CHAPTER XI
POTENTIAL PRODUCTION OF OBSERVABLE TRANSIENT ELECTROMAGNETIC EVENTS FROM SMALL NEAR-SURFACE NUDETs.
(With contributions from Dr. Conrad Longmire)

XI.1. Introduction. The primary premise for this investigation is that lightning and transient middle atmospheric electromagnetic events (TREMEs) are a source of "clutter" which may limit operational treaty monitoring. During the course of the investigation, it occurred to us that if we "invert" the problem, then we might consider that TREMEs may also be generated as a unique "signature" for low-yield, low-altitude NUDETs which may be exploited in operational treaty monitoring. The fundamental question is whether such events generate detectable TREMEs. These TREMEs might result from one or more of the following phenomena:

(1) The NUDET generates a sufficient charge moment that an observable Schumann resonance signal results.
(2) The NUDET generates sufficient EMP to couple with the ionosphere to produce an elve.
(3) The NUDET induces lightning which, in turn, has sufficient current (with appropriate polarity and charge moment to cause a sprite or Schumann resonance signal.
(4) The NUDET-induced electric field from the Compton current generated by the γ-ray deposition is sufficient to cause an electric breakdown at high altitude similar to a sprite.

In this chapter, we discuss the possibilities for the production of TREMEs by small near-surface NUDETs, and the character of such TREMEs should they be produced.

XI.2. Measurable charge moments from small near-surface NUDETs: In Figure 1, we show the compilation results of Williams (reported in Huang et al, 1999) which correlate the type of TREME with the charge-moment of the parent lightning event as determined from the Schumann-resonance signal (see description of Schumann resonance elsewhere in this report). It appears, from this type of distribution, that elves are, in general, associated with the lower end of the charge-moment magnitude distribution, and sprites are associated with the upper part of the charge-moment distribution. There clearly is overlap and it is not yet clear where "sprelves" occur on this distribution. One can use the charge-moment distribution to arrive at general arguments for the minimum magnitude required for an event. It is clear that events exhibiting relatively small (<100 C-km) charge moments are detectable with Schumann resonance and can give rise to elves. However the elve is more likely the direct effect of the EMP coupling to the lower ledge of the ionosphere rather than the charge-moment driving the quasi-electrostatic field to breakdown. Sprites appear to require charge moments >100 Coulomb-kilometers which are easily detectable with Schumann resonance techniques.

It has been well-established that large atmospheric tests like Ivy Mike generate easily detectable Q-bursts (charge moments that "ring" the earth-ionosphere waveguide as measured via Schumann resonance - Fellman, 1973). However, small (a few tens-of-kT) surface NUDETs themselves appear to generate charge moments of only a few Coulomb-kilometers. If one takes a canonical effective current of 100 A m^{-2} over a surface area represented by 500 m radius, with a peak current duration of 50 ns, one derives a charge of ~8 Coulombs. Assuming the shell is ~10 m thick, the charge moment is ~ 0.08 C-km, insufficient to produce a measurable Schumann resonance signal above the natural background. Similar events detonated above a few tens-of-kilometers, however, may yield larger charge-moments, because of the larger space-charge associated with the fireball (Roussel-Dupré, 1999).

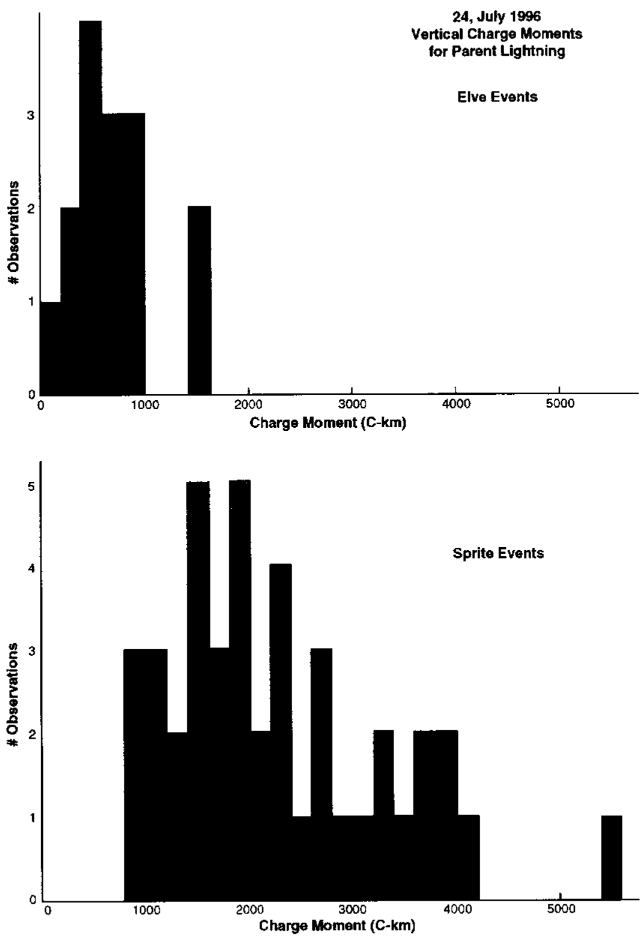

Figure 1. Compilation of charge moments vs number of observations, indicating the association of type of TLE event with the magnitude of the charge moment (Williams).

Holzer (1972) measured the magnitude of charge moments in small surface bursts to be 1-3 Coulomb-kilometers, a range of numbers well above that estimated above. The estimate above assumes a 50 ns time constant for the *peak* current and an effective conducting shell of only 10 meters. Holzer's results suggest that the local current and effective shell dimension generated by the prompt γ-rays are not sufficient to describe the effective charge moment (and hence the radiated field – see below). Holzer determined that the charge moments persisted in the surface bursts measured for several *minutes* during the rise of the fireball. The effect of such persistence is not known but Q-bursts, as measured by Schumann resonance have time constants much shorter than this. Thus such a charge-moment waveform would be very difficult to detect against background lightning activity. Although there remain a number of unresolved questions associated with correlation of Schumann resonance with small near-surface NUDETs, it would appear that event detection via such measurements would be impractical since the signal would be less than the natural background.

<u>XI.3. Elves produced from NUDET EMP:</u> As described above, there is a class of elves that appears to be generated by the EMP from the parent CG (Inan et al, 1996). NUDETs are known to generate EMP and lightning, although the waveforms of the two are not likely to be the same. (Gardner et al, 1984). Dr. Conrad Longmire (private communication, 1999), one of the leading experts on nuclear EMP, has suggested that the EMP from even small nuclear events should be sufficient to induce D- and E-region transient electrodynamic effects.

What EMP characteristics of low-yield, low-altitude NUDETs might give rise to uniquely identifiable transient electrodynamic signatures in the lower ionosphere? Unfortunately, we cannot discuss the details of EMP associated with nuclear events in this context. However, some general conclusions can be drawn to suggest an approach to answering the question. If we assume that the EMP mechanism is correct for the production of at least one class of elves, then we can qualitatively determine the likelihood that small NUDETs might generate similar events.

Although several researchers have attempted to relate the production of elves to the peak current in the parent discharge, the fundamental parameter for EMP-atmospheric coupling is the time-rate-of-change of the current, dI/dt. Thus the time-waveform is required to fully understand the coupling which produces the elve. Generic waveforms for lightning have been derived, and example of which is given by Gardner et al (1990):

$$I(t) = \frac{kI_{pk}}{\exp[-(t-t_o c \; + \; \exp[t-t_o)/\tau_f]} \qquad (1)$$

where k is an empirical constant, 1.025, I_{pk} is the peak current of the discharge, τ_r is the rise time constant, usually chosen to be 2.5E-07 s to maximize the rate of rise at 10^{11} A s^{-1} at t_o, τ_r is the fall time constant, approximately 50 μs. The Fourier transform of this yields the frequency spectrum. When one compares the frequency spectrum so-obtained with that of a "typical" frequency spectrum from a NUDET (Gardner, 1990), they are similar only in the frequency range of about 0.1-10 MHz, which, it turns out, is a critical range.

The lower ledge of the ionosphere exhibits electron densities approaching 10^3 cm^{-3}. The critical plasma frequency, at which maximum coupling occurs, is given approximately as 9000 $N_e^{½}$ where N_e is the electron density. Thus the critical frequency is approximately 0.3 MHz, near the lower edge of the range of similar frequencies. From this simple argument, one could conclude that Longmire's suggestion is correct – that small NUDETs might well produce observable transient events. The caveat is, of course, that the types of lightning that give rise to TREMEs is not as simple as that given in equation (1) above, nor is the waveform of the EMP for small low-altitude events equal to that of high-altitude EMP (HEMP). These differences must be taken into account. The NLDN system now has the ability to generate waveform information on lightning events so that there is now a basis for direct comparison of the NUDET EMP waveform with that of natural lightning.

If one assumes that nuclear EMP produces elves at the lower ledge of the ionosphere, can they be seen by a space-based detector? We know from ground observations that elves are very transient, apparently persisting for less than 1 ms.. However, the ground-based perspective is through a narrow altitude extent (<10 km) while a space-based perspective has the advantage of "limb-brightening" resulting from a line-of-sight through a few hundred km. The answer to the question lies in Figure 2, the shuttle-based airglow brightening observations of Boeck et al (1992) which are thought to be associated with an elve. There was a clearly defined and persistent brightening in the airglow layer seen above a large lightning event. The persistence (>1 s) is due to the long radiative lifetime of the oxygen green line, not observable from the ground due to the lack of effective sight path. If nuclear EMP produces elves, then they should be observable from space.

Figure 2. Example of a transient optical-electromagnetic event in the airglow layer recorded from the space shuttle (Boeck, et al., 1992). The arrow points to the transient event. The white arrow points to the parent lightning event.

It is important to note that an elve is not a point source. It exhibits a spatial extent of a few hundred kilometers, thus offering both a detection source and a confusion source, depending on the detection scheme and discrimination algorithm used.

XI.4. NUDET induced lightning events: We know that sprites are associated (almost always) with positive CGs. NUDETs also can produce lightning of positive polarity (Gardner et al, 1984) as is well-documented in the public literature for large events like Ivy Mike. Such lightning might be a secondary source of sprites and/or elves to be associated with smaller NUDETs. Whether smaller events produce lightning which may, in turn, produce sprites and/or elves is debatable, but not well-established in the public literature.

There is a paucity of data on nuclear lightning phenomena (which might produce TREMEs) and much of the analysis has concentrated on the large-yield Ivy Mike event (Uman et al, 1972, Gardner et al, 1984, Fernsler, 1985, Williams et al, 1988). Information on thresholds for nuclear lightning is not publicly available but there remains considerable uncertainty on the topic. Shelton (1999) suggests that the "Grable" event (Figure 3) exhibited evidence of nuclear lightning but this may be confused with the discharge in the torus, shown in the Figure. Unfortunately, definitive confirmation of nuclear lightning associated with "small" nuclear tests events is not available and the current data records (DASIAC) are insufficient to determine any such details. There have been suggestions of a threshold yield (Longmire, 1999) which cannot be discussed in this context. The detection and understanding of nuclear lightning was not a high priority during the test series and very little definitive data was obtained on the phenomena. It has been suggested that "nuclear lightning may, in fact, be common, even though its detection is not" (Fernsler, 1985).

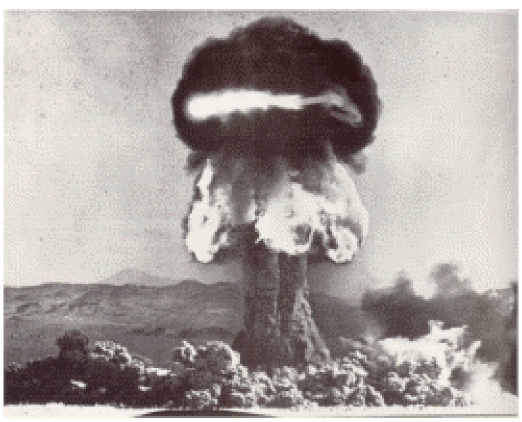

Figure 3. Image of the "Grable" event, 25May1953 – "small", perhaps confused with Precila, reported to have exhibited evidence of nuclear lightning. (Image courtesy of Frank Shelton, 1997).

Although natural and nuclear lightning may appear similar, their causative mechanisms are different. Initiation of nuclear lightning is primarily controlled by the gamma flux from the burst (Gardner et al, 1984), which has no counterpart in natural lightning. Gardner et al (1984) derived a robust model for the occurrence of nuclear-induced lightning, and Fernsler (1985) both corroborated and expanded the model to derive the basic parameters of the lightning. Nuclear lightning is associated with saturated fields of the order 30 kV/m and exhibit a length of a several hundred meters. Their current is estimated to be several hundred kA and can transfer several hundred Coulombs of charge. Thus it is plausible that nuclear lightning exhibits electrodynamic parameters, including charge moments, appropriate for the production of TREMEs. However, the production of the conditions necessary for nuclear-induced lightning from small (few kT) NUDETs remains highly speculative.

XI.5. NUDET-induced production of electric breakdown at high altitude - a nuclear sprite:

We have shown above that it is quite likely that even small near-surface bursts may cause the formation of an elve. The elve will typically exhibit a very short time constant, a few hundred microseconds, although a long-axis geometry would likely result in a longer time-constant die to the increased line-of-sight. Following the suggestion by Longmire, we have also investigated the possibility that the field associated with a small near-surface NUDET might be sufficient to induce a dielectric breakdown, yielding optical emissions similar to (or the same as) a sprite. In this case, the event would exhibit a duration of a few milliseconds, and a spatial extent of tens-of-km to perhaps 100 km across. The apparent vertical extent of the nuclear sprite, determined by the atmospheric conditions and details of the field, might be 20-30 km (see below).

From discussions with Conrad Longmire (recent private communications, 2000), we have determined that results of the Low-altitude EMP (LEMP) code suggests that the saturated field associated with Compton current induced by γ-rays is approximately 30 KeV m^{-1} and is impressed in the shell of ~10 meters (the LEMP code is no longer supported). Since this is the saturated field, it is relatively insensitive to device yield. However, this is not the radiated field. The radiated field is approximately 30% of the local field and exists over the range of approximately 1 km. Thus the radiated field is $\sim 10^7$ V m^{-1}. Outside of the 1 km range, the field drops approximately as the inverse of the distance. Above a near-surface burst, the field "looks" like a vertical dipole, thus the field strength exhibits a sinθ dependence, where θ is the angle from zenith. The horizontal fields (along the ground) are much more complex due to the interface with the conducting earth. Longmire suggested that John Malik (Los Alamos) had published a compilation of measured fields from small surface bursts. To-date, we have not located the reference.

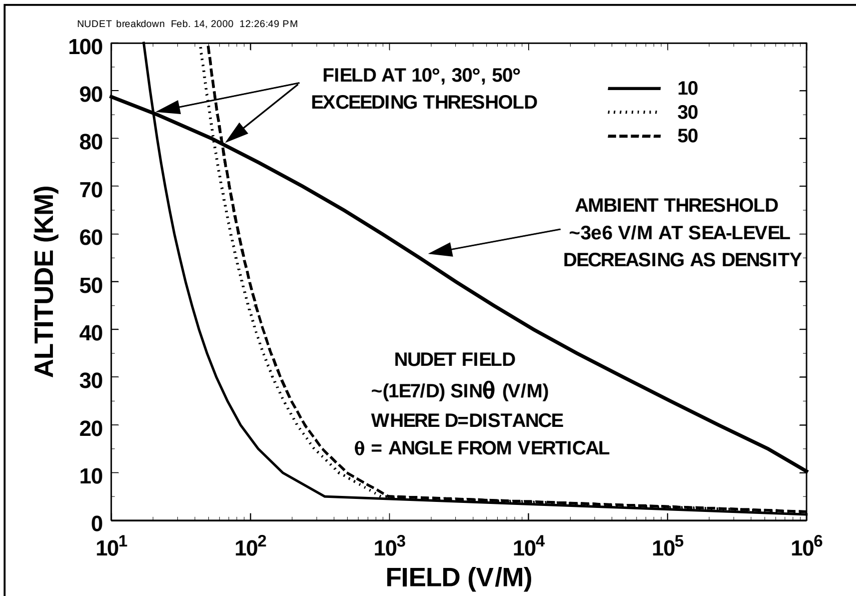

Figure 4. Calculated radiated field from a small near-surface NUDET compared to the ambient threshold breakdown field

We show the behavior of the field in Figure 4 (left). In this figure, three NUDET fields are shown as a function of altitude for three angles of θ - 10°, 30° and 50°. Also shown on this plot is the classical threshold curve for dielectric breakdown as a function of altitude. What is evident from the plot is that above approximately 80 km, the NUDET radiated field exceeds the ambient threshold and breakdown will occur, forming a nuclear sprite.

This presentation is admittedly idealized and there are a number of details requiring investigation. This assumes, for example, that the atmosphere exhibits a negligible conductivity which would reduce the radiated field. This is arguably true for nightime conditions but daytime conditions would result in a higher conductivity. Above approximately 90 km, the ionospheric ledge will tend to short the field, putting an upper limit on the altitude. The details of the ionospheric ledge will also play an important role in determining the character of the nuclear sprite. The sprite intensity will be determined by the details of the radiated field, whose character has not yet been fully investigated. Longmire is in the process of "re-visiting" this topic. Inspection of Figure 4 suggests that the nuclear sprite would have the general morphology of a "donut", which is different that the classical sprite produced by positive lightning.

Notwithstanding the caveats, these results are suggestive that even small near-surface NUDETs generate conditions for the formation of a sprite, in addition to the elve discussed above. These phenomena will exhibit different waveforms, the elve being very short lived (< 1 ms) and the sprite being longer lived (~10 ms). These types of events might be a source of clutter for NUDET detection and location since they will not have the characteristics of a point source. Conversely, if it can be shown that small near-surface NUDETS typically produce sprites and/or elves, the phenomena may offer a supplementary detection scheme in the event that the small NUDET cannot otherwise be detected (e.g. cloud obscuration). This is a topic for suggested investigation.

XI.6. References:

Boeck, W.L., O.H. Vaughan, R. Blakeslee, B. Vonnegut, M. Brook, Lightning-induced brightening in the airglow layer, Geophys. Res. Lett., ***19***, 99, 1992.

E. Fellmann, Analysis of Schumann resonance simultaneously recorded at two distant stations, PhD thesis, Saarbrucken, 1973.

Fernsler, R.F., Analytical model of nuclear lightning, NRL Memorandum Report 5525, 1985.

Gardner, R.L., L. Baker, J.L. Gilbert, C.E. Baum, D.J. Ansersh, Comparison of Published HEMP and natural lightning on the surface of an aircraft, p 491, Lightning Electromagnetics, R.L. Gardner, ed. Hemisphere Publishing, Corp., NY 1990.

Gardner, R.L., M.H. Frese, J.L. Gilbert, C.L. Longmire, A physical model of nuclear lightning, Phys. Fluids, 27(11), 2694, 1984

Holzer, R.E., Atmospheric electrical effects of nuclear explosions, J. Geophys. Res., 77 (30), 5845, 1972.

Huang, E.W., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson and C. Wong, Criteria for sprites and elves based on Schumann resonance observations, J. Geophys. Res., 104, 16943-16964, 1999.

Inan, U.S., W.A. Sampson, Y.N. Taranenko, Space-time structure of optical flashes and ionization changes produced by lightning EMP, Geophys. Res. Lett., ***23*** (1) 133, 1996

Roussel-Dupré, Private Communication, 1999

Shelton, F. H., Reflections of a Nuclear Weaponeer, Shelton Enterprises, 1988

Shelton, F., Private communication, 1999

Uman, M.A., D.F. Seacord, G.H. Price, E.T. Pierce, Lightning induced by thermonuclear detonations, J. Geophys. Res., 77, 1591, 1972

Williams, E.R., C.M. Cooke, K.A. Wright, The role of electric space charge in nuclear lightning, J. Geophys. Res., 93, 1679, 1988

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