# Fiber-Optic Instrumentation for Lethality Assessment

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*At the request of the Missile Defense Agency, APL provided fiber-optic blast initiation detectors (BIDs) to detect the warhead "first light" signal for the U.S. Flight Test I in July 2004 and the Pacific Phoenix Flight Test in May 2006. The target-based BIDs provided long-range detection of rapid optical flashes while rejecting changes in background lighting, including solar illumination. After successfully detecting, discriminating, and reporting the warhead bursts, the BIDs were presumably destroyed by incoming fragments within milliseconds. After both tests, the BID data were fused with hit-detector data with sufficient fidelity to piece together the intercept geometry between the target and the intercepting missile vehicles and thus to gauge the performance of the interceptors. The flight-qualified BID is an advanced fiber-optic instrument that is used to acquire valuable data for lethality assessment. This article describes the BID technology as well as several other closely related fiber-optic technologies that are in various stages of development and use at APL.*

## INTRODUCTION

APL has provided specialized flight instrumentation for many years, starting with the variable-time, or proximity, fuze in World War II. The target-based instrumentation described in this article is used to quantify the target experience during flight and the final moments of the endgame, when the interceptor overtakes the target. Target-based lethality instrumentation offers a unique vantage point for measuring the performance of the interceptor. During post-test analysis, data acquired by target-based instrumentation are used to infer the likelihood that a threat payload would have been rendered harmless by the intercept.

The blast initiation detector (BID) technology developed at APL is a good example of how critical measurements can offer tremendous insight into the final moments of an intercept. The BID rapidly detects the "first light" from a fast optical flash, such as that which is generated by a detonating warhead, while rejecting slower optical signals, including the plume of the interceptor and the Sun emerging from behind a cloud. Thus, the BID provides a distinctive temporal reference point for the intercept in the target telemetry stream.

The proof of concept for APL's BID technology was established during wind-tunnel testing in early 2000 and during a high-speed sled test at Holloman Air Force Base in November 2000.[1] The wind-tunnel testing validated the design of the high-temperature light guide (HTLG) used to receive optical signals.[2] During the sled test, a fiber-optic BID was installed in a target that was suspended over the end of a test track. A warhead then was fired down the test track and detonated near the target, as seen in Fig. 1. The BID detected the warhead detonation before the warhead fragments impacted the vehicle. The BID and fragment hit data then were used to measure the standoff distance of the warhead at the time of detonation. This calculation agreed with the known geometry within ~2%.

## BID DESCRIPTION

The BID is an array of high-speed optoelectronic detectors developed at APL that

- Provides a rapid digital electronic output pulse whenever a sufficiently fast and sufficiently bright optical input signal is observed within the fields of view (FOVs) of the detectors,
- Rejects slower-changing optical signals, and
- Remains operational through the demanding flight environment and vehicle heating profiles.

Rapid optical signatures, such as a warhead detonation or an intercept flash, have very rapid rise times compared with other optical sources. The BID does not respond to slower-changing optical signals, such as the flickering intensity of a rocket plume from an incoming interceptor or the Sun emerging from behind a cloud. The BID is designed to survive fairly severe shock, vibration, and thermal environments. The number of detectors usually ranges between 3 and 12, depending on the expected blast location and the availability of mounting locations for the optical access ports. The first U.S. flight test, USFT-1, used 12 optical channels to maximize coverage of the FOV. The Pacific Phoenix BID test used six channels, although only three externally looking channels were used because the target had only three locations on which to mount the HTLGs. The other three channels were used to monitor interior compartments of the vehicle. The Pacific Phoenix test showed that success might still be achieved using a small number of channels when those channels are strategically placed and oriented to cover the expected blast locations.

Figure 2 is the block diagram of the BID, an array of optoelectronic sensors made of light-collecting elements and an electro-optics module (EOM). The EOM converts the optical signals into electrical signals and processes them to detect and discriminate fast optical signals with sufficient brightness. The light-collecting elements are optical fibers or HTLGs, although the BID also can be used in an open detector configuration (EOM only). The fiber optics used in the above flight tests had no additional optics to amplify the optical signals. The lengths of the HTLGs were tailored to match the routing requirements for installation within the target vehicles. HTLGs have been manufactured up to 15 m long, although short lengths of 1 or 2 m usually will suffice. The optical inputs terminate at six standard threaded

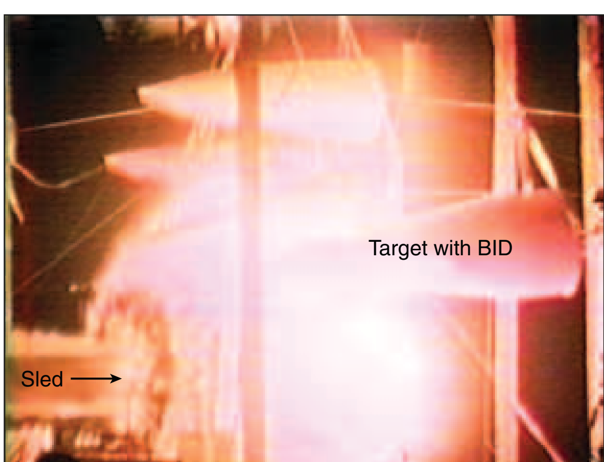


**Figure 1.** This high-speed photograph shows the target with the BID as the warhead begins to explode.

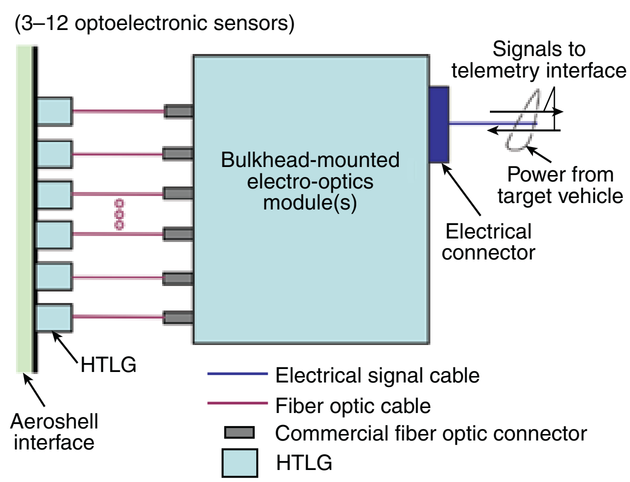


**Figure 2.** Block diagram of the BID. The BID is a target-based optoelectronic system that detects the "first light" from a rapid optical flash and rejects slowly changing optical signals. The first-light signal provides a temporal reference point for the intercept in the target telemetry.

