fig 7b, graphic of mounting of front end fiber components on metal mounting plate.

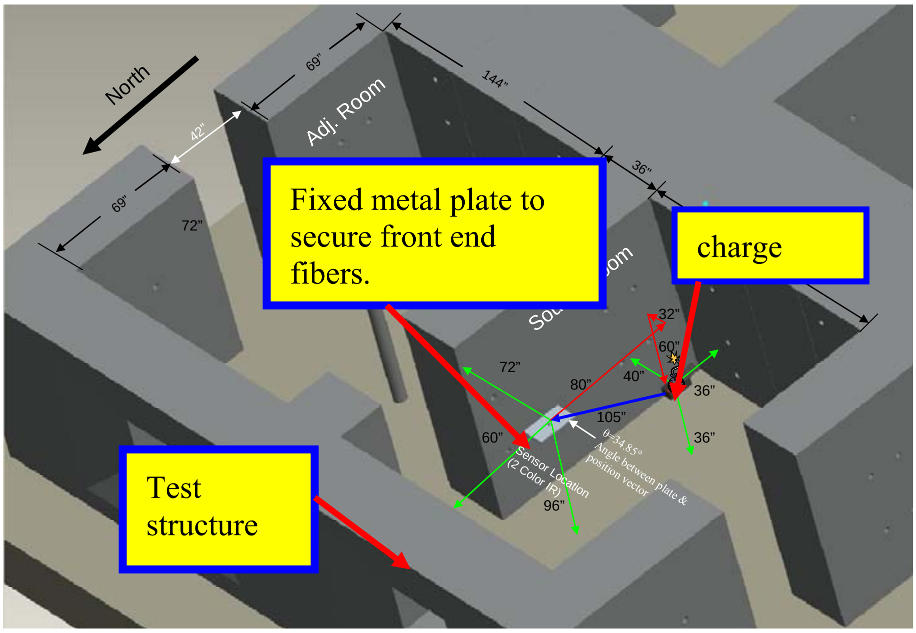


Figure 7c, configuration of structure used for event in which fiber optic front end was fielded. The charge was 105” (8’ 9”) from front end fiber locations which were fixed at a measurement point with a metal plate secured to the test structure.

The photo detectors were physically protected in a sealed area away from the blast location within a protected room of the test structure. The fiber optic cables came in to the front end of the photo detectors with the narrowband IR band pass filters, and the conditioned output voltages from the photo detectors was then conveyed to be recorded on the DAS via 1200 ft.of 50 Ω coaxial cable (RG-58). Figure 8 is an overall diagram of the fiber optic pyrometry system. The photo detector, after it processes the optical signal, produces an electrical data signal that can have an output amplitude level of up to 5 volts. To ensure that the DAS processed this signal to produce accurate data, it was configured so that the signals into the data recorder (RRS) after signal conditioning (SCA) did not result in a signal that over ranged the system which would result in distorted (clipped) data.

