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The Electromagnetic Pulse From Nuclear Detonations

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Models of the processes whereby a nuclear detonation emits a coherent electromagnetic pulse fall into three classes: those involving Compton electron currents produced by interaction of prompt γ radiation from the detonation with the environment, those involving photoelectron currents produced by the similar interaction of primary X radiation from the detonation, and those involving perturbation of the ambient magnetic field by the expanding plasma surrounding the detonation point. For each model considered the cause of the asymmetry in the current system necessary for the radiation of a signal is discussed. These causes include the earth-atmosphere interface, the atmospheric density gradient, anisotropy of the environment by virtue of the presence of the earth's magnetic field, nonuniform emission of the energetic radiation (γ and X rays) by the detonation, and asymmetries of the delivery vehicle and device case. The available experimental data are then examined in the light of the models. These data suffice to establish the models as probably being correct in their identification of the principal processes whereby the nuclear electromagnetic pulse is generated, but they are inadequate for a quantitative assessment of the accuracy of the models.

Contents

Nuclear detonations are generally realized to be strong sources of coherent electromagnetic radiation (the electromagnetic pulse) within the very low and low-frequency (VLF and LF) radio bands (3–300 kHz) [*U.S. Department of Defense*, 1962, pp. 502–506]. However, the very broad range of frequencies over which significant radiation can be emitted is less commonly realized, although it has long been known [*Mark*, 1959]. Frequencies roughly between 1 Hz and 100 MHz are significant in the signal generation mechanisms discussed here. Although the fraction of the detonation energy deposited in the electromagnetic pulse is small, the total energy available in a nuclear detonation is sufficient to make it a powerful radio source.

Standard references on nuclear effects [*U.S. Department of Defense*, 1962] and nuclear test detection [*Mark*, 1959; *Latter et al.*, 1961] consider the processes by which a nuclear explosion emits an electromagnetic pulse only briefly, and attention is limited primarily to the VLF-LF bands. More recent articles on nuclear test detection include several [*Cotterman*, 1965; *Dickinson and Tamarkin*, 1965; *Pierce*, 1965; *Sollfrey*, 1965] that discuss the electromagnetic pulse. Although interest in the high-frequency components of the signal is evident in these articles, the generation process is again only mentioned briefly. Detailed treatments of several of the mechanisms by which these signals can be produced are available in the literature, but the absence of any general survey of this literature is remarkable. It is hoped that this situation will be remedied here.

Attention will be confined to the coherent pulse as distinct from thermal radiations or synchrotron radiation [*Peterson and Hower*, 1963], for example. The perturbations of other electromagnetic signals by a nuclear detonation through its modification of the propagation medium [*Pierce*, 1965] will not be discussed. The slower (periods of the order of 10 s or greater) geomagnetic field fluctuations produced by high-altitude detonations [*Maeda et al.*, 1964] are also not discussed, although some of these fluctuations could reasonably be treated as examples of mechanisms considered here. Although the effects of propagation upon the nuclear signal are sometimes considerable [*Jean and Wait*, 1965; *Sollfrey*, 1965; *Johler*, 1967], they are also beyond the scope of this discussion.

Although the emphasis given here to generation mechanisms is necessary for understanding the production of the signal, it biases the discussion heavily in favor of theoretical work. Perhaps such emphasis is unavoidable; this work seems somewhat more readily available than the results of experimental investigations are. The signal characteristics derived in the theoretical studies can be misleading, however, particularly if only one mechanism is considered. The actual signal produced is the result of all the mechanisms in concert, and the cumulative addition of the contributions, with appropriate phasing, from every mechanism must be considered in any interpretation of signal features.

A great deal of work on the generation of an electromagnetic pulse by nuclear detonations, including the initial formulation of most of the generation mechanisms, remains available only in classified reports (J. Malik, personal communication, 1972). This literature has purposely not been examined in the preparation of this review in order to avoid the often difficult task of sifting out those points that remain sensitive. I regret that this choice precludes the giving of adequate credit to those responsible for the development of much of our present understanding of the electromagnetic pulse. A brief summary of early work has been prepared by *Hart* [1973].

Classification of Mechanisms

Two principal processes have been identified by which energy is released by a nuclear detonation as a coherent electromagnetic pulse. These are denoted the 'Compton electron' and the 'field displacement' models by *U.S. Department of Defense* [1962, pp. 502-506]. In the Compton electron model the radiated field is produced initially by the charge and current distribution associated with the motion of energetic Compton electrons. These electrons are produced by interaction of prompt γ radiation from the detonation with the environment. In the field displacement model the radiated field results from the exclusion of the earth's geomagnetic field from the highly ionized fireball surrounding the detonation point. In addition to these two models the photoelectron currents that result from the interaction of thermal X radiation with the environment may generate a significant signal in some cases [*Karzas and Latter*, 1965]. This interaction constitutes the third model that will be examined here.

The dependence of the signal characteristics upon those of the detonation varies greatly from one radiation mechanism to another. This variation can usually be attributed to one or both of two principal causes: the driving energy available to one mechanism does not depend upon the detonation characteristics in the same manner as that available to another, and the interactions between the detonation products and the environment that are important in one mechanism do not depend upon the detonation characteristics in the same manner as those that are important in another do. The three general models defined above differ primarily in the form of the available driving energy. A number of distinct mechanisms will be discussed below, each of which can be associated with one of these general models. For a single model the various mechanisms that it encompasses differ primarily in the relative importance of the various interactions that occur between the detonation products and the environment. The particular interaction responsible for the asymmetry in the charge distribution is commonly used to name the mechanism. Table 1 lists the mechanisms that are considered here and indicates their relation to the principal models.

A number of mechanisms are denoted by the symmetry characteristics of the radiated signal, e.g., electric dipole radiation. Although this terminology is explicit in its description of the polarization and radiation pattern of the signal, it is insufficient to define completely the mechanism of interest. Furthermore, it can sometimes be misleading in its implications about the generation process, as will be illustrated when the signal that results from interaction of Compton electrons with the earth's magnetic field is discussed.

COMPTON ELECTRON MODEL

General

A nuclear detonation releases of the order of 0.1% of its energy in the form of prompt γ radiation within a time interval of the order of 10^{-7} s. The photon number distribution as a function of energy, $dN_\gamma(E)/dE$, in which N_γ is the total number of γ photons emitted and E is the photon energy, peaks sharply near 0.5 MeV. The energy distribution, $E[dN_\gamma(E)/dE]$, has a broad maximum between 0.5 and 2 MeV [*Mark*, 1959; *Pierce*, 1965]. For the purpose of discussing the major characteristics of the electromagnetic pulse produced by these γ rays the detonation can be considered to be a point source of a short pulse of monoenergetic γ photons of a few MeV energy.

The γ photons interact with molecules in the material surrounding their point of origin primarily by the Compton process, the result being that the molecules are ionized as Compton electrons are produced. These electrons receive a total of about 1 MeV of energy per γ photon. The multiple scattering of the γ photons and the energy spectrum of the Compton electrons need not be treated in detail here; the interaction process can be adequately represented as the production of a single 1-MeV Compton electron, moving radially outward, by each γ photon.

