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Interpretation of Early Magnetic Transients Caused by High-Altitude Nuclear Detonations [1]

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A high-altitude nuclear detonation produces magnetic disturbances which propagate to points remote from the detonation area. The worldwide magnetic disturbances occurring within a few seconds after the detonation are discussed. Data from Starfish are presented to show the general characteristics of the early-time magnetic field behavior. Various interpretations of these results are discussed. In particular, there is a signal occurring within a few tenths of a second after the detonation. This is interpreted to be the conventional electromagnetic pulse produced by asymmetric absorption of gamma rays in the lower atmosphere. The pulse propagates to far distances in the earth-ionosphere cavity. In addition, worldwide data show a second signal occurring within 1.5 to 2 sec after the Starfish detonation. This is also interpreted as an electromagnetic wave propagating in the earth-ionosphere cavity. It is generated by a bomb-induced magnetohydrodynamic wave which propagates downward from the vicinity of the detonation and is converted to electromagnetic form at the lower boundary of the ionosphere.

1. Introduction

The high altitude tests of *Hardtack* [Matsushita, 1959; McNish, 1959; Obayashi, 1963], *Argus* [Newman, 1959], and *Fishbowl* [Maeda et al., 1964] have shown that nuclear detonations disturb the geomagnetic field, and that these disturbances are propagated to points remote from the detonation.

From the measurement of geomagnetic disturbances at worldwide stations and from the more or less well-known properties of a nuclear detonation, it is possible to extract information about properties of the intervening region. This region, between the source of excitation and the measuring station, we shall call the geomagnetic environment. The nuclear detonation acts as a source of excitation of the geomagnetic environment. Measurements of the disturbances at various stations are related to the characteristics of the excitation and of the geomagnetic environment through which the signal propagates. However, from what has been said, it should not be assumed that the bomb serves as a point source of excitation; rather, there are various mechanisms by which a nuclear detonation may excite geomagnetic disturbances at great distances from the detonation point, in addition to those which produce local excitation.

In this paper we discuss the mechanisms which have been advanced to explain the signal received at short times (within a few seconds) after a high altitude detonation occurs. The principle source of experimental information that we shall refer to is *Starfish* of the *Fishbowl* series, since the time of occurrence (09h oom 09s GMT on 9 July 1962), height of detonation (400 km), yield (1.4 megatons) and place (over Johnston Island) have been announced [Brown et al., 1963].

We are interested in the geomagnetic signals which occur within times of the order of 1 sec, for several reasons:

(1) It is only recently that broad research effort has been directed toward the study of geomagnetic disturbances with periods smaller than about 1 sec. Consequently much of the data on nuclear detonation-induced perturbations of the geomagnetic field deal with changes of the order of minutes or longer. These longer time data have been reviewed by Maeda et al., [1964] for Starfish. Although a large amount of isolated data have been accumulated for the 1-sec magnetic field variations, it has not hitherto been discussed systematically.

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(2) The interaction of the solar wind with the magnetosphere is currently being studied intensively. However, the source of excitation, the solar wind, has properties which are not well known and certainly not well localized in time and space. This introduces difficulties into attempts to deduce short-time magnetospheric behavior from a study of natural geomagnetic storm phenomena. Since the high-altitude nuclear detonation induces short-time (as well as long-time) perturbations in the geomagnetic environment, it does afford a unique opportunity to study the short-time behavior of the geomagnetic environment [Ward, 1963]. It is particularly important for this study that the time of detonation of the nuclear explosion, in contrast to a geomagnetic storm onset, is known precisely.

In this paper we discuss the geomagnetic perturbations measured at times within a few seconds after detonation for Starfish. In section 2 the observational data are described and classified, together with a description of the requirements imposed by these data on any proposed interpretations. Section 3 contains several interpretations given for the prompt signal and section 4 gives interpretations of the second signal. The last section deals with additional problems introduced in instances where the observed data do not conform with proposed explanations.

TABLE 1. *Table of magnetic data (Starfish)*

Station	Observer	(Amplitude, time of arrival)[a]	Approximate ground distance	Approximate bearing[b]
			km	
Palo Alto, Calif.	Breiner [1963]	($>20\gamma$, ~ 2 s)	5, 200	45° E
Redondo Beach, Calif.	Crook et al., [1963]	(0.3γ, 1 ± 1 s) (7.5γ, 3 ± 1 s)	5, 400	50° E
College, Alaska	Wilson and Sugiura [1963]	(Not given, 2.11 ±0.06 s)	5, 600	5° E
China Lake, Calif.	Ashburn et al., [1962]	(1.2γ, 1.5 s)	5, 600	50° E
Victoria, British Columbia	Caner and Whitham [1962]	($>18\gamma$, 2.2 ± 0.1 s)	5, 700	30° E
Amberley, New Zealand	Gill [1962]	($\sim 10\gamma$, 4 ± 2 s)	6, 900	180° -
Ottawa, Canada	Baker and Strome [1962]	(1.3γ, 3 ± 2 s)	9, 100	45° E
Westford, Mass.	Balser and Wagner [1963]	(Not given, $\sim$0 s) (Not given, $\sim$2 s)	9, 400	50° E.
Scott Base, Antarctica	Gill [1962]	(Earth Current, 2 ± 1 s)	10, 000	180°
Dumont D'Urville, Antarctica	Roquet et al., [1962, 1963]	(Not given, 3 ± 1.5 s)	10, 000	160° W
Huancayo, Peru	Casaverde et al., [1963]	(0.3γ/s, ±0.5 s) ($\sim 12\gamma$, 1.8 ± 0.1 s)	11, 000	85° E
Jicamarca, Peru	Casaverde et al., [1963]	(0.2γ, 0 s) (large Signal, 1.8 s)	11, 000	85° E
Chambon-la-Foret, France	Roquet et al., [1962, 1963]	(Several tenths γ, -0.2 ± 0.2 s) (Several γ, 2 s)	12, 600	65° E
Kerguelen Island	Roquet et al., [1962, 1963]	(Not given, -0.3 ±0.5 s)	13, 500	130° W

[a] Time after burst (09h oom 09s GMT, 9 July 1962).
[b] Relative to Geomagnetic North at Johnston Island.

2. Observations for Starfish

Data previously reported in the literature are shown in table 1. It is seen that many of the stations located around the world measure a signal of several gammas or greater at from 1.5 to 2 sec after the detonation time. (This is referred to as the *second signal.*) At several of these stations, a signal of the order of 1/10 to 1/100 of the amplitude of the second signal is measured within a few tenths of a second after the detonation. (This is referred to as the *prompt signal.*)

Data taken at various other sites in the Pacific and elsewhere are shown in table 2. One sees a generally similar behavior to the data of table 1. The structure of the signal is actually more complex at the near-in stations (e.g., Kaui) and in the conjugate area (e.g., Samoa, Tongatapu) than the data presented in table 2 would indicate. This will be discussed below.

The band-pass characteristic of the equipment used to make the measurements presented in table 2 has been presented by Tepley et al., [1963] for Kaui and Tongatapu. The equipment characteristic for Wake, Samoa, and Trinidad is similar. The equipment has a high-frequency cutoff in the neighborhood of 10 Hz.[2] This implies that magnetic signals which are detected by such magnetometers, such as the prompt signal mentioned below, will appear to be practically devoid of frequencies above this. Also, the energy content below 0.1 Hz is greatly diminished because of the band-pass characteristic of the equipment.

Although it is difficult to classify the data on the basis of amplitude, a few facts emerge:

(1) The prompt signal is measured within tenths of a second at stations all over the earth. Its amplitude is of the order of tenths of gammas with frequencies found to be upwards of 1 Hz.

(2) The second signal appears at stations around the world within 1.5 to 2.2 sec after the detonation. There is no obvious dependence of this time on distance from the detonation. Its amplitude varies widely with station, but generally is greater than 1 gamma. Its frequency is found to be somewhat less than 1 Hz.

TABLE 2. *Table of magnetic data from various other sites (Starfish)*

Station	(Amplitude, time of arrival)[a]	Approximate ground distance	Approximate bearing[b]
		km	
Kaui, Hawaii	(Not given, <0.1 s) (17γ, ~ 1.95 s)	1, 330	55° E
Wake Island	(Not given, 0 s) (3γ, 1.5 s)	2, 600	95° W
American Samoa	(Earth Current, 0 s) (Earth Current, 2 s)	3, 300	175° E
American Samoa	(60γ, 1.6 s)	3, 300	175° E
Tongatapu	(Not given, <0.2 s) (27γ, 1.7 s)	4, 200	180°
Trinidad	(Not given, 0 s) ($\sim 5\gamma$, 1.9 s)	11, 600	95° E
Trinidad	(Earth Current, 0 s) (Earth Current, 1.5 s)	11, 600	95° E

[a] Time after burst (09h oom 09s GMT, 9 July 1962).
[b] Relative to Geomagnetic North at Johnston Island.

3. Interpretation of the Prompt Signal

It is well known that a nuclear detonation at high altitude generates an electromagnetic pulse [Glass-

[2] 1 Hz equals 1 cycle per second.

tone, 1962; Kompaneets, 1958; Karzas and Latter, 1962] in the region of the atmosphere where gamma-ray absorption occurs (20 to 50 km). While the pulse may have frequencies as high as 100 MHz, most of the energy is contained at lower frequencies, around tens of kilohertz. This pulse will propagate in the earth-ionosphere cavity at close to the velocity of light, with the lower frequencies being attenuated less. Thus the pulse may be expected to appear at any station in a time less than about 1/8 sec.

Besides the electromagnetic pulse, there are several other possible mechanisms which can generate a magnetic disturbance at large distances from the detonation within a few tenths of a second.

3.1. Neutron Decay Beta Effects

Neutrons are emitted by the bomb in all directions. These travel very quickly to far distances and decay into a proton and an electron. The electron in turn will spiral along the geomagnetic field line and produce a magnetic disturbance either by Cerenkov radiation [Davis and Headrick, 1964] or by creating enhanced ionization in the D and E regions [Crain and Tamarkin, 1961; Field, 1963] (enhanced S_q effect). It is also possible for the neutron decay protons to produce a similar effect, although it takes them longer to arrive at a given station than the electrons. The difficulty with this mechanism is that the magnetic field line through a station such as Chambon-la-Foret in France, which recorded the prompt pulse, is not accessible to line-of-sight neutrons. Furthermore, the multiple scattering that the neutrons would have to suffer in reaching the proper magnetic field lines would decrease the magnitude of the neutron (and hence the beta) flux by many orders of magnitude over the value for line-of-sight stations.

3.2. Whistlers

Whistlers were produced by Starfish [Allcock et al., 1963]. Basically, these waves are guided by the geomagnetic field, so that their effects would be expected to be confined to the conjugate regions.

We conclude that the only mechanism which can account for a magnetic disturbance at stations all over the world within a few tenths of a second after detonation is the electromagnetic pulse (generated below the ionosphere) which propagates in the earth-ionosphere cavity at light speed.

4. Interpretation of the Second Signal

There have been several different mechanisms proposed to explain the second signal. These are discussed and criticized.

4.1. Magnetohydrodynamic Wave Propagation

One proposed explanation is that the early-time disturbances are magnetohydrodynamic waves initiated in the detonation region by the displacement of the geomagnetic field by the highly conductive fireball [Glasstone, 1962; Leipunskii, 1960]. The magnetohydrodynamic waves then propagate in the upper ionosphere (above 1000 km) to the vicinity of the observation point in ducts, as was proposed by Bomke et al., [1960] in connection with Argus. According to these authors and to Berthold et al., [1960] (who analyzed the amplitude dependence of the signals from Argus III), it is possible to account for the early-time signal in Argus III (corresponding to the second signal in Starfish) as being the ordinary magnetohydrodynamic (fast magnetoacoustic) mode. Another Argus III signal, arriving later, within tens of seconds after detonation, is attributed to propagation of the extraordinary (pure Alfvén) mode.

This concept suffers from several difficulties. One point is that the time for propagation of the magnetohydrodynamic wave from its altitude above 1000 km to the observing station was not included by Bomke et al., [1960] in computing arrival times. With this correction, magnetohydrodynamic wave arrival times become considerably too long. A second point is that the wave must propagate at velocities greater than minimum in order to account for the short time delay of the early-time Argus III signal or the second signal of Starfish. However, refraction would tend to keep the ordinary mode propagating in the duct near 400 km altitude where the Alfvén velocity is a minimum. The extraordinary mode, which is guided by the geomagnetic field lines, would propagate at higher altitudes and therefore higher velocities. However, this wave would appear to be limited to producing disturbances in the conjugate region.

A modification of this theory which increases the velocity of magnetohydrodynamic wave propagation in the ionosphere has been proposed [Caner and Whitham, 1962]. The modification is that the magnetohydrodynamic wave is a shock wave which propagates at several times the Alfvén velocity. While this concept is quite likely correct close in to the detonation, it can be shown theoretically that the shock wave would be expected to decay into a small amplitude wave over the distances of propagation involved. Furthermore, the amplitude of the second signal measured at many stations is of the order of tens of gammas for Starfish. Allowing for the possibility of attenuation through the E region, the amplitude above this region might be about 1000 gammas which is a factor of 50 less the ambient field amplitude. This would imply that the disturbance, if it propagates magnetohydrodynamically, is a small amplitude wave at most stations listed above.

4.2. Neutron Decay Beta Effects

The mechanism of ionization produced by neutron decay beta rays may be invoked to explain the second signal of Starfish. However, since stations whose magnetic field lines are not accessible to line-of-sight neutrons received the second signal, this concept does not appear to offer an acceptable explanation.

4.3. Magnetohydrodynamic Excitation of the Earth-Ionosphere Cavity

It was recognized from the Argus tests [Newman, 1959] that the early-time signal (occurring within 4 sec after detonation) of Argus III might not be accessible to explanation as propagation by purely magnetohydrodynamic means. A different model was therefore developed [Kahalas, 1960] which has also been discussed by other authors [Caner and Whitham, 1962; Roquet et al., 1963] on the basis of Starfish data. In this model, the fireball of a nuclear detonation creates magnetohydrodynamic waves as before. Some of this wave energy propagates downward (at magnetohydrodynamic speeds) and is converted into electromagnetic waves in the lower ionosphere. This electromagnetic wave then propagates in the earth-ionosphere cavity around the earth at close to light speed. The time delay in the observed signal, in this model, comes mainly from the time it takes a magnetohydrodynamic wave to propagate from the detonation point to the lower ionosphere.

For Starfish, occurring at 400 km height, the calculation of the propagation time from 550 to 80 km by Francis and Karplus [1960] may be used. For the ordinary wave the time is 1.4 sec. Although this time is computed for a daytime ionosphere and Starfish occurred at night, it may be expected that the bomb's radiations would perturb conditions to approximate a daytime state. For Argus III, which took place at a height above the Starfish altitude, the observed time delay would be expected to be somewhat greater than for Starfish. However, Starfish increased the ionization in the lower ionosphere, so that the Alfvén velocity may have been sufficiently diminished to offset the higher altitude of Argus III.

Thus, the concept of magnetohydrodynamic wave excitation of the earth-ionosphere cavity would explain how a signal could occur at widely separated stations around the earth at approximately the same time.

There are problems associated with this explanation. For Starfish there is an apparent spread in arrival times from 1.5 to 2.2 sec. The time delay, however, does not increase in a systematic way for stations further from the detonation. A possible explanation may be that the spread of onset times for different stations is caused by difficulties in reading the record for the exact instant of onset. However, if the mechanism of magnetohydrodynamic excitation of electromagnetic waves in the earth-ionosphere cavity is valid, then a new mechanism for the onset of natural geomagnetic storms seems to be indicated.

5. Anomalous Near-in and Conjugate Region Effects

The presentation of the data given above is substantially correct, but there are deviations from the simple picture at near-in and conjugate region stations. This would imply that the physical processes occurring are more complicated than the theoretical interpretation presented above might indicate. In particular, one might expect that close enough in to the region of detonation, anomalous signals might be observed which have not been attenuated by propagation to large distances over the earth's surface. In the same vein, the guiding effect of the geomagnetic field on both waves and charged particles should lead to special effects in the conjugate regions.

There are several anomalies which have been noticed in the data. Figure 1 shows the magnetic disturbance at Wake Island, 2600 km away. It is seen that there are two onsets, one at about 1.5 sec and another at slightly greater than 2 sec. Figure 2 shows the magnetic record at Samoa, 3300 km away. Again the same phenomenon of two apparent onsets appear.

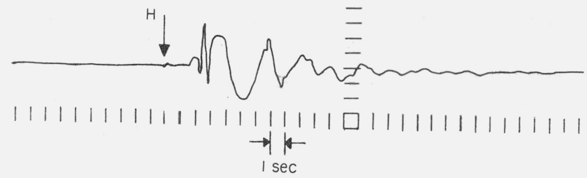

FIGURE 1. *E-W magnetometer Wake Starfish.*

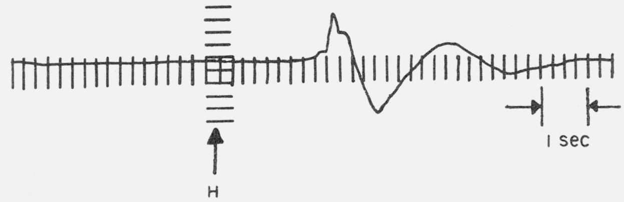

FIGURE 2. *E-W magnetometer Samoa Starfish.*

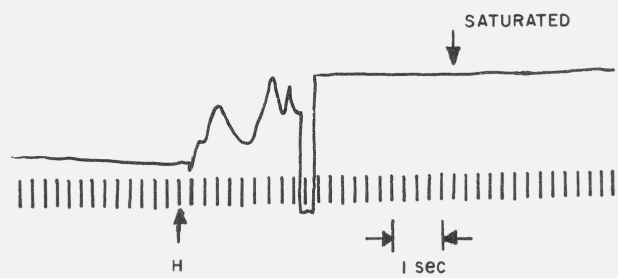

FIGURE 3. *Earth current E-W Samoa Starfish.*

Another anomaly involves the observation at Wellington, New Zealand, of a magnetic signal appearing at 0.6 ± 0.2 sec after the detonation [Christoffel, 1962]. This correlates very closely with the observed time of arrival of a whistler at the same site [Allcock et al., 1962]. It is suggested that the magnetic disturbance measured at Wellington may have been associated with the whistler. Figure 3 shows the earth-current record at Samoa in the conjugate region. There is apparently an onset in the vicinity of 0.5 sec, which suggests again a whistler arrival at this site.

Such anomalous effects indicate that a great deal is yet to be learned about magnetic disturbances from nuclear detonations and their relationship to extremely low-frequency wave propagation in the terrestrial atmosphere.

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