PROMPT WORLD-WIDE GEOMAGNETIC EFFECTS OF
HIGH-ALTITUDE NUCLEAR EXPLOSIONS

by

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B.Sc., University of Alberta, 1960

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in the Department
of
GEOPHYSICS

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

March, 1964
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The University of British Columbia,
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Date March 3, 1964
ABSTRACT

A brief summary of observational data is presented, covering the disturbances recorded within seconds of high-altitude nuclear detonations, with particular emphasis on the "phase B" signal recorded at H+2 seconds following the "Starfish" test of July 9, 1962. The salient characteristics of this signal are specified, and a number of suggested models are analysed in detail. Although no conclusive decision can be reached on the basis of presently available data, the most likely mechanism appears to be hydromagnetic waves along the field line through the detonation point, with energy conversion into electromagnetic modes at the mirror points.
ACKNOWLEDGEMENTS

Work on this report was begun at Victoria Magnetic Observatory (Dominion Astrophysical Observatory). I should like to thank Prof. J.A. Jacobs for providing the facilities for its completion. Valuable suggestions and criticism have been received from Prof. T. Watanabe of the Department of Geophysics, University of British Columbia, Dr. K. Whitham of the Dominion Observatory, and Dr. J.F. Kenney and Dr. H.R. Willard of the Boeing Scientific Research Laboratories.

I should like to thank the Director of the Signals Research and Development Establishment (U.K. Ministry of Aviation), and Dr. C.F. Sechrist of HRB-Singer Inc., for supplying unpublished data.
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INTRODUCTION

This report examines in detail one narrow aspect of geomagnetic disturbances set up by high-altitude nuclear tests - the world-wide signals recorded within a few seconds of detonation, with particular emphasis on the major oscillatory signal, the start of which was recorded at many locations about 2 seconds after the detonation, and which we have designated "phase B". Slower geomagnetic arrivals as well as radio propagation effects have been reported and analysed by several observers (for example, Maeda et alia, 1964). Although all these effects are obviously related in as far as the source is concerned, the actual mechanisms involved appear to be entirely different, thus justifying the separate treatment of an isolated feature such as the "phase B" signal.

The main interest of this signal lies in its broad similarity with certain types of natural geomagnetic pulsations (pearls, or type-A oscillations). Having the advantage of a controlled source (at least in time and location), it therefore provides an interesting opportunity for complementing the study of possible natural micropulsation mechanisms - even though the analogy with natural phenomena can only be followed to a limited extent. Although no explicit conclusions are drawn in this respect,
the proposed mechanisms have been narrowed down to essentially the same as those which are being considered as explanations for pearl-type micropulsations.

This report will be limited to a discussion of global geomagnetic effects recorded within a few seconds of the detonation, and it will not include isolated local effects in the vicinity of the launch zones or conjugate areas. The observational data will first be presented fairly briefly. A number of possible mechanisms will then be considered on a qualitative basis, with rough order-of-magnitude quantitative support. It should be mentioned at the outset that no fully acceptable unique solution is proposed. In particular, theoretical work is required on hydromagnetic-electromagnetic energy conversion at very low frequencies. However, this investigation should provide a useful basis for more detailed work on any particular mechanism. In view of the large release of energy in various forms, a unique solution may not be possible on the basis of the presently available data, since combinations of several different mechanisms may be involved.

The energy output of a nuclear explosion is $10^5$ Joules per Kiloton. For an unshielded fission explosion in space this is distributed roughly as following (Glasstone, 1963; Latter and LeLevier, 1964): Approximately 30-70% in x-rays (1 to a few Kev energy range), 0.01-1% in prompt
γ-rays (mean energy about 1 Mev), 0.1-1% in prompt neutrons (0.1 Mev to a few Mev), and the remainder in kinetic energy of fission products, with a few percent in delayed radiation.
4.

OBSERVATIONAL DATA

The relevant tests for which information is available are the following:

Aug. 1958: two tests in the Pacific above Johnston Island, "Teak" at an altitude of 70-80 km, "Orange" at 30-40 km. The announced yield was "in the Megaton range". Sowle (1961) estimated the yield as about 4 Megatons for "Teak" and 2-4 Megatons for "Orange".


July 9, 1962: Johnston Island, yield estimated at 1.4 Megatons, altitude 400 km, code name "Starfish".


None of the lower altitude (under 100 km) tests produced major global geomagnetic effects. Most of them produced both fast (onset time within 1 second - McNish, 1959) and slower following bay-type disturbances at locations within about 1000-2000 km of the launch area, falling off rapidly with distance. Some sharp effects were also observed at the conjugate points. Lawrie, Gerard, Gill
(1959) and Obayashi (1963) have summarized and interpreted these effects. However, no major world-wide effects were observed, in spite of the high yields.

For the higher-altitude Argus tests, effects were observed at magnetic stations at widely separated locations (Eschenbrenner et alia, 1960), in spite of the low yields. Amplitudes were very small (fraction to a few gammas), and recordings were obtained only on sensitive equipment - in some cases barely above the background level. Berthold, Harris and Hope (1960) have summarized this data in detail for Argus III (Sept. 6, 1958). The arrival times were plotted against station to detonation point distances. The slope of a straight line fitted to the first arrival points indicated a ground-level propagation velocity of 3050 km/sec. No probable error was specified for this result.

Similar global effects were recorded following the "Starfish" test of July 9, 1962, but with considerably higher amplitudes - presumably due to the higher yield. The test was announced well in advance, and a countdown transmitter could be monitored. Nevertheless, a surprisingly small amount of high-quality unclassified data has been collected in geomagnetism. With a few notable exceptions very few stations improved their operating techniques for this particular period in order to obtain timing accuracies of ±0.1 seconds or better (in particular accurate absolute
timing on the record itself and speed-up of recorders). Also, the hour time-mark obliterated the first arrival at many locations, particularly on slow-speed magnetograms. Finally, the amplitude of the signals was unexpectedly large. At almost all locations the instrument settings were too sensitive and the traces went off-scale. Consequently very little valid amplitude data has so far become available, and this report is based almost entirely on timing considerations, particularly from the 4 following stations:

Victoria, B.C., Canada - Dominion Observatory
College, Alaska - University of Alaska
State College, Pa., U.S.A. - HRB Singer Inc.
Christchurch, England - Signals Research and Development Establishment

The Christchurch data were particularly valuable in view of the long distance coverage, and in view of the high quality of the available recordings - complete three-component sets of high-speed high-sensitivity as well as broad-band lower-sensitivity recordings. Figures 1, 2 and 3 show the high-speed recordings for Victoria, State College and Christchurch, and Figure 4 the frequency response of the instrumentation used. The relevant data for the 4 stations is summarized in Table 1 below. Consecutive lines contain the following information: a) great circle distance (km) to Johnston Island; b) delay time (seconds) for the first arrival.
FIG. I VICTORIA MAGNETIC OBSERVATORY
DECLINATION (MAGNETIC E-W)
0.5 GAMMA/DIVISION

UNIVERSAL TIME

STATE COLLEGE, PENNSYLVANIA

FIG. 2 - GEOMAGNETIC MICROPULSATIONS - 9 JULY 1962
(HORIZONTAL COMPONENT)
AFTER SECHRIST (1962)
COURTESY HRB - SINGER INC.
FIG. 3  CHRISTCHURCH, ENGLAND  
COURTESY SRDE
FIG. 4 MAGNETOMETER CHARACTERISTICS: VICTORIA, STATE COLLEGE, CHRISTCHURCH
The detonation time \( (H=0) \) is 0900:09.025 ± 0.025 secs, as deduced from the sharp cut-off of the countdown transmitter and other recorded radio effects (Hanley, 1962; Caner and Whitham, 1962); c) probable and maximum errors for the delay time - the latter includes the uncertainty in origin time; d) components recorded, and estimated peak-to-peak amplitude (in gammas) of the first movements (all off-scale); e) reference.