The Compton electrons interact in turn with the surrounding molecules to produce large numbers (about 3×10^4 per MeV Compton energy) of low-energy secondary electrons. The importance of the secondary electrons in the radiation of the electromagnetic pulse depends primarily upon their density. If this density is sufficiently great to make the region in which they are produced highly conducting, significant conduction currents flow in response to the electric fields that are generated by the Compton currents. The conduction currents are opposed to the Compton currents and thereby limit the net radiating current. At late times after the Compton currents have subsided, the conduction currents are ultimately responsible for the restoration of charge neutrality.

If the γ photons were uniformly emitted in all directions into a homogeneous isotropic environment, the Compton and conduction currents would be symmetric about the detonation point, and no signal would be radiated. The radial electric field that is produced by the radial variation of the Compton current density would be confined to the region in which the Compton current occurs in this case.

Asymmetries in the Compton current distribution about the detonation can occur in several ways. These can be conveniently divided into three types. First, the emission of γ rays by the detonation may not be uniform. Second, the distribution of the material with which the γ photons and Compton electrons interact may not be spherically symmetric about the detonation point. Third, the interaction of the Compton electrons with any ambient magnetic field depends upon the relative direction of the two. Examples of each of these effects will be discussed.

Nonuniform Emission of γ Photons

Deposition in a homogeneous atmosphere. Consider first the consequences of a nonuniform emission of γ photons by a detonation in a homogeneous atmosphere. Such a model has been examined by *Kompaneets* [1958] and more recently, by *Gilinsky* [1965], who called attention to a number of oversimplifications in Kompaneets' model. Kompaneets and Gilinsky demonstrate how a departure from spherical symmetry in the γ photon emission produces a corresponding departure in the radial Compton currents and in the secondary electron conductivity. For a small dipole asymmetry in the γ emission, the case considered specifically by them, the resultant charge distribution has a net dipole moment, and the radiated fields are of the electric dipole type.

Near the detonation point the secondary electron density increases rapidly to a magnitude sufficient for the conduction current to nearly cancel the Compton current. The growth of the radial electric field ceases at this time. Although the details of this development depend somewhat upon the time dependence of the γ flux, the radial field is generally restricted to a nearly constant maximum value over a substantial region surrounding the detonation point. The value of the radial field within this 'saturation' region is essentially independent of the detonation yield but is sensitive to those parameters that determine secondary electron density. *Gilinsky* [1965] found

TABLE 1. Principal Mechanisms for the Generation of a Nuclear Electromagnetic Pulse

Source of Radiating Current	Cause of Asymmetry in Current	Examples
Interaction of prompt γ radiation with surrounding material	Nonuniform emission of prompt γ rays	Deposition in uniform atmosphere Charge deposition on device case
	Inhomogeneity of environment	Atmospheric density gradient Earth-atmosphere interface Nonuniform device material
	Anisotropy of environment	Earth's geomagnetic field
Interaction of primary X radiation with surrounding material	Nonuniform emission of primary X rays	Interaction with ambient electrons
	Inhomogeneity of environment	Atmospheric density gradient
	Anisotropy of environment	Earth's geomagnetic field
Expansion of fireball	Anisotropy of environment	Earth's geomagnetic field

the field to be given by $\alpha R/\mu q$, where α is the attachment rate of electrons to neutral molecules (the principal loss mechanism for electrons in the atmosphere at low altitudes), R is the Compton electron range, μ is the secondary electron mobility, and q is the number of secondary electrons produced per unit energy of the Compton electrons. This expression yields a field of the order of 2×10^4 V/m at sea level. The limit of the saturation region is fairly sharply marked by the onset of a rapid decrease of the radial field with increasing distance.

The saturation region grows rapidly during the period of high γ flux to a size determined primarily by the prompt γ yield of the detonation. The region is typically of the order of 1-km radius for a detonation of tens of tons prompt γ yield at sea level [*Latter et al.*, 1961], where a 1-t yield is equivalent to 4.2×10^{16} ergs. The γ flux is proportional to $\exp(-r/\lambda)/r^2$, where r is the radial distance and λ is the mean free path for the γ photons. For all but very small yields the exponential factor in this expression dominates the spatial dependence of the γ flux at the limit of the saturation region, a consequence being the logarithmic dependence of the radius of this region upon yield.

The size of the source region is sufficiently large, in the sense that the time required for a signal to pass across it is appreciable in relation to the temporal variation of the radiating currents, that this size strongly influences the spectrum of the radiated signal. An estimate of the dominant frequency range in the signal can be obtained by noting that the high conductivity in the saturation region effectively limits the radiating currents to the outer boundary of this region [*Sollfrey*, 1965]. The charge density produced near the limit of the saturation region by the Compton current can roughly be considered to be an initial distribution of charge on the surface of a conducting sphere; nonuniformity of this distribution gives rise to surface currents. These currents can be expanded in a series of their natural modes of oscillation on the sphere. For the dipolar asymmetry considered here, only the lowest (dipole) electric mode exists, for which the natural frequency of oscillation is $(3)^{1/2}c/4\pi a$ for an infinitely conducting sphere in vacuum or about 40 kHz for a saturation radius a of 1 km [*Sollfrey*, 1965]. The spectral peak of the radiated signal decreases slowly with increasing yield, since the radius of the saturation region increases logarithmically with yield.

Kompaneets [1958] essentially considered only this relaxation phase of the currents, neglecting radiation from the Compton currents that flow during the establishment of the 'initial' charge distribution at the saturation radius. *Gilinsky* [1965] included the Compton currents and demonstrated that Kompaneets' approximation leads to the loss of the first half cycle of the radiated wave form. The short duration of the Compton currents also suggests that higher frequencies than those estimated above might also be significant in the radiated signal, even though the source cannot radiate coherently as a whole at the higher frequencies. The Compton current is confined to a relatively thin shell that expands with the γ pulse at near light speed. Thus the transverse (radiated) electric fields, which accompany nonuniformities in the charge distribution in this shell, add coherently at different radial distances. The very rapid initial rise of the radiated signals calculated by Gilinsky can be attributed to this expansion of the current system. Their subsequent rate of variation is governed by the source size and is consistent with the spectral peak frequency given by the oscillating sphere model.

Since the source is not small in relation to all the significant wavelengths in the radiated signal, the close relationship between the dipole form of the γ emission asymmetry and that of the radiated signal found by Kompaneets and by Gilinsky depends upon the assumptions that the γ asymmetry is small and that it is purely dipolar, as was noted by *Gilinsky* [1965]. The restriction that the asymmetry be small insures that the conduction current term, which involves both the radial field asymmetry and the conductivity asymmetry, is small in comparison with the terms that involve one or the other of the two (radial field or conductivity) asymmetries but not both. Higher-order multipoles are introduced into the current distribution by the product of these two factors. Higher-order multipoles are also introduced directly into the charge distribution if the γ emission asymmetry is not purely dipolar, of course. Such higher-order terms are insignificant if the source is small but cannot be ignored when it is not.

The strength of the radiated signal calculated by *Kompaneets* [1958] and by *Gilinsky* [1965] is proportional to that of the asymmetry in the γ emission but only weakly dependent on yield. This behavior can be understood qualitatively in terms of the model of radiation from currents on a spherical surface. The current structure and its intensity depend strongly upon the form and strength of the γ emission asymmetry but not upon the yield, which serves basically to fix only the radius of the sphere. The strength of the signal would be expected to depend somewhat upon the yield even if the current intensity is strictly yield independent because the ratio of the radiated field intensity to that of surface currents on a sphere increases with increasing radius [*Morse and Feshbach*, 1953].