905 series SMA-type connectors on the EOM, shown in Fig. 3. A single nine-pin electrical connector provides input power and seven single-ended CMOS outputs. The seventh channel is the logical "OR" of the six receivers and provides signal redundancy. The output digital signals are provided to a data system for time-stamping and subsequent telemetry. The standard BID draws ~5 W of power. An internal DC/DC converter enables operation using DC voltage inputs between 12 and 18 V.

The EOM consists of six parallel inputs, followed by thresholding, logical ORing, and buffering. For each channel, after optical-to-electronic conversion, the input circuit attempts to nullify any changing input. Sufficiently bright signals with rise times on the order of 100 $\mu$s or faster cannot be nullified. If the change in the input optical signal is so rapid that the first stage cannot null it out, then the signal passes through to an amplifier. If the amplified signal exceeds a voltage threshold, then a digital output pulse is produced on that channel. BID events are not latched. Each channel automatically resets after an optical event so that subsequent optical events will produce additional electrical pulses.

The input sensitivity of the BID is set such that direct viewing of the Sun will not damage or blind the detector. In addition, the circuit is designed to reject normal statistical fluctuations of solar radiation. Thus, there are no solar keep-out constraints on using the BID for a particular test. Camera flashes are used to test the system after installation. The BID will reliably respond to electrical-discharge-type camera flashes out to a range of ~100 m in direct sunlight and produce digital pulses on each illuminated channel.

## HIGH-TEMPERATURE LIGHT GUIDE

One of the main technological hurdles that was overcome during the development of the BID was the need to detect optical signals through the aerothermally heated target vehicle skin. In the case of a detonating warhead or an intercept flash viewed from an off-board platform, the optical signal occurs in the space outside the target vehicle and must be received and converted to an electrical signal. Aerothermal heating can raise the temperature of outside surfaces to hundreds of degrees, limiting the use of external sensors. Optical windows or domes could be used to pass the optical signal into the inside of the vehicle, but these are expensive and difficult to apply in severe shock, vibration, and thermal environments. The solution was found through the development of the HTLG.[2–4]

The HTLG, shown in Fig. 4, provides a means to receive or project optical signals across a high-temperature interface such as the exterior skin of an aerothermally heated vehicle. It is composed of a proximal end that usually terminates in a standard 905 series SMA-type connector, a jacketed bundle of optical fiber elements that are made of either borosilicate glass or quartz, and a high-temperature-tolerant distal tip. The high-temperature operation usually is limited to the distal tip of the light guide, where it is exposed to the highest temperature extremes, although the whole assembly could be fabricated with high-temperature-tolerant materials. Figure 5 shows a close-up of the high-temperature distal tip, where a freely rotating threaded jam nut is used to secure the distal tip to the vehicle structure. Only the very tip of the light guide protrudes through the skin to the outer surface of the target.

The HTLG is fabricated using patented methods that include the use of specialized inter-fiber filler material and manufacturing techniques. Figure 6 shows a backlighted cross section of the HTLG, where each individ-

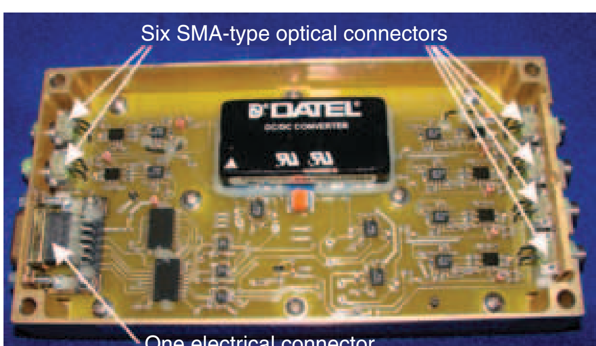


**Figure 3.** Six-channel BID EOM. Optical signals are delivered to the EOM via the HTLGs that terminate at mating SMA-type connectors on the EOM. All electrical connections, including power, ground, and digital output signals, are made through a single connector.

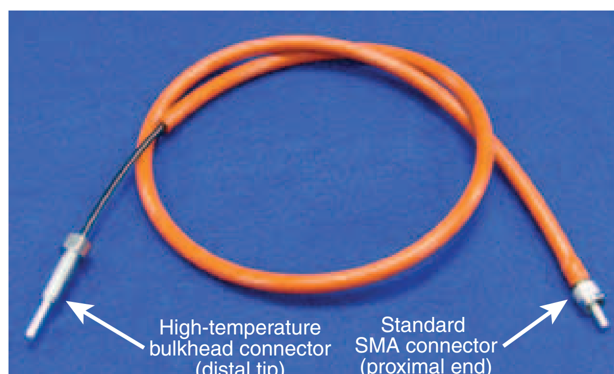


**Figure 4.** HTLG assembly. The HTLG is a specially designed bundle of optical fibers with a protective sheath and end connectors that are used to receive and route optical signals across a high-temperature interface. The HTLG provides adaptability by using tiny, flexible optical fibers as the optical medium. Light that enters the guide through the high-temperature bulkhead connector propagates through the fiber strands onto a detector within a mating SMA connector.