<table>
<thead>
<tr>
<th>Victoria College</th>
<th>State College</th>
<th>Christchurch</th>
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<tr>
<td>5400</td>
<td>5600</td>
<td>9600</td>
</tr>
<tr>
<td>2.0</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>±0.1 (0.2)</td>
<td>±0.06 (0.1)</td>
<td>±0.1 (0.3)</td>
</tr>
<tr>
<td>( D &gt; 20 )</td>
<td>( F &gt; 5 )</td>
<td>( NS &gt; 10 )</td>
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<tr>
<td>( Z &lt; 0.5 )</td>
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An important group of observations comes from the network of the U.S. Army Electronics Research and Development laboratory. These have not been published, but a summary of the results was presented in a paper at the IUGG meeting (Bomke et alia, 1963). A strong oscillatory signal was recorded at H+1.9 seconds simultaneously at all the stations of this network (Florida, Maine, South Carolina, New Jersey as well as Hawaii and Samoa). No probable error was given for this figure; ±0.1 seconds is probably a reasonable estimate. A sharp broad-band pulse containing higher frequencies (but of much lower amplitude) was recorded at the instant of detonation at Samoa and Hawaii.

A third group of observations comes from the network of the "Institut de Physique du Globe" of the University of Paris (Roquet, Schlich and Selzer, 1962). Two of the stations, Chambon-la-Foret in France and Kerguelen in the Indian Ocean, reported the instantaneous arrival at H+0 (±0.1 to ±0.2 seconds), followed by a very strong and sharp reinforcement of the perturbation at Chambon about 2 seconds later (Roqu et alia, 1963). The third station, Dumont d'Urville in the Antarctic, reported a major arrival at H+2 ± 1.5 seconds.

Finally, high-resolution ELF recordings obtained at Byrd in the Antarctic (Lokken, private communication) and at Westford, Mass. (Balser and Wagner, 1963) show both the
instantaneous pulse and the higher-amplitude, lower-frequency signal at H+2, with distinct separation between the two signals. Because of the high-frequency passbands of these systems (5-35 cps for Westford, 2-30 cps for Byrd) no conclusions can be drawn regarding the waveform of the second signal on these recordings.

There are many other recordings, but since absolute timing accuracies are ±0.5 to ± a few seconds they do not add any useful information from the point of view of timing - although they are important for an examination of geographic coverage. As pointed out by Roquet, Schlich and Selzer (1963) the evidence for global synchronism is overwhelming. We can identify the following distinct effects:

"phase A": an instantaneous pulse, low-amplitude, high-frequency content (> 2 cps), at H+0 (± milliseconds to ±0.1 seconds).

"phase B": a second, major oscillatory signal starting at H+2 simultaneously (±0.1 to 0.2 secs) all over the globe. The period is initially about 3.5 to 4 seconds, and appears to decrease to about 2-2.5 seconds by the fifth oscillation. This period decrease is not definitely proved, since at most stations the traces went off-scale and the zero reference shifted. In view of the rapid amplitude decay a reliable frequency measurement becomes difficult.
PHASE A - INTERPRETATION

Interpretation of the "phase A" signal does not present any particular difficulties; there are two possible mechanisms:

a) a spheric, presumably excited by the prompt γ-ray emission (which occurs within microseconds and deposits most of its energy at altitudes of about 20-30 km), or possibly by electrostatic (charge separation) effects. It is probably reinforced by Schumann oscillations of the earth-ionosphere cavity. This is confirmed by the Byrd ELF recording which has excellent time resolution - the fundamental Schumann frequency can be clearly identified on the first signal (Lokken, private communication). The first signal on the Westford ELF recording is reported to be similar to that observed for lightning strokes (Balser and Wagner, 1963).

b) the second possible mechanism is effects of neutron-decay betas. This will be discussed in more detail at a later stage.

The reason why not all stations recorded the "phase A" signal is almost certainly a combination of instrumental limitations and rapid amplitude fall-off with distance. The frequency response of most of the detectors used falls off very rapidly beyond a few cps; for example the 3 db high-frequency cut-off points for Victoria, State
College and Christchurch (broadband record) are 5 cps, 1.5 cps and 2 cps respectively. A very low-amplitude signal at 8 cps would therefore be masked by background activity and/or instrument noise, whereas it shows up on records obtained either at close locations (Hawaii, Samoa), or with specialized ELF equipment (Byrd, Westford), or with low-noise high-frequency sensitive equipment such as that used by the French network.

PHASE B - INTERPRETATION

Interpretation of the "phase B" signal is far more complicated and controversial. The salient characteristics of this signal are summarized below, and any suggested mechanism must take these points into account:

a) global synchronism (±0.1-0.2 secs)
b) 2 second delay after explosion (±0.1-0.2 secs)
c) extremely sharp rise (over 20-30 gamma/sec)
d) initial period 3.5-4 secs (i.e. frequency 0.28-0.25 cps)
e) amplitude heavily damped
f) large initial amplitude (about 30-50 gamma)
g) altitude-dependence (occurs only when the source is above F layer)
h) decreasing period, to about 2-2.5 secs (?)
Before beginning a discussion of possible mechanisms, it is useful to reconsider the Argus III data to check whether it could fit some of the above characteristics. The relevant figure from Berthold et alia (1960) is reproduced in Figure 5. If we visualize the full vertical scale (i.e. extended to zero distance) it becomes obvious that the slope of a line based on a number of points bunched over a narrow range is extremely sensitive to errors in individual point positions. The Azores observation is not very reliable - to quote from Newman's (1959) original paper: "there may be a signal between plus 4 and plus 6 seconds". This leaves 5 points, all in the range 12000 - 13700 km, i.e. covering only about 15% of the total range. Considering the probable errors of some of the observations, it becomes obvious that any slope derived on this basis is not too reliable. In fact, it can be clearly seen that a vertical line (i.e. global synchronism) would fit the data just as well or better (see dotted line on Figure 5). This is strengthened by Troitskaya (1961), who reported that the arrivals recorded at the Soviet telluric stations (extending over 120° in longitude) were simultaneous to within 1 second. The exact delay time is unfortunately not known, since the effective origin time has not been published. It would be very interesting to know whether the delay is of the order of 2 seconds also, or whether it is dependent on yield and altitude. It is not clear whether the papers by Berthold
FIG. 5 Replotted recordings, giving an indication of velocities of two signals from Argus III. AFTER BERTHOLD, HARRIS, HOPE (1960)
et alia (1960) and Bomke et alia (1960) were based on access to unpublished origin time data, or whether the origin time was derived from extrapolation of the distance-time lines for later arrivals. In the latter case, the same objections apply as previously discussed for the 3050 km/sec velocity, and the origin time can be considered unknown to \( \pm 2 \) secs, i.e. a 2 second delay is possible. However, if these papers were based on access to reliable origin information (which is a likely assumption), the delay indicated by the data is about \( 4 \pm 0.5 \) seconds. Troitskaya (1960) reached a similar tentative conclusion, based on the time spacing between a first impulse-type arrival (assumed at \( H+0 \)) and the second (oscillatory) signal.

