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Author(s): Bob Kelly, P-14

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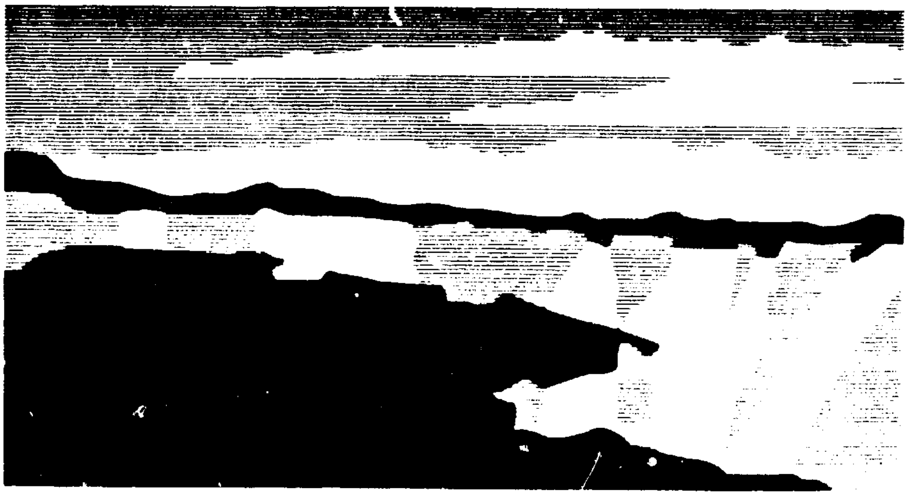

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EMP from a Chemical Explosion Originating in a Tunnel

Bob Kelly
P-14, MS D410
Los Alamos National Laboratory
Los Alamos, NM 87545
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Electromagnetic pulses generated by a chemical explosion deep in a tunnel have been detected by sensors placed on both sides of the portal. These detectors consisted of antennas, current transformers, B-dots, and D-dots. The main objective was to collect data for nonproliferation studies complementary to and in cooperation with seismic methods. The electric field strength at the portal was computed from the data to be on the order of 50 millivolts per meter, with a Fourier transform indicating that most of the energy occurs below about 3 MHz. Several of the sensors displayed periodic sharp spikes probably not related to the device. Surface guided waves were detected along power and ground cables plus the railroad track. Time dependent surface current and charge were measured on the portal door, which serves as a secondary source for external radiation.

Introduction

An electromagnetic pulse, caused by a chemical explosion, was detected in the portal area of N-tunnel at the Nevada Test Site. The main purpose was to collect data for nonproliferation studies complimentary to and in cooperation with seismic measurements. Whereas emplacement of the device in a cavity tends to mitigate seismic signals, it tends to enhance EMP production and vice versa.

The experimental objectives were: (1) Characterize the EMP secondary source at the portal, (2) Observe surface guided waves along the interior cables, (3) Determine time dependent current and charge on the portal door, (4) Investigate possible guidance of a pulse by the railroad tracks, (5) Measure any device generated signal on the phone and ground lines, (6) Detect radio frequency emission near the portal, (7) Attempt a comparison of the EMP generated from chemical and nuclear explosions.

Typical electric field strengths were several tens of millivolts per meter just outside the portal, with Fourier transforms indicating that the energy density resided mainly below about 3 MHz. Surface guided waves were detected in the vicinity of detector cables, power and ground cables, and the railroad track. The portal door (a wire mesh) serves as a secondary radiation source as shown by non-zero time dependent surface charge and current. Many of the sensors displayed sharp, periodic spikes most likely not shot related; their origin is unknown at this writing except for those at 60 Hz and those on the phone line.

<u>Condensed Abridgment of a Brief Summary of Basic Theory</u>

Chemical explosions are caused by a rapid exothermic chemical reaction, which produces a gas and results in heat transfer. The normal chemical reaction that occurs in an explosion is combustion. Fuel elements, such as carbon or hydrogen react with oxidizing elements such as oxygen or a halogen. The system is capable of producing large quantities of carbon dioxide, carbon monoxide, water, and nitrogen, along with considerable heat.

Subsequent to detonation, an explosion produces an electromagnetic pulse (EMP). The spectrum and intensity are functions of such parameters as explosive type and particle size. There appears to be a time delay between detonation and emission, which may depend upon the mass of the explosive and the ignition method. The polarization, field strength, and radial dependence depend partly upon the receiving sensor location. The proximity of the explosive to the earth's surface affects the signal. Often, two distinct pulses are recorded. The first is directly associated with the explosion, whereas the second is probably dependent upon the height of the charge above ground. Keep in mind that the combustion products include heavy ionized atoms. The ignition method also influences the signal. For example, flame ignition of spherical charges lead to signals that differ from those initiated by an electric detonator.

There are several qualitative explanations of the EMP emission. For example, one possibility mentioned in the literature is generation produced by electric sparks between detonation products and case fragments. Probably the major contribution originates in an asymmetric separation of the positive and negative ions from the high explosive products as a result of high temperature. The asymmetry may originate in a number of ways such as the geometry of the immediate surroundings, current leads in electric detonation, and single point flame ignition. Recall that the generation of a dipole isn't sufficient for radiation; the dipole moment must have a nonzero second time derivative, which is equivalent to a nonzero first time derivative of the current.

There is some inconclusive evidence that the time delay between detonation and the appearance of EMP is proportional to the cube root of the explosive mass. There is further evidence of a functional dependence of the electric field strength on the mass. A statistical analysis of an excess of 100 experiments at various distances from several different charge masses shows that the magnitude of the electric field is directly proportional to the explosive mass.

In order for the electromagnetic pulse to propagate through a tunnel, it first must be coupled from the device to the tunnel. This problem partly depends upon the nature of the emplacement. For example, suppose the explosive is placed in an excavated cavity with one or more connecting tunnels. During, and for some time following the explosion, a time-dependent electromagnetic field is established in the cavity. The cavity size and shape, plus the device location play a role in determining the EMP frequency spectrum.

The coupling problem consists of extracting a portion of the energy from the cavity via a tunnel. Clearly the tunnel has its own natural modes, and these are excited to an extent depending upon the electric and magnetic field orientations at the tunnel-cavity interface at any instant of time. It's clear that any arbitrary opening to the cavity will allow an electromagnetic pulse to enter. If there are conductors, such as cables or railroad tracks in the tunnel, the mode distribution is modified to include the possible existence of the extremely important transverse electromagnetic mode (TEM), which isn't possible in the absence of a conductor isolated from the tunnel walls.

A waveguide mode (non-TEM) may be propagated through a tunnel for all wavelengths less than approximately twice the largest transverse dimension. Wavelengths larger than this cutoff value are not propagated and therefore do not transport energy by this mode. All of the propagated modes are lossy ones because at the tunnel boundary, part of the energy is reflected and part is refracted into the surrounding medium. The refracted portion constitutes energy extracted from the wave and hence corresponds to a loss. Furthermore, the medium has a nonzero conductivity that enchances the loss.

The waveguide mode assumes tunnel propagation in the absence of conductors threading parallel to the walls. In practice, there are normally power lines, telephone lines, coax cables, pipes, railroad tracks, etc., which render the analysis to be more complicated. Yet, the very presence of a longitudinal conductor makes possible the existence of a TEM mode with no cutoff frequency. In addition, a conductor parallel to the walls can support a surface wave. One may define a surface wave as a wave propagating along an interface between two different media without radiation. A surface wave is bound to a surface, and radiation occurs only at curvatures, nonuniformities, and discontinuities.

The main characteristics of a surface wave are that its phase velocity is typically less than that in the surrounding medium and that the field strength decreases over a wavefront as one recedes from the surface; this is characteristic of a inhomogeneous wave such as is experienced in total internal reflection. Thus, the energy density decreases away from the surface.

The attenuation of the surface wave is complex because it depends upon the conductor location and frequency in addition to both conductor and tunnel wall electrical properties. At low frequencies (perhaps less than 10 MHz), the attenuation increases approximately at a rate proportional to frequency and goes through a maximum, corresponding to maximum tunnel wall absorption. As frequency increases, the attenuation begins to decrease because the energy density is becoming more concentrated around the wire with wall effects being less important. The attenuation goes through a minimum and begins to increase with increasing frequency. This enhancement is caused by the finite conductivity of the conductor as it affects the surface wave. The placement of the conductor in the tunnel has an important effect on attenuation. Minimum attenuation occurs when it's located at the geometric center, and it increases as the conductor approaches the tunnel wall.

The phase velocity is also affected by conductor placement. If the conductor is located at the tunnel center, v is less than the speed of light in vacuum, c. As it moves towards the wall, v increases and becomes greater than c. Note that this doesn't violate relativity, because the energy travels at the signal velocity (usually the same as group velocity).

The following is a theoretical speculation regarding the radiation pattern from the portal. Assume that a TEM wave is emitted from the portal. Recall that most likely this is the dominant mode because of the presence of conductors parallel to the tunnel (such as cables and railroad tracks). This wave will be an approximate inhomogeneous plane wave at the source (portal). It's inhomogeneous because the field strength varies over a surface of constant phase (wave front). This variation is unknown, so it will be ignored in the rough analysis. Temporarily, assume the wave to be monochromatic, then the angular distribution of radiated energy would approximate a Fraunhofer diffraction pattern. In practice, the wave isn't monochromatic, but may be thought of as a superposition of many monochromatic waves, each producing similar diffraction patterns but with different angular locations of nulls and secondary maxima and with different amplitudes. Thus, it's very likely that the superposition will wipe out the individual field variations and produce a relatively smooth radiation pattern, most likely peaked in the forward direction. This pattern would be further modified due to ground reflection and possible reflection from hills.

The portal serves as a secondary source of radiation. This is especially true for the NPE experiment because of the wire grid door. There are three important propagation modes for radiation from the portal to receiving sensors: (1) propagation along the earth's surface, (2) as a direct wave plus possibly the superposition with a ground reflected wave, (3) a sky wave by ionspheric refraction.

The ground wave follows the earth's contour. It's attenuated rather well for frequencies above 3 MHz. The electric field is mainly perpendicular to the earth's surface, but it always has a forward tilt. The phase velocity is less than the speed of light in vacuum, and the energy density drops off with altitude.

In the far field free space, both E and H have a l/r dependence. If the direct wave has a ground reflected wave superimposed upon it, then E and H drop off as $1/r^2$. The field strength varies approximately as the product of both source and receiving antenna height. These characteristics result in a weak EMP signal much beyond the horizon. On the other hand, a temperature inversion enhances over-the-horizon propagation via atmospheric refraction.

Skyway propagation is by means of ionospheric refraction. As applied to EMP, this mode is useful only over a long distance, typically measured in hundreds or thousands of kilometers. Due to the fact that the ionsphere is an absorbing, anisotropic, dispersive, birefringent medium, sensitive information may be lost.

Experimental Set-Up

Four types of sensors were used: antennas, current transformers, B-dot and D-dot detectors. All were placed in the immediate vicinity of the portal.

(1) Antennas. Five antennas were employed: Horizontal and vertical dipoles, resonant at 50 MHz, a vertical monopole at the same resonant frequency, a horizontal 10 MHz dipole, and a helix. Note that these antennas are viewing fundamentally time domain phenomena, so that the frequency listings mainly tell the antenna length. The helix was designed to check for possible high frequency components in the 300 MHz range.

(2) Current transformers. Current transformers were placed around a main power line, a main ground line, a diagnostic cable, and a phone line. These measure the theta component of the surface guided magnetic field (not its time derivative) which can be translated into a sheath current. Unfortunately, access to the device location was denied at every request, so that there's no guarantee that any of the three cables actually led to the device vicinity.

(3) B-dots and D-dots. B-dots measure the time derivative of the tangential component of the magnetic field (equivalent to a surface current) and the time derivative of the normal component of the electric field (equivalent to a surface charge), respectively. These were placed on the wire mesh portal door and the railroad track.

Electric Field Strength

Electric field strength (magnitude of the E vector) is important for at least two reasons. First, the field strength is a major factor in the possibility of detection of the EMP at a given location for a given detector sensitivity and noise background, and this includes propagation through the ionosphere. Second, field strength is a function of yield or source strength, so that in principle, the latter may be estimated from E.

There were several spikes in the voltage vs time plot for both vertical and horizontal dipoles. In the block chart shown below, time is in milliseconds measured from detonation initiation, and electric field strength is in millivolts per meter A blank in some of the horizontal dipole slots simply means that the signal wasn't clear enough to be certain of its validity.

	16	19	33	48	50	65	81	t in ms
vertical dipole	35	43	52	90	40	16	43	$\lvert E \rvert$ in mV/m
horizontal dipole				34	34		27	$\lvert E \rvert$ in mV/m

The average field strength for vertical polarization is on the order of 50 mV/m, whereas it's about 30 mV/m for horizontal polarization.

Fourier Transforms

The Fourier transform is important because sensors, amplifiers, and any other associated circuit elements are bandwidth limited. Thus a knowledge of the EMP frequency spectrum expected from a typical explosion aids in its detection. The reader should keep in mind that EMP is a time domain problem - not frequency domain. Most electromagnetic theory texts assume an imaginary exponential time dependence throughout, which is equivalent to a Fourier transform.

The transforms derived from the time plots are system transforms, namely, a convolution of the actual field at the antenna location with the antenna response, cable response, amplifier characteristics and any property of the digitizer.

The spectrum of nearly all of the sensors may be summarized by saying that most of the electromagnetically propagated energy was contained in the range of frequencies below about 3 MHz. There was a sharp drop in energy density for any frequency above 3 MHz. Four of the sensors had short time duration amplitude variations: monopole at 0.4 MHz, ground coil at 0.2 MHz, coax coil at 0.7 MHz, and the power coil at 1 MHz. The reason for these narrow variations is unknown as of this writing.

Spike Frequencies

Most of the sensors displayed sharp, periodic spikes on voltage vs time plots. Even though the origin of those spikes is unknown, it seems reasonable to assume that they're not caused by the device. A box displaying those frequencies is shown below.

vert. dipole	horiz. dipole	10 MHz horiz. dipole	helix	mono-pole	gnd coil	coax coil	pwr coil	door B-dots	phone coil
2.5 kHz 16 kHz	16 kHz	430 Hz	6.9 kHz	160 Hz	60 Hz	60 Hz	55 kHz	60 Hz	79 Hz 300 Hz

The 60 Hz spikes on the ground coil, coax coil, and door B-dots surely must originate in the line current frequency. The reason it doesn't show on the power coil is most likely because a high pass filter was used in anticipation of a 60 Hz signal. The phone coil spikes may possibly be explained by the four phase ringing voltage with a fundamental of 20 Hz (4 x 20 = 80) and a 300 Hz base frequency of the dial tone. No device information was recorded on the phone coil.

Cable Currents

Current transformers were placed around three cables in the tunnel (ground line, power line, a diagnostic cable). Hopefully, all three led from the portal to near the device, but permission to check this was always denied. The surface waves guided by these cables induce sheath currents by virtue of the near discontinuity of the transverse tangential component of the magnetic field at the outer conductor. By knowing the voltage to current transfer function of the coils, the following peak sheath currents were indirectly measured: ground coil - 0.05 amps; coax coil - 0.07 amps; power coil - 0.014 amps. It should be noted that the measured power coil current should be too low because a high pass filter eliminated the low frequency components.

Portal Door and Railroad Track Current and Charge Densities

B-dot and D-dot detectors were placed on the portal door and on one of the train track rails. Recall that a B-dot placed on a conducting plane measures the time derivative of the tangential magnetic field which may then be converted to surface current per unit length (the length being perpendicular to the field vector). A D-dot measures the time derivative of the normal component of the electric field (actually displacement vector) which may then be converted to surface charge density.

The peak current density on the track was about 6 amp/m which translates to about a half amp total at its peak on one of the rails for a very short pulse. The peak charge density was calculated to be about two nanocoulombs per square meter. Although several requests were made to assure a continuous rail from the portal to near the working point, all attempts to verify this by walking the tunnel were denied - we'll never know.

The portal door is actually a wire grid which should have surface currents and charge induced on it by the propagating waves. The D-dot on the door failed, but the two B-dots (one vertical and the other horizontal) measured a peak vertical current density of 6.4 amps/m and a horizontal current density of about 1.6 amps/m. Notice that this is in qualitative agreement with the results from the vertical and horizontal dipoles in that vertical polarization was stronger than horizontal.