Charge deposition on device case. Nonuniformity of the prompt γ emission can also produce a signal from a high-altitude detonation occurring effectively in a vacuum. In this case, the γ radiation produces a distribution of electric dipoles over the outer surface of the device material by the escape from this material of Compton electrons produced near the surface [*Karzas and Latter*, 1962*a*]. Any nonuniformity in this distribution results in a net electric dipole moment that radiates. This mechanism has obvious similarities with that just discussed. The principal differences here between the two are that the source size is determined by the size of the device case and that the secondary electron (conduction) currents in the ambient medium, in which the radiating Compton currents flow, are not likely to be important. The signal from this mechanism is small in comparison with that produced by the γ ray interaction with the atmosphere below the detonation, and its amplitude will be further reduced when it is observed near the earth's surface by absorption in the ionization produced by this and by the X ray interaction with the atmosphere.

Inhomogeneity of Environment

The second means to be considered here whereby radiation can be emitted by Compton currents is an asymmetry in the distribution of material about the detonation. Examples of such asymmetries are the density gradient in the earth's atmosphere, the earth-atmosphere interface, and nonuniformity of the device case. These examples will be examined briefly. A thorough study of the second of these is not available; some useful deductions can be made about the nature of the signal in this case from fairly simple considerations, however.

Atmospheric density gradient. In an atmospheric nuclear detonation the motion of each Compton electron away from its parent atmospheric molecule creates an elementary electric dipole. If the γ photon mean free path at the detonation altitude is appreciably less than the atmospheric scale height, the number of these dipoles produced above the detonation essentially equals that of those produced below it. However, the Compton electron range is somewhat greater above the detonation than below it because of the atmospheric density gradient. Consequently, those elementary electric dipoles created above the detonation have a greater moment, on the average, than those created below the detonation, and a net vertical electric dipole moment results. The temporal variation of this moment is determined initially by the asymmetry in the Compton electron current, but it soon becomes strongly influenced by the asymmetry in the air conductivity. The latter asymmetry results primarily from the difference in the secondary electron attachment rate above and below the detonation. Nonuniformity of the atmospheric water vapor content, upon which the secondary electron mobility depends, can also produce additional asymmetry in the air conductivity. The vertically polarized signal radiated by this varying electric dipole is often denoted the 'air asymmetry' signal.

For low-altitude detonations the signal generation process that results from the atmospheric density gradient is in many respects similar to the one that results from the nonuniform emission of γ radiation by a detonation. If the detonation yield is sufficiently small, only the dipole component of the charge and current asymmetries produced by the density gradient is significant, and the problem becomes essentially identical to that of a weak dipole asymmetry in the γ radiation. The latter problem has been examined by *Kompaneets* [1958] and by *Gilinsky* [1965], as discussed above; more recently, *Gilinsky and Peebles* [1968] have considered the air asymmetry signal directly in this approximation.

If the detonation altitude is increased, the γ photons travel a greater vertical distance, on the average, than they would for a lower-altitude detonation. Consequently, the average difference between the atmospheric density at the point of interaction of an upward-going photon with an air molecule and the density at the point of interaction of a downward-going photon also increases. The difference between the average range of the Compton electrons produced above the detonation and that of the Compton electrons produced below the detonation is proportional to this density difference. Thus the net dipole moment and the signal that it radiates increase with increasing detonation altitude for a detonation in the lower atmosphere [*Latter et al.*, 1961]. A larger yield increases the radiated signal in a similar manner [*Mark*, 1959; *Latter et al.*, 1961]. The yield dependence is weak, however, because the extent of the region in which the γ flux is appreciable increases as the logarithm of the yield.

The strength of the radiated signal grows uniformly with increasing detonation altitude until the γ photon mean free path at the detonation height becomes an appreciable fraction of the atmospheric scale height. Significant numbers of the γ photons emitted upward escape the atmosphere without interaction with it for detonations at greater heights. Thus the growth with increasing altitude of the dipole moment created by each interacting γ photon is increasingly compensated above the detonation by the reduction of the number that interacts. This compensation does not occur below the detonation, and the dipole moment created there continues to grow as the altitude increases until the altitude approaches that at which the γ photon mean free path equals the atmospheric scale height, about 25 km.

As the detonation altitude continues to increase, the major region of interaction of the γ photons with the atmosphere becomes that region below the detonation in which the mean free path of a downward-going photon becomes equal to the atmospheric scale height [*Mark*, 1959]. The charge created above the detonation by upward-going photons continues to decrease in importance relative to this charge deposition below the detonation. For high-altitude detonations, only the interaction of the γ photons with the atmosphere around 30-km altitude is significant for signal generation by this mechanism, and the signal is reversed in polarity from that radiated through the same mechanism by a detonation in the lower atmosphere.

As was noted above (see section on deposition in a homogeneous atmosphere) in the discussion of the signal produced by an asymmetry in the prompt γ emission from a detonation, the expansion of the current system about the detonation at essentially the speed of light produces significant components in the spectrum of the radiated signal up to frequencies that are characteristic of the time scale of the prompt γ emission, of the order of 100 MHz for a nominal γ flux rise rate of $10^8\ s^{-1}$ [*Karzas and Latter*, 1962*a*, *b*]. The early portion of the radiated wave form shows structure on this time scale; this structure is sensitive to the details of the γ flux time history, as demonstrated by *Gilinsky and Peebles* [1968]. After this initial phase the rate of signal variation is determined primarily by the size of the current system, and the frequency of the spectral peak can be estimated from the oscillating sphere model [*Sollfrey*, 1965], discussed above, for detonations in the lower atmosphere.

Since the radius of the highly ionized region about the detonation increases with increasing detonation altitude, the predominant spectral components in the radiated signal decrease in frequency with increasing altitude. For detonations at intermediate and high altitudes the size of the region beneath the detonation over which a dipole moment is created indicates that the peak radiation from this mechanism will occur at frequencies substantially below the tens of kHz dominant frequencies of signals from low-altitude detonations.

Earth-atmosphere interface. The second example of the effect upon the Compton current distribution of an asymmetry in the distribution of material about the detonation is that of the earth-atmosphere interface (the 'ground' asymmetry). This interface eliminates a portion of the charge distribution created below the detonation. Thus the net dipole moment of the charge distribution rapidly increases as the detonation altitude decreases for detonations less than a few γ mean free paths above the surface, and the strength of the radiated signal increases correspondingly [*Mark*, 1959; *Lippmann*, 1960; *Latter et al.*, 1961]. The radiated field is estimated [*Latter et al.*, 1961] to have a strength of the order of 10^4 V/m at 1 km for a surface detonation. The spectral characteristics of the signal and its temporal separation into a rapidly varying early component that is sensitive to the γ flux time history and a component whose rate of variation is determined by the size of the source region are not grossly altered in going from a detonation in the atmosphere to one on the earth's surface.