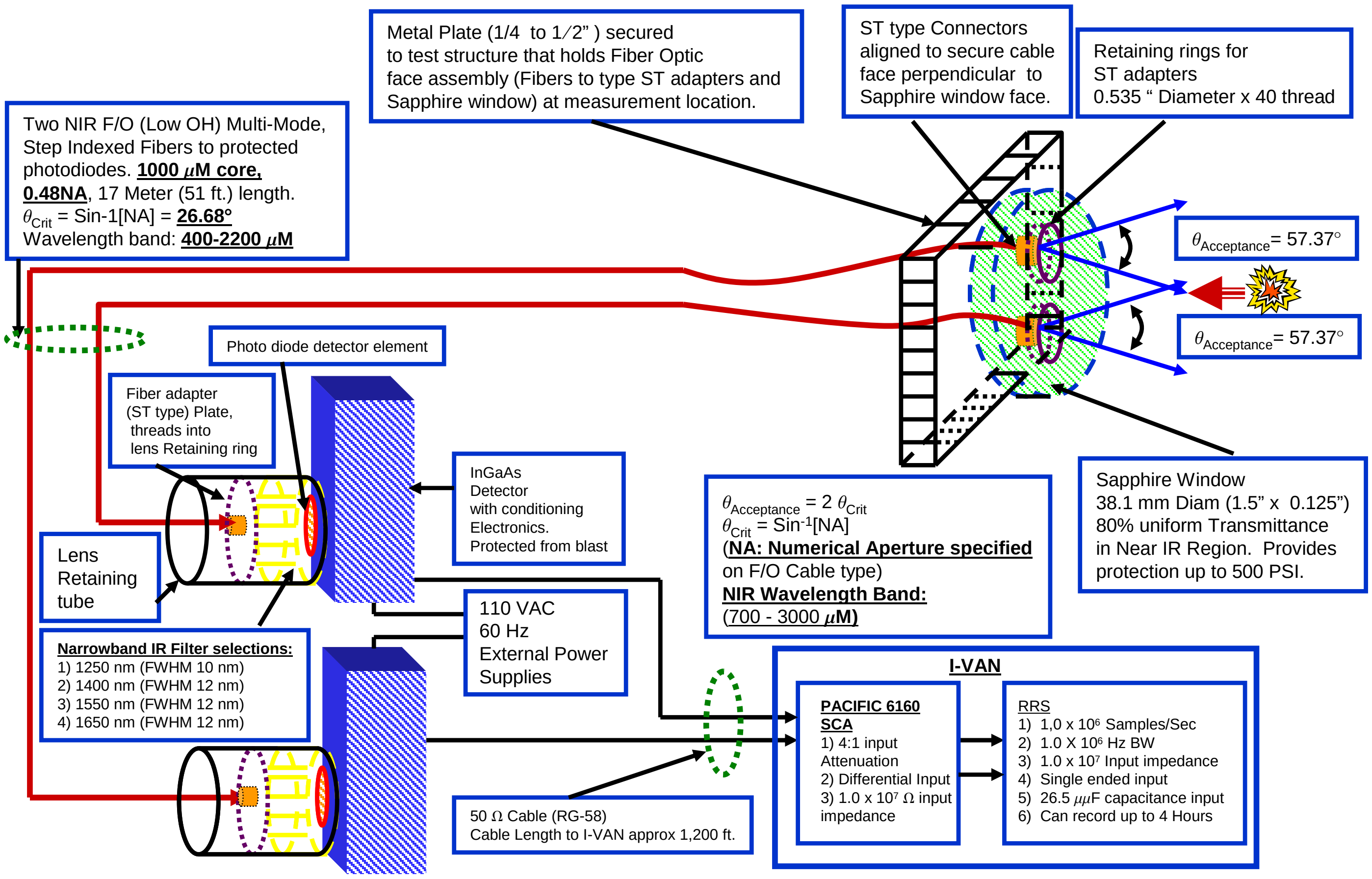


Figure 8, diagram of fiber optic pyrometry system.

V Results and Summary

Four Color IR

The four color IR system has produced consistent high quality data that was fast response

(300 µSec), high temperature (> 3000 Kelvin), and sufficient event duration (100-1000 mSec) from all of the events that it was fielded on. It is completely self contained in a durable mount system designed by the instrumentation branch of DTRA that allows it to be fielded in a blast environment (without fragmentation) up to 500 psi.

The results of the events for both of the four color IR tests are presented in figure 9a. For both of these tests, the fireball engulfed both sensors which survived in their gage mounts, and recorded accurate data for the effective duration (1 to 2 seconds) of the event. These two tests were conducted with the location of the sensors remaining the same, as well as the same type of charge being used for both tests as well. The presentation of the data for both events in figure 9a shows the consistency of results. Three of the four records exhibited the same general trend and the record produced by sensor 1 (test 1) had a different trend most likely due to the close proximity of blast debris interfering with this sensor measurement.

Fiber Optic Pyrometry system

The fiber optic pyrometry system was designed as a low cost improvement to the four color IR system, as it provides for a greater flexibility in selecting specific measurement points within a test bed. The four color IR has the physical limitation of being able to emplaced only where its mount canister can be embedded within the test bed.

The optical fibers can be placed at the desired point of measurement with the photo detectors physically separated and protected from the blast. The distance between the sensing fiber front end and the photo detectors allows for the inexpensive and expendable front end to acquire accurate data in a harsh environment without concern if the front end is destroyed in the test. This system also allows the flexibility of selecting two or more (for greater accuracy in the temperature calculation) narrowband IR filters for an optimal ratio set (selected to avoid interference from H_20, CO or CO_2 species). The narrow band IR filters are typically stock items from a COTS provider and are easily acquired.

