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PORTABLE, SOLID STATE, FIBER OPTIC COUPLED DOPPLER INTERFEROMETER SYSTEM FOR DETONATION AND SHOCK DIAGNOSTICS

K. J. Fleming, O.B. Crump
Sandia National Laboratories
Albuquerque, New Mexico, 87123

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VISAR (Velocity Interferometer System for Any Reflector) is a specialized Doppler interferometer system that is gaining world-wide acceptance as the standard for shock phenomena analysis. The VISAR's large power and cooling requirements, and the sensitive and complex nature of the interferometer cavity has restricted the **traditional** system to the laboratory. This paper describes the new portable VISAR, its peripheral sensors, and the role it played in optically measuring ground shock of an underground nuclear detonation (UGT). The Solid State VISAR uses a prototype diode pumped Nd:YAG laser and solid state detectors that provide a suitcase-size system with low power requirements. A special window and sensor was developed for fiber optic coupling (1 kilometer long) to the VISAR. The system has proven itself as a reliable, easy-to-use instrument that is capable of field test use and rapid data reduction employing only a personal computer (PC).

INTRODUCTION

Detailed analysis and accurate models of shock phenomena and high speed motion require an instrument that is capable of measuring the high acceleration of surfaces accurately and non-intrusively. Dent blocks and stress gauges can only infer the **final** velocity of detonations while critical information pertaining to the acceleration is unknown. A versatile instrument that optically measures acceleration, displacement and velocity is VISAR. The VISAR (Velocity Interferometer System for Any Reflector) uses coherent, single frequency laser light to illuminate a target that has some reflectivity. The reflected light is collected and routed through a modified, unequal leg, Michelson interferometer. As the target moves, the resulting Doppler information is detected and electronically analyzed, then the data are converted to velocity and displacement time histories using software operating on a personal computer (PC). The sensitivity, accuracy, and high bandwidth of VISAR are attributed to the optical method of measurement and its 400 MHz bandwidth is primarily limited only by the electronics in the system.

Although the VISAR technique is excellent to measure shock phenomena, there are some limitations with the conventional VISAR, such as; inherent sensitivity to adverse environments found outside the laboratory, hazardous unenclosed laser beam, high current, voltage and cooling requirements, and inability to measure devices not in the "line of sight" of the laser beam, e.g. through smoke, tunnels, or inside chambers. In an attempt to improve on the versatility of VISAR, a solid state system with fiber optic coupling and rugged components has been developed and rigorously tested in harsh environments. The fiber optic coupled sensor used to send and collect the light at the target is unique from previous techniques and, in recent tests, has performed flawlessly even after four months encapsulation in curing concrete. The solid state VISAR described in this paper was used to measure

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ground shock generated by a nuclear detonation at the Nevada Test Site (NTS).

BACKGROUND

The VISAR was invented by Barker and Hollenbach[1] primarily for measuring free surface velocities of materials in gas gun experiments. An improved version of VISAR, developed by Hemsing[2], electronically inverts and adds the 180° out-of-phase optical signals that were previously wasted, which effectively cancels target self-light effects and doubles the signal intensity. During fast shock jumps, the system may miss Doppler information which can cause discrepancies in measured velocity. For this reason, Kennedy and Crump[3] developed the double-delay-leg system. This VISAR takes the return light, splits the optical signal and routes it through two interferometer cavities with different sensitivities. The data can then be more accurately reduced by comparing the results of the two systems. The conventional VISAR has many sensitive components mounted on an optical table but the Fixed-Cavity VISAR (developed by Stanton, Crump and Sweatt[4],) simplifies the interferometer cavity by cementing the movable components together. The result is a rugged, small, easy-to-use system that requires a minimal amount of adjustment.

A low cost, portable VISAR using a diode laser and a fiber optic coupled sensor has been developed by Fleming and Crump[5] with successful velocity measurements taken on electrical slappers. The diode's invisible laser light makes alignment to the target difficult and the aberated, high divergence beam profile of the laser is difficult to propagate through space for any extended length. Both problems are solved by the development of an imaging fiber optic coupled sensor[6] that has intra-optic video capabilities. The sensor allows for remote target measurements and verification of the correct area of target illumination.