Nonuniform device material. The case signal, the final example of a material asymmetry to be considered here, was originally examined as a possible source of a useful high-frequency electromagnetic signal for the ground-based detection of nuclear detonations in space [*Karzas and Latter*, 1962*a*]. A related mechanism has already been discussed briefly in connection with asymmetries in the γ ray emission. Although these mechanisms have since been superseded as the principal source of the high-frequency signal produced near the earth's surface by such detonations [*Karzas and Latter*, 1965], they remain possible mechanisms for the production of a signal outside the earth's atmosphere. Thus their discussion seems warranted.

Electrons produced within the case material by Compton scattering of the γ radiation from the detonation penetrate the outer surface of the case if their range is greater than their distance from this surface. The outward motion of these electrons from the surface creates an electric dipole layer upon it; nonuniformity in this layer produces a net dipole moment and consequently, radiation. Such a nonuniformity will result whenever the γ flux near the outer surface of the material is not uniform, as happens, for example, if the case thickness varies or as is more likely, the γ flux is asymmetric.

Radiation occurs primarily during the initial establishment of the surface dipole distribution, early in the rise of the γ flux. This distribution changes relatively slowly subsequent to its production as long as the γ flux continues, even though this flux may vary appreciably. The signal strength is independent of the detonation yield and the material thickness under these conditions as long as these do not combine to make the attainment of the quasi steady state dipole distribution marginal. Secondary electron conductivity is not important at altitudes for which this signal may be significant.

For an exponentially rising γ flux and a hemispherical case at a distance a from the detonation center the signal amplitude is proportional to $(\alpha a)^2 E$. The rate of rise of the γ flux is α, and the Compton electron energy is E. The rise rate of the γ flux determines how many Compton electrons are emitted per unit area of the surface before a quasi steady state is attained between those leaving the surface and those returning to it. Thus the number of electrons leaving the surface in this period is proportional to the surface area. These two factors and the distance traveled from the surface by the Compton electrons fix the total dipole moment created over this surface. This distance depends in turn directly upon the initial energy of the electrons as they leave the surface. *Karzas and Latter* [1962*a*] estimated a radiated field of 10^3 V/m at 1 km for representative values of the parameters.

The upper limit of significant frequencies in the signal is determined by the time taken to establish the surface dipole distribution, which is roughly the reciprocal of the rise rate of the γ flux or of the order of 10^{-8} s [*Karzas and Latter*, 1962*a*, *b*], and by the dimensions of the case. The latter factor dominates when the difference in propagation time from different portions of the surface is greater than the γ flux rise rate at early times.

Anisotropy of Environment

The interaction of Compton electrons with an ambient magnetic field, such as the earth's geomagnetic field, is the third major mechanism whereby the Compton current can be made asymmetric. This mechanism has been studied in detail both for atmospheric [*Karzas and Latter*, 1962*b*] and for high-altitude [*Karzas and Latter*, 1965] detonations. The general process is the same for both these cases: the Compton electrons are deflected from their initial radial motion away from the detonation by their interaction with the ambient magnetic field. Thus the signal is commonly denoted the 'geomagnetic' or the 'turning' signal.

The electron deflection constitutes a transverse current whose size and direction depend upon the direction and speed of the Compton electron motion relative to the direction of the magnetic field. This current differs basically from the radial current in that it does not produce charge separation to first order. For high-altitude detonations the Compton electrons of principal interest for signals at the earth's surface are those produced near 30-km altitude in the atmosphere, where the γ photon mean free path is similar to the atmospheric scale height. For atmospheric detonations below this altitude regime the radiated signal is produced a few γ mean free paths from the detonation point.

The variation with altitude of the region in which the γ photons interact with the atmospheric molecules has been discussed above in conjunction with the generation of a signal by the atmospheric density gradient. There, the variation is intimately related to the production of the current asymmetry necessary for the radiation of a signal. Although this variation also influences the dependence of the signal characteristics upon burst height and yield in the interaction of the Compton electrons with the geomagnetic field, the atmospheric density gradient that is responsible for the variation is not essential to the production of a signal by the latter mechanism. Thus when only the geomagnetic component of the signal is discussed, the density gradient is properly ignored for low-altitude detonations in which the γ mean free path is substantially less than the atmospheric scale height.

The transverse Compton current exists predominantly in a shell that moves outward from the detonation at light speed with the prompt γ pulse. Thus the transverse electric field produced by this current is augmented coherently at different radial distances from the detonation, and a short pulse of radiation results. If the γ flux is sufficiently intense, the buildup of the secondary electron conductivity limits this growth of the transverse field by attenuation of the contribution to the signal from currents deep within the source region. In this case, the amplitude of the radiated signal depends in a complex manner upon the detonation yield and altitude through the variation with changes in these parameters of the boundary of the source region and consequently, of the value of the saturation field at it. For a 1-kt explosion this saturation condition prevails for detonation altitudes of a few hundred kilometers or less [*Karzas and Latter*, 1965]; an increase in yield extends the detonation height below which saturation occurs.

For atmospheric detonations the peak value attained by the transverse field in the region in which the signal is generated was found by *Karzas and Latter* [1962*b*] to be proportional to $(\alpha + \beta)BR^2/\mu$, where α is the rise rate of the γ flux, β is the electron loss rate, R is the Compton electron range, B is the static magnetic field strength, and μ is the secondary electron mobility. The square of the Compton electron range enters into this relationship because this range affects linearly both the secondary electron density and the transverse distance traveled by the Compton electron. At altitudes of a scale height or more above the earth's surface the electron loss rate is generally small in relation to the rate of rise of the γ flux and can therefore be ignored. A peak field at the outer boundary of the source region of the order of 10^3 V/m was calculated by Karzas and Latter for a detonation at sea level where the rise rate of the γ flux and the electron attachment rate are similar.

In the 30-km altitude range in which the Compton currents occur for high-altitude detonations the Compton electrons travel through a significant fraction of a Larmor radius before stopping. Thus the transverse motion of these electrons is limited in a complex fashion by a combination of their gyroradius and their range. The appreciable turning of these electrons also causes them to fall significantly behind the γ flux pulse, the coherence of the Compton current consequently being reduced. These factors make difficult a simple representation of the dependence of the peak field upon the various parameters for high-altitude detonations. Some simplification is obtained if the prompt γ pulse is represented by a δ function. This idealization is made possible by the reduced dependence of the peak field upon the rise rate of the γ flux, a result of the spread of the Compton current shell behind the γ pulse. *Karzas and Latter* [1965] estimated the saturated transverse field to be of the order of 6×10^4 V/m for typical parameter values and a δ function γ pulse. For detonation altitudes sufficiently great that saturation does not occur the peak signal amplitude is proportional to the prompt γ flux intensity in the signal generation region. The signal has a peak value of about 20 V/m for a 1-kt detonation at 1000-km altitude with 10^{-3} of the total yield in prompt γ radiation [*Karzas and Latter*, 1965]. Since the signal amplitude is proportional to the γ flux intensity in the signal generation region, which is at a relatively constant altitude near 30 km in this case, the amplitude decreases inversely as the square of the distance of the detonation from this region.