A number of different mechanisms will now be discussed in detail; some of these are obviously unsuitable to explain the "phase B" signal, but since at one time or another they have been considered, we have included them briefly. We have attempted to present a number of possibilities with a minimum of personal bias, in order to provide a broad basis for a more detailed discussion of one or two specific mechanisms which we consider as most likely. No claim is made that all possibilities have been considered - others can almost certainly be proposed, particularly if complex combinations of different mechanisms are considered. However, in view of the sharp and clearly defined nature of
the signal we feel that a relatively simple explanation is more likely - preferably one which ties in with "prompt" detonation effects rather than with delayed fission-product decay.

The listing of mechanisms has been divided into two groups; I: direct "overhead" effects; II: secondary focus mechanisms.

I. DIRECT EFFECTS

1) **Hydromagnetic waves, at or near detonation altitude:**
The fission "bubble" expands at a rate of about 100-1000 km/sec (Latter and LeLevier, 1963). It is highly diamagnetic and therefore acts as a piston on the earth's magnetic field, setting up hydromagnetic waves in the different modes. Some of these can almost certainly be identified among the later arrivals, but in as far as "phase B" is concerned they do not fit the requirement of global synchronism, since the relevant propagation velocities are of the order of a few hundred to a few thousand km/sec - far too low to account for the simultaneous arrivals at distant locations.

Caner and Whitham (1962) proposed hydromagnetic shock wave in the ionosphere as one possible explanation.
This was based on records from one station (Victoria) only, and on the assumption that the 2 second delay represented a propagation time. As soon as it became evident that the two second interval represented a "fixed delay" this mechanism had to be ruled out.

2) **Hydromagnetic waves in high-altitude ducts:** This was proposed by Bomke et alia (1960) for the Argus III results and assumes that the energy is propagated within "ducts" at the altitudes of maximum Alfvén velocity, i.e. 2000-3000 km. The delay time for the energy to reach these ducts was assumed negligible, and the actual nature of the injection mechanism is not clear - hydromagnetic wave propagation to the ducts, or expansion of the diamagnetic bubble, would both required delays of the order of seconds. The only possible injection mechanism which would not introduce significant delay is the prompt x-ray or γ-ray pulse. However, in the absence of any sharply defined "duct" boundary it is difficult to see how significant energy could be converted into hydromagnetic waves along the ducts.

Quite apart from the time-delay objection, it is not clear why significant amounts of hydromagnetic energy should be refracted into such ducts. Some energy could be trapped (even though inefficiently) in such a high-velocity
layer, but most of the energy would be conducted in the lower-velocity ducts (particularly since the detonation occurred almost inside such a low-velocity duct). We would therefore expect an almost continuous effect, with amplitudes increasing as the slower signals arrive. This does in fact apply to the Argus III test, where later arrivals, although sometimes distinctly separate, were recorded with larger amplitudes (Berthold et alia, 1960; Troitskaya, 1960). However, it does not fit the Starfish data.

The main argument against this mechanism as far as the Starfish data is concerned is of course the global synchronism and 2 second delay. Propagation velocities at these altitudes are finite, even though very high, and propagation delays over the distances involved would vary between 2 and 6 seconds.

3) Ionization effects due to neutron-decay betas: The prompt neutron emission can account for some effects directly, but these must be limited to the geometrically accessible regions, since neutron paths are not bent or deflected. However, beta particles which have decayed from these neutrons can be guided down to ionospheric altitudes by magnetic field lines, and therefore produce ionization effects in regions not directly accessible to the neutrons
themselves. For a fission explosion, the neutron-decay betas have terminal energies of 0.78 Mev, with a very broad maximum centered at about 0.25 Mev (Zmuda et alia, 1963b).

This mechanism was first proposed by Crain and Tamarkin (1961) to explain sudden changes in ionization following the Aug. 1958 tests. It has been further developed recently by Sechrist (1962), Zmuda et alia (1963a,b), Willard and Kenney (1963), Kenney and Willard (1963), and others. There seems very little doubt that this mechanism accounts for at least some of the observed prompt VLF effects. The known existence of such a mechanism (as contrasted with the mainly hypothetical nature of some of the other proposals) makes it very tempting to apply it to the geomagnetic data as well, but there are two major objections:

1) The fixed time delay. Over the distances involved the onset times at different locations should vary between milliseconds and fractions of a second (on the assumption of mean neutron energy of 1 Mev, i.e. ejection velocities of $1.4 \times 10^9$ cm/sec). However, should the origin spectrum contain an unexpectedly large flux of very low energy neutrons, the delay times could indeed reach 2 seconds at some remote locations, but in that case there is no global synchronism. For the predicted fission spectrum, the onset time would be practically instantaneous (within the time resolution used in this report, i.e. ±0.1 to 0.2 seconds).
This mechanism could therefore account for some of the "phase A" arrivals, but not for "phase B". For the "Orange" test in 1958, Benioff (quoted by Hodder, 1960) reported small (fractional gamma) signals instantaneous with the detonation (±?) at two locations remote from the detonation point (> 7000 km), but on field lines accessible to neutron-decay betas. Field (1962) attributed these signals to neutron decay betas.