THEORY OF OPERATION

In a typical experiment, a laser beam is focused to a small spot onto a target of interest. The reflected light is collected and routed to the interferometer cavity *(figure 1)*. A dichroic mirror is inserted into the light collecting assembly to transmit the laser light and reflects the other wavelengths (This technique is valuable for viewing the target, allowing for precise alignment of the laser beam.).

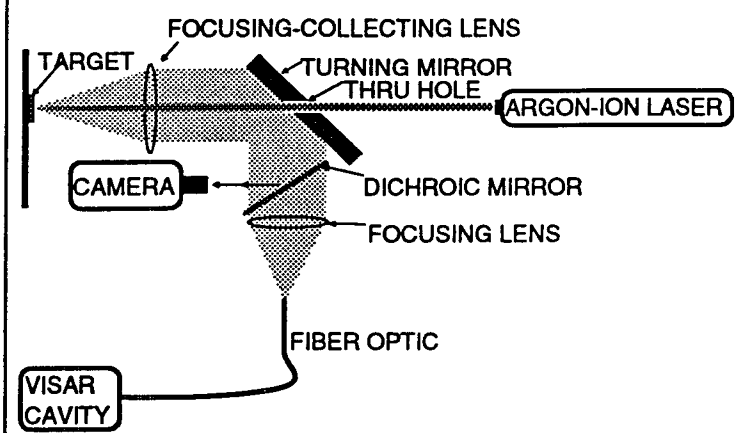

figure 1. Conventional method for collecting Doppler information from target.

The return light, containing equally distributed *S* and *P* polarization components, is collimated and sent through the interferometer cavity *(figure 2)*. A 50/50 beamsplitter separates the light so that one beam travels through the glass "delay bar" and the other travels through air and an 1/8 wave retarder before recombining and producing an interference (fringe) pattern .

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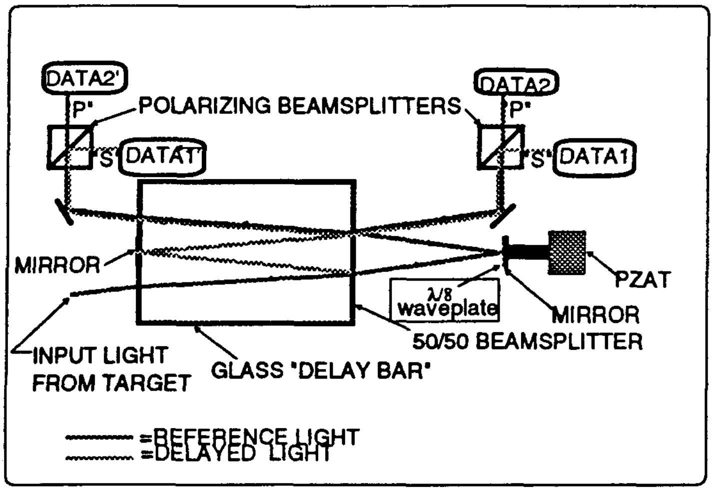

figure 2. Fixed cavity VISAR schematic showing beam paths and piezo angular translator (PZAT). "Data" figures are photodetectors.

In order to obtain quality fringe patterns, the image distances in both legs of the interferometer must be equal to within a few thousandths of a inch. If both legs of the interferometer are air, the measured distance would be equal. However, the refractive properties of glass make the image distance in the glass *delay* leg farther away than the image distance in the air *reference* leg. This relationship is defined by:

$$x=h(1-1/n) \qquad (1)$$

where h is the delay leg length and n is the index of refraction. The distance the light has to travel in the delay leg is farther than the reference leg **and** the velocity of light is slower in glass than in air. Using the relationship from equation (1), the delay time τ is given by:

$$\tau=(2h/c)(n-1/n) \qquad (2)$$

where c is the speed of light in a vacuum. Using these relationships, the fringe count $F(t)$ relates to target velocity $u(t-\tau/2)$ as[7]:

$$u(t-\tau/2)=\frac{\lambda F(t)}{2\tau(1+\Delta\nu/\nu)}\cdot\frac{1}{1+\delta} \qquad (3)$$

in which λ is the wavelength of the laser light, $\Delta\nu/\nu$ is an index of refraction correction factor if a window is used, and δ is a correction factor with wavelength for dispersion in the delay bar. Equation (3) may be manipulated to obtain the *velocity-per-fringe* (VPF)* constant for the interferometer. The VPF equation is:

$$\mathrm{VPF}=\frac{\lambda}{2\tau(1+\Delta\upsilon/\upsilon)}\cdot\frac{1}{1+\delta} \qquad (4)$$