The time required for the signal to rise to its saturated value is determined by the lag of the conductivity buildup behind that of the Compton current for low-altitude detonations. This lag is fixed in turn by the rise rate of the γ flux, which is of the order of 10^{-8} s [*Karzas and Latter*, 1962*a*, *b*]. Consequently, the signal spectrum extends to the order of 100 MHz. Since the transverse component of the Compton current produces no charge separation to first order, the duration of the signal is similar to that of this Compton current and therefore to that of the prompt γ pulse. This duration is of the order of 10^{-7} s [*Mark*, 1959]. Thus the signal spectrum has nearly constant amplitude at frequencies below the order of 5 MHz. Both the rise time and the duration of the signal are increased by the lag of the Compton currents behind the prompt γ pulse for high-altitude detonations. Consequently, the high-frequency limit of the spectrum of the signals from these detonations is reduced in relation to that from detonations in the lower atmosphere.

This signal is sometimes denoted the magnetic dipole signal. The name is suggestive; the Compton current flow responsible for the signal initially forms a cylinder about the geomagnetic field. Thus it is similar in form to a magnetic dipole current system. The lack of charge separation, and the consequent cessation of the radiated signal with that of the current, is a general characteristic of current distributions that produce magnetic multipole radiation. The radiation pattern and polarization of the signal is also consistent with a magnetic dipole source for a low-altitude detonation.

For high-altitude detonations, however, the signal contains two principal components. One of these has the dipole radiation pattern discussed above. The second has an electric quadripole radiation pattern. The component of the transverse Compton current that produces this signal results from the shift in the direction of the Lorentz force as the Compton electron acquires appreciable transverse velocity. This signal component is not significant in relation to the dipole component for low-altitude detonations because the Compton electron range is only a small fraction of a Larmor orbit. The signal polarization is that of radiation from an electric-type source, in which the charge moves from the equator of a spherical surface to both poles simultaneously and then back. However, the charge separation produced by this flow is not significant to first order in the radiation of the high-frequency signal; consequently, the duration of this signal is basically that of the Compton current.

PHOTOELECTRON MODEL

General

The photoelectrons created by the interaction of the primary X radiation with the material surrounding the detonation can produce an electromagnetic pulse through mechanisms similar to those discussed in the previous section for Compton electrons. For atmospheric detonations the greater mean free path and more rapid emission of the prompt γ radiation relative to the X radiation causes preionization of a substantial region surrounding that in which the photoelectron currents flow. The conductivity of this larger region is normally sufficient to absorb any signal produced by these currents [*Karzas and Latter*, 1965]. Moreover, the conversion of X ray energy into lower-frequency electromagnetic radiation is much less efficient than that of γ ray energy; the much greater fraction of the total detonation energy carried by the X rays is thereby partially compensated for.

For high-altitude detonations the regions in which the two types of radiation (prompt γ and primary X) interact with the atmosphere are separated. Maximum prompt γ interaction with the atmosphere occurs at an altitude of the order of 30 km, whereas the maximum primary X ray interaction occurs in the 80- to 100-km altitude range [*Latter and LeLevier*, 1963]. The signal generated by the photoelectrons does not necessarily pass through the ionization produced by the γ ray interaction in this case. As the detonation altitude increases, the ionization produced in the interaction regions decreases, and the conductivity of the γ ray region is insufficient to absorb the X ray signal for detonations above a few hundred kilometers.

Nonuniform Emission of X Ray Photons

The nonuniform emission of X ray photons by a detonation and their subsequent interaction with the earth's atmosphere would not normally be expected to contribute significantly to the electromagnetic pulse. As was noted above, the photoelectron currents are shielded by the ionization produced by the γ radiation for detonations in the lower atmosphere. This shielding region will be produced only beneath the detonation, however, for detonation altitudes appreciably above 30 km. Thus it is conceivable that the electromagnetic pulse could result partly from this mechanism under some circumstances. The models discussed above that have been developed to describe the γ ray interaction with the atmosphere presumably could be adapted to describe the X ray interaction as well, but this development will not be pursued here. For high-altitude detonations the asymmetry caused by the atmospheric density gradient seems likely to dominate any nonuniformity in the X ray emission.

Johnson and Lippmann [1960] have examined a related mechanism for high-altitude detonations that is of some interest, even though it has since been superseded as a potentially important signal source by other mechanisms. They consider the transfer of momentum from the X ray pulse to the ambient electrons about a high-altitude detonation that results from Thomson scattering of the X ray photons by these electrons. If the X ray emission is asymmetric, the radial current produced by the motion of electrons has a net electric dipole moment, and a signal is radiated. The signal amplitude is proportional to $\sigma n Y$, where σ is the Thomson cross section, n is the ambient electron density, and Y is the X ray fraction of the detonation yield. Johnson and Lippmann estimated a signal strength of about 0.6 mV/m at 1 km from a 1-mt detonation in an ambient medium with an electron density of $10^3/\text{cm}^3$. Although the title 'photoelectron model' is something of a misnomer for this mechanism, it shares the basic characteristic that it obtains its driving energy from the primary X radiation.

Inhomogeneity of Environment

The deposition in a nonuniform atmosphere of X radiation from a detonation also appears not to have been examined as a potential mechanism for production of an electromagnetic pulse. As was already noted, for low-altitude detonations the photoelectron currents produced by the X radiation will be shielded by the conductivity of the more extensive region of γ ray interaction with the air. For detonation altitudes above about 30 km, however, this shielding exists only below the detonation, and as noted for nonuniform X ray emission, it is conceivable that the radiated pulse could result partly from the X ray interaction with the atmosphere in some circumstances.

Anisotropy of Environment

The signal generated through the turning of the photoelectrons by the earth's magnetic field has been examined by *Karzas and Latter* [1965]. The theory of this mechanism is essentially the same for both the X ray photoelectrons and the γ ray Compton electrons. For detonations sufficiently distant (a few times 10^4 km for a 1-kt yield and greater for larger yields) the conductivity produced by the photoelectrons is insufficient to limit the field in the signal generation process. In this case, the peak signal amplitude is proportional to the yield (for a constant fraction of the total yield in the primary X radiation) and inversely proportional to the square of the detonation distance from the signal generation region, at 80- to 100-km altitude. The peak signal amplitude is about 0.6 V/m for a 1-kt detonation at 10^5 km (if the X ray yield is assumed to be half the total yield). The X ray mechanism produces a larger signal than that of the comparable γ ray mechanisms for such distant detonations, primarily as a result of the larger fraction of the detonation energy that the X rays carry.

At lower detonation altitudes the field generated by the X ray mechanism is limited by the conductivity that is also produced. For detonations sufficiently low that both the X ray and the γ ray mechanism are conductivity limited (below a few times 10^2 km for a 1-kt detonation with the prompt γ yield 10^{-3} of the total yield and greater for larger yields), the signal produced by the prompt γ radiation is substantially larger than that produced by the primary X radiation. Although it is difficult to isolate all the differences in the detail of the γ ray and the X ray interactions that cause the dominant signal to differ in this case from that when the conductivity is insignificant, two major factors are that field saturation removes the yield dependence of the signal amplitude and that the conductivity is greater for a given secondary electron density at the higher altitude at which the X ray interaction occurs.

FIELD DISPLACEMENT MODEL

If a nuclear detonation occurs in an ambient static magnetic field, such as that of the earth, the subsequent expansion of the intensely ionized plasma created about the detonation point will be accompanied by radiation of an electromagnetic signal. The nature of this signal can be roughly determined by calculation of the magnetic dipole moment required to cancel the ambient field in the volume finally occupied by the plasma. Given the energy available in the plasma to expand it against the restraining force of the ambient field, the volume occupied by the plasma can be estimated by equating the interaction energy of the ambient field with a magnetized sphere of this volume to the energy available for expansion of the plasma. The dipole moment is proportional to this volume and therefore to the energy. The rise time of the signal can also be estimated, once the expansion volume has been determined, if the mass of the expanding plasma is known, since this mass and the energy in the plasma determine the speed of expansion. Reasonable estimates of the plasma mass and available energy give a rise time of the order of 0.5 s, in order of magnitude agreement with those of observed signals from the Argus detonations [*Leipunskii*, 1960].

Several shortcomings of this estimate become evident when more detailed calculations are performed [*Lutomirski*, 1967]. The energy expended in the plasma expansion is not all contained in an alteration of the static magnetic field, as is assumed if the interaction energy is equated to the work done in the expansion. The signal amplitude is also taken to be equal to the static field of the equivalent magnetic dipole. Although this assumption is consistent with that used to determine the plasma volume, the field observed is often the radiation field.

A similar radiation process occurs for an atmospheric detonation. The energy available for the plasma expansion is determined by rather different factors in the two cases, however. For a high-altitude detonation the primary X radiation represents a portion of the detonation energy that is not available for expansion of the plasma. For an atmospheric detonation the primary X radiation is absorbed about the detonation and enlarges the fireball by ionization of the surrounding air. Thus this energy is not lost to the plasma expansion. However, the fireball expansion in the atmosphere does work primarily against the ambient air rather than against the magnetic field. Consequently, only a small fraction of the energy expended in the fireball growth represents coherent electromagnetic radiation.

Karzas and Latter [1962*b*] have estimated the amplitude of the static field established by the fireball expansion for an atmospheric detonation. This field is more likely to represent the signal from such a detonation than that from one at high altitudes, since the plasma expansion speed for the former is very small in relation to the speed of signal propagation, which is that of light, whereas that for the latter can be comparable to the Alfvén speed with which its signal propagates away from the source. The magnitude of the peak field is of the order of that of the earth's field at the outer limit of the fireball and decreases as the inverse cube of the distance beyond this point, as is appropriate for a quasi-static field. The signal duration is determined by the relaxation of the fireball ionization, which is of the order of 1 s for a 1-kt detonation at sea level and increases with increasing yield (as the ⅓ power) and with increasing burst height. These times are sufficiently long that other factors can be expected to be significant in determining the signal duration.

SUMMARY OF THE THEORETICAL RESULTS

The basic characteristics of the signals produced by the different mechanisms discussed above are summarized in Table 2 for detonations at various altitudes. It is evident from Table 2 and from the relative attention given above to the various mechanisms that the prompt γ radiation from a nuclear detonation is thought to be responsible for most of the coherently radiated electromagnetic energy. This circumstance is somewhat remarkable, given the small fraction of the yield energy that appears as prompt γ radiation.

Before the experimental data are considered, the caution given previously should be recalled: the radiated signal can be expected to display the contributions from several mechanisms working in concert rather than that from a single dominant one. This circumstance makes the organization of these data according to generation mechanism impractical. Rather, the frequency ranges covered by the different measurements provide a more useful classification.

EXPERIMENTAL RESULTS AND THEIR INTERPRETATION

A number of experimental observations of the electromagnetic signals produced by nuclear detonations have been reported. These data suffice to show that the mechanisms that have been advanced to describe the generation of these signals are probably correct, but the data are not well suited for a detailed evaluation of the theoretical results. We shall therefore only briefly review the experimental data.

A substantial literature exists of observations of micropulsation signals with periods of a few seconds produced by high-altitude detonations [*Selzer*, 1959; *Berthold et al.*, 1960; *Troitskaya*, 1960; *Bomke et al.*, 1964; *Maeda et al.*, 1964]. These signals are thought to be generated through the field displacement mechanism. That such observations have not encouraged a greater amount of work on this source

TABLE 2. Signal Characteristics for Different Source Mechanisms

	Near-Surface Detonation[a]			Atmospheric Detonation[a]			High-Altitude Detonation		
		Spectrum[c]			Spectrum[c]			Spectrum[c]	
Mechanism	Peak Amplitude[b]	Peak	Upper Limit	Peak Amplitude[b]	Peak	Upper Limit	Peak Amplitude	Peak	Upper Limit
Compton electron									
Nonuniform emission	∝ asymmetry[d]	VLF/LF[e]	VHF[f]	∝ asymmetry[d]	VLF/LF[e,g]	VHF[f]	$<10^3$ V/m[b]	HF[h]	VHF[f]
Environmental inhomogeneity	10^4 V/m[d,g]	VLF/LF[e]	VHF[f]	?[i,j]	VLF/LF[e,g]	VHF[f]	?	ELF[g]	VHF[f]
Environmental anisotropy	10^3 V/m[d]	HF[k]	VHF[f]	10^3 V/m[d,i]	HF[k]	VHF[f]	6×10^4 V/m[l] 20 V/m[m]	MF	HF
Photoelectron									
Nonuniform emission	...	...	...	?[n]	VLF/LF[g]	?[o]	1 mV/m	?	HF[p]
Environmental inhomogeneity	...	...	...	?[n]	VLF/LF[g]	?[o]	?	ELF[g]	?[o]
Environmental anisotropy	...	...	...	?[n]	HF[p]	?[o]	10 V/m[l] 0.6 V/m[m]	MF	HF
Field displacement	5×10^{-6} Wb/m²[q]	Sub ELF	Sub ELF	5×10^{-6} Wb/m²[q]	Sub ELF	Sub ELF	?	Sub ELF	Sub ELF

(*a*) A few to ~30-km altitude for Compton electron mechanisms and to ~80-km altitude for photoelectron mechanisms. (*b*) Scaled to nominal distance of 1 km from detonation point. (*c*) Frequency ranges are: ELF, 10 Hz–3 kHz; VLF, 3–30 kHz; LF, 30–300 kHz; MF, 0.3–3 MHz; HF, 3–30 MHz; VHF, 30–300 MHz. (*d*) Increases slowly with increasing yield. (*e*) Decreases with increasing yield. (*f*) Determined by rate of γ flux rise. (*g*) Decreases with increasing detonation altitude. (*h*) Determined by size of device case. (*i*) Increases with increasing detonation altitude. (*j*) Less than near-surface detonation for low altitudes. (*k*) Determined by duration of prompt γ pulse. (*l*) For a 1-kt detonation below a few times 10^2-km altitude for Compton electrons and below a few times 10^4 km for photoelectrons; altitude limit increases with increasing yield. (*m*) For a 1-kt detonation at 10^3-km altitude for Compton electrons and at 10^5 km for photoelectrons; amplitude proportional to yield and inversely proportional to square of detonation distance from signal generation region. (*n*) Conceivably significant for detonations in the 30- to 80-km altitude range. (*o*) Determined by rate of X ray flux increase. (*p*) Determined by X ray pulse duration. (*q*) Quasi-static field; decreases inversely as cube of distance from detonation point.

mechanism appears due principally to the predominant effect that propagation is thought to have upon the observed signal characteristics [*Berthold et al.*, 1960; *Bomke et al.*, 1960, 1964; *Kahalas*, 1965; *Kovach and Ben-Menahem*, 1966; *Field and Greifinger*, 1967].

There are some basic inferences concerning the source mechanism for these signals that can be drawn from the data, however. A notable feature is the common delay relative to the detonation times of the signals observed at widely different distances from the detonation [*Roquet et al.*, 1962; *Bomke et al.*, 1964]. This delay is consistent with initial propagation of the signal as a modified Alfvén wave downward through the ionosphere from a generation region near the detonation point, a picture that fits naturally the field displacement model of signal generation. The apparently simultaneous onset of the signal at different locations on the earth's surface results from its much faster (light speed) dispersal beneath the ionosphere once it has traversed this region.

Micropulsation records with sufficient time resolution and sensitivity also show a nearly instantaneous response at the detonation time [*Abercrombie*, 1963; *Casaverde et al.*, 1963; *Roquet et al.*, 1963; *Bomke et al.*, 1964]. If the response of the receiving system extends up to 10 Hz without too much attenuation, this signal component appears as an oscillation in the 7- to 8-Hz range, which corresponds to the lowest Schumann resonance frequency. The fast onset of this signal component indicates that it is generated beneath the ionosphere, in common with the VLF and higher-frequency radiation from these detonations. Thus it is natural to associate this signal component with the Compton electron model, as has been suggested by *Bomke et al.* [1964].

Finally, *Zablocki* [1966] has reported measurements in the micropulsation to lower ELF range at a relatively short distance (15.7 km) from two low-altitude detonations of the 1958 Hardtack test series in Nevada. The polarization of the signals observed in these measurements implies a nearly vertical electric dipole source, as would be expected from the Compton electron model of signal generation as a result of the earth-atmosphere interface or of the atmospheric density gradient, rather than the magnetic dipole source that would result from the field displacement model.

Systematic relatively wide band observations in the VLF (nominally, 3- to 30-kHz) range have been made for some time in the course of whistler studies [*Helliwell*, 1965]. Whistlers are for the most part lightning sferics that have been highly dispersed by propagation through the magnetosphere from one hemisphere to the other guided by the earth's magnetic field. They can also be produced by nuclear detonations, however, as was first noted by *Lippmann* [1960]. Such whistlers have been observed from nuclear detonations of various yields at both low and high altitudes [*Mck. Allcock et al.*, 1963; *Helliwell and Carpenter*, 1963; *Dinger and Garner*, 1963]. The relatively undispersed signals propagated to the observation point by multiple reflection between the ionosphere and the earth's surface were also recorded in these observations, all of which were made at distances of several hundred kilometers or more from the detonation points. These data do not provide examples of wave forms or quantitative information on their amplitude spectra (these would differ from those near the sources in any event as a result of propagation attenuation), but the data certainly verify the generation of substantial signals in this frequency range by nuclear detonations.

It is also significant that the dispersion characteristics of whistlers produced by high-altitude detonations are typical of signals initially generated beneath the ionosphere and that relatively little dispersed subionospherically propagated signals are also observed from these detonations [*Helliwell and Carpenter*, 1963]. These characteristics are consistent with generation of the signal according to the Compton electron (or the photoelectron) model, which involves the interaction of γ (or X ray) photons with the atmosphere below the altitude at which appreciable dispersion of the signal could be produced by the ionosphere.

In addition to these data the subionospherically propagated VLF wave forms recorded at large distances from the July 9, 1962 (Starfish) [*Crook et al.*, 1963], and the August 1, 1958 (Teak) [*Croom*, 1965], high-altitude detonations, from a number of surface and near-surface detonations of the 1958 Hardtack series in the Pacific and Nevada [*Tepley*, 1966], and from the February 13, 1960, French detonation at Reggane [*Delloue*, 1960] have been reported. The amplitude spectra of the Teak and Orange (another high-altitude detonation on August 12, 1958) signals have also been sampled in the ELF (nominally, 10-Hz to 3.0-kHz) range at 80 and 320 Hz [*Croom*, 1965]. Finally, wide band (10- to 1000-Hz) ELF wave forms were also recorded at large distances from the surface and near-surface Hardtack detonations [*Tepley*, 1966]. The characteristics of these various detonations are summarized by Glasstone [*U.S. Department of Defense*, 1962, pp. 671–681].

Latter et al. [1961] give a maximum amplitude of $10^3/R$ V/m for signals observed in the 10- to 100-kHz frequency range at distances R greater than 1000 km from kiloton yield detonations at the earth's surface. They also note that an amplitude minimum is observed for detonations at a few kilometers altitude, for which the net dipole moment produced by the earth-atmosphere interface and the atmospheric density gradient should be minimum. An example of the VLF wave form observed at a great distance (8000 km) from a surface detonation is shown in Figure 1 [from *Tepley*, 1966]. The maximum center-to-peak amplitude of this wave form, about 60 mV/m, is within a factor of 2 of $10^3/R$. The peak amplitude of the VLF wave form recorded by *Delloue* [1960] at 2500 km, on the other hand, is about an order of magnitude smaller than that suggested by this expression. There is evidence of saturation or limiting in Delloue's recording, however.

We also note that the R^{-1} distance scaling given by *Latter et al.* [1961] is a much simplified representation of the effects of long-distance propagation upon a VLF signal. The detailed calculations made by *Johler* [1967] for a representative signal suggest a somewhat more rapid decay of the broad band peak

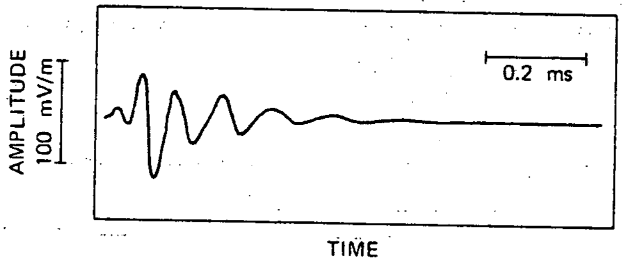

Fig. 1. The VLF wave form recorded at Los Angeles from a surface nuclear detonation at about 8000-km distance (Event Holly of Hardtack Phase I, detonated at 1830 UT, May 20, 1958, at Eniwetok) [after *Tepley*, 1966].

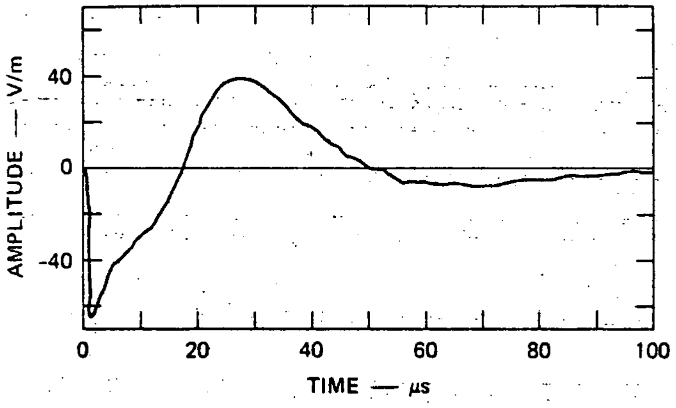

Fig. 2. Broad band wave form recorded at 44.6 km from a nuclear detonation [after *Johler and Morgenstern,* 1965].

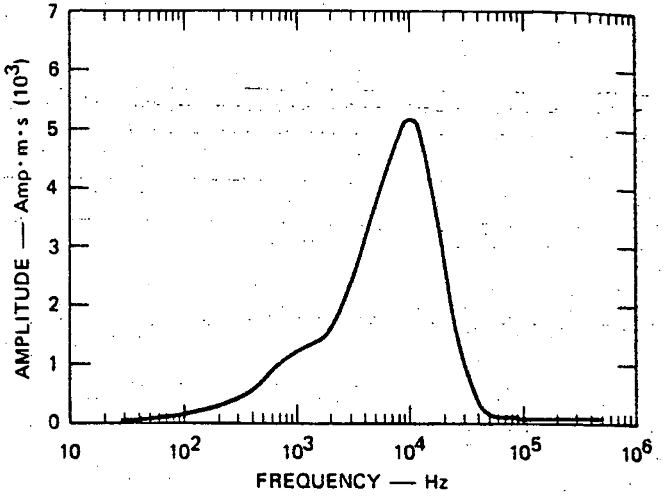

Fig. 3. Amplitude spectrum of source current moment for a broad band wave form recorded at 44.6 km from a nuclear detonation [after *Johler and Morgenstern,* 1965].

signal amplitude with increasing distance than this expression. The wave form used by Johler, which was measured by a broad band receiver at 44.6 km from a detonation [*Johler and Morgenstern,* 1965], and the amplitude spectrum of the current moment of its source, represented as an infinitesimal electric dipole, are illustrated in Figures 2 and 3, respectively. The calculated peak amplitude after propagation of this wave form to various distances is equal to $10^3/R$ at a distance of about 2500 km, there being a larger amplitude than this at shorter distances and a smaller amplitude at longer distances.

The observed peak amplitude at 44.6 km of the wave form used by Johler is about a factor of 3 smaller than the $10^4/R$ V/m maximum value for the signal at relatively short distances from a surface detonation determined by *Latter et al.* [1961] on the basis of the Compton electron model. The frequency at which the source spectrum peaks, about 12 kHz (Figure 3), is also consistent with that expected theoretically from this model of the signal-generation process. The large VLF/ELF broad band signal-amplitude ratios obtained by *Tepley* [1966] also indicate a decrease in spectral amplitude of the signal with decreasing frequency in the lower VLF and the ELF range.

The VLF wave forms and the 80- and 320-Hz narrow band measurements recorded for the high-altitude detonations provide little basis for comparison with the mechanisms that have been discussed for such detonations. The data, which were all recorded at large distances, can be expected to be affected greatly by propagation, and the available theoretical results do not include quantitative estimates in this frequency range. Even with these limitations, however, the data are of some interest.

Both the Teak wave form recorded at about 13,000 km by *Croom* [1965] and the Starfish wave form recorded at about 5400 km by *Crook et al.* [1963] show irregular oscillations with quasi periods in the VLF range; the former also has considerable energy content below 1 kHz. Presumably, the VLF oscillations of these wave forms reflect primarily propagation and receiving system characteristics rather than any intrinsic peak in the signal spectrum. Neither the air asymmetry nor the turning signal of the Compton electron model would be expected to have spectral peaks in the VLF range for these detonations. The large ratios relative to the average value of 7 observed for sferics from distant lightning of the signal amplitude at 320 Hz to that at 80 Hz recorded by *Croom* [1965] for Teak and for Orange perhaps suggest an appreciable difference in the spectra of these two types of sources at ELF, but it is not clear that the source distances for the lightning and the nuclear observations were sufficiently similar to permit direct comparison. *Crook et al.* [1963] estimate a peak amplitude of about 9 V/m from the strongly limited VLF wave form recorded by them for Starfish. This amplitude is substantially larger than the one that would be expected in this frequency range for a near-surface or an atmospheric detonation. No absolute amplitudes are available for Croom's data.

Data that illustrate the higher-frequency components of the electromagnetic pulse are extremely rare. *Theobald* [1963] has given an example, reproduced in Figure 4, of what is thought on the basis of its radiation pattern to be the Compton electron turning signal, observed at an unspecified distance from a low-altitude (tropospheric) detonation during the 1962 Pacific test series. *Cotterman* [1965] provides a second example of this type of signal for an unspecified detonation. These data confirm the HF (nominally, 3- to 30-MHz) content of the signal generated by this mechanism, but they provide no basis for evaluation of the calculated signal amplitudes.

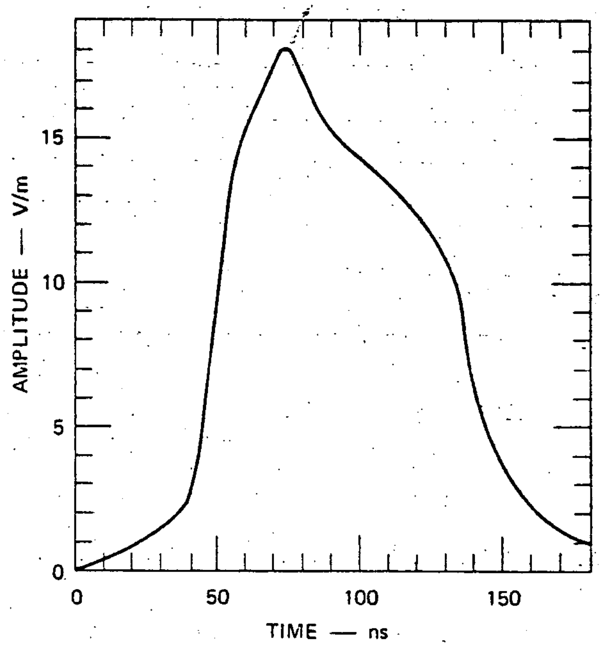

Fig. 4. The turning signal from a low-altitude nuclear detonation [after *Theobald,* 1963].

Further evidence of the HF content of the electromagnetic pulse is provided by its observation in Japan [*Nishikori et al.*, 1963] and in New Zealand [*Andrew*, 1962; *Hanley*, 1962] as a sudden flash of noise or an atmospheric click superimposed upon radio transmissions being monitored at the time of the Starfish high-altitude detonation. These observations, which were made at frequencies between 760 kHz in the MF (nominally, 0.3- to 3.0-MHz) range and 20 MHz in the HF range, strongly suggest generation of the signal beneath the ionosphere. The lower frequencies normally do not penetrate the ionosphere, and the higher also are reflected when they are incident upon the ionosphere at the highly oblique angles characteristic of observations at these large distances around the earth's surface from the source.

It may seem surprising that there is not a larger body of observational literature, especially in the VLF-LF band in which the study of sferics from lightning discharges is an active field of investigation. At relatively close distances (<1000 km) from the source the nuclear signal differs appreciably from a lightning sferic, and the two can be distinguished readily. Beyond this distance, however, the filtering properties of the wave guidelike propagation of VLF signals between the earth's surface and the lower ionosphere greatly reduce the difference between them. Thus it is usually necessary to examine a signal closely in order to determine whether it is a nuclear pulse or a lightning sferic [*Mark*, 1959; *Latter et al.*, 1961]. The characteristics of the nuclear wave form illustrated in Figure 1, for example, are typical of a common class of sferics [*Caton and Pierce*, 1952]. This difficulty, coupled with the rapid rate at which sferics occur, precludes casual observation of the nuclear pulse in the VLF-LF range.

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