Sensor and Simulation Notes

Note 526

23 February 2008

Discrimination of High-Altitude EMP in the Presence of Lightning Environments for Ground-Based Sensors

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Abstract

This paper discusses techniques for reliably detecting the presence of a high-altitude EMP event. This involves emphasizing detector response to HEMP relative to lightning based on the properties of the two environments. Various hardening and redundancy features are included.

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This work was sponsored in part by the Air Force Office of Scientific Research.

1. Introduction

For both military and civilian purposes, one would like to reliably detect the presence of the high-altitude nuclear electromagnetic pulse (HEMP) resulting from an exoatmospheric nuclear detonation. Knowing that there are other potential electromagnetic environments, in particular lightning, one would like his EMP detector not to be triggered by such events. So the problem is to design a set of detectors which are insensitive to lightning, but sensitive to HEMP.

The HEMP environment is described in [4, 7]. For present purposes we are concerned with the large (up to 50 kV/m) fast (few ns rise) early-time pulse. By comparison the lightning environment (cloud to ground) can have currents as large as 100 KA (or even larger), and a maximum rate of rise of around 7×10^{11} A/s [6] (or say 10^{12} A/s).

For the present discussion let us assume that our EMP detector is to be placed on the ground surface. (An airborne detector will have a different optimal design.) So we must look at the relative signals from HEMP and natural lightning at the ground surface, and design our detector accordingly.

2. Properties of the Lightning Environment

Lightning comes from the electrical breakdown of air. As such, the low frequencies have a very large electric-field component. If we compare electric and magnetic fields

$$
\begin{aligned}
&|\vec{E}_{low}| \Big/ |Z_0 \vec{H}_{low}| >> 1 \\
&Z_0 \equiv \text{wave impedance of free space} \\
&\quad \simeq 377\ \Omega
\end{aligned}
\tag{2.1}
$$

we find a dominant electric field. This will lead us toward measuring the magnetic field as a discriminant.

Noting the relative rates of rise of HEMP as compared to natural lightning will lead us toward time-derivative measurements as an added discriminant.

Putting these two phenomena together leads us toward measuring B-dot to increase the relative strength of the HEMP versus lightning signal in our detector.

3. Measuring the Incident HEMP

As indicated in Fig. 3.1, the HEMP is characterized by angle of incidence and polarization as

$$
\begin{aligned}
&\theta \equiv \text{angle of incidence (with respect to vertical } z \text{ axis)} \\
&\vec{1}_h \equiv \text{horizontal polarization vector} \\
&\vec{1}_h \bullet \vec{1}_z = 0 \\
&\vec{1}_v \equiv \text{“vertical” polarization vector} \\
&\vec{1}_v \bullet \vec{1}_z = \sin(\theta) \\
&\vec{1}_i \equiv \text{direction of incidence} \\
&\vec{1}_i \bullet \vec{1}_z = -\cos(\theta) \\
&\vec{1}_v \times \vec{1}_h = \vec{1}_i \ , \ \vec{1}_h \times \vec{1}_i = \vec{1}_v \ , \ \vec{1}_i \times \vec{1}_v = \vec{1}_h
\end{aligned}
\tag{3.1}
$$

The incident field is approximately a plane wave propagating in the $\vec{1}_i$ direction. The electric field is polarized in some combination of vertical $\vec{1}_v$, and horizontal $\vec{1}_h$ directions with