b) The second major objection is amplitude. For a 1.4 Megaton fission bomb, the number of ion pairs formed by deposition of betas at the relevant altitudes (80-100 km) is about 75 per cm$^3$ in one second. A rough estimate of the amplitude of the resulting geomagnetic effects can be obtained by comparison with the diurnal fluctuations (Field, 1963). For mid-latitude stations, $H_p$ ~ 20-50$\gamma$, $N_o$ ~ $10^4$/cm$^3$, the resultant signal would be of the order of 0.1 to 0.5 gamma. If the prompt deposition (at the first pass) alone is considered, the amplitudes would be even lower. Using Kenney and Willard's (1963) figures, the number of ion pairs formed in a 1 cm$^2$ flux tube over Victoria would account for an increase of only about 7 ion pairs per cm$^3$ in the relevant region, i.e. a 0.01 to 0.05 gamma signal. Recent estimates (Kenney, private communication) indicate a possible increase in these values by a factor of 10. However, they would still be too low (by a factor of about 100) to account for the observed 30$\gamma$ signals.
4) Fission-product decay betas: The decay of fission products provides a far more copious source of betas than the decay of the prompt neutrons. The bulk of their energy is deposited at altitudes of 80 km and below (mean energy about 1 Mev). However, deposition is spread over a period of seconds following the detonation. Also these electrons cannot be rapidly transported across the field lines and their prompt effects must be confined to the field lines directly accessible to fission products. The upwards-expanding diamagnetic bubble confining the fission products provides a means for spreading these beyond the immediate field line through the detonation point. Since at these altitudes the magnetic field is the dominant factor for stopping expansion of the bubble, its terminal dimensions can be estimated. Latter and LeLevier (1963) have shown that the terminal cross section area $A$ of the flux-tube containing the bubble is

$$A(\text{km}^2) = 3 \times 10^4 \left(1 + \frac{Z}{R_E}\right)^4 Y^{2/3}$$

where $Z$ - altitude in km, $R_E$ - earth radius in km, and $Y$ - explosion yield in Kilotons. The corresponding deposition area $A_0(\text{km}^2)$ at altitude 80 km is

$$A_0 = (1 + \frac{Z}{R_E})^{-3} \cdot A$$

For the "Starfish" test ($Z = 400$ km, $Y = 1400$ Kilotons), $A = 480 \times 10^4$ km$^2$ (Radius = 1240 km) and $A_0 = 400 \times 10^4$ km$^2$ (Radius 1130 km). These are maximum values, based on the
assumption that the entire energy output goes into expanding
the bubble. A more reasonable proportion would be about 0.5
to 0.7 of total yield.

Even though a small proportion of the decay elec-
trons (about 5% - Colgate, 1963) is ultimately injected into
higher L-shells through magnetic instabilities, the bulk of
the deposition is limited to the area \( A_0 \). The prompt ground
effects due to ionization are therefore limited to a range of
about 20° at each conjugate area (i.e. about 15°S to 35°S
and 15°N to 35°N), and the mechanism is inadequate to explain
the geographic extent of the "phase B" signals - quite apart
from other objections (timing, sudden onset). Transverse
drift would of course extend the longitudinal coverage, but
even for very high energy electrons the drift rate is far
too slow to account for "phase B" arrivals.

5) Setting up of local conditions: One possible mechanism
suggested by Selzer (private communication) is that the 2
second delay represents a "setting-up" time of conditions at
the point of observation rather than a propagation or origin
delay. In other words, the actual triggering impulse
reaches all over the globe simultaneously (within the avail-
able time resolution) and "..the two second delay would have
been the time necessary for the process, involved in each of
these local excitation, to be performed" (Roquet, Schlich and Selzer, 1963). The triggering mechanism is not specified, but either the "phase A" pulse or neutron-decay betas could fit the timing requirements. However, it would appear to be almost impossible to reconcile the sharp sudden commencement with this hypothesis. Unless some sort of breakdown effect can be formulated, any such process would be gradual from the instant of impulse arrival, rather than sharply defined at H+2.

II. SECONDARY FOCUS MECHANISMS

We are now considering a group of possible mechanisms which we have called "secondary focus" type for want of a better name. These imply energy in some form impinging on an interface (or other critical region) and setting up a secondary focus of disturbance from which energy is re-emitted at (or close to) the speed of light. The two-second delay would be accounted for by propagation delay between primary source and secondary focus, or by the time required to set up the necessary conditions for emission at the secondary focus, or a combination of both. We feel that in view of the close synchronism of the signals recorded at widely separated locations, such a "secondary focus" mechanism
is far more likely than a direct primary "overhead" effect at each station.

The actual nature of the energy conversion and of the speed-of-light transmission mode are as yet unspecified—the required theoretical work is beyond the scope of this preliminary investigation. It should be pointed out that the term "e.m. wave radiated from a secondary focus" must be used only with reservations, particularly if the disturbance is to be propagated in the earth-ionosphere wave guide. At the frequencies involved (0.25-0.30 cps) the free-space wavelengths are over $10^6$ km, i.e. orders of magnitude greater than the dimensions of the wave guide or the propagation distances. The static ($1/d^3$) and induction ($1/d^2$) effects both become comparable to radiation effects at distances less than $1/6$ of a wavelength.

On the other hand we could consider the signal as a series of impulses, with recovery in between. The observed sine-shaped fluctuations would then be explained by filtering through the transmission medium and/or instrumentation. This would in fact fit some of the proposed mechanisms better than a monochromatic source emission, but it still leaves unspecified the mode in which these impulses are propagated at the speed of light.
1) Neutron-decay betas. We have previously considered (and rejected) the direct overhead ionization effects of neutron-decay betas at each station. However, because of the focusing effect of the field-line geometry, a high proportion of them will be deposited in the conjugate areas and in the auroral zones (Kenney and Willard, 1963). This could provide a possible triggering mechanism for secondary disturbances. The main objections to this theory are: a) the 2 second time delay - the deposition is practically instantaneous at the time-scales considered, i.e. milliseconds to about 0.2 seconds, and b) the previously considered amplitudes. This mechanism is almost certainly responsible for the (instantaneous?) auroral displays reported from auroral zone locations, and probably also for the abnormally high-amplitude horizontal component deflection reported from an auroral zone magnetic observatory (Meanook; Cook, private communication). It is however unlikely to be responsible for the global "phase B" signal.

It should be pointed out that if our assumed neutron spectrum (i.e. fission explosion) is incorrect, this mechanism may have to be reconsidered. In particular, if a very large flux of very low energy neutrons is produced, a longer delay (2 seconds) could be accounted for in the case of an auroral zone secondary focus, and the mechanism may be theoretically possible as far as the timing is concerned.
However, the available amplitude data point towards a source in the detonation area rather than in the auroral regions (Bomke et alia, 1963).

2) **Fission-product decay betas.** We have previously discussed the effects of fission-product decay betas, and concluded that they do not fit "phase B" observations in as far as direct overhead ionization effects are concerned. However, the relatively concentrated deposition of these betas in the conjugate area could provide a possible secondary-focus mechanism. The transit time of the betas along the field lines is practically instantaneous at the time resolutions considered, which raises the question of the 2 second delay. The expansion time of the bubble is of the right order of magnitude. Colgate (1963) estimated 2.5 seconds as the time required for the bubble to reach its terminal dimensions $R = 1000$ km. A precise figure would be difficult to obtain in view of the uncertainties in parameters — in particular, the proportion of the total yield which is available for expansion of the bubble could vary between 30% and 70%.

A continuous process rather than a sudden release could be expected, since energetic electrons would be continuously escaping from the bubble during expansion. However,
the expansion of the bubble may actually provide some sort of energy "filtering" mechanism - higher energy electrons would lose energy in expanding the bubble against the pressure of the magnetic field, until at the time the expansion is stopped (H+1.9 sec?) a reasonably monoenergetic flux is released to spiral to the conjugate areas and to trigger the secondary disturbance. This mechanism does not explain the oscillatory nature of the signal (since the mirroring electrons have much shorter periods), but it appears to fit the timing requirements for the initial impulse of "phase B".

The spectral characteristics of fission decay decay betas have been discussed by Zmuda et alia (1963a), but the general arguments for this particular mechanism are practically unaffected by the precise spectral distribution, since the beta transit time to the conjugate area is short compared with 2 seconds, even for low energy electrons.

3) Hydromagnetic Electromagnetic conversion at the lower Ionosphere boundary.

A very simple, and therefore attractive, model was tentatively proposed by Bomke et alia (1963). A hydromagnetic wave propagates vertically downward from the detonation point, and on reaching the lower ionosphere boundary sets up a secondary disturbance which is then propagated at the speed of light. The conversion efficiency between hydro-
magnetic (h.m.) and electromagnetic (e.m.) waves at a sharp interface (which is satisfied at the wavelengths involved) is of the order of one to a few percent. Kahalas (1960) obtained a figure of 1%, but pointed out that his derivation was based on assumptions which are not necessarily valid for the lower ionosphere.

The propagation time for a hydromagnetic wave between the detonation point and 80 km altitude could possibly account for the 2 second delay. A precise computation of this propagation delay would be meaningless, since the properties of the medium below the detonation point would have been drastically altered by the prompt radiation (x-rays in particular). An estimate of limiting values has been worked out in Appendix II. A 2-second delay appears to be at the extreme limit of the acceptable range for radiating temperatures up to 2 kev, but would be well within the acceptable range for higher-temperature devices (fusion bomb?).

There are two objections to this model: a) The monochromatic nature of the observed signal does not fit the essentially impulsive (i.e. broadband) origin disturbance. Although selective propagation could explain the predominance of certain frequency bands (Jacobs and Watanabe, 1962), it is unlikely that this could be effective enough over the short pathlength involved to account for a sharp
frequency selection as observed.

b) The main objection against this mechanism is the fact that lower altitude tests (in particular "Teak", at or just below 80 km) do not produce similar effects. Admittedly the conversion of explosion kinetic energy into hydromagnetic forms is considerably more efficient at the higher altitudes. Nevertheless, considering how close the "Teak" detonation was to this hypothetical "secondary focus" altitude, some comparable effects (even if with much lower amplitudes) should have been observed, with a reduced or zero delay. It should be mentioned that this argument is somewhat complicated by the possibility that shielding experiments may have been included in some of the tests. For example, relatively simple devices can reduce the prompt radiation flux by factors of 100 or more, and the mean energy levels by factors of 10-20 (Latter, Herbst and Watson, 1961; Latter and LeLevier, 1963). Also the actual type and construction of the bomb, in particular the casing material, has a strong influence on the spectrum of the emitted prompt radiation. Although shielding experiments may have been included in some of the smaller tests, it is very unlikely that major ones such as "Teak" included any such complications. Nevertheless, it should be kept in mind that not only do we have a minute sample, but we do not even have reliable origin information on these few tests. Consequently any arguments as to why only certain tests do or do not produce certain results must be used with caution.
4) **Hydromagnetic impulse guided along the field-line.**

In this mechanism a hydromagnetic impulse is guided along the field-line through the detonation point, with partial reflections at each end. The mechanism is effectively a variant of the previous one, but might also explain the oscillatory nature of the signal, the observed period, and the absence of similar effects from lower-altitude tests. It would also fit the damped amplitude effect, and the "bounce" period is of the right order (3-4 seconds).

A simple consideration of the geometry involved indicates a major timing vs. period objection. Figure 6 shows the relevant field-line, drawn to scale. It is obvious that if t (the initial delay, H→P) is 2 seconds, T (the first bounce period, P→R) cannot be as low as 3.5-4 seconds. There is, however, a possible explanation for the discrepancy - the "reflection point" P is in the direct radiation zone, and the medium around it undergoes vast instantaneous changes in ionization due to prompt radiation, in particular x-rays (which for the spectrum of a fission bomb deposit most of their energy at altitudes of 70 to 90 km) - see Appendix II. The γ-rays deposit energy down to lower altitudes (about 20-30 km for the Mev energy range). Although the ionization due to the prompt γ-ray pulse decays within microseconds, some persisting net ionization at these lower altitudes (over a few seconds) results from delayed
FIG. 6 FIELD LINE THROUGH THE DETONATION POINT
"STARFISH" TEST OF JULY 9, 1962.
fission-product $\gamma$-rays. It is therefore possible that for the first pass ($H\rightarrow P$) the medium was practically opaque to h.m. waves, or that the necessary (interface sharpness?) conditions at point $P$ did not exist. The initial "secondary focus" would therefore be set up at point $R$ in the southern hemisphere. This removes the timing-geometry objection: for $t (H\rightarrow R) = 2$ seconds, $T (R\rightarrow P) = 3-4$ seconds is quite reasonable. Crain (1963) has shown that at the relevant altitudes (75 km) the x-ray induced ionization decays with time-constants of the order of a few seconds. Consequently, when the reflected wave reaches $P$ (i.e. after 5-6 seconds, $H\rightarrow R\rightarrow P$) the "interface" may have sufficiently recovered to permit efficient energy conversion ($h.m. \rightarrow e.m.$) and reflection. The very slight reverse movement which preceded the main movement on several recordings (e.g. Victoria, Figure 1, or Jicamarca - see Figure 5 of Casaverde et alia, 1963) may represent the effect of the "aborted" first $H\rightarrow P$ pass. The fact that the delay $H\rightarrow P$ was only slightly less than $H\rightarrow R$ would be reasonable, in view of the large x-ray induced initial increase in ionization over the $H\rightarrow P$ section - see Appendix II.

There is an interesting ambiguity in this model. Does energy emission occur at both mirror points (i.e. are there 2 secondary sources), or does only the southern focus exist, with the northern end having recovered sufficiently
to permit passage of the hm wave and reflection, but not for
efficient h.m. → e.m. energy conversion? In as far as
timing data are concerned, this question can be restated as:
does the observed 3.5-4 second period represent the transit
time for a one way bounce (R→ P or P→ R), i.e. focus at each
end, or does it represent a full mirror period (R→P→R), i.e.
focus at southern end only? Even under normal conditions
the Alfvén velocities are not known to better than a factor
of 1.5-2, and with the artificial ionization changes over
parts of the path it becomes impossible to compute the mirror
period with sufficient accuracy to resolve the above ambi-
guity. The limiting cases fit just about equally the two
possibilities. For undisturbed night-time conditions, the
mean Alfvén velocities at altitudes of 350, 500, 750 km are
800, 1000 and 2000 km/sec respectively (Jacobs and Watanabe,
1962), and a full mirror period of 4 seconds is possible.
Under disturbed conditions these velocities are reduced by
a factor of 2 or more, and the 4-second period would have to
be the time per one-way transit, i.e. focus at each end.
The ambiguity might be resolvable on theoretical grounds
once the exact conditions for reflection and energy conver-
sion are established. In any case, the overall validity of
this model is in no way affected by this ambiguity.

We are well aware of the weaknesses in this qual-
titative treatment, and considerable theoretical work on the
conditions for h.m. → e.m. energy conversion must be carried out before such a model is fully acceptable. It does, however, fit the experimental timing data extremely well - it is the only theory so far which fits all the specified conditions, including the decrease in period. This could be explained by the fact that on the first pass the ion density over parts of the path would have been significantly increased by detonation products travelling faster than the h.m. wave, and the Alfvén velocity (which is inversely proportional to the square root of the ion density) would be lower than normal. As the artificial ionization decays (time constants of the order of seconds) the Alfvén velocity increases and the bounce period decreases. The observed 20%-30% decrease in bounce period over about 15 seconds would indicate an effective initial increase in ion density of 50%-70% - not unreasonable for this particular path which is partly in the prompt radiation zone and also along the guided path of fast betas.

There is some independent (though very weak) confirmation for a "source" of 3-second period oscillations in the southern hemisphere. Poletti and Gadsden (1962), from amplitude comparisons of telluric recordings at two New Zealand stations with identical instrumentation, conclude that the source of 3-second period pulsations must have been "a few hundred kilometers, at most, to the north of Lauder
(50° geomag. lat.)", i.e. at about 40°S geomag. This is of course much further south than point R (by about 20°, i.e. 2000 km). Also the pulsations referred to are not those of "phase B" (which were unfortunately off-scale at both stations), but some later arrivals. Consequently no great emphasis can be put on this evidence in support of the proposed model. Although it may be relevant, it is probably due to some entirely different conjugate-point effect.

5) **Hydromagnetic wave along the field-line.** Some of the points discussed for the previous model can also be applied to a long-period hydromagnetic wave propagating along the field-line through the detonation point. The 2-second delay would represent the propagation time of the wave front to the conjugate point. The distinction between this model and the preceding one should be clearly understood. In the preceding model we considered a hydromagnetic impulse (i.e. broadband "wave-packet") which is propagated along the field-line. 0.25 p.p.s. represents the repetition rate of the impact of this impulse on the interface, not a wave frequency. The higher component frequencies of the pulse are either not converted into electromagnetic forms, or are filtered out by propagating media and/or instrumentation. In this model we consider a single hydromagnetic standing wave, frequency 0.25 cps, with direct coupling to a 0.25 cps
electromagnetic wave at an interface.

The main objection to this mechanism is the monochromatic nature of the signal. It is however possible that preferential excitation of the eigen periods, combined with selective h.m. to e.m. conversion of certain frequency bands, could provide a suitable explanation. The fundamental characteristic period can be estimated by numerical integration

\[ T = \int \left( \frac{2}{V_A} \right) \, ds \] over the field-line (Obayashi and Jacobs, 1958). It lies between about 6 and 15 seconds (using the Alfvén velocities for night time during periods of maximum and minimum sunspot activity respectively). In view of the increase in ionization due to radiation, and of the extreme distortion of the field-line by the diamagnetic bubble, a precise determination of eigen-periods is impossible. The observed periods are therefore well within an acceptable range of values for the first harmonic.

This mechanism fits the observational data in all respects. The decrease in period is also obtained - as the artificially-induced increase in ionization decays, the Alfvén velocity increases and the eigen-period decreases. There appears to be no obvious way of distinguishing between this and the preceding model on the basis of the observational data, but we feel that the standing-wave model is preferable, even if only on aesthetic grounds alone. It does not involve any elaborate considerations of geometry or focus.
location, and it does not require complex filtering mechanisms to explain the observed quasi-sinusoidal signals.

6) **Protons guided along the field-line.** The major source of prompt protons from a fission process is neutron decay. The protons have essentially the same kinetic energy as the parent neutrons. The energy distribution of prompt neutrons from a fission process has been discussed in detail by Bonner, Ferrel, Rinehart (1952), Hill (1952), and Watt (1952). In the energy range 0.075 Mev to 17 Mev it can be roughly represented by the semi-empirical formula given by Watt (1952):

\[ N(E) = 4.75 \times 10^6 \sinh \left( \frac{E}{2} \right)^{1/2} \exp \left( -E \right) \]

No information is available for energies below 75 keV. Figure 7 shows a plot of the energy distribution up to 7 Mev. The spectrum has a very broad maximum centered at 0.8 Mev - emission is practically constant (within a few percent) between 0.4 Mev and 1.3 Mev. Even though energies range to above 18 Mev, most of the neutrons are below 2 Mev, the fall-off being practically exponential above 2 Mev.

For this particular field-line the two-way mirror period of 1 Mev protons is about 2 seconds (Zmuda et alia, 1963a), 3 seconds for 0.4 Mev, and 4 seconds for 0.25 Mev, which is of the right order for the observed "phase B"
FIG. 7 ENERGY SPECTRUM OF FISSION NEUTRONS

Intensity - Arbitrary Units $N(E)$

Neutron Energy (MEV)
periods. In this connection it should be mentioned that Zmuda et alia (1963a) reported 10-second period cyclic VLF effects over the NPG-APL/JHU path, which they tentatively attributed to 0.4 Mev protons mirroring over NPG. In view of the uncertainties in field-line geometry and other parameters, it is possible that the two effects could be reconciled to fit the mirroring of protons with the same energy (say 0.3-0.4 Mev) along different field-lines.

The same objections of timing-geometry (initial delay vs. period) which were discussed in one of the preceding mechanisms, can be made to this mechanism and the same solution can be proposed, viz. the first reflection and energy conversion occurs at the southern end. Here again the same ambiguity as in the previous model arises: does a "focus" exist at each end, or only at the southern end. In this case, however, the ambiguity can be solved. The relevant reflecting altitudes are higher (about 100 km for 0.4 Mev protons), and the x-ray induced ionization decays far more slowly at these altitudes than at 80 km. For altitudes 95 to 115 km the decay constant varies between 400 and 3000 seconds (Crain, 1963), depending on the exact altitude and magnitude of the ionizing pulse. If this model is at all valid, there can be only one "secondary focus" (at the southern end), and the 3.5-4 seconds represent a full mirror period, i.e. protons with energies 0.25 to 0.20 Mev.
This provides the possibility of an experimental check on the validity of this model. Observed signal amplitudes should be higher near the conjugate point than near the detonation point. This does not appear to be the case, but the evidence is based on only one set of observations: Bomke et alia (1963) reported that the amplitude recorded at Hawaii was higher than that recorded at Samoa by a factor of about four.

Another major objection to this mechanism is the sharpness of the commencement, and the clearly defined frequency of the subsequent swings. In view of the broad energy distribution spectrum of the protons, a continuous (seconds rise time) commencement and complex waveforms could be expected. Also this model provides no explanation for the decreasing period. However, should the emission turn out to contain a major, reasonably monoenergetic source of low-energy (0.2-0.4 Mev) protons, the mechanism may have to be reconsidered in more detail. It should be pointed out that the presented spectral distribution data refer to emitted neutrons in general. The spectrum of the proportion which escapes the debris area would probably be shifted toward the low-energy end due to shielding by the debris. (The shift could be considerable if deliberate neutron shielding had been part of the test, but this is unlikely in view of the bulk of the necessary shields.) However, the
general feature (i.e. broad maximum, almost 2 Mev "wide") would presumably remain unchanged, even though it may be centered around a lower energy, so that this does not fit the requirement for a monoenergetic flux.

CONCLUSION

The preceding discussion indicates that hydro-magnetic standing waves along the field-line through the detonation point provide the most likely explanation for the "phase B" signal. It is the only one of the mechanisms discussed in this report which fits all the observational data, and is not dependent on a knowledge of the bomb type (fission and/or fusion).

Whatever the triggering mechanism, further theoretical work is required on the energy conversion mechanism at the secondary focus, and on the speed-of-light propagation of the secondary disturbance.

No unique solution is claimed - other models are possible, and with the limited amount of data a sensitive enough criterion for distinguishing between the different mechanisms is hard to define. Some additional lines of approach to this problem are suggested in Appendix I, which may yield the necessary information if additional observational data become available.
APPENDIX I

ADDITIONAL LINES OF APPROACH

1) More precise timing considerations. There are apparent time discrepancies of the order of 0.1-0.2 seconds between some of the basic stations. These are almost certainly not real, being probably due to differences in the recorded components or other factors. If a network of highly accurate (better than 50 milliseconds), identically instrumented observations become available, useful information could probably be extracted which would distinguish between the different models. Unfortunately, because of the relatively slow rise time of natural "sudden" geomagnetic phenomena, most researchers in this field have not developed or applied the timing techniques and disciplines which are required for this type of work. Highly standardized instrumentation and recording of the same magnetic-coordinate component are also necessary for high-accuracy timing work, since the exact commencement of the disturbance is otherwise hard to define. In view of the difficulty in assembling even a few suitable (±0.1 sec) observations on a global scale, it is doubtful whether a set of such ±0.05 sec data exists, at least in the unclassified domain.
2) Amplitude considerations. The present report has been based almost entirely on timing considerations. An analysis of amplitude-location relations could go a long way towards the removal of the ambiguity between the different mechanisms, through the determinations of focus location, attenuation characteristics, and possible anisotropies in propagation. Unfortunately the data published so far are unsatisfactory from this point of view, for two reasons:

a) Most of the magnetic recordings obtained with the appropriate bassband went off-scale during the first "phase B" fluctuations. This means that only a lower amplitude limit can be assigned, depending on the full-scale range of the particular instrumentation - which varies between 0.5 and 50\(\pi\) for different stations. Recorders fitted with scale-limit (bias) stepping mechanisms introduced an uncertainty of 1 or even 2 steps (i.e. 1-2 full scale ranges) because of the unusually rapid full-scale excursions - see for example Baker and Strome (1962).

b) Variability in recorded component and in instrumentation. Quite apart from tellurics (which cannot be included for amplitude comparisons) there are 6 normally acceptable ways of choosing a single-component recording (D, H, Z, X, Y, F), of which five are usually recorded with either amplitude-linear or rate-of-change detectors. This means eleven different methods - quite apart from the widely varying frequency response characteristics. This makes it almost
impossible to extract amplitude comparisons to better than an order of magnitude, even if the recordings had remained on scale. Also, vertical components, particularly at the frequencies involved in the "phase B" signal, are far too heavily dependent on local geologic conditions to be useful for amplitude comparisons. In view of the availability of commercially-manufactured total force instruments, it was to be hoped that at least a number of total-field amplitudes would have been available from identical equipment. However, in some cases the large and rapid variations of the "phase B" signal were beyond the range which could be effectively recorded (because the counting period becomes comparable with the time scale of the fluctuations), and "phase B" recordings on some total-field instruments must be used with caution. For example, Unterberger and Byerly (1962) reported that two Rubidium Vapour magnetometers operating at the same location (5 feet apart) gave coherent recordings up to H+2 secs and after H+30 secs, but not during the "phase B" fluctuations. Judging from the published record reproductions, the same comment probably applies to the total-field recording obtained at Ottawa (Baker and Strome, 1962).

To summarize, the normal observation routines and standard instrumentation were not designed to cope with the extraordinary features of this artificial geomagnetic disturbance.
3) **Geographic coverage.** All the stations which reported major (large amplitude) and clearly-defined "phase B" arrivals lie in a geomagnetic longitude band about 205° wide (240° to 85°). This may be suggestive of some sort of broad field-line guiding effect, or at least of some hemispheric limitation, although it is probably fortuitous - it may simply represent the geographic distribution of stations having the appropriate sophisticated instrumentation and advance notification of the test. Bomke et alia (1963) reported highly isotropic propagation for the USAERDL stations (which cover a 105° band in geomagnetic longitude to the east of Johnston Island). A definite answer to whether isotropy applies on a global scale as well will have to await publication of records from other continents - in particular from the Soviet telluric network with its extended longitude coverage.

Two isolated reports which do not fit into an isotropic global coverage pattern remain to be explained, but both are of limited significance until confirmed by other observations.

a) A single channel (D) record obtained by the UK Signals Research and Development Establishment at Ascension (Geographic coordinates: $\delta = 8^\circ S, \lambda = 14.3^\circ W$; Geomagnetic latitude $\lambda' \sim 1^\circ S$) indicates a peak amplitude of under 0.5 gamma. The frequency response of the system is roughly
linear between 0.03 and 0.2 cps, with 3 db points at 0.007 and 2 cps. However, there is some possibility that the effective response to rapid fluctuations may be low because of abnormal pen response limitations (Stevens, private communication). In comparison, H and F geomagnetic recordings of "phase B" obtained at two other equatorial stations, Huancayo and Jicamarca (both at $\lambda' \sim 1^\circ S$), indicate amplitudes comparable to those obtained at higher latitudes (Casaverde et alia, 1963). However, the induction magnetometers at these two stations were recording H (magnetic N-S), whereas D (magnetic E-W) was recorded at Ascension.

b) A telluric recording at Alert ($\phi = 82.5^\circ N$, $\lambda = 62.5^\circ W$; $\lambda' = 86^\circ N$) failed to give a measurable response (Caner and Whitham, 1962). Detection sensitivity of the instrumentation is a few mV/km, and response time about 1 second. In comparison, a telluric "phase B" recording at Lincoln, New Zealand, exceeded hundreds of mV/km (Gill, 1962). To judge by the published record reproductions, the amplitude may have exceeded 1 V/km. Similarly, on telluric recordings obtained at Prince Albert, Sask. ($\phi = 53.2^\circ N$, $\lambda = 105.9^\circ W$; $\lambda' = 62^\circ N$), the amplitude is well in excess of the 30 mV/km full-scale range (Graystone, 1963). At Meanook ($\lambda' = 61.8^\circ N$) the amplitude probably exceeded 100 mV/km (Cook, private communication). It should be pointed out that the Alert recording was obtained on a field survey (Law et alia, 1963), not as part of a regular observatory operation. It is
consequently of limited reliability, because of the instru-
mental uncertainties inherent in temporary installations.

Normally, stations which do not record any sig-
nificant effects do not publish "negative" reports. However,
the location of other possible "blind spots" could help to
resolve the ambiguities between the proposed mechanisms.
For example, if confirmed by other reports, the absence of
E-W components in the disturbance at equatorial stations would
permit significant deductions to be made about the horizon-
tal polarization of the disturbance, and could provide an
answer on the nature of this disturbance. The need for
more three-component recordings is evident. Alternatively,
confirmation of a gap at very high geomagnetic latitudes
(>80°) would be strong evidence for a broad field-line
guided mechanism rather than an isotropic e.m. wave.

We would therefore be very interested to hear from
stations with appropriate instrumentation (time resolution
1 second or better, detection sensitivity of a few gammas,
frequency response to about 1 cps) which did not record any
significant pulsational activity at H+2 seconds (i.e. at
0900:11s U.T. on July 9, 1962). Identification of "bs" or
"crochet" type events on standard magnetograms is not
directly relevant since the longer-period "main" phase is
probably due to entirely different effects, in particular
charged particle drifts (see for example Pisharoty 1962, and
APPENDIX II

X-RAY IONIZATION AND ALFVEN VELOCITIES
BELOW THE DETONATION POINT

In a discussion of the different mechanisms it was pointed out that the propagation time of a hydromagnetic wave between the detonation point and an altitude of 80 km could not be accurately computed because of the ionization increase below the explosion. However, some limiting values can be derived, since the main prompt ionizing effects over this path are due to x-ray energy deposition.

There are two major uncertainties in the parameters used for computation of these effects: a) the x-ray yield, which could vary between 30% and 70% of the total yield, depending on the type and construction of the bomb; b) the x-ray temperature of the radiating materials, which ranges between $kT = 0.5\text{ kev}$ and 2 kev for an unshielded explosion.

Since the energy from high temperature explosions is deposited mainly at lower altitudes where recovery is very rapid (Latter and LeLevier, 1963), lower temperature devices would have the maximum effect on the mean Alfvén velocities over the entire path. Consequently an upper limit for the propagation delay can be obtained by considering a 0.5 kev bomb with an x-ray yield 75% of the total yield.
(i.e. 1050 kilotons for "Starfish"), and a lower limit for 2 kev and 350 kilotons. The energy deposition as a function of altitude has been computed using the saddle-point method outlined by Latter and LeLevier (1963):

\[ E(z) = \frac{15}{\pi^4} \left( \frac{\pi}{2} \right)^{1/2} \frac{3 \cdot 4 \times 10^3}{(kT)^3} r(z) \cdot \left[ c \cdot h(z) \right]^{1/8} \exp \left[ - \frac{4}{3} \left[ c \cdot h(z) \right]^{1/4} \right] \]

where \( E(z) \): the energy deposition (ergs/cm\(^3\)) per unit x-ray flux

\( kT \): the x-ray temperature in kev

\( r(z) \): the density at altitude \( z \) (gr/cm\(^3\))

\( h(z) \): the total mass per unit area of the atmosphere between the explosion and altitude \( z \)

and \( c = 10.2 \times 10^3 / (kT)^3 \)

The values of the parameters \( r(z) \) and \( h(z) \) have been derived from the ARDC model atmosphere (Minzner, Champion and Pond, 1959).

The x-ray flux at any altitude is given by

\[ F(z) = 3.2 \times 10^8 Y / R^2, \]

where \( Y \) is the x-ray yield in kilotons, and \( R \) the distance in km, i.e. \( R = 400 - z \) for "Starfish".

Multiplying \( E(z) \) by \( F(z) \) for each altitude gives the magnitude of the ionizing pulse, and since \( 2.1 \times 10^{10} \) ion pairs are produced for each erg of deposited energy, the resultant ionization \( \Delta N \) can be computed. Figure 8 shows the values of \( \Delta N \) at altitudes from 50 to 350 km, for 0.5 and 2 kev temperatures and an x-ray yield of 1050 kilotons.
The corresponding Alfvén velocities as a function of altitude have been derived and are plotted in Figure 9. The propagation time delay between altitudes of 350 and 80 km based on these velocities is

\[ T_{\text{max}} = 46 \text{ seconds} \ (0.5 \text{ kev}, 1050 \text{ kilotons}) \]
\[ T_{\text{min}} = 10.6 \text{ seconds} \ (2 \text{ kev}, 350 \text{ kilotons}) \]

Some qualifying comments should be made:

1) The ambient ionization has been neglected, since nighttime ion densities are several orders of magnitude below the x-ray ionization densities.

2) Ionization by other prompt energy emissions has been ignored. In particular, neutron products and the low energy tail of the \( \gamma \)-ray pulse contribute to ionization in this region. However, energy considerations and a few check-computations showed that their contribution would amount to about 1-2\% of the x-ray effects, which can be neglected as far as the Alfvén velocities are concerned.

3) The saddle-point method gives a good approximation to the values obtained by exact numerical integration methods for altitudes up to about 120 km (Latter and LeLevier, 1963). Above this height the divergence becomes progressively worse, the saddle-point derived values being consistently lower than the exact values. Above 200 km it is little better than a rough estimate. Nevertheless, for computations of Alfvén velocities this is quite adequate, since about 60\% of the total time delay is introduced between altitudes of 120 and
FIG. 8  X-RAY IONIZATION BELOW THE DETONATION POINT
FIG. 9 ALFVÉN VELOCITIES BELOW THE DETONATION POINT
80 km. A factor-of-2 error in ionization densities over the rest of the path would affect the total delay time by a maximum of 20%.

4) No attempt has been made to even estimate conditions just below the explosion point (i.e. 350-400 km altitude). The difficulty has been avoided by postulating that the piston itself was still driving through most of this layer (i.e. negligible time delay - expansion velocities are about 100-1000 km/sec). The triggered hydromagnetic wave was then assumed to have started at an altitude of 350 km. Most of the bubble expansion is upwards into less resistant medium (Colgate, 1963), and 50 km appears to be a reasonable estimate of the maximum downward range of the expansion.

5) The values of the parameters $r(z)$ and $h(z)$ are suitable mean values, but Johnson (1961) has emphasized that actual values at any one time could be significantly different. Some check calculations have been carried out, using extreme values for these parameters, and the overall effect on the delay time is of the order of ±2 to 5%. A further possible ±1 to 2% error is introduced by the variations in the mean molecular weight.

To summarize, as far as the "minor" sources of error are concerned, the delay times should be considered +25%, -5%, i.e.

$T_{\text{max}} = 44 - 58$ seconds

$T_{\text{min}} = 10 - 13$ seconds.
A further major uncertainty is introduced by the shock-wave nature of the disturbance. The piston velocity is at least an order of magnitude greater than the Alfvén velocity in the medium below. The hydromagnetic Mach number

\[ M = \frac{1}{\sqrt{2}} \left[ \frac{\alpha}{\alpha_0} + \left( \frac{\alpha}{\alpha_0} \right)^2 \right]^{1/2} \]

where \( \alpha \) is the density behind the