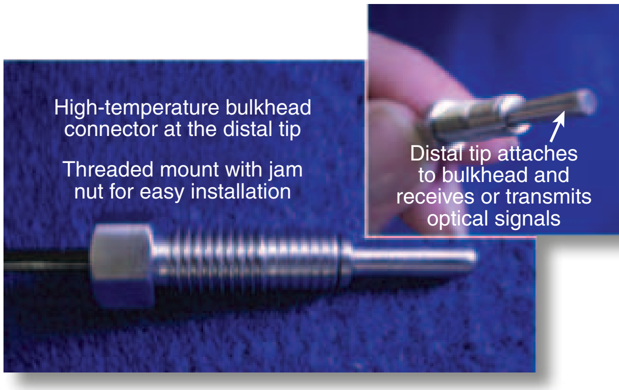


**Figure 5.** The distal tip of the HTLG is attached to the vehicle via a threaded jam nut. The flat polished tip is positioned within the boundary layer on the exterior surface of the vehicle.

ual fiber strand is illuminated from the opposite end of the bundle. The use of hundreds of small strands of optical material serves two purposes. First, the small fiber strands are very flexible, which allows the HTLG to be routed around other objects within the vehicle. A single solid optical material of the same cross section would be too rigid for bending around objects inside the vehicle. It also would be susceptible to fracture under the intense shock and vibration of the flight environment. The HTLG provides a robust window for the optical signal that withstands the flight environment very well and has modest installation requirements. Second, the use of multiple smaller strands provides excellent redundancy for the optical signal. If a small number of the individual strands were to fail, most of the optical signal still would reach the detector at the other end. The HTLG enables transmitting or receiving optical signals across an interface that may be as high as 2000°F, which is important because the "eyes" of the BID often need to be oriented toward the front of the vehicle in the direction of the incoming interceptor. As high-speed vehicles streak through the atmosphere, severe aerothermal heating occurs, particularly on the forward-facing load-bearing surfaces.

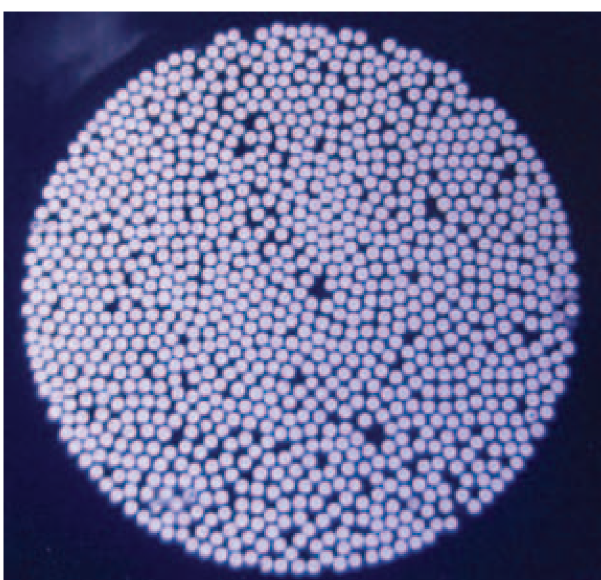

**Figure 6.** Backlighted cross section of the HTLG used in the BID. Each fiber strand in the photograph is 50 $\mu$m in diameter. Specially formulated high-temperature epoxy is used between the fiber strands to bond hundreds of individual fibers into a highly flexible optical conduit. The whole cross section shown here is contained within the tip of an SMA connector part.

The HTLG provides the only known reliable means of transferring high-speed optical data across a high-temperature interface without using a window or a dome. Wind-tunnel testing has demonstrated that the optical materials and all other materials used in the high-temperature distal tip of the light guide can operate at the temperature extremes without loss of optical throughput or FOV. In addition, the HTLGs successfully withstood the environmental conditions of the USFT-1 and Pacific Phoenix flight tests.

As noted above, HTLGs may be made by using either borosilicate glass or quartz as the optical material. The borosilicate glass version has a much larger FOV than the quartz version because of its larger numerical aperture. For the BID application, the larger FOV is important because it is not known in advance precisely where the optical flash will occur. The wind-tunnel testing indicated that the upper bound for the borosilicate glass HTLG is ~1200°F. The quartz version can be used to view combustion processes and can withstand temperatures up to ~2000°F.

Many hot surfaces have large temperature gradients, and it may be advantageous to recess the optical aperture of the HTLG below the hottest part of the surface. The high-temperature distal tip of the HTLG has a shoulder that is used for this purpose. This shoulder can be shimmed using stackable washers to adjust the precise location of the optical aperture. In the BID application, the optical aperture is positioned within the boundary layer on the outside of the vehicle to maximize the FOV. In a combustion-monitoring application, the optical aperture may be recessed into the sidewall of the combustion chamber, where it is slightly cooler.

The HTLG has gone through many adaptations since the initial units were tested in a wind tunnel. The HTLGs for the USFT-1 BID had significantly shortened and strengthened jam nuts on the distal tips and an increased optical cross section from 40 to 80 thousandths of an inch. In addition, the stainless steel monocoil used to protect the fibers in earlier builds was replaced by a polyimide sheath augmented by a kink-resistant vanguard layer of silicone tubing.