The temperature results shown in figure 9 of this event were calculated from the six ratios available from the four NIR band pass filters. A type K thermocouple was also used which acquired the long term environmental temperature of the test. The data all exhibited the same general character with an effective measurement duration of 140 mSec, and an average initial peak temperature of 4500 Kelvin, trending towards the long term measurement of the thermocouple of 1200 Kelvin. The measurements calculated from the ratio sets of 1250/1550 nM and 1250/1650 nM had the closest measurement character and this suggested that this would be a good set to continue to use on future tests. An average of their values is also presented (Black curve).

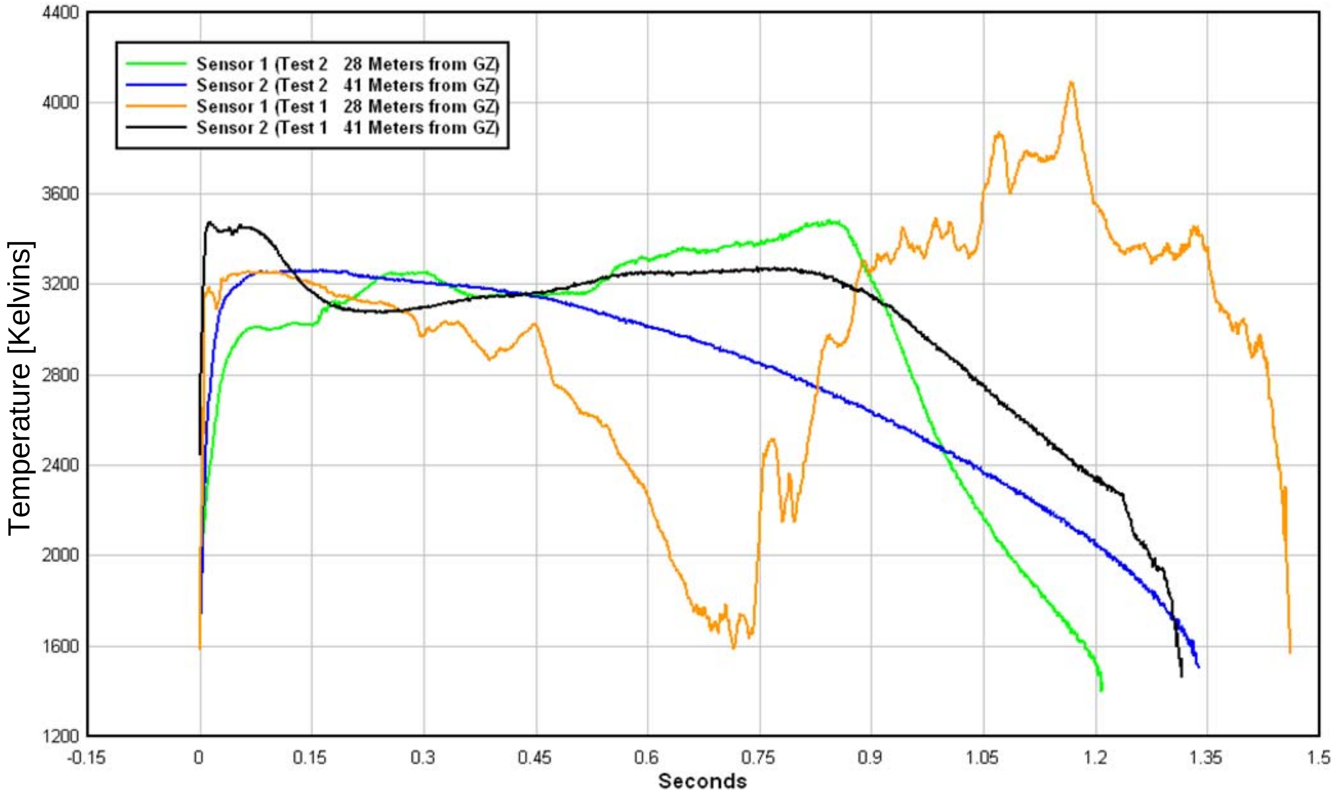


Figure 9a, four color IR event results.

