BLAST INSTRUMENTATION FOR TARGET VEHICLES

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A Blast Initiation Detector (BID) was developed for use onboard targets to detect the first light from fragmenting warheads. The measured time of first light can be used with the measured time of first fragment impact to compute the standoff distance, a key measure of interceptor performance. A high speed sled test afforded an opportunity to demonstrate and validate the BID/Hit Panel standoff measurement for the first time under conditions of known geometry with a moving warhead. The BID/Hit Panel standoff distance measurement was in agreement to within seven percent of the known geometric standoff distance. Lessons learned during from the BID are being used to develop a Blast Position Detector (BPD) that measures the blast time and position independent of hit panel data.

INTRODUCTION

APL has provided target-based instrumentation for ballistic missile intercept tests for several years. Increasing support for missile defense systems has fostered the development of the technology. During the early 1990s, hit panels were made at APL to detect the arrival of fragments from detonating warheads. This early work culminated in the successful DTR-1A intercept back in 1997. The hit panels on the target clearly showed the first fragment impact location and the damage propagation pattern.

Another instrument known as a Blast Initiation Detector (BID) was developed at APL for use on Lance targets and more recently extended for use on Hera targets, which are used in SM-2 Blk 4A interceptor tests. The BID is an electro-optical instrument that rapidly detects the first light from the warhead and provides a temporal reference point for the warhead event within the target telemetry. The primary use of the BID data is that it can be used with hit panel impact data to compute standoff distance, a key measure of interceptor performance. Figure 1 illustrates the concept. The main idea is that by measuring the fragment travel time, the standoff distance can be computed from assumed fragment speeds.

The BID for the Hera target was developed concurrently with testing and analysis. Testing centered on the use of the Avery Advanced Technology Development Laboratory cell 4 aerothermal test facility. During wind tunnel testing the optical fiber design performance was validated under anticipated aerothermal loads. The optical fibers were also tested to failure to gain insight into the failure mode. The BID analysis centered on the development of a mathematical model of the electro-optical Blast/BID system. The model was used to guide the design to ensure microsecond response times and limited shot-to-shot response time variability. Rapid response with limited variance is necessary to ensure that the BID detection is telemetered out before the target is destroyed and to limit the uncertainty introduced during the standoff distance computations. Following the completion of development, the five production units and one sled test unit were installed into the targets. During the sled test, the BID detected the warhead burst in less than ten microseconds. The BID data was used along with hit panel data on the same target to compute the standoff distance. The computed standoff was within seven percent of the known geometric standoff distance. This was the first time the BID/hit panel

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Abstract

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technique was used to compute standoff in a moving warhead test. The BID lessons learned are being used to develop a standalone Blast Position Detector (BPD) that is capable of resolving blast position independently from Hit Panel data or fragment velocity uncertainties.

BID DESCRIPTION

The Hera BID is comprised of an electronics module that connects to six optical fibers. The optical fibers connect the external environment of the target vehicle to the electronics module and provide for the detection of the first light from the warhead. A block diagram of the system is shown in Figure 2. The optical fibers are made of multistranded borosilicate glass fibers enclosed in a 20 inch long stainless steel shroud. The high numerical aperture of the glass provides for a wide field-of-view. A close-up view of the ends of the optical fibers is shown in Figure 3. The end with the connector attaches to the BID electronics box. The distal tip protrudes into the airstream. The optical fibers can withstand temperatures as high as 1200 °F. The BID and other instruments are installed aboard the target vehicle as shown in Figure 4. The fields-of-view of the six fibers cover the anticipated blast zone so that at least one fiber can see each expected blast location. Figure 5 illustrates the blast region for a ten microsecond response time. An installed Hera BID is shown in Figure 6. The six optical fibers terminate on the aeroshell.

WIND TUNNEL TESTING

Wind tunnel testing was used to address the concerns about high temperatures on the exposed fiber tip.[1] Figure 7 illustrates the airstream penetration of the exposed distal tip of a fiber. The test hardware was fabricated to simulate the BID optical/aeroshell environment upon re-entry. The circular plate in Figure 7 shows the instrumented portion of the wind tunnel test hardware and is representative of a small section of the aft bulkhead of the forward section of the target vehicle. The materials and the construction geometry were duplicates of the actual flight hardware. The test fixture was instrumented as shown in Figure 8 and installed into Cell 4 of the wind tunnel test facility at the Avery Advanced Technology Development Laboratory. During the tests, two laser beams were toggled onto the optical fiber at two differing angles of incidence, approximately 25° and 35° off-axis. Temperatures, pressure, qualitative infrared thermal images, Schlerien images, and relative optical throughput were recorded during four tests. The Schlerien images revealed the shock structure at the BID fiber distal tip protrusion (Figure 9). The infrared images showed the basic heating trend of the test fixture (Figure 10). The cooling effect of the thicker material in the bulkhead is clearly visible. Figure 11 is reverse color image of the laser beams that were incident on the optical fiber. The lasers became visible in the wind tunnel water vapor.

The wind tunnel tests demonstrated that the BID optical fibers could withstand the aerothermal environment on the outside of the target vehicle. The optical fibers exhibited continuous throughput and maintained field-of-view for the full three minutes tests. The rated survivability temperature for the BID optical fibers is 1200 °F.

BID LATENCY ASSESSMENT

The time of the blast is needed in conjunction with warhead fragment velocity and hit location data to compute the standoff distance of the warhead during the endgame analysis. It is important that any latencies or delays associated with the detection processes are understood to allow for the correct interpretation of the timing data reported by the telemetry. This section details the timing latency assessment for the Blast Initiation Detector (BID) that is planned for use aboard Hera target vehicles during flight interceptor demonstration tests.

The BID latency is the time delay between the occurrence of the first fragment motion (first light) from the interceptor warhead and the first registration of this event in the target telemetry stream. In general, the BID latency is a function of the fiber orientation, the fiber locations, the numerical aperture of the fiber, the diameter of the fiber, the number of fibers, the distance of the blast to the first response fiber aperture, the gain of the amplifier, the coupling of the amplifier, electronic delays within the amplifier, the cable length from the BID output to the telemeter, and the sampling rate of the telemeter. Since the cabling delays are approximately equal and common to both the BID and the hit panel instruments, they do not factor into the standoff distance computations.

For the Hera target application, six forward looking fibers, equally spaced around the circumference of the forward section, are used to receive the blast signal. Since the value of the BID latency can be corrected for, if known, it is the variance and therefore the standard deviation of the BID latency that is minimized by design. The number of fibers, the fiber orientation, and the alternating current (AC) coupling approach were selected to minimize the variance of the BID latency, within the constraints imposed by available fiber mount positions.

The analysis indicates that worst case BID latency will be approximately 25 μsec and that the BID latency will be less than less than 10 μsec for greater than 98 percent of intercept scenarios where no direct interceptor contact is involved.[2]

The analysis indicates that the timing uncertainty associated with the BID and hit panel signals will introduce very small uncertainty into the standoff distance computation and the endgame geometry analysis. The uncertainty in the BID timing is small enough so that the largest error terms in the standoff distance computations will most likely be in the fragment velocity uncertainty. In practice, the BID latency should be small enough to ignore for most purposes.

Analysis also indicates that a small percentage of intercepts would result in direct hits, in which cases the BID registration may not occur before Hit detector registration.

Target-Centric Coordinate System

A three-dimensional rectilinear coordinate system was defined with respect to the target vehicle and was used for all blast simulations. The positive Z-axis coincides with the axial centerline of the target vehicle and passes through the nose. The six BID fibers (1–6) are located slightly forward of the origin (Figure 12).

Letting β be the angle between the target axis and the optical fiber axis, expressions for the distance from the blast to the optical fiber ρ_f and the cosine of the off-optical-axis viewing angle γ are provided in Figure 12.

For the Hera application, 200 simulations of the endgame interception event were run to provide a representative set of endgame blast locations with respect to the target vehicle.[3] The significant data in these simulations were the α and ρ values. For analytical purposes, $\Delta\theta$ was treated as a variable with a uniform distribution over the range of ($-30° < \Delta\theta < 30°$) for each α and ρ value. The fiber was oriented at $\Delta\theta = 0°$. For each of the 200 α and ρ pairs, 31 values of uniformly distributed θ were used to provide a representative set of 6200 blast locations. The β value for the Hera target is 45° and was selected to minimize BID latency variance given the constraints of available mounting locations and fiber bend radius. The value of d is 0.77 feet and b is 0.70 feet.

It is clear from the simulated intercepts that the missile may come in contact with the target vehicle prior to detonation. Based on the representative set of blast locations and a spherical warhead approximation, there is a possibility of sustaining a direct warhead intercept. In these intercept scenarios, the Hit detector signal may occur in the absence of or prior to the BID signal. For this reason, the simulated blast locations corresponding to these intercept scenarios were removed from the data set for BID latency analysis.

AC versus DC Coupling

In general, the optical signal from the blast can be coupled into the BID by either direct current (DC) or AC coupling. In DC coupling, signal registration occurs when the incident light intensity exceeds a preset level. In AC coupling the signal registration requires the rate of rise of the incident light intensity to exceed a preset level and the first stage cannot be saturated by the ambient light.

The five identified possible interference sources with AC coupling are the following: (1) cloud shadowing, (2) intercept shadowing, (3) intercept reflections, (4) ground reflections, and (5) glow rise. In cloud shadowing, the target passing out of a cloud shadow could, in general, register a BID event as the sun rapidly comes into view. This is not likely to be a problem at intercept altitudes. Intercept shadowing occurs when the target passes out of the shadow cast by the incoming interceptor. This is also a very low probability event, given the required orientation of the sun, interceptor, and target system. Intercept reflections can occur when the sunlight reflects off the target and becomes incident on the BID fibers. Similarly, ground reflections, such as from a lake, could be bright enough to register a BID response. Both types of reflections are considered very low probability events not likely to occur in the time frame of interest (the 10 μsec detection window). Glow rise is caused by the rise in incident radiation on the BID fibers that is due to the aerothermal heating of external vehicle surfaces as they come into view. The target glow and the interceptor glow each contribute to this noise source. The rate of glow rise should be well below the threshold rate of rise. The BID threshold rate of rise also limits the likelihood of the other events causing a false BID signal. As a point of reference, a camera flash bar with a risetime of 2 milliseconds is too slow to be seen by the Hera BID. Based on this reasoning, the probability of false BID registration causing confusion during the endgame is very low with AC coupling.

The most likely interference source from DC coupling is from the sun. An arena test at Naval Surface Warfare Center/Dahlgren Division (NSWC/DD) on 26 August 1999 demonstrated that DC coupling with a threshold set high enough to exclude sun interference can introduce excessive latency (215 μsec) and more importantly excessive BID latency variance.[4]

The DC-coupled Lance target BID latency is still acceptably low due to the use of larger optical fibers and the further aft mounting positions.

There are numerous advantages to using AC coupling. Since the AC-coupled BID has no significant interference sources, the gain in the electronics may be set much higher. This effectively reduces the detection threshold and the latency for all blast locations and leaves the bulk of the any standoff distance uncertainties in the warhead fragment velocity.

Endgame Timeline

Figure 13 illustrates the timeline associated with the endgame events. If T_B and T_H are the time stamps in the telemetry stream associated with the first BID event and the first fragment hit event, respectively, then the best estimate of the actual fragment travel time is T_F, as expressed below where expected values have been used for the BID and Hit Panel latencies.

$$T_F = [T_H - E(\tau_H)] - [T_B - E(\tau_B)]$$

System Standard RMS Error

The BID/Hit panel System Timing Standard Error σ_s is the RSS uncertainty in T_F, and is expressed below as the RSS value of the standard errors associated with the BID and the Hit detector, both measurements being performed independently.

$$\sigma_S = \sqrt{\sigma_B^2 + \sigma_H^2}$$

Analysis indicates that the system timing error introduced by the BID and Hit Panel latencies is dominated by the BID geometric latency and is approximately 2.4 µsec.

This error is very small and not significant for endgame analysis interpretation. Thus it is clear that the bulk of the error in the standoff distance computations will arise from uncertainty in the fragment velocities, not in the target-based instrumentation. Even if the actual geometry represented a worst case for BID geometric latency, the uncertainty in standoff distance due to BID timing would be less than 1 foot, and because worst case geometric latency occurs at large standoff distances, this uncertainty would not prevent resolution of the endgame geometry.

Ramifications for Endgame Analysis

It may be possible to use second BID event data to further resolve the blast orientation. For this reason, the latency of the second BID signal is called the diagnostic latency (τ_d). The diagnostic latency may be used to validate or refute the computed endgame geometry based on the first BID event.

There are two corrections for the standoff distance estimation as well: (1) The fragment hit location will be at a different location than the origin of the target-centric coordinate system; and (2) The physical size of the warhead should be accounted for since the fragments do not, in fact, propagate from the center.

SLED TEST RESULTS

A Blast Initiation Detector (BID) in the forward section of the target was used to detect the blast signal during a recent sled test.[6] The test geometry is shown in Figure 14. The measured BID response time was 9.4 µsec. Figure 15 shows the blast at the moment of detonation. Evaluation of test data demonstrates the utility of computing standoff distance based on the BID measurement of warhead flash and hit panel reports of fragment impact. The agreement between the computed standoff distance and the known geometrical standoff distance for the sled test was approximately seven percent. The difference can be explained by the use of an assumed fragment velocity value that was extracted from a probabilistic distribution of actual fragment velocities. Such close correlation between the known standoff and the computed standoff could not be accomplished without very small BID and hit panel response times.

BLAST POSITION DETECTOR

The BID provides a scalar measurement of the blast initiation time. If hit panels are also on the target then the standoff distance can be computed. The BID/hit panel standoff distance computation provides some information on the spatial proximity of the warhead. However, additional information is needed to resolve the geometry. The Blast Position Detector (BPD) is an electro-optical system for resolving the blast position and initiation time in target-centric coordinates. The BPD does not rely on the availability of the of the hit panels or assumptions regarding fragment speeds. The BPD is a standalone system that measures the spatial and temporal characteristics of the warhead from the perspective of the target. The arrangement of detectors on the BPD provides for multiple measurements of the warhead event. These multiple measurements comprise a blast latency vector. For a suitable arrangement of detectors, it is possible to show that the blast latency vector can be transformed into a measurement of warhead location and initiation time that is independent of the exact magnitude of the warhead optical signal. The technology for BPD is being currently being developed at APL.

CONCLUSIONS

Testing and analysis were used to guide the BID development process. The BID/hit panel combination of target-based instruments was used to measure standoff distance in a moving warhead ground test. The computed standoff was in agreement with the known geometric standoff to within seven percent. The next step beyond the BID is a Blast Position Detector (BPD). The BPD is a standalone system of electro-optical detectors that can be used to measure the blast position and initiation time in target-centric coordinates.

ACKNOWLEDGMENTS

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Blast Initiation Detector (BID) Concept

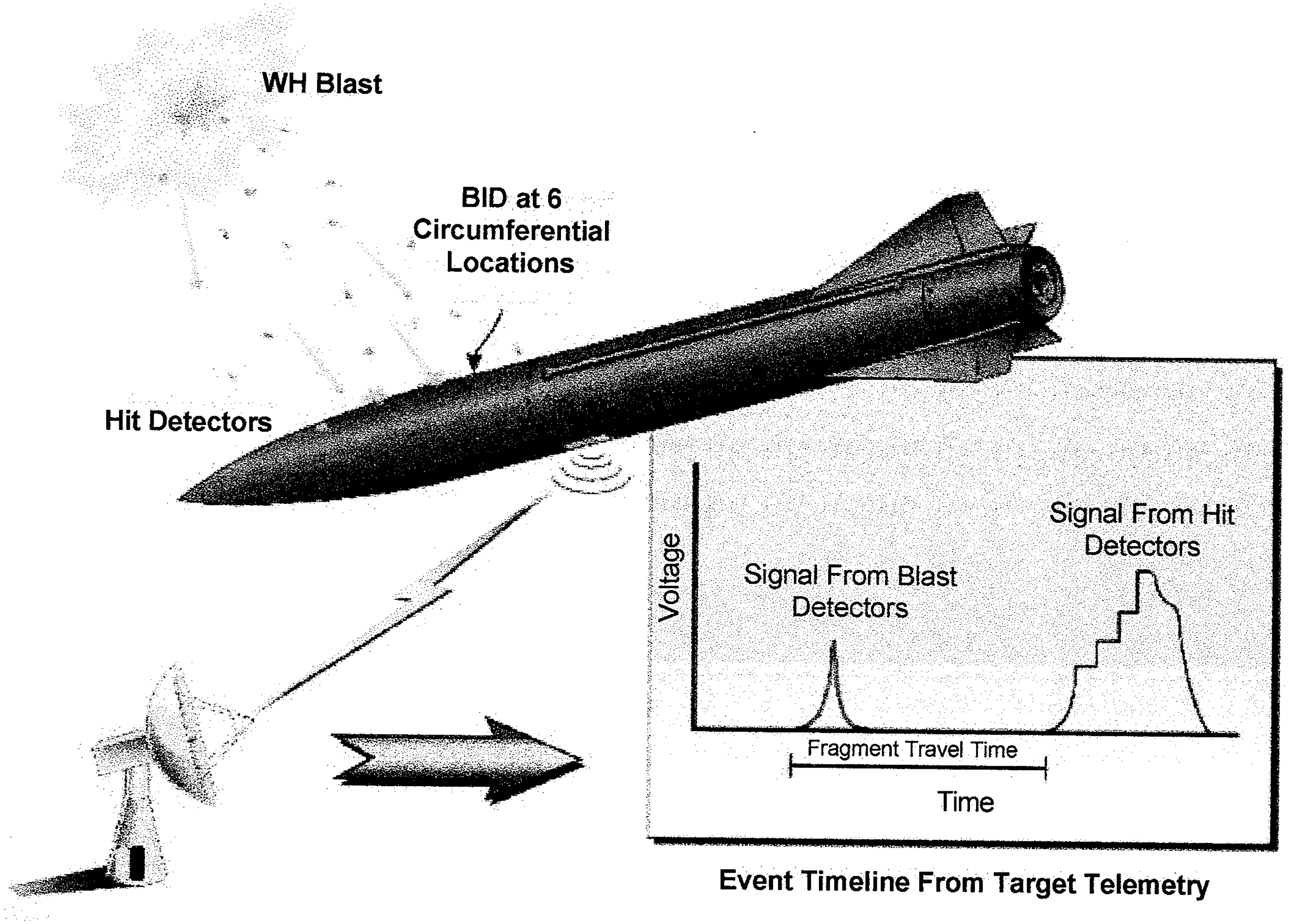
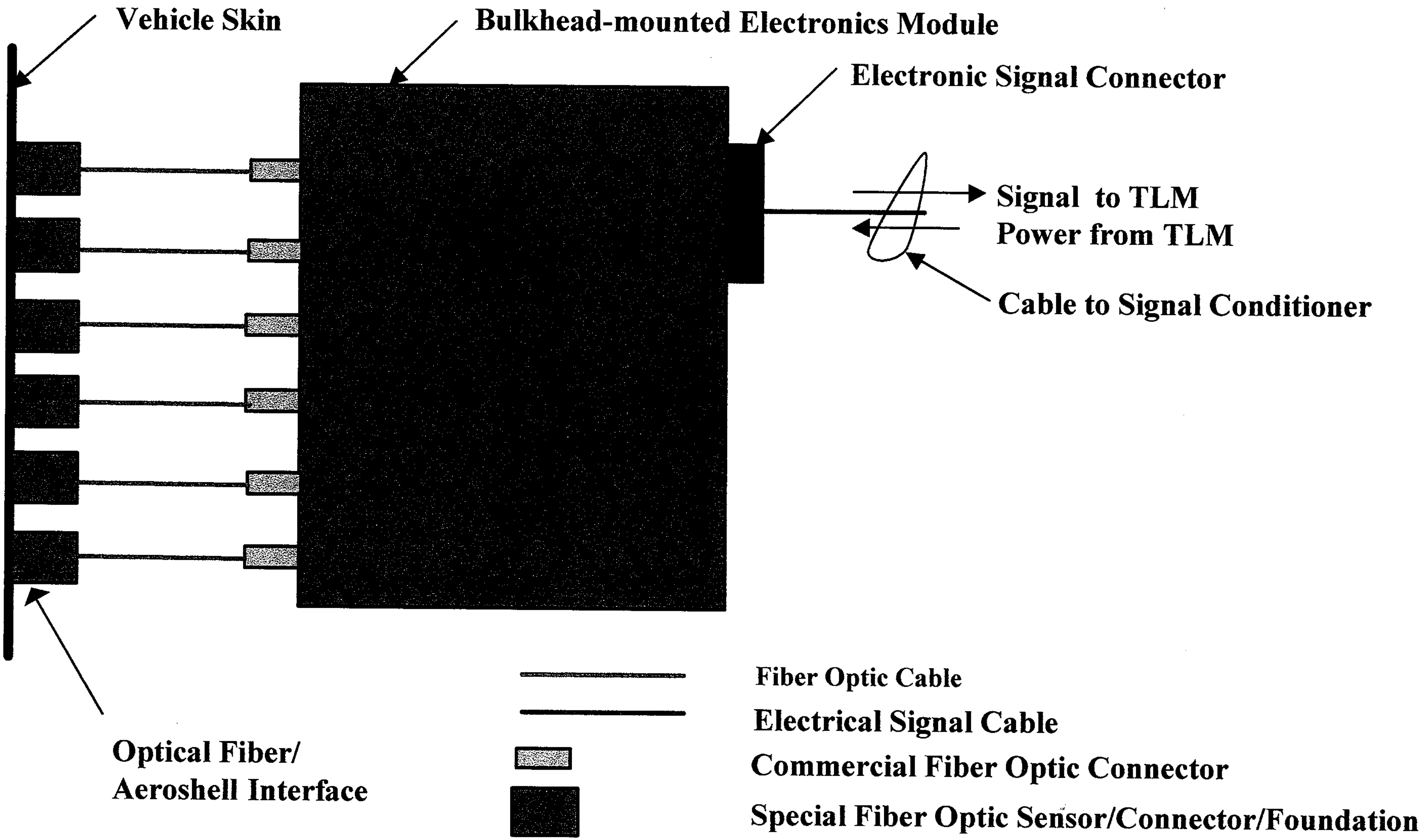


Figure 1

BID Block Diagram



Vehicle Skin

Bulkhead-mounted Electronics Module

Electronic Signal Connector

Signal to TLM

Power from TLM

Cable to Signal Conditioner

Optical Fiber/
Aeroshell Interface

— Fiber Optic Cable

— Electrical Signal Cable

▨ Commercial Fiber Optic Connector

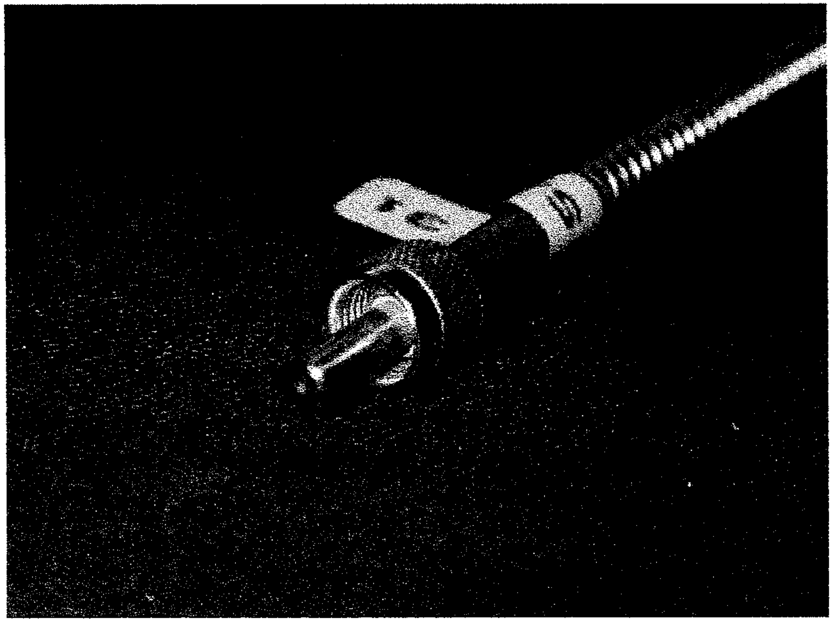
■ Special Fiber Optic Sensor/Connector/Foundation

Figure 2

BID Fiber Ends

Distal Tip

Proximal Tip



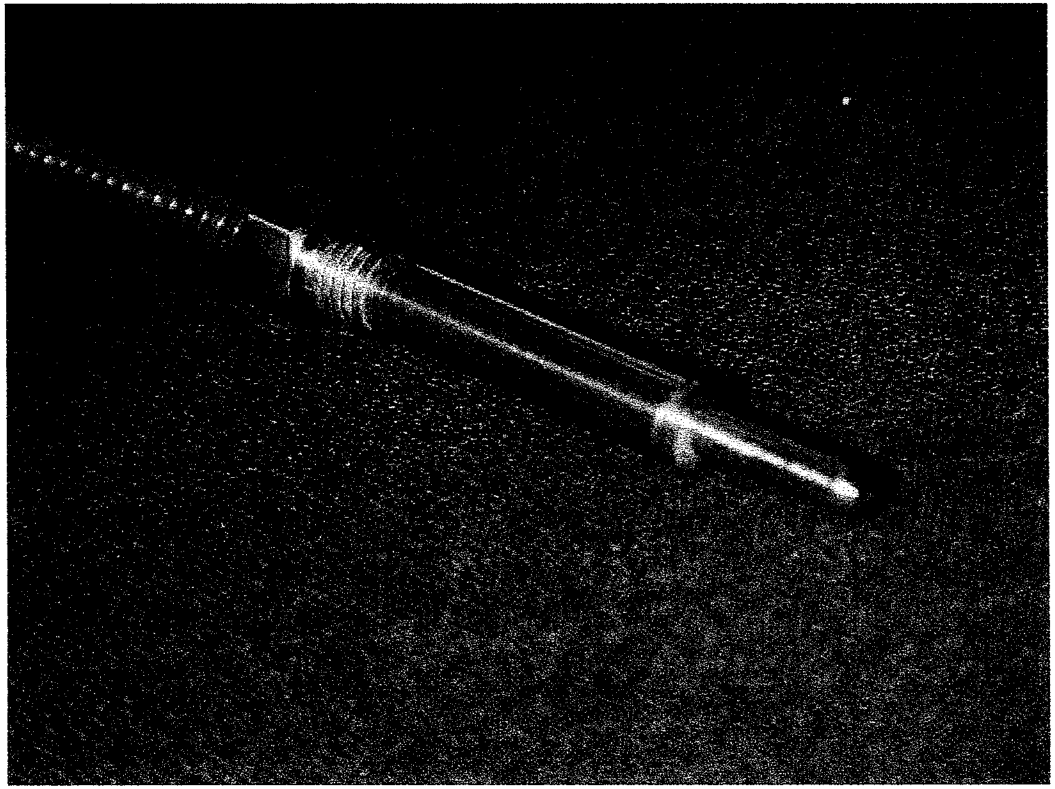


Figure 3

Instrument Locations (Figure 1)

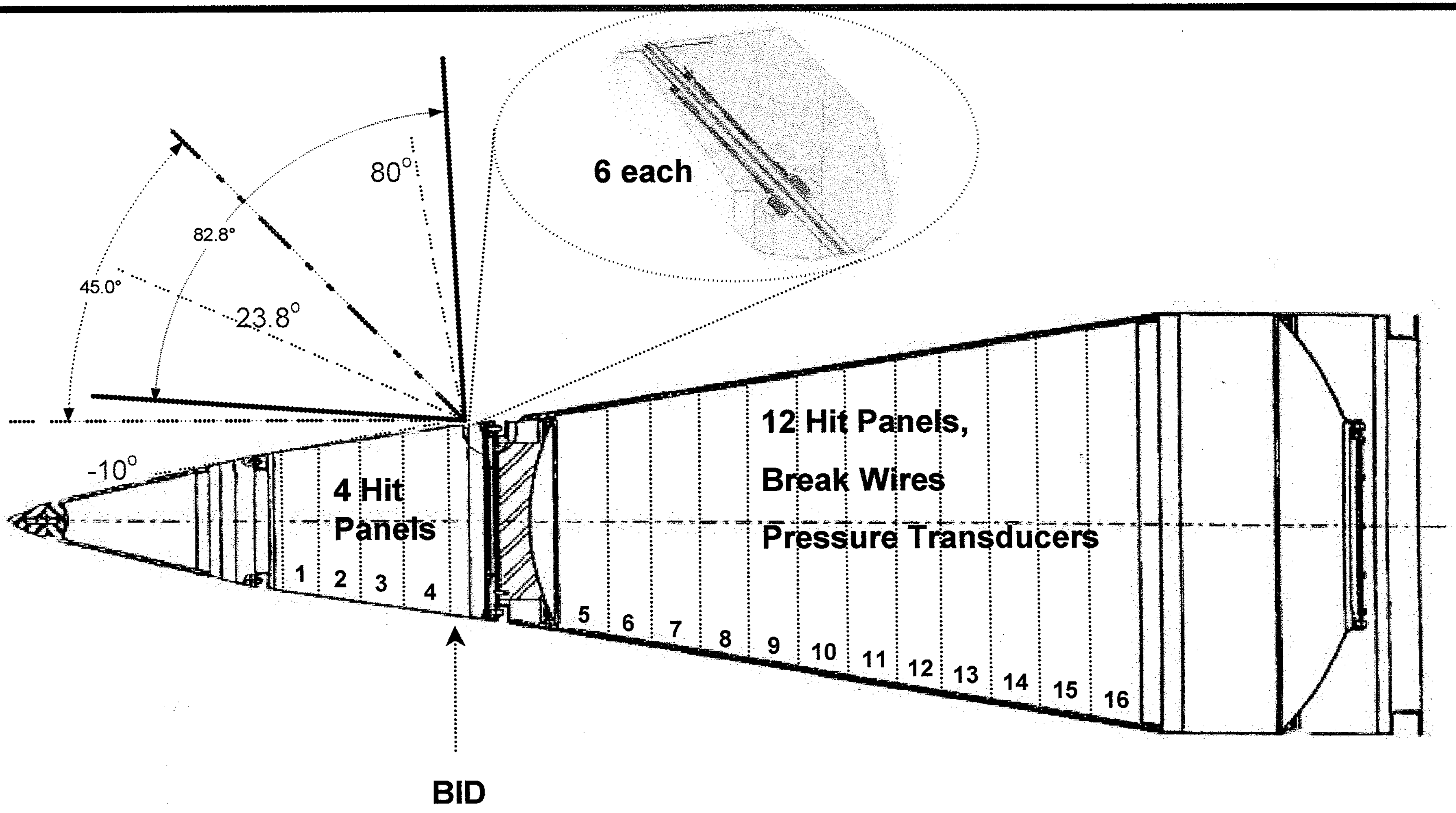
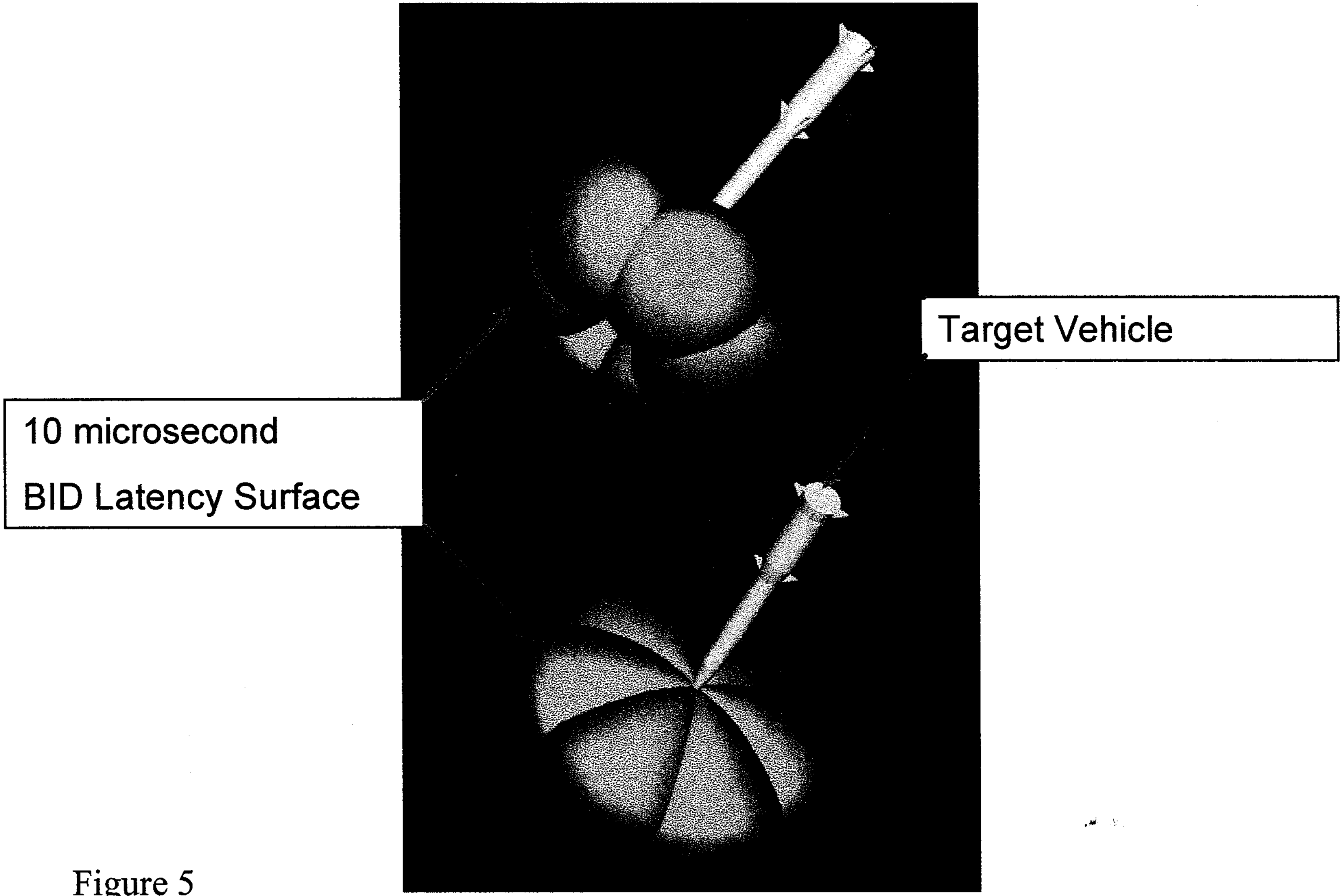


Figure 4

ILLUSTRATION OF LATENCY SURFACES (LOBES CORRESPOND TO SIX OPTICAL FIBERS)



Target Vehicle

10 microsecond

BID Latency Surface

Figure 5

BID Installed in Sled Test Target

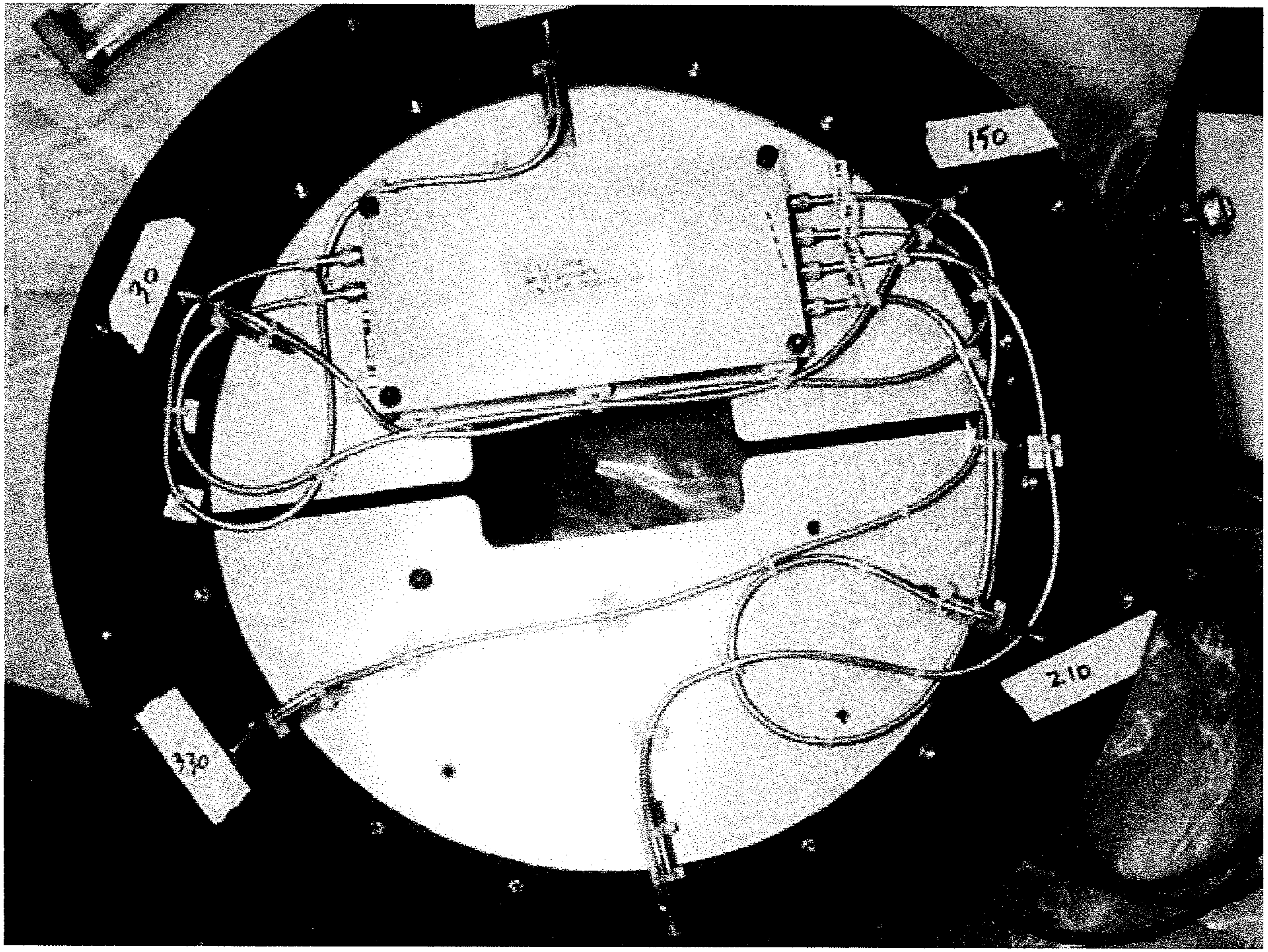
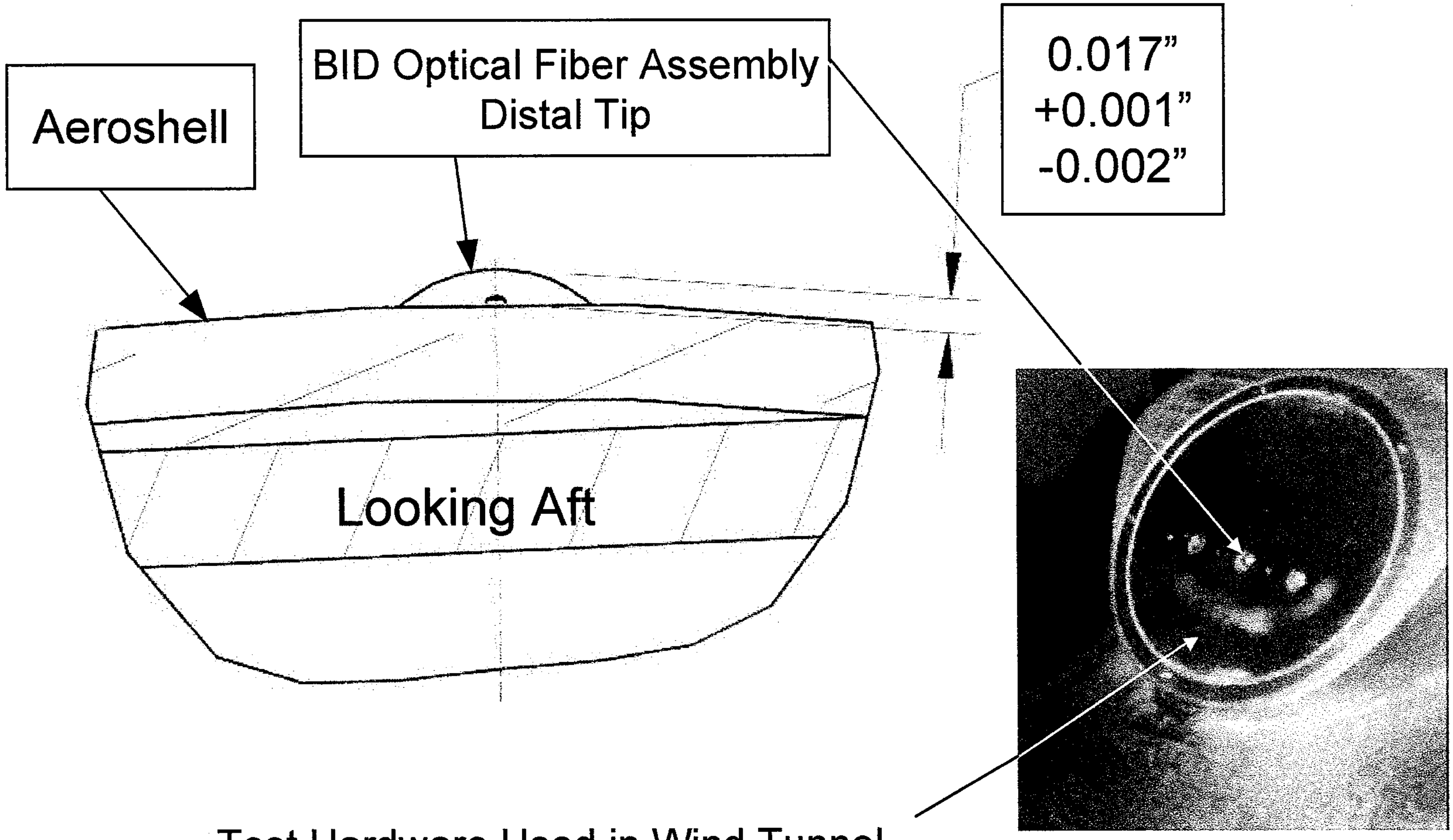


Figure 6

BID Optical Fiber Airstream Penetration



Aeroshell

BID Optical Fiber Assembly Distal Tip

0.017”
+0.001”
-0.002”

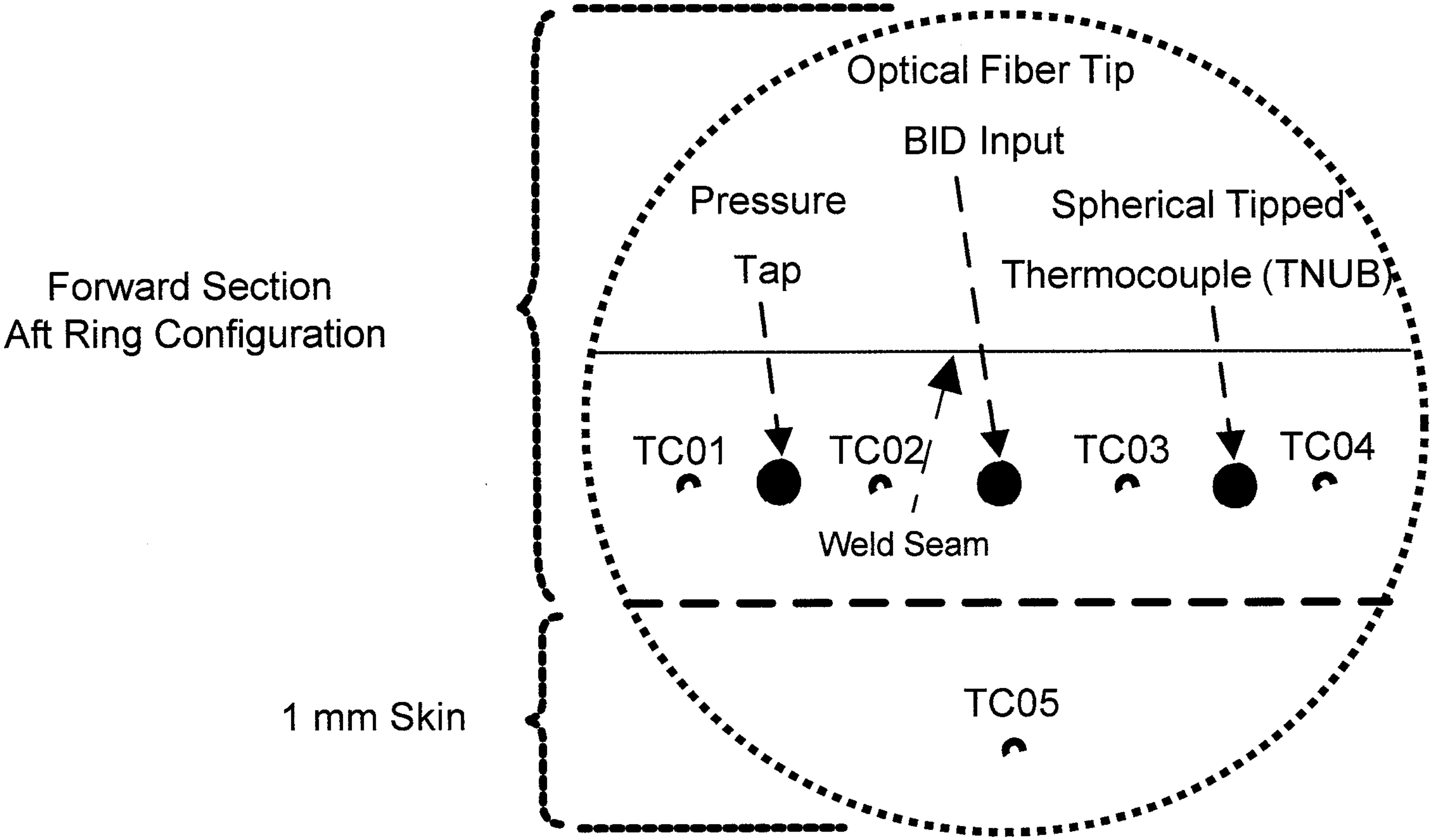
Looking Aft

Test Hardware Used in Wind Tunnel
Proof-of-Concept Tests
of Optical/Aeroshell Interface

Oblique View

Figure 7

BID Test Instrumentation Locations

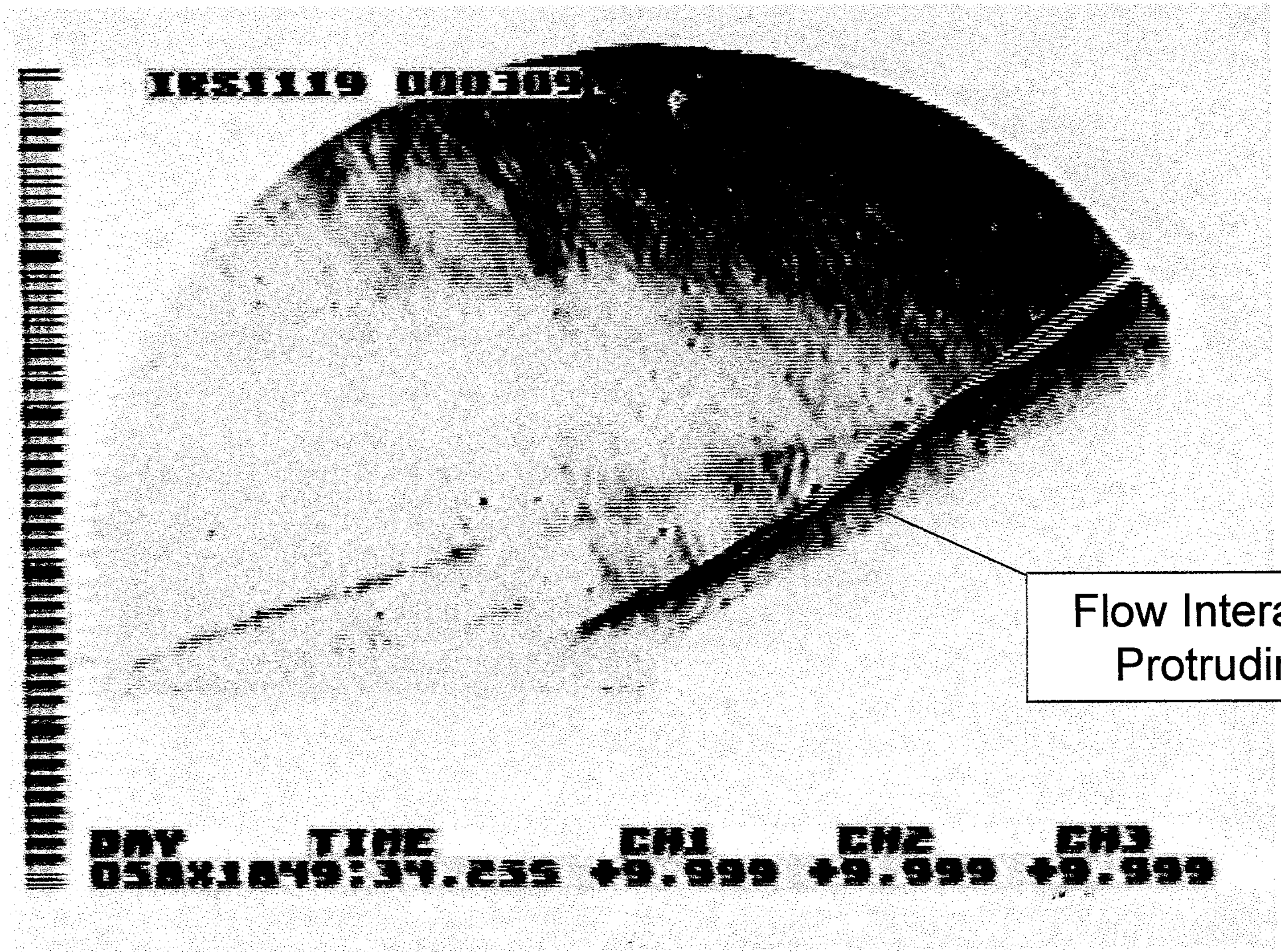


● Mounting Hole Configurations

◠ Skin Temperatures

Figure 8

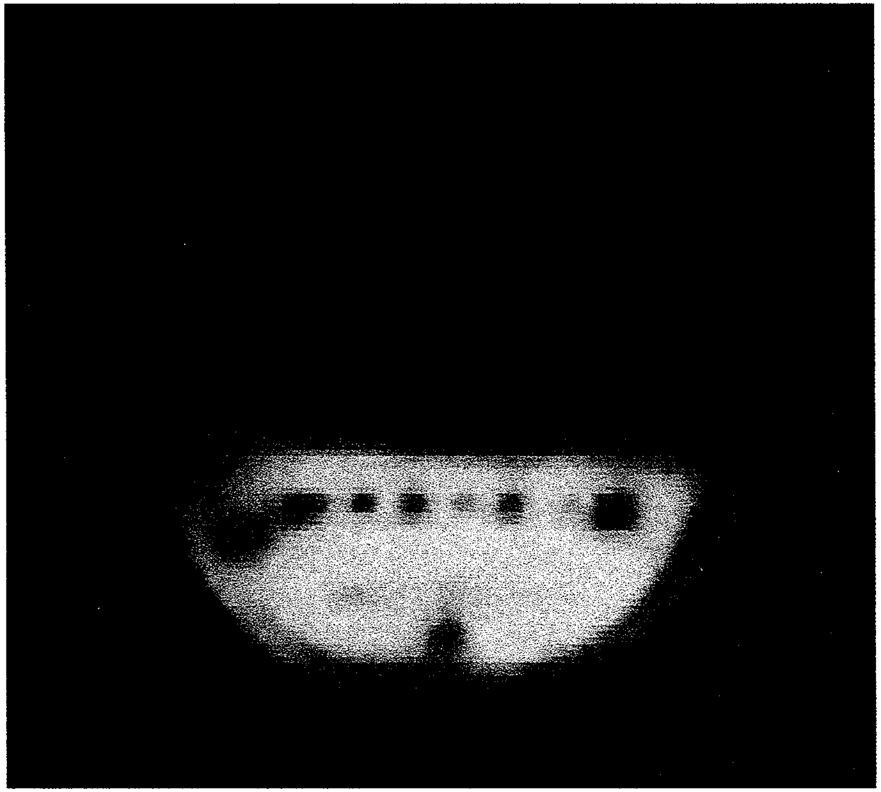
Schlerien Images of Protruding BID Optical Fiber



Flow Interaction at Protruding Tip

Figure 9

Infrared Image of BID Test Hardware (Cooler upper half due to thicker bulkhead material)



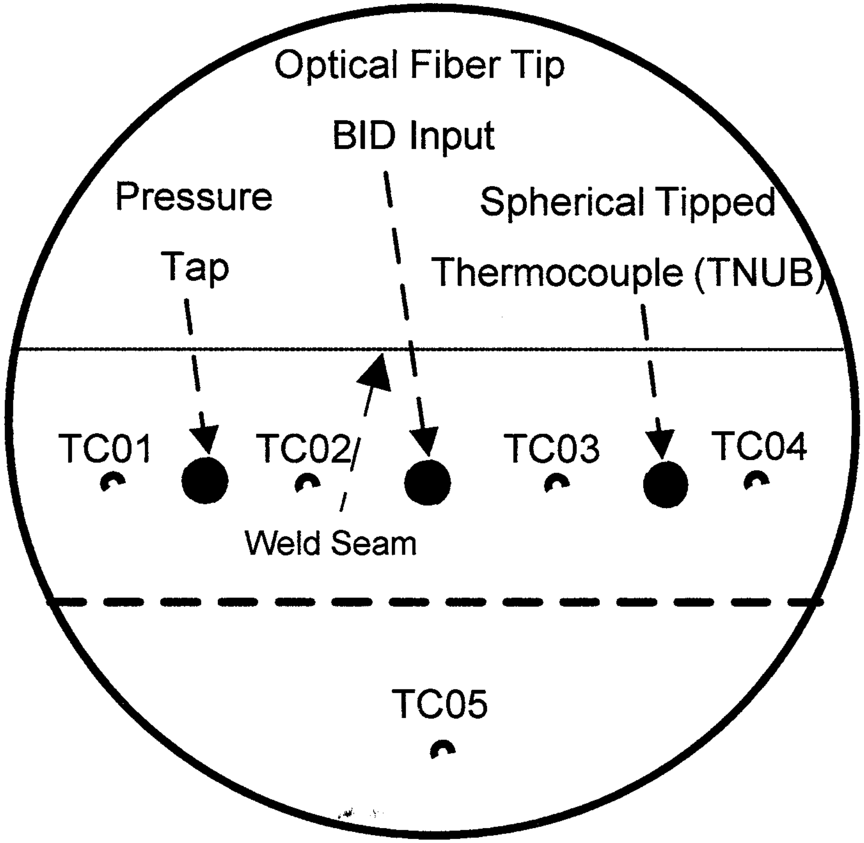


Figure 10

INVERSE COLOR Laser Beam Images Rendered Visible by Water Vapor

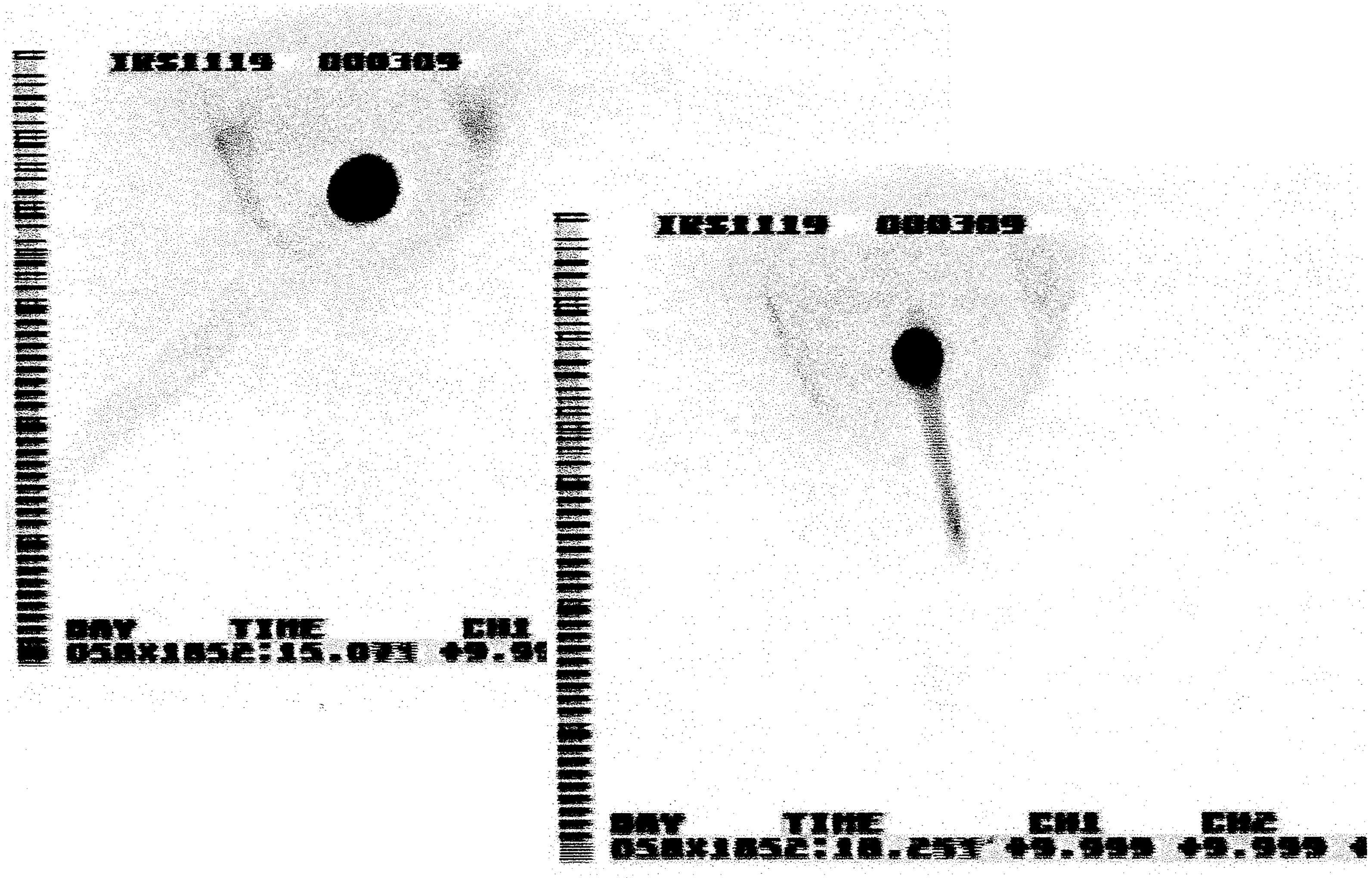


Figure 11

Target-Centric
Coordinate System Geometry

$$\rho_f = \sqrt{\rho^2 + d^2 + b^2 - 2\rho(d\cos\alpha + b\sin\alpha\cos\Delta\theta)}$$

$$\cos\gamma = \rho_f^{-1}\,[\cos\beta(\rho\cos\alpha - d) + \sin\beta(\rho\sin\alpha\cos\Delta\theta - b)]$$

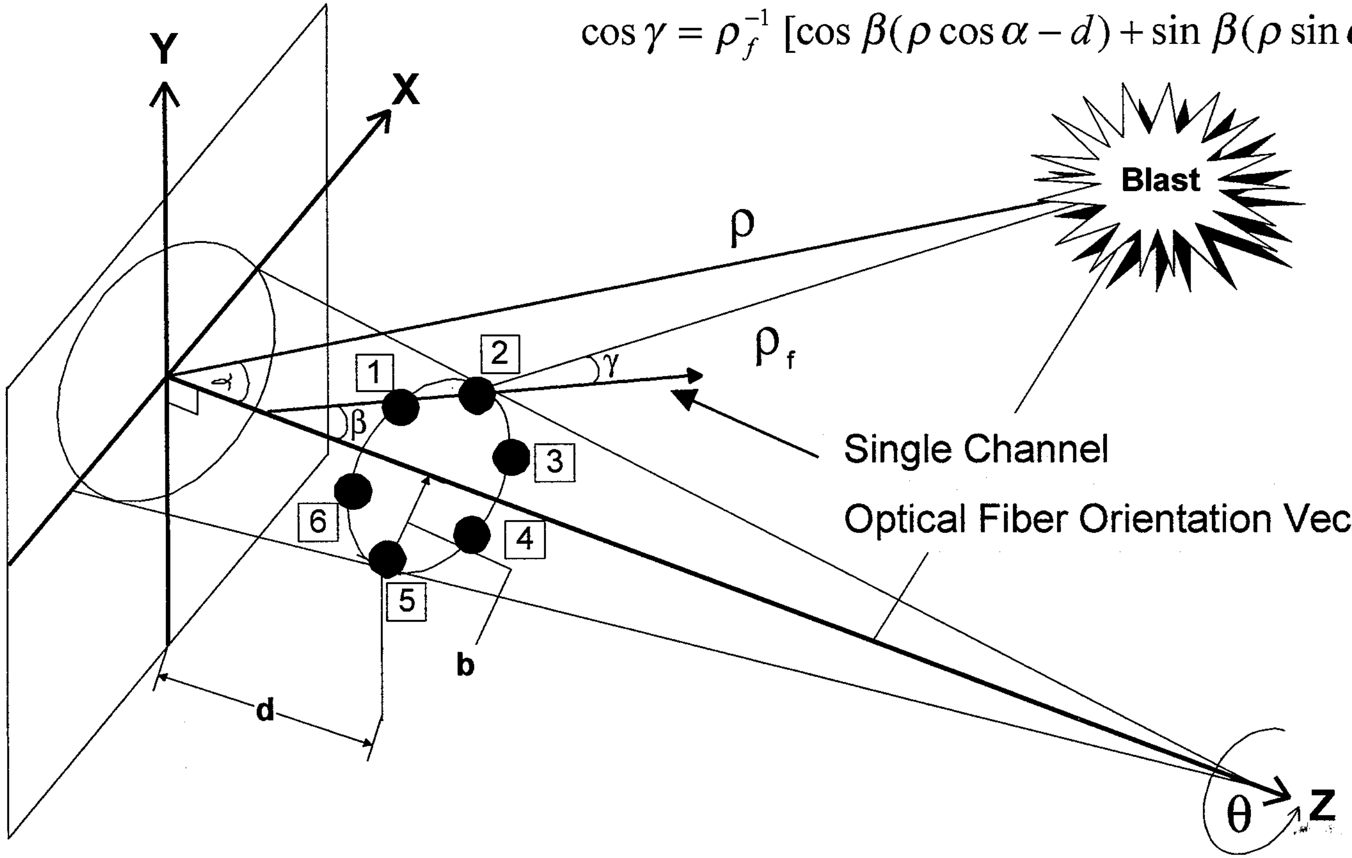
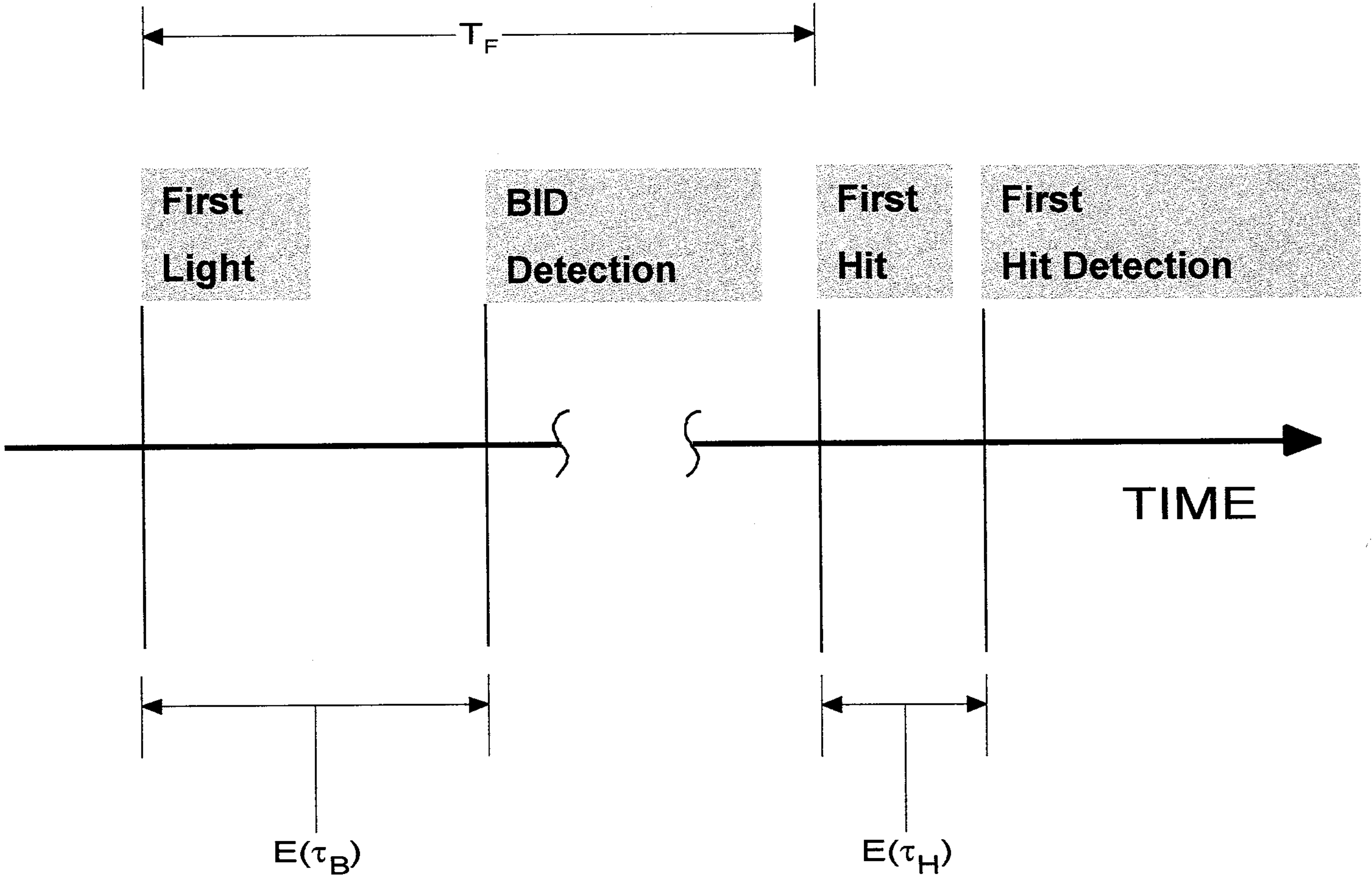


Figure 12

Endgame Timeline



T_F

First Light

BID Detection

First Hit

First Hit Detection

TIME

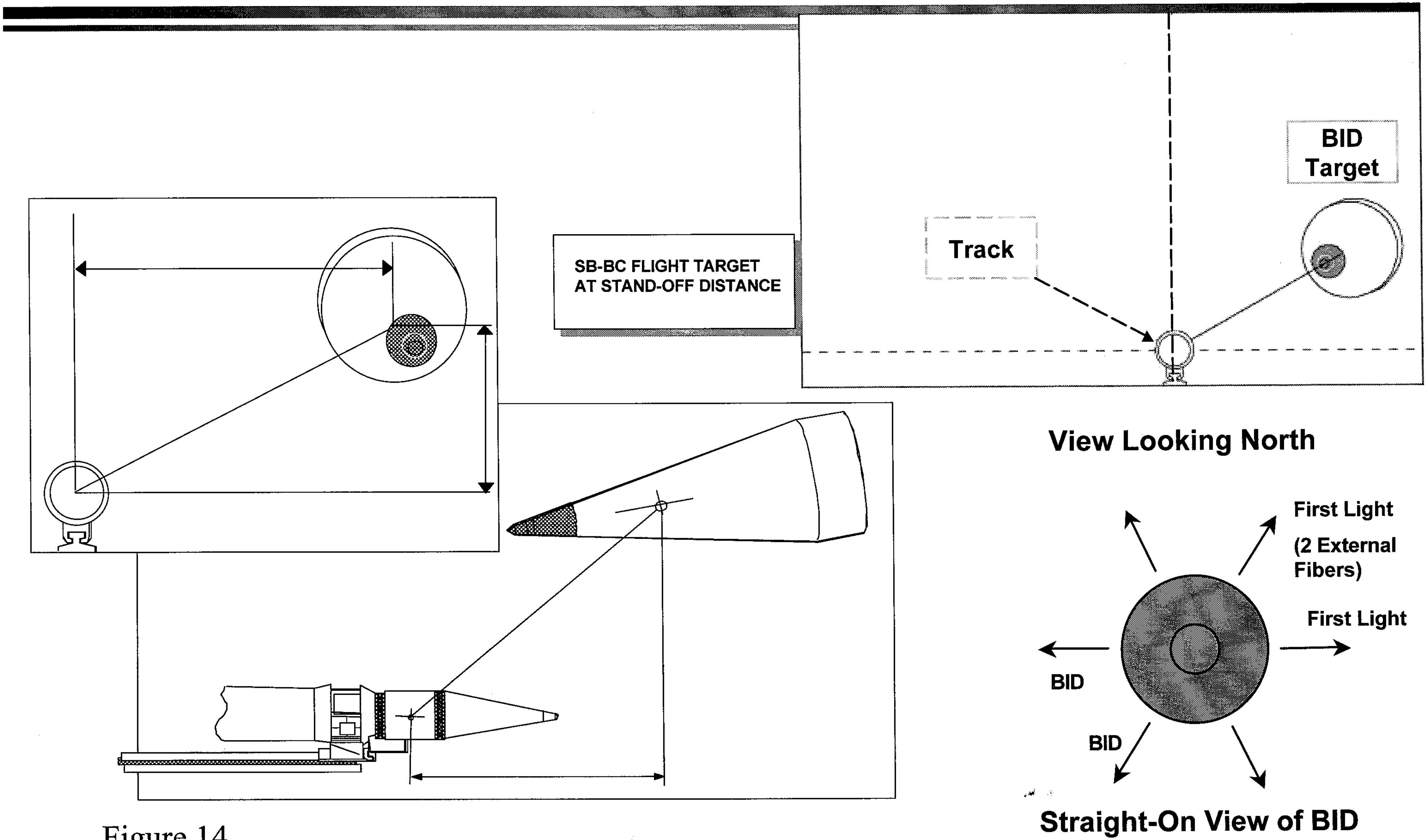
$E(\tau_B)$

$E(\tau_H)$

$$T_F = [T_H - E(\tau_H)] - [T_B - E(\tau_B)]$$

Figure 13

Test Geometry



SB-BC FLIGHT TARGET AT STAND-OFF DISTANCE

View Looking North

Straight-On View of BID

Figure 14

Test Photograph

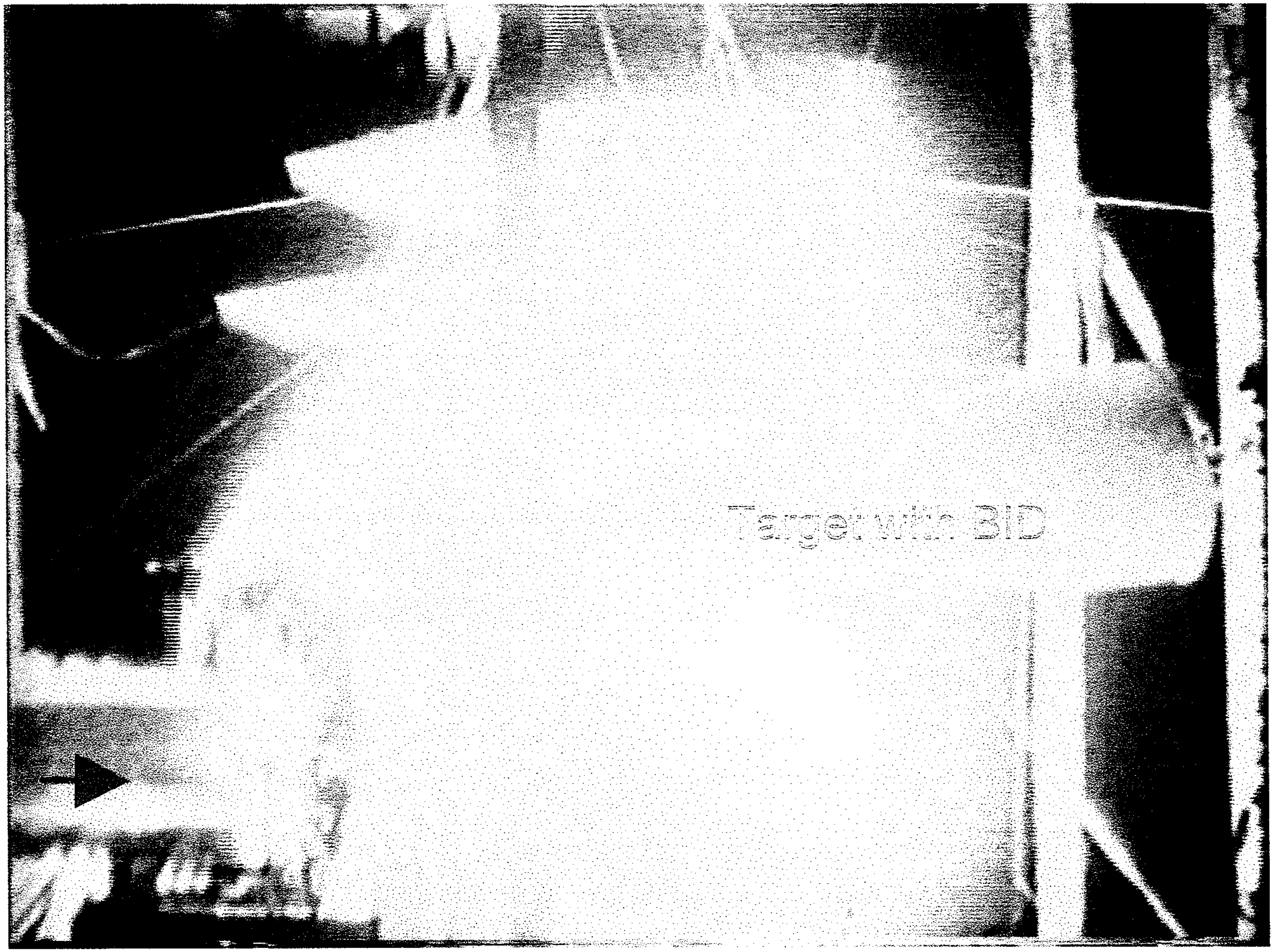


Figure 15