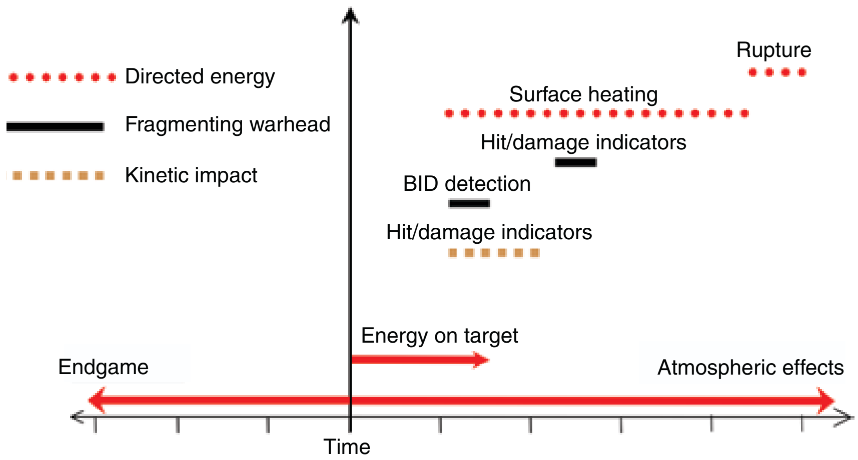


**Figure 7.** Different energy-delivery mechanisms have different timelines with respect to physical effects on the target. A kinetic kill inflicts damage in the shortest amount of time. The fragmenting warhead timeline is slightly longer because of fragment travel time. A directed-energy kill usually takes even longer to deposit the required energy on the target.

## TIMELINES FOR TARGETS

Three distinct energy-delivery mechanisms are used to project physical damage onto missile targets: directed energy, fragmenting warhead, and kinetic impact. Directed energy involves the use of laser beams or other directional beams to project energy onto the target from a distance. In the case of a fragmenting warhead, the interceptor nears the target and then detonates a warhead. Fragments from the warhead intercept the target and cause the damage to the target structure. The kinetic impact approach uses the kinetic energy of the interceptor to destroy the target vehicle. Figure 7 shows the timelines associated with the three approaches. With directed energy, the damage depends on heating the target, resulting in a relatively slow timeline. In the fragmenting warhead scenario, the warhead detonates at some standoff distance from the target. The first energy on the target is the optical signal from the warhead, which is detected by the BID. Shortly thereafter, the fragments arrive on the target and impart damage. This scenario is illustrated in Fig. 8. In close-up warhead situations, the blast wave from the detonation also may contribute to the damage. The kinetic impact mechanism has the fastest timeline. The energy from the interceptor arrives all at once, and the damage is inflicted rapidly as the two vehicles collide.

The BID initially was designed for the Navy Area Program for use in fragmenting warhead applications. The idea was to provide a temporal reference point in the target telemetry for the destruction of the target. If a warhead is sufficiently characterized so that the fragment velocity distributions are known *a priori*, then the BID can be used in conjunction with hit detectors to calculate the standoff distance of the interceptor at the time of detonation. The BID is not limited to fragmenting warhead applications and may be used wherever it is desirable to detect rapid, rising optical signals and to reject all others.

## RESULTS FROM FLIGHT TESTS OF THE BID

In 2003–2004, at the request of the Missile Defense Agency (MDA), APL provided a fiber-optic BID to detect a warhead first-light signal during USFT-1, the first flight test of the BID. The USFT-1 application required much greater sensitivity than the BID used in the sled test mentioned earlier. The electronics were completely redesigned with an auto-nullifying front end and optimized gain. The form, fit, and function of the earlier BIDs were retained while still achieving a significant boost in sensitivity by a factor of ~300. The enhanced BID provides long-range detection of rapid optical flashes while it rejects changes in background lighting and other slower optical signals. The enhanced BID can stare directly into the Sun without damaging the detector or inadvertently activating the sensor. Twelve optical channels were arranged on the target symmetrically facing outward and forward. Figure 9 shows a cross section of the target vehicle with the final installation of the BID. The reddish HTLGs are attached to the bulkhead every 30° around the vehicle. Two 6-channel BIDs were used to produce the

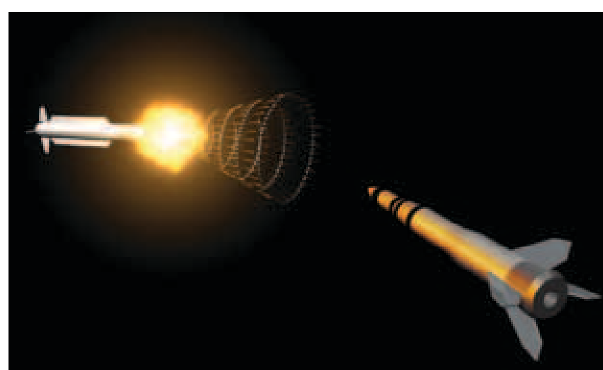

**Figure 8.** Graphical depiction of an interceptor with a fragmenting warhead destroying a target. The BID detects the first light from the warhead. Hit detectors on the target then detect fragment impacts when the warhead fragments arrive on the target. The fragment travel time can be used to compute the standoff distance of the interceptor.

12-channel arrangement, which maximized the FOV of the overall system. The positions and forward-looking orientation of the distal tips of the light guides were selected to optimize the FOVs based on preflight trajectory analysis. The USFT-1 BID used borosilicate glass HTLGs to provide a broad detection region. During the successful USFT-1, the interceptor delivered a warhead that destroyed the target vehicle. The BID was presumably destroyed by incoming fragments only milliseconds after successfully detecting, discriminating, and reporting the warhead burst.

The USFT-1 target had a hit-detection system that was designed to detect the location and arrival time of warhead fragments on the surface of the vehicle. The warhead flash activated a temporal sequence of 9 of the 12 BID channels before the first fragment impacted the vehicle. The pattern of BID signals indicated the direction of the warhead to within 30°. The timeline of the BID detection signals relative to the hit-detection signals was used to compute the standoff distance.