With these relationships, VISAR interferometer cavities with different sensitivities can be designed for optimal performance with regard to anticipated velocity versus Doppler resolution parameters. In any experiment, it is helpful to know that everything is operating correctly. Active feedback from the measuring instrument is a good method of assuring proper operation. The piezoelectric angular translator (PZAT) performs one such function by electrically moving a mirror in the cavity, effectively changing the reference leg dimension. When the dimension changes by $\lambda/2$, a 180° phase change occurs which effectively simulates the fringe record for a velocity change equivalent to one-half the VPF value. The return interference signal is monitored and the experimenter is now able to verify that the system is functioning correctly. In *figure 2,* one component of light passes twice through the 1/8-th wave retarder, which makes it 90° out of phase with the other component. The polarizing beam splitting cubes then separate the S from the P light and each beam is sent to a photo detector coupled to a digitizer.

Recording two 90° out of phase signals is advantageous because the interference pattern produced is a sinusoidal plot. Phase resolution of the signal is poor when the intensity of the sine wave is at a maxima or minima. Thus, recording two sinusoidal traces 90° out of phase insures that at any point in time one of the signals will be in a region of good resolution.

* The VPF is a numerical constant unique to an interferometer cavity, typically given as mm/us or km/s. For instance, a cavity with a VPF of 1 would have an interference pattern of a 360° sine wave for a target accelerating to 1 mm/us.

Also, target acceleration or deceleration can be discriminated. During target acceleration, one signal pattern will lead the other by 90° and a deceleration will cause the opposite to occur.

SOLID STATE VISAR DEVELOPMENT

The original intent for the development of the Solid State VISAR was for a portable "in house" tool that could be shared by several experimenters and used in the laboratory or in the field. At the same time, the Defense Nuclear Agency (DNA) was interested in optical based instrumentation for use at the Nevada Test Site (NTS). One particular experiment required an "up close" measurement of ground shock generated by the detonation. Since the nuclear event yields radiation and electro-magnetic fields, optical sensors are preferred because of their relative insensitivity to EMP and radiation. Also, the sensors require no electricity which adds a greater margin of safety to personnel. The following are some of the requirements for the system to function:

- Doppler measurement over kilometer-length fiber optics
- Rugged system, operating on 120 VAC
- Must run several days with no adjustments
- Sensors must withstand mechanical and chemical abuse
- Window and sensors must survive concrete encapsulation and measure ground shock at a distance of 7 meters from the detonation
- Data acquisition bandwidth limited to 20 MHz

EXPERIMENT DESCRIPTION

Measurement of ground shock produced by the detonation is important because it contains valuable information used for analyzing and modeling of the test. This ground shock measurement method uses a window, with fiber optic coupled sensors connected to the VISAR cavity. The window is oriented towards the device so that the induced motion is normal to the face of the glass cylinder. Laser light is injected into the fiber optic, to the sensor which focus the light onto the reflective coating deposited on the front of the window in contact with the grout material. The reflected light is collected and injected into the return fiber optic which is connected to the VISAR cavity, then the entier area is filled with concrete. When the device detonates, a shock wave is transmitted through the concrete and into the window where the shock wave imparts a particle velocity in the window. The Doppler shift, which corresponds to the particle velocity, is transmitted through the fiber optic to the VISAR cavity. The fringe data are converted to electronic signals and stored on digitizing oscilloscopes (digitizers).