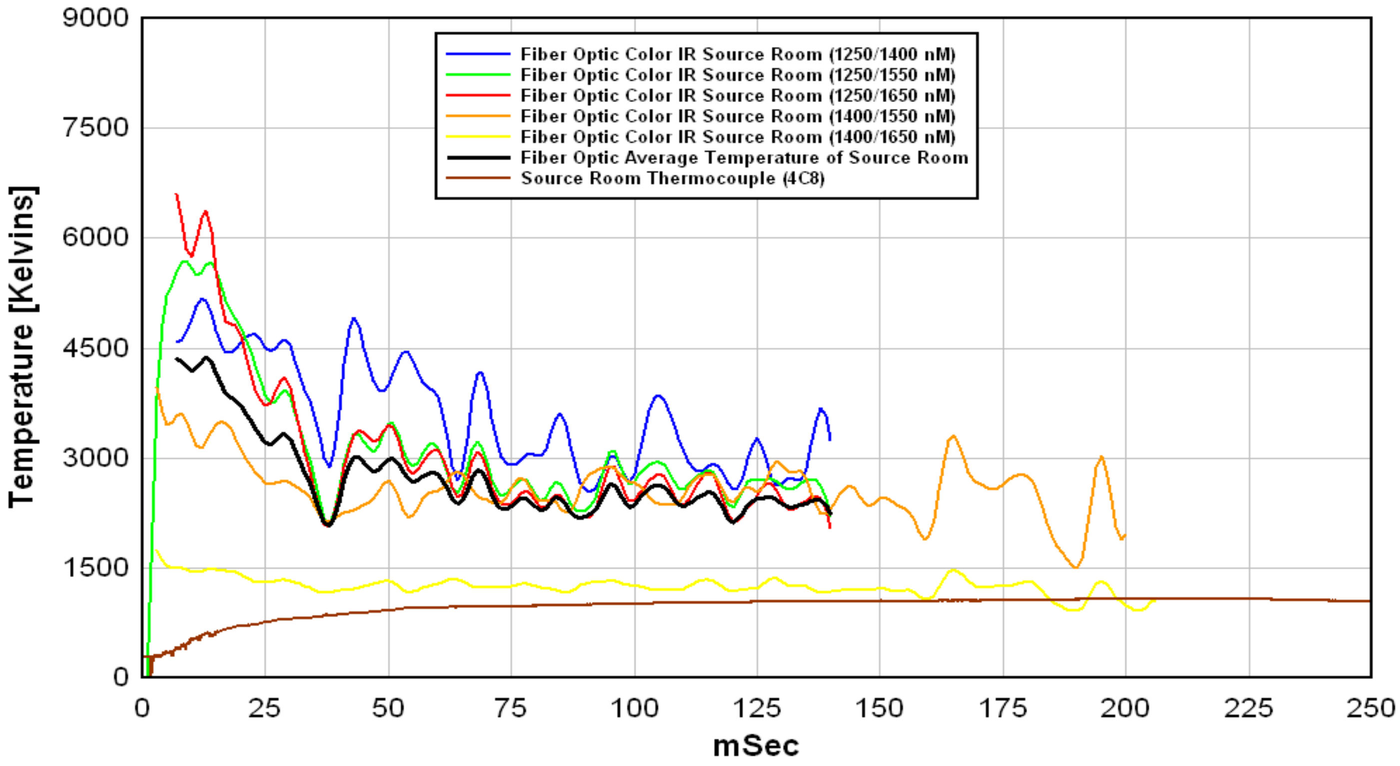


Figure 9b, fiber optic pyrometry event. Results from the ratio measurements presented along with their average. Thermocouple result also shown for general temperature environment.

Acronyms and Abbreviations

ADC	Analog-to-Digital Converter
DAS	Data Acquisition System
HE	High Explosive
DTRA	Defense Threat Reduction Agency
TDR	Transient Data Recorder
COTS	Commercial off the Shelf
SCA	Signal Conditioning Amplifier
NA	Numerical Aperture
NIR	Near Infra Red
IR	Infra Red
NIST	National Institute Standards and Technology
PbS	Lead Sulfide
InGaAs	Indium Gallium Arsenide
TEC	Thermo Electric Cooling
I-VAN	Instrumentation Van
ICU	Instrumentation Control Unit
FWHM	Full Width Half Maximum.
WMD	Weapons of Mass Destruction