In May 2006, the BID achieved its second successful flight test, this time with a Standard Missile flying against a Lance target during the Pacific Phoenix mission. Figure 10 shows a cross section of the Lance target with the BID installed. This test used a six-channel BID configuration. Three of the channels were looking for the warhead outside the vehicle and the other three were looking for rapid optical flashes inside the vehicle. Two of the three external channels detected the warhead flash prior to the first impact. The interior BID channels registered the same damage propagation pattern as the hit detectors. Again, these data were fused with sufficient fidelity to piece together the endgame geometry between the two vehicles.

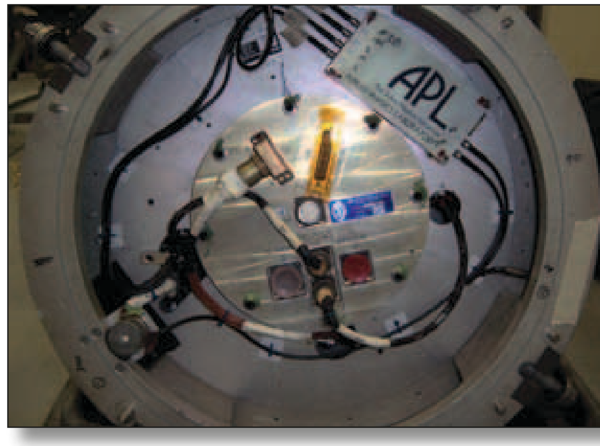


**Figure 10.** The BID on the Pacific Phoenix mission was installed in a six-channel configuration. Three channels were used to detect the external warhead flash and three were used to detect light within interior compartments of the target vehicle.

**Figure 9.** The 12-channel BID is shown installed on the USFT-1 target. The BID comprises the two 6-channel electro-optical modules and 12 high-temperature fiber-optic light guides seen in red. The unit in the center is part of the hit-detector system, which was not provided by APL.

Through two successful flight tests, the BID successfully measured crucial high-speed flight data that have allowed engineers and scientists to reconstruct the final moments of the endgame and gauge the performance of the interceptor. The successful correlation of the BID data with other data sources validates the BID performance and demonstrates that the combination of BID and hit-detector data provides a reliable target-based measure of interceptor performance.

## OTHER FIBER-OPTIC APPLICATIONS

Optical sensing methods often have many advantages over distributed electrical sensors within harsh environments. By using fiber optics for distributed signal routing, the need to distribute electrical power can be greatly reduced. The electrical power is needed only at the EOM module. In addition, optical fibers have inherently high bandwidth. High-bandwidth optical signals that enter one end of an optical fiber emerge at the other end intact with no special signal conditioning requirements. In contrast, high-bandwidth electrical signals require special techniques and shielding that tend to drive up the cost of a distributed electrical system. Optical signals are immune from electromagnetic interference. This property is particularly useful in lethality instrumentation, where the high energies involved with destroying a vehicle can generate spurious electromagnetic events that can interfere with electrical signals. Distributed optical sensing also eliminates ground loops and the need to isolate sensors electrically from the vehicle frame. In addition, distributed optical sensing removes the possibility of remote damage on the vehicle causing a short circuit that damages the electronics and invalidates the measurement. There is no conductive path back to the EOM, which can be mounted deep inside the vehicle, where it is relatively safe from harm for the necessary length of time.

Given the many advantages of distributed optical sensing, it is not surprising that BID technology has many applications in areas beyond fragmenting-warhead-type intercepts. For example, a modified BID has been used as a fiber-optic triggering system for high-speed test events. In late summer 2002, a modified BID was successfully used as a fiber-optic trigger during an aircraft vulnerability ground test at the Weapons Survivability Laboratory at China Lake.[5] In this test, the BID was integrated with the high-speed camera triggering system that was used to acquire video footage of a shoulder-fired missile entering a live C-130 turboprop engine. In addition to immunity from electromagnetic interference, the advantage of using the BID in this application was that the data system did not have to rely on a manually generated trigger. The BID was modified to not reject slower-changing optical signals and used plastic fibers in lieu of the HTLGs. Then the optical signal from the incoming interceptor was successfully used as a positive trigger for the high-speed cameras. This system currently is being extended to provide an optical triggering capability at the Pacific Missile Range Facility.

In 2006, the HTLG was successfully modified and extended to enable a completely optical means to detect passing rotor blades within high-speed machinery as part of a machinery diagnostics project for the Defense Advanced Research Projects Agency (DARPA). In the DARPA application, the HTLG was bifurcated into transmit and receive bundles. Light was coupled into the transmit bundle and exited the distal tip. When a high-speed rotor blade passed by, light reflected off the blade back into the distal tip and was detected at the receive end of the bifurcated light guide. The interior of the test chamber can reach high temperatures with oil spray, but the HTLG was able to operate well in this environment. This was the first time that the HTLG was used to transmit and receive high-speed optical signals. The bifurcated HTLG provided a unique optical sensor for precisely determining the blade tip position.

The HTLG can be used to measure incident energy levels in directed-energy applications. A miniature integrating sphere adapter for the HTLG is envisioned for directed-energy measurement.[6] Figure 11 illustrates the concept of the miniature integrating sphere on the distal tip of the HTLG. The use of a tiny aperture on the integrating sphere greatly attenuates the incident beam energy and enables the distal tip of the HTLG to receive beam energy from a wider FOV than the distal tip alone. Furthermore, the multiple reflections within the integrating sphere allow the HTLG to be installed tangent to the surface, where the beam is incident. The use of high-temperature-tolerant materials in the HTLG and the miniature integrating sphere can provide a sensor that can withstand high beam energies for longer measurement times than could be provided by coupling the high-power laser energy directly into detectors. The borosilicate light guides pass optical signals with wavelengths out to ~2 $\mu$m, which covers many directed-energy applications such as that used by the Airborne Laser program.

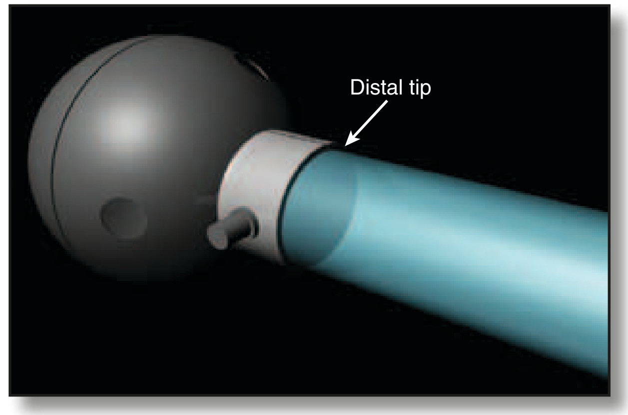


**Figure 11.** Miniature integrating sphere on the distal tip of the HTLG. The sphere attached to the distal tip of the HTLG attenuates incident beam energy, extends the survival time of the sensors, and allows sensors to be installed on the exterior of a target surface.

The HTLG also may be used for high-speed data communications. Most RF telemetry links from target vehicles are limited to 10–20 Mbps. Because the HTLGs can withstand the high temperatures on the exterior of vehicles, they may be used to broadcast spoiled-beam high-speed telemetry in numerous directions to off-board receivers. Figure 12 illustrates a 12-channel system that could broadcast high-speed data into an expanding ring around the target vehicle. The off-board receivers could be located on a booster sensor platform, an aerial observation platform, or possibly even a satellite. The bandwidth of the optical channels is at least 3 orders of magnitude greater than the RF telemetry link, easily achieving 10 Gbps. Vast amounts of information could be transferred over such a link, even if the link is only established for a short time.

One problem with current hit-detection systems is that they require dozens of channels to provide hit-detection coverage of a surface. In contrast, a simple two-channel fiber-optic system based on precise measurement of the speed of light could yield a hitpoint measurement in a kinetic-impact-type intercept. The Light-Speed Hitpoint Sensor[7] concept is illustrated in Fig. 13. A surface of interest is wrapped with a single long optical fiber wound in a continuous spiral pattern. Each fiber loop is adjacent to the last loop. An energetic projectile impacting the fiber at a hitpoint generates two counter-

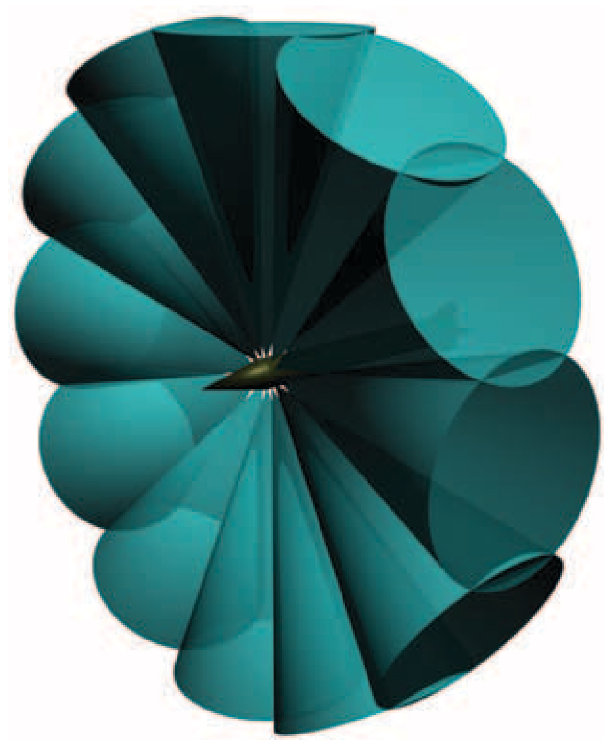

**Figure 12.** Spoiled-beam optical communications concept using 12 HTLGs. High-speed data can be transmitted off a target vehicle into the surrounding space in multiple directions to be received by off-board receivers (not shown). Because of the high bandwidth of optical communications, a short-lived link to a receiver can transfer vast amounts of data.

rotating light pulses that propagate through the fiber. A two-channel high-speed EOM measures the time difference between the arrivals of the pulses at the ends of the fiber. This time difference is used to compute the impact point on the surface. For example, if the impact point were exactly at the midpoint of the fiber, the two optical pulses would arrive simultaneously at the high-speed EOM. A deviation from this position away from the center point would result in one pulse arriving before the other, and similarly in the other direction, the pulse arrival times would be transposed. A temporal sampling rate of 10 GHz in the high-speed EOM corresponds to a spatial resolution of 2 cm in hitpoint uncertainty along the fiber. Because the surface of interest may not reach high temperature extremes, a standard optical fiber may be used in lieu of an HTLG for this application.

Another type of hit detector that employs optical sensing elements is the Planar Optical Penetration Sensor (POPS). Figure 14 shows the operation of the POPS element. An energetic projectile generates light within the optical central layer, which acts as a planar optical waveguide. The light is confined within the optical central layer and propagates into an optical fiber that is attached to the planar sensing element on an edge. The optical pulse within the fiber indicates energetic penetration of the POPS element. In September 2002, several POPS units were installed in the Weapons Survivability Laboratory at China Lake during a warhead arena test. The test provided proof-of-concept data demonstrating that the POPS sensing elements reliably produce robust data that clearly indicate the timing of energetic penetration events.

Figure 15 illustrates how POPS elements can be shaped into overlapping bands and attached to a curved surface to act as a hit-detection system. In this overlapping arrangement, each penetrating projectile generates two optical pulses in the POPS elements that are coupled into attached optical fibers. Each pulse pair corresponds to a penetration event within a ring on the surface. This arrangement has the additional advantage that the timing between pulses can be used to compute the normal velocity of the penetrating projectile. Figure 16 illustrates how this concept can be extended further to use multiple POPS

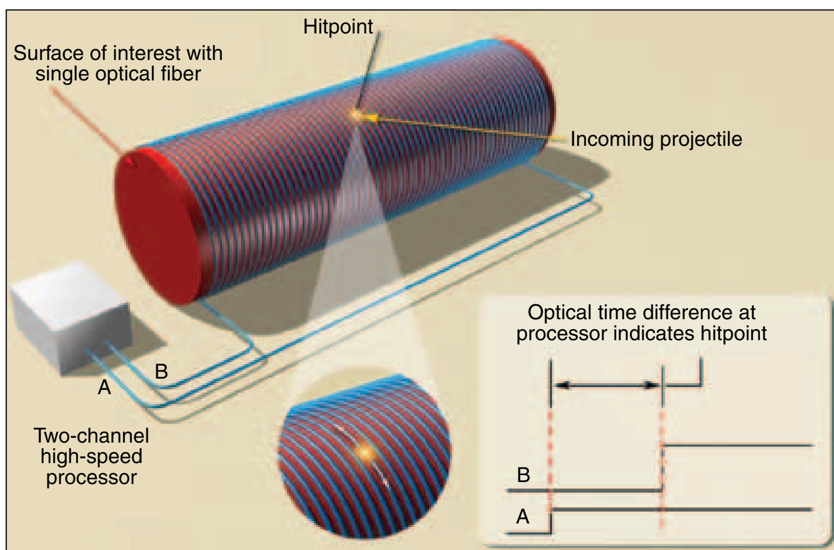


**Figure 13.** Light-speed hitpoint sensor. A surface of interest is wrapped by an optical fiber. The ends of the fiber are connected to a two-channel high-speed electro-optical processor. An incoming projectile impacts the surface at the hitpoint, generating two counter-rotating optical pulses that propagate through the fiber to the high-speed processor. The measured time difference between the arrival of the optical pulses indicates the impact location.

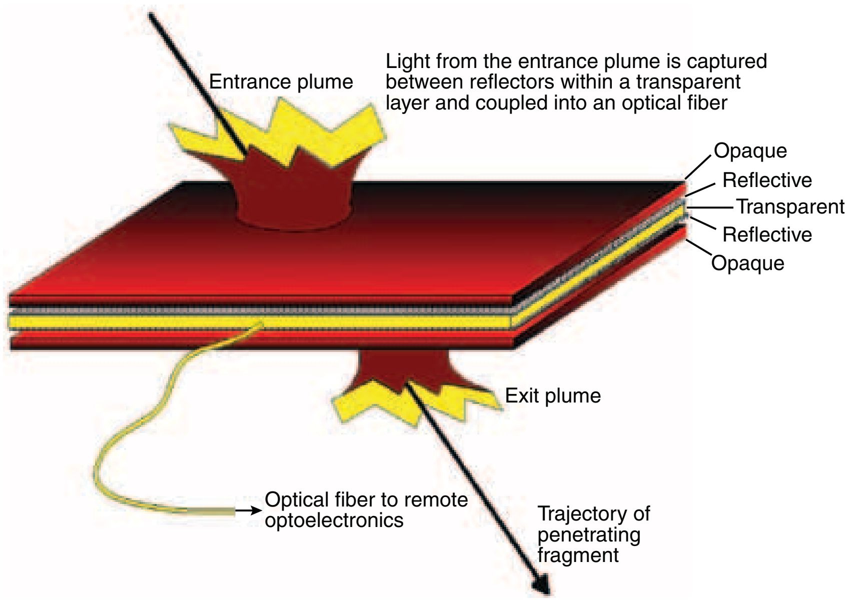


**Figure 14.** Surface-based POPS. The POPS is an optical sensing element that couples the light generated within a material into an optical fiber. The presence of a rapid optical pulse within the fiber indicates a penetration event through the surface. The POPS element can be made very thin and flexible to accommodate curved surfaces of interest.

elements to measure the trajectory impact location and velocity vector. As the projectile passes through the individual POPS elements, a light pulse is generated that couples into optical fibers (not shown) that are attached to each POPS element. The timing between the successive optical pulses is used to compute the exact impact location and velocity vector. The details of the matrix computations are described in a MATLAB program listing in the referenced patent.[8, 9]

The spatial diversity of the stack of tilted surfaces ensures a unique solution.

A BID variant called a blast position detector also may be used to measure the three-dimensional location, initiation time, and intensity of an energy pulse, as described in another related patent.[10] For a location measurement in three-dimensional space, at least four of the sensors must have the source within view simultaneously. The system can resolve the location of the source by the differences in the coupling efficiency of each sensor to the source as determined by channel input sensitivity settings and the positions and orientations of the optical apertures. The optical sensing elements could be HTLGs or standard fiber optics, depending on the thermal requirements. For a warhead detection application, ~36 circumferentially mounted outward-facing HTLGs would be required to cover the expected blast zone. The warhead location, relative to the target vehicle, would be computed by analyzing the response times of a group of four detectors. The system has three advantages:

- No hit-detection system is required.
- No fragment velocity assumptions are used to compute standoff distance.

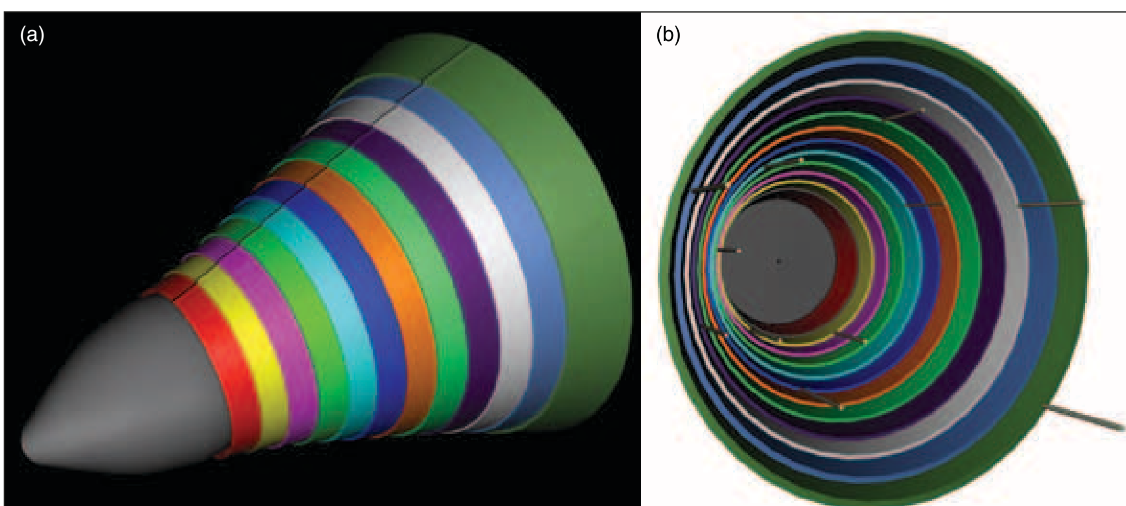


**Figure 15.** POPS sensors can be overlapped like shingles to provide better measurements. Each penetration event generates successive optical pulses in two fibers. The timing between the pulses can be used to infer the normal velocity of the penetrating object. (a) Successive POPS bands overlap to simultaneously provide finer axial resolution and normal velocity measurements. (b) Staggered fiber-optic data conduits provide improved sensor survivability.

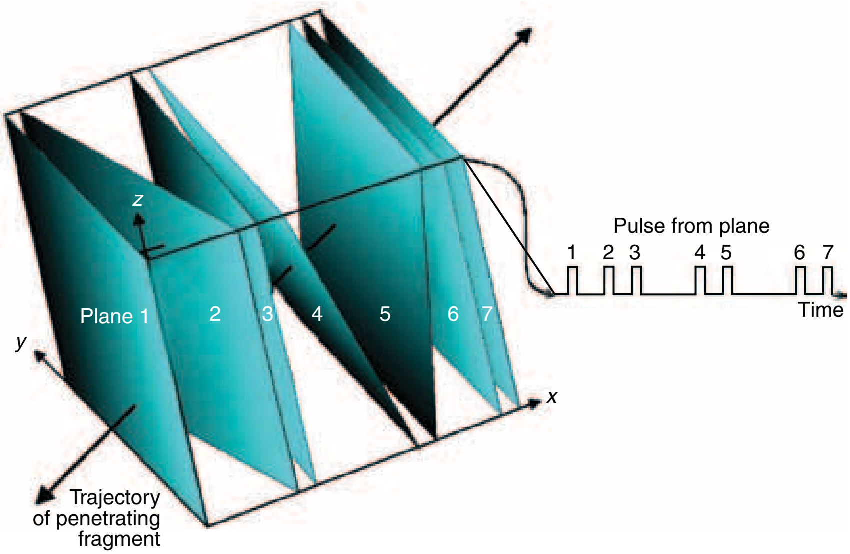


**Figure 16.** Trajectory measurement system. Each blue plane is a POPS element and has an attached optical fiber (not shown). As a high-speed projectile passes through the structure, an optical pulse is generated within each optical fiber. The timing between the optical pulses can be used to uniquely determine the exact three-dimensional trajectory and velocity of the projectile. The stack of POPS elements can be compressed into a thin optical sensor.

- The measurement is not based on time-of-flight measurements of the optical signals, allowing the use of modest signal processing.

The system requires a spatially homogeneous source over the detection time frame and exploits the spatial diversity of the arrangement of sensors.

## CONCLUSIONS

The enhanced BID acquired critical flight data during USFT-1 in 2004 and Pacific Phoenix in 2006. More recently, it acquired critical flight data during Flight Test Maritime-14 (FTM-14) in 2008 and Stellar Daggers in 2009, for a total of four successful flight tests in four attempts. The reliability of the system and the value of the data that it provides have now been established. The BID also has spawned the development of new technologies, including the HTLG and the optical sensing variations described in this article. The new measurement capabilities that are enabled by new types of sensors will provide improved data sets that will continue to be used to critically assess system performance. For target instrumentation, the telemetry data sets and the information that they contain serve as the flight data recorders for the event. It is essential that the best instrumentation techniques be used to prevent poor-quality data sets that can lead to poor decision making. Optical sensing, in general, has many demonstrated advantages over techniques that often are being used today. To take advantage of the benefits of optical sensing, it is essential that we extend the applications of distributed optical sensing within the flight instrumentation communities.

**ACKNOWLEDGMENTS:** The BID-related activities have been sponsored by numerous organizations. We thank Greg Walls and Mary Ann Stasiak of the MDA's Targets and Countermeasures program for sponsoring the BID efforts. We also would like to thank David Olivares and Greg Molvik, who have served as project managers for BID work at APL; Bruce Kuehne, the program manager for the Pacific Phoenix activity; Dave Erickson, Pacific Phoenix project lead; Michael E. White, Air and Missile Defense Business Area Executive; Joe Mulé for his continuous and long-standing support of target instrumentation activities; Richard Cusick (retired) for his vision; John Klimek, Chuck Rodeffer (retired), Jim Kouroupis, Angela Barrios, Dale Clemons, Robert Walsh, and Nathan Rolander for their contributions to the BID efforts; and Paul Wescoat and the Technical Services Department team for fabrication. Finally, we are grateful to Jacob Elbaz, who illustrated many of the concepts described in this article.

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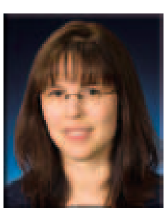
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