The mechanism for triggering the digitizers is a time of arrival (TOA) gauge. The TOA gauge is simply a loop of fiber optic protruding in front of the window with a laser connected to one end and a photodetector attached to the other. When the shock wave breaks the fiber optic, laser light no longer reaches the detector and the output voltage drops, triggering the digitizers to record the VISAR data.

The characteristics of the window and the material transmitting the shock wave into the window **must** be known for accurate particle velocity measurements. The simplest way to use a window is to choose a material that has already been characterized. Unfortunately, the unusual laser wavelength and the large window thickness required for adequate recording time (40 us) did not allow previously characterized materials to be used. The material chosen for the window used in this experiment is Schott BK-7 glass, which has good broadband optical transmittance and is available in the thickness required (8" thick x 14" dia.). Several specimens of BK-7 as well as cored samples of the concrete were analyzed for their shock properties by impacting them into other known window materials, then into themselves using a gas gun as the target accelerator. The results from the analysis, commonly called a Shock Hugoniot, determine whether the material is suitable for the shock pressure predicted for the event. The data also correlate the impedance mismatch at the grout/glass interface. The anticipated shock pressure for the NTS test, at 7 meters from the device, is ≈ 70 kBar in the grout. ***Figure 3*** is a display of the type of plots for the shock pressure tests obtained using BK-7 as the impacted material. Although at pressures above 90 kBar, the non-linear "shock-up" makes particle velocity correlations more difficult.

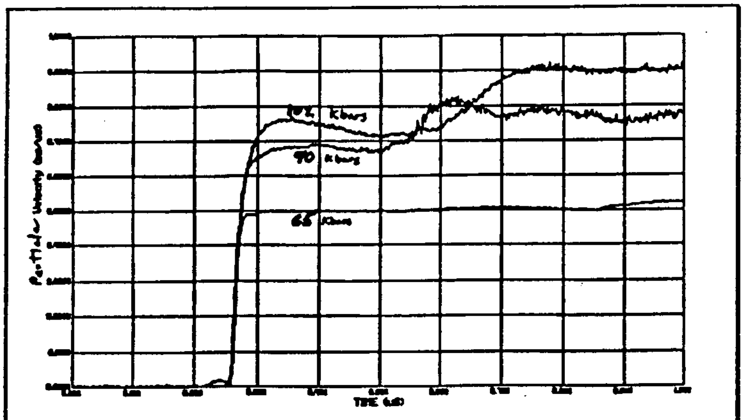

figure 3. BK-7 shock profile characterization for 65, 90, 102 kBar impact pressure.

The VISAR designed for the underground test contains a diode pumped Nd:YAG laser operating at 1319 nm wavelength, with a CW output of 160 mW, and a 5 kHz, single frequency linewidth. This laser is a good choice for this system because it is stable, has low sensitivity to optical feedback, and the wavelength exhibits very low attenuation and high bandwidth in silica fiber optics. This high performance is due, in part, to the self cancellation of different wavelength-dependent dispersion effects that occur in the fiber. The photodetectors in the system are comprised of indium-gallium-arsenide (InGaAs) photodiodes coupled to low noise/high gain operational amplifier circuitry. The peak sensitivity for these detectors is at 1320 nm wavelength, which not only affords greater sensitivity, but also increases the signal to noise ratio. The linear response range for the detector/amplifiers is DC to 125 MHz with a linear response better than 3% and an output voltage of 40 mV/uW of light at 1320 nm wavelength (The flat linear response is critical for accurate data collection).

One of the most critical parts of the system design is the fiber optic coupled sensors. ***Figure 4*** illustrates the sensor used for collecting the Doppler information.

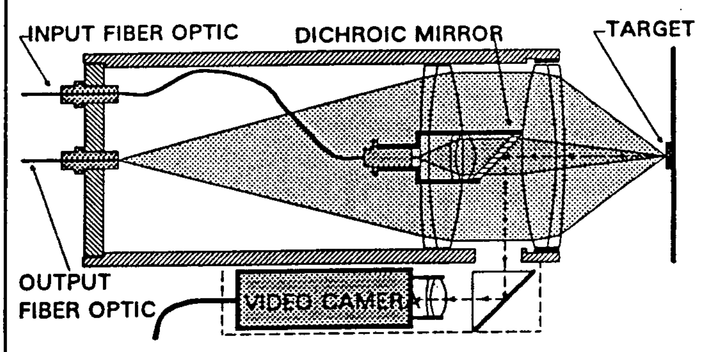

figure 4. Drawing of imaging optical feedback sensor for VISAR.

