LASL-79-84

1 November 1979

Light Flash Produced by an Atmospheric Nuclear Explosion

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CONTRACT W-7405-ENG. 36

Current concern regarding nuclear-weapon proliferation has re-emphasized the interest in detecting nuclear tests conducted anywhere in the world. Such tests could be conducted underground or in the atmosphere. One means of detecting atmospheric nuclear explosions utilizes a "bhangmeter," an optical sensor developed during the years of US atmospheric nuclear tests. It detects and records the extremely bright and characteristic flash of light from an atmospheric explosion. The high intensity of the light flash makes this a sensitive technique, and the distinctive signature of the light signal reduces the likelihood of errors in identifying the detected signal as a nuclear event. In addition, timing information in the light signature can be used to infer the energy released by the nuclear explosion, i.e., the yield.

This review describes the light flash that would be detected by a bhangmeter from an atmospheric nuclear explosion and the method by which the yield of the explosion is obtained. It presents the physical processes that produce the light flash and determine its characteristics, and incorporates an analysis showing that naturally occurring signals would not be mistaken for that of a nuclear explosion.

CHARACTERISTIC SIGNATURE

Figure 1 shows the light-flash signature of a 19-kiloton atmospheric nuclear test conducted in Nevada on May 1, 1952. The two distinct light peaks, with a dimmer but still luminous minimum between them, are characteristic of the optical signature of all atmospheric nuclear explosions below about 30 km altitude. A nonlinear (logarithmic) time scale is used to display this curve so that details can be shown of the very fast first-peak and minimum-signal regions.

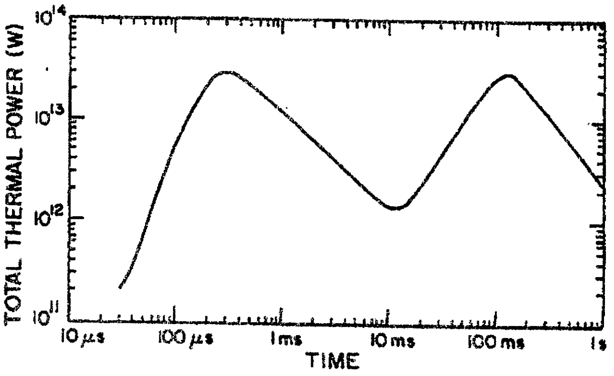

Fig. 1

The total pulse length exceeded one second. The time of the first peak in this signature occurred at about 300 μs (this is called first-maximum time); the minimum signal occurred at 12 ms (minimum time); and the second peak occurred at about 130 ms (second-maximum time). Note that although the two peaks appear to be very similar, this apparent similarity is due to the distortion caused by the logarithmic time scale. Actually, the second peak lasted about 100 times longer than the first peak and contained about 99% of the total radiated energy, which was about one-fourth of the yield.

For yields different from 19 kilotons, the light curve shape is very similar to that in Fig. 1, but the times at which first maximum, minimum, and second maximum occur are different. The minimum and second-maximum times are directly related to yield; therefore, measurements of these times can be used to infer yield. Approximate scaling laws that relate yield to time-to-minimum and, less accurately, time-to-second-maximum, are given in Fig. 2.

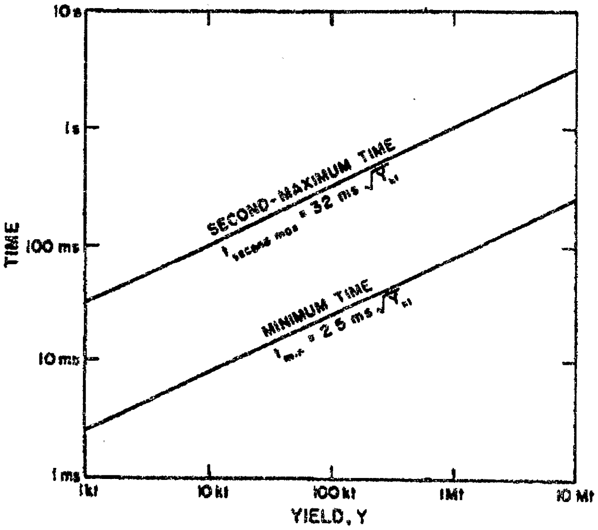

Fig. 2

The independence of the light-signature pulse shape from yield is due to the fact that the processes producing the light do not depend on the construction of the nuclear device. In an atmospheric nuclear explosion, a huge quantity of energy is released into the atmosphere surrounding the device. The energy is released so nearly instantaneously, and into such a small volume, that extremes of temperature and pressure are reached. A fireball is created that grows very rapidly. It soon becomes so large, with so much air engulfed in it, that subsequent growth and light emissions do not depend significantly on any source characteristic except yield. Because of this, the characteristic shape of the light signal is very similar for all nuclear events. This similarity has allowed the discussion of a generic nuclear-explosion signature without regard to details of the source, and allows the following source-independent discussion of the physical processes that produce the characteristic double-peaked light pulse.

FIREBALL PHYSICS

Within the first microsecond after detonation, the entire nuclear yield is deposited in the bomb materials, heating them to extremely high temperatures in the range of 10^7 K (degrees Kelvin). Some of this energy is immediately radiated away in the form of x rays and extreme ultraviolet radiation, but this radiation is immediately reabsorbed in the air within the first few meters surrounding the device. The air is thereby heated to a very high temperature, in the range of 10^8 K, with a corresponding increase in pressure to several thousand atmospheres. This heated air and the hot bomb vapors (debris) in the interior constitute the initial fireball. The fireball subsequently expands through a combination of radiative and hydrodynamic processes. An intense shock wave (thin region of highly compressed air) is formed at the surface, which expands outward at a high velocity. Inside the shock, the energy is rapidly redistributed through emission and reabsorption of ultraviolet radiation.

The time variation of light emission during the first pulse in Fig. 1 is controlled by the radial growth of the shock. Although the shock surface is intensely luminous, the shock is opaque to visible light, thus concealing the air and bomb debris in its interior. As the shock expands, it engulfs cold air, causing its temperature to decrease, with a corresponding decrease in brightness. The optical energy emission rate (power) is proportional to the fireball brightness times the area of its surface. After detonation, the optical power first increases, because the increase in surface area outweighs the decrease in brightness. Later, it decreases, because the decrease in brightness is dominant.

During the early expansion and cooling of the fireball, the ultraviolet radiation in the interior decreases rapidly until it cannot effectively redistribute the energy. Thereafter the shock temperature falls more rapidly than the temperature in the interior. As the expansion proceeds, the shock continues to cool, and as it does so, it becomes less and less opaque to visible light, while also becoming less luminous. A point is reached, corresponding to the minimum optical power region in Fig. 1, where the shock becomes sufficiently transparent to allow light from the hotter interior to begin to escape, causing the optical output to begin increasing. Further growth of the shock results in increasing transparency and a further increase of the luminosity of the inner region.

As the expansion continues further, the temperature of the inner fireball decreases, due to the combined effects of hydrodynamic expansion and loss of energy by radiation. This cooling eventually results in the decrease in luminosity following the second maximum in Fig. 1. After the second maximum, the inner fireball gradually becomes transparent, revealing the bomb debris inside, whose brightness also decreases with time.

The majority of the total energy radiated by the fireball comes from the second peak, which is not very different in its instantaneous brightness, relative to the first peak, but it lasts about 100 times longer. By the time this "thermal pulse" is over, the available energy has either been radiated away, trapped in the debris and entrained air of the fireball, or it is propagating in the shock wave, which is now well outside the visible fireball.

To illustrate the physical processes described above, Fig. 3 shows three fireball photographs from the 19-kiloton nuclear test of Fig. 1. All three photographs are reproduced at about the same linear scale, showing graphically the growth of the fireball from first maximum (a) through minimum (b) to second maximum (c).

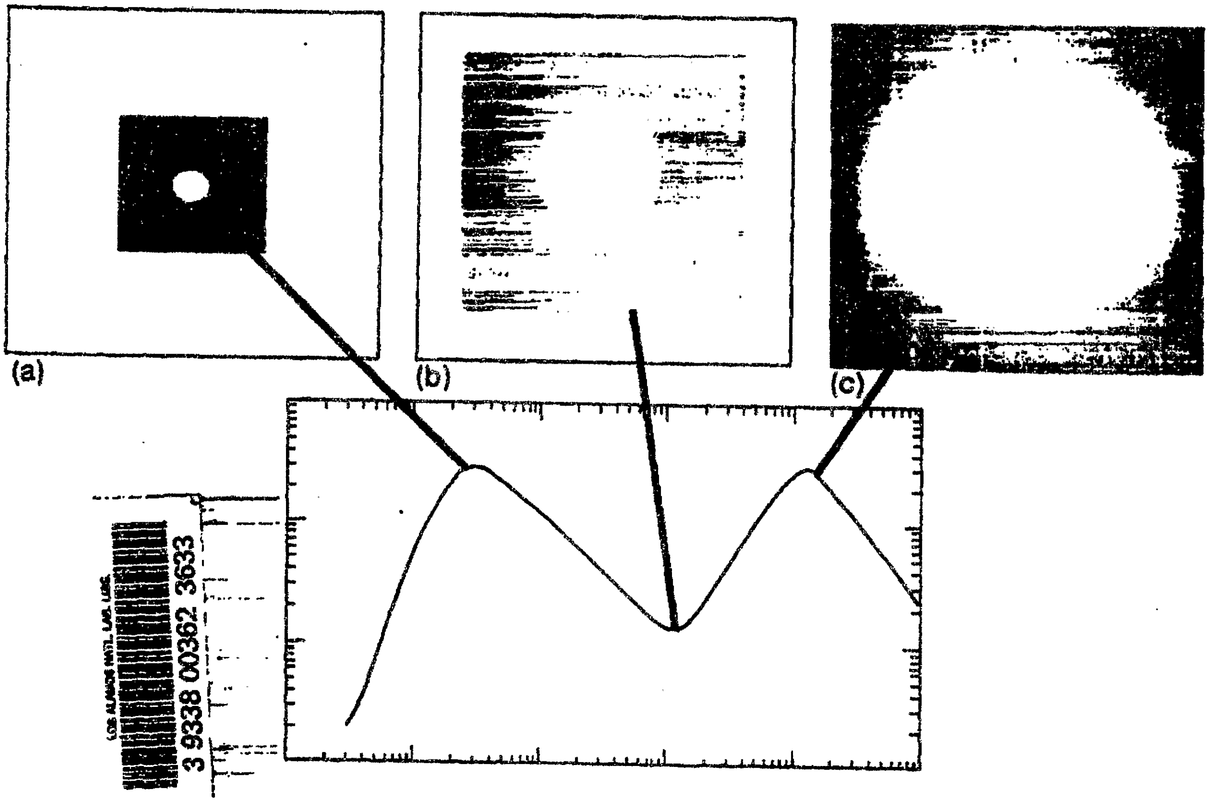

Fig. 3

Figure 3(a) corresponds to a time of 405 μs after detonation and shows the highly radiant shock front at about its maximum intensity. The fireball diameter at this time was 50 m.

Figure 3(b) shows the dim 200-m fireball at minimum time. The radiation from the shock surface was weak, and the shock was beginning to transmit light from the hot inner region. The bright spots, known historically as "measles," are speculated to be small, hot vortices of air or bomb debris just behind the shock front.

Figure 3(c) shows the fireball just prior to second maximum, at which time the shock was transparent and the inner fireball was radiating strongly. The diameter was 355 m. The smoke trails visible alongside the fireball were from rockets launched to probe the fireball and the surrounding air.

UNIQUENESS

The two-peaked character of the light pulse, together with the very large energy radiated during the second maximum, make it unmistakable that this light signature originated in a nuclear explosion. For a one-kiloton explosion the thermal pulse radiates one-fourth kiloton (about 10^{12} joules) in a half second. The peak radiated power during that time, about 4×10^{12} watts, is more than ten times larger than the total electrical generating capacity of the United States. Pulsed light sources do occur in nature, or can be built, that match either this power level or the pulse duration. However, no other source is known that matches both.

In particular, natural lightning has been suggested as a source that could produce the pulse shape and intensity required to simulate a nuclear-explosion light flash. Lightning pulses are not energetic enough for this, even the rare "super bolts," which emit 10^9 joules of visible-light energy in a single short-lived intense stroke. The closest lightning simulation to the timing and intensity characteristics would require an ordinary stroke followed by a long-lived "super-bolt" stroke, producing 10^9 joules of visible light in ~100 ms. This assumption is conservative because although long-lived ordinary strokes have been observed, long-lived super strokes have not. The postulated lightning signal would have a peak radiated power of approximately 10^{10} watts, which is about 400 times smaller than that of a one-kiloton explosion. To achieve the pulse shape and peak-radiated power simulating a one-kiloton nuclear explosion, lightning would have to be both 400 times more energetic and 100 times longer in duration than ever observed for the super bolts.

Thus, because the nuclear signature is orders of magnitude more energetic than any other terrestrial phenomenon that might simulate it, the light signature of an atmospheric nuclear event is unmistakable.

SUMMARY

This review has described: the use of the light flash of an atmospheric nuclear explosion as an optical detection/yield determination method; the physical processes governing the light signature; and the reasons why natural signals cannot be confused with nuclear explosions.

All these are typical results of the weapons-research program at the Los Alamos Scientific Laboratory, which has included research into the effects of nuclear explosions in the atmosphere. Techniques developed in this program are being used in continued atmospheric research and in research addressing the physical processes associated with nuclear weapon development.

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