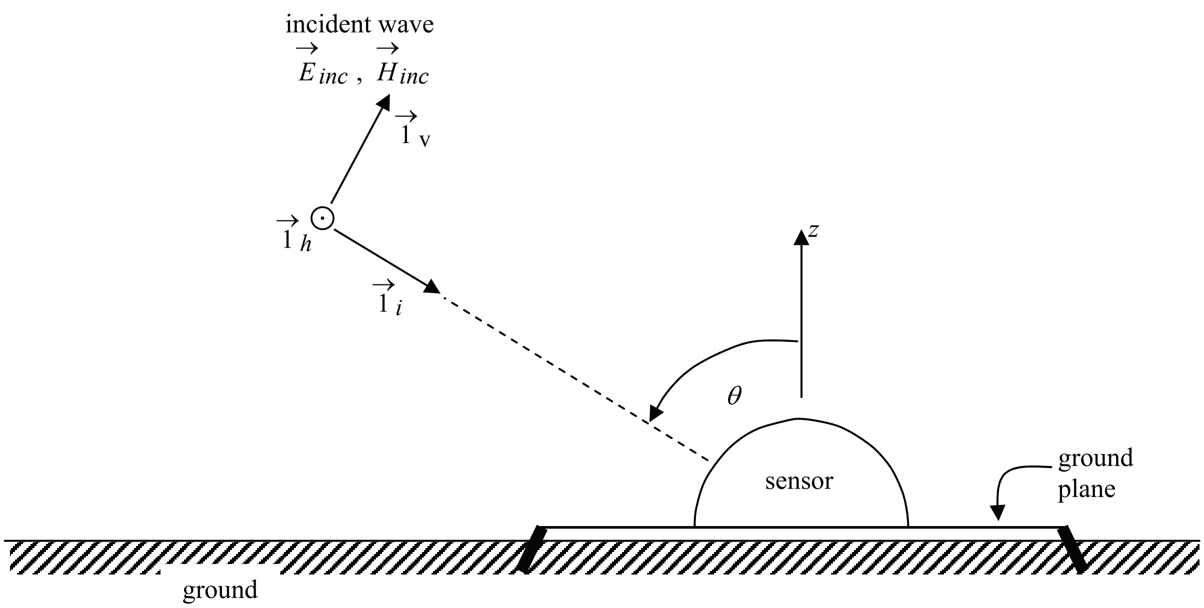

Fig. 3.1 Incident HEMP Waveform

$$\vec{1}_i \times \vec{E}_{inc} = Z_0 \vec{H}_{inc} \tag{3.2}$$

Consider two cases for the incident electric-field polarization, $\vec{1}_e$, the general case being a combination of the two. For $\vec{1}_e = \vec{1}_v$ (vertical polarization) we have at the sensor

$$\begin{aligned} \vec{E} &= 2\sin(\theta)\ |\vec{E}_{inc}|\ \vec{1}_z \\ \vec{H} &= 2\vec{H}_{inc} = 2|\vec{H}_{inc}|\ \vec{1}_h \end{aligned} \tag{3.3}$$

assuming a perfect (unity reflection) ground plane. Here we note the reduction of the electric with respect to the magnetic field by the factor $\sin(\theta)$.

Consider next horizontal polarization. In this case we have at the sensor

$$\begin{aligned} \vec{E} &= \vec{0} \\ \vec{H} &= 2\cos(\theta)|\vec{H}_{inc}|\ \vec{1}_z \times \vec{1}_h \\ |\vec{H}| &= 2\cos(\theta)|\vec{H}_{inc}| \end{aligned} \tag{3.4}$$

So here we have no resultant electric field at the ground plane. There is s till a resultant magnetic field, except in the limiting case of θ near $\pi/2(90^\circ)$.

Considering both polarizations we see a clear advantage in measuring the magnetic field. This is consistent with the case in Section 2 based on lightning considerations.

In Fig. 3.1 we indicate that the electromagnetic-field sensor is located on a ground plane situated on the earth surface. This reduces the problem of electromagnetic scattering from inhomogeneities in the earth near the sensor. For this purpose, the ground plane is electrically peripherally connected (“grounded”) to the local earth to minimize electromagnetic-field penetration under the ground plane for the important high frequencies.

The present ground-plane concept is similar to that discussed in [1] for the case of a sea-water platform.

4. General Sensor Concept

Based on the discussion in the previous sections we concentrate our attention on sensing the time derivative of the magnetic field from HEMP on a ground-based platform.

4.1 All directions of B-dot parallel to earth surface

Our basic sensor concept is then based on B-dot loops mounted on our sensor-station ground plane. The loop axes are, of course, parallel to the ground plane. The question then beomes: how many such loops and with what aximuthal orientations?

Figure 4.1 shows a possible configuration of N loops with axes spaced at angles of $2\pi/N$ around a circle. There might be a central conducting tube for the loop return to the ground plane. With connection of both ends of the loop to the ground plane, and a signal entry position on each loop, the ground plane itself is part of each loop. In

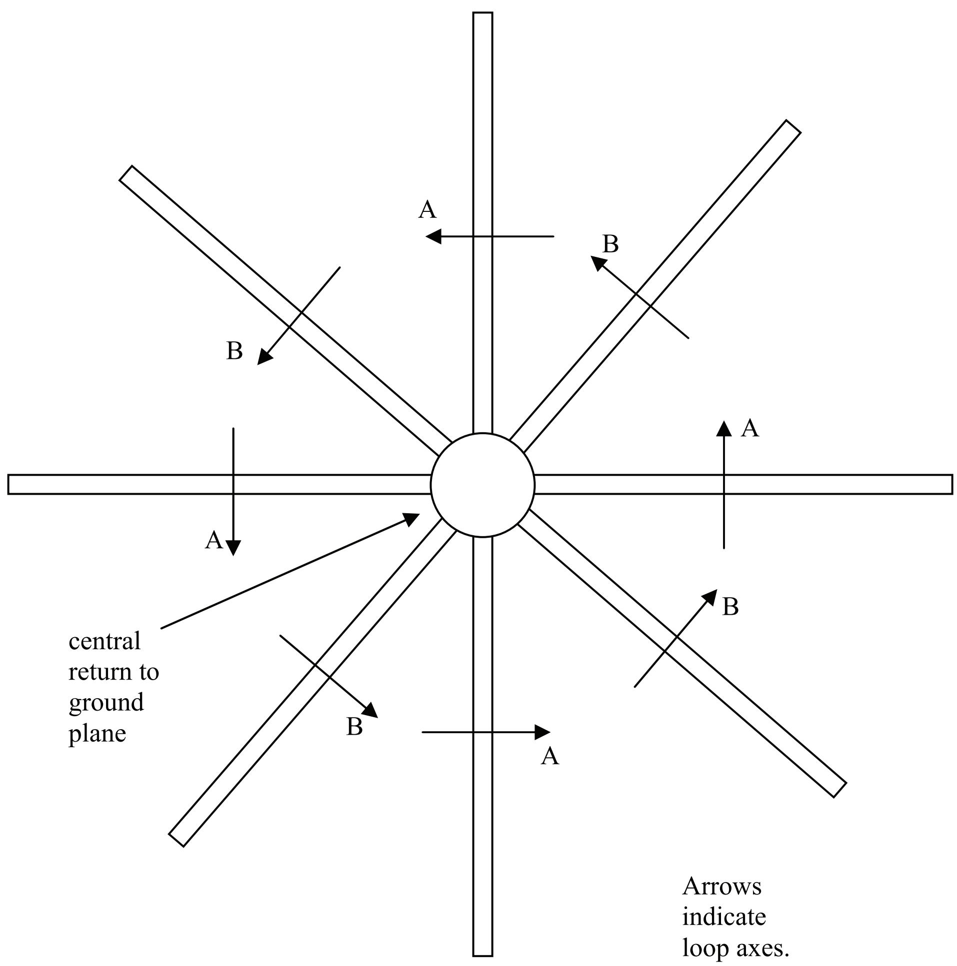

Fig. 4.1 Multiple Loops on Ground Plane: Top View.

addition the loops may have a common circular (or polygonal) disk for a top cap to lower loop inductance. See [5 (p. 104)] for a possible configuration (in that case for lightning).

If one does not know a priori the azimuthal direction of incidence of the HEMP, one can take the signals from all the loops, and perhaps rectify them producing signals of one sign (e.g., full wave rectification) from each loop. Then with peak detectors one can find the largest signal. If this signal is above some threshold, one can count this as a HEMP event. For reliability (false alarm prevention) one may divide the loops into two or more sets (as A and B in Fig. 4.1) and run these as separate channels with independent electronics, power supplies, etc. One can then require that all channels register a HEMP event within a small time window.

This leaves the question of how many loops each channel should have. If ϕ_ℓ represents the orientation of the ℓth loop in a channel, then two such loops which are neither parallel nor antiparallel ($\phi_2 \neq \phi_1$ and $\phi_2 \neq \phi_1 + \pi$), give the minimum number. If, in addition, one wishes a more symmetrical configuration, then N = 3 or more per channel is appropriate. As the orientation of the magnetic field (resultant at the ground plane) varies in azimuth (0 to 2π) the peak loop signal also varies from a normalized value of 1 down to $\cos(\pi/N)$. Larger N gives a more uniform peak signal as the azimuthal orientation is varied.

Noting that the risetime of the HEMP can vary, one might include filters to slow the fastest rises to some more nominal value (e.g., 10 ns) so that the response to various nuclear events may be more uniform. Then one can set the detector level to some appropriate nominal HEMP amplitude (e.g., 10 kV/m or 1 kV/m).

4.2 Nearby lightning

Now suppose that there is a nearby lightning strike. How close must it be to trigger our HEMP detector? Let the HEMP be characterized by 10 kV/m with a τ=5 ns time constant on the rise. This gives for incident vertical polarization (horizontal magnetic field) a peak B-dot of

$$\frac{dB}{dt} = \frac{2\,E}{c\,\tau} \simeq 1.3 \times 10^4 \;\; T/s \tag{4.1}$$

with the factor of two coming from the ground-plane reflection.

Let the nearby cloud-to-ground lightning be characterized by a peak I-dot of about 10^{12} A/s. This gives a peak B-dot at a sensor a distance of r away (near field) as

$$\frac{dB}{dt} = \frac{\mu_0 \text{ I-dot}}{2\pi r} \simeq \frac{2\times 10^5}{r} \quad T/s \tag{4.2}$$

Setting the two B-dots equal gives

$$r \simeq 15\, m \tag{4.3}$$

as the distance lightning needs to approach the sensor to trigger the detection circuitry. If the HEMP sensitivity is increased, then the radius for lightning sensitivity correspondingly increases.

4.2 Multiple spaced sensor stations

To avoid the problem of very close lightning strikes one can have multiple such HEMP detectors spaced distances large compared to $2r$ apart. Then a single strike location can trigger at most one such sensor station. By monitoring two or more such spaced stations false lightning triggers can thereby be avoided.

Multiple sensor stations (three or more) can also help by providing redundancy. By voting among M stations, and obtaining M-1 (at least) positive indications, allows for the failure of indication (electrical fault) from one station. Thereby one can have one station fail and still have an operable system of detectors. As discussed previously a false positive in one station channel is not sufficient to give a station positive.

4.4 Connection of stations to voting site

One must also be concerned with electromagnetic interference from lightning on the cables linking the sensor stations to the voting site (and in the voting site itself). Various techniques for adequate interference suppression can be adopted. These include shielding, isolation by use of isolation transformers and/or motor generators, relay closures to indicate signals, and uninteruptable power systems (UPS) involving local batteries and charging systems. Examples of some of these may be found in the techniques used for lightning measurement at Langmuir Laboratory on South Baldy peak near Socorro, NM, USA [3].

4.5 Testing

One can be assured of proper system operation by use of appropriate calibration devices (EMP simulators). An appropriate antenna can be brought to a sensor station and placed near (or even surrounding) the sensor. The level of B-dot to trigger the channels can then be verified empirically. If a fault is found in any channel repairs can be made.

5. Concluding Remarks

So it appears quite possible to make a reliable HEMP detector which avoids false positives and can even (by redundancy) avoid false negatives. Its sensitivity can be designed appropriately and can even be designed so that its sensitivity can be adjusted as conditions warrant.

The present paper is concerned with a ground-based HEMP detector. An airborne HEMP detector has different design requirements. In particular the platform (e.g., aircraft) can strongly influence the sensor response. This can be minimized by techniques discussed in [2].

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