Laser radiation is injected into a 50 micron graded index, multimode fiber optic connected to sensors which image the fiber optic onto the rear surface of the window. The return light reflected from the window's front surface is collected and injected into a 100 um step index, multimode fiber optic connected to the VISAR cavity. A redundant sensor is linked to the VISAR cavity in the event of damage to primary sensor (***figure 5***). Correctly designing the optical train is paramount to attaining good signal strength that won't degrade under harsh environmental conditions After the sensors are encapsulated in 100 foot thick concrete, re-aligning is impossible.

There was some concern about stress induced polarization after observing wildly fluctuating *S* and *P* ratios when the fiber optic was bent. These fluctuations in polarization change the sine-cosine relationship critical to accurate data analysis. In most cases, this polarization problem occurs when highly polarized laser beams are injected in short lengths of fibers. The root cause is the modes are not fully mixed and stressing the fiber optic redistributes these modes causing a change in the polarization. Since there was no room for error on the real test, three solutions were incorporated to remedy the problem: a mode scrambler to pinch the fiber optic into a serpentine shape was installed, a long fiber optic was used to mix the modes, and a rotatable linear polarizer was installed at the entry into the interferometer cavity. The modifications worked well.

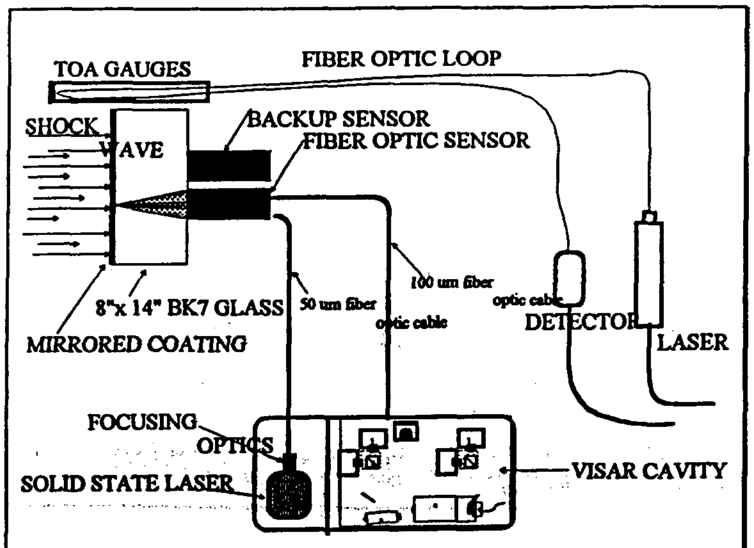

figure 5. Diagrammatic layout of the window, sensors, time-of-arrival (TOA) gauges, VISAR cavity, and laser.

The sensors perform three functions; collimating and focusing the laser radiation onto the front surface of the window, collecting the return light, and injecting the light into the return fiber optic. The sensor configuration was similar to *figure 4* except that the camera is omitted, because there was no need to see the front window surface.

Although the primary function of the TOA gauge is to trigger the digitizers, utilizing the TOA array provided additional shock data. Several gauges were placed around the window with the tips of the TOA's staggered to intercept the shock wave front at different points in time *(figure 6)*. As the shock front breaks the TOA's, the digitizers record the time-of-break that is then correlated to the shock's arrival time and velocity.

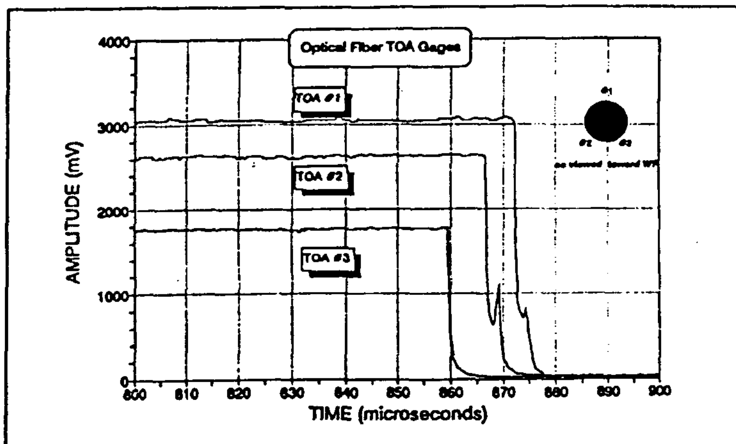

figure 6. Data from three TOA gauge fiber break sensors.

EXPERIMENTAL RESULTS

The VISAR and TOA gauges performed with strong, clean signals recorded on all instrumentation channels. The Doppler information, in unreduced form, is shown in *figure 7*. The signal strength is at 1 V peak to peak which is well above the noise floor that has, in the past, caused difficulty in accurate data reduction. The 90° phase relationship between the two traces indicates the stress induced polarization problem was cured.

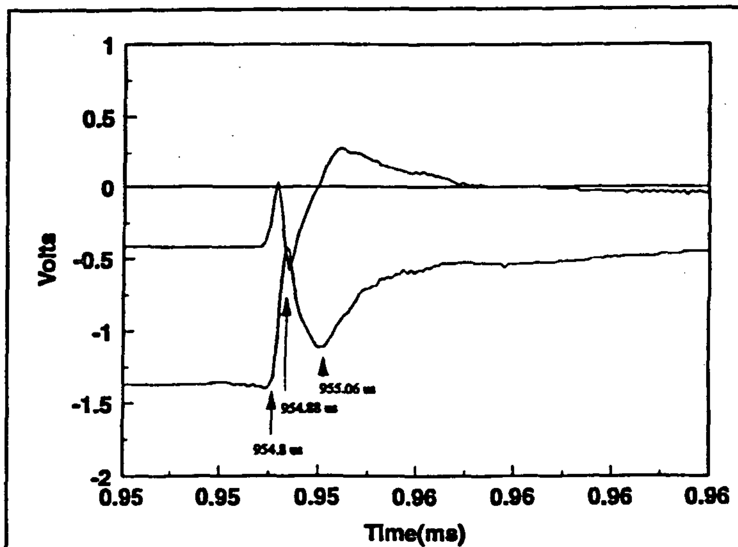

figure 7. Unreduced digitized data from VISAR illustrating the 90° out -of-phase relationship.

Figure 8 shows the reduced data. There is an impedance mismatch between the BK-7 and the grout but the shock Hugoniot for these materials is known and was used in calculating the final particle velocity.

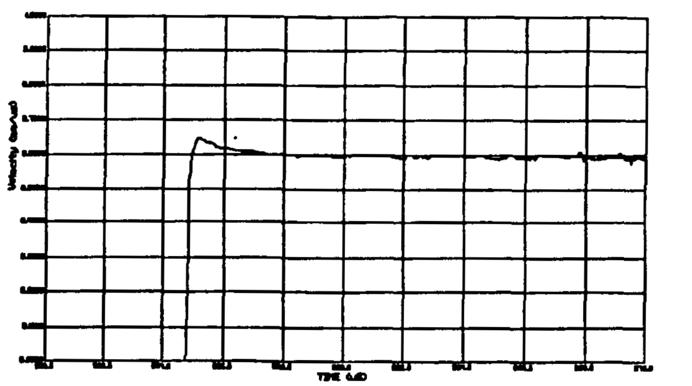

figure 8. Particle velocity for the BK-7 window at the grout/window interface. Maximum pressure= 85 kBar.

The peak recorded particle velocity was on the order of 0.6 mm/μs, which corresponds to a pressure at the interface of 85 kBar. The results indicate that the yield of the device was greater than expected (60 kBar). The choice of BK-7 was fortunate becaus if fused silica was available and used the data would have been lost because it is known to become opaque at pressures above ≈ 82 kBar. The BK-7 is apparently able to withstand slightly greater shock pressures before going opaque and at 1/3 the cost, it is significantly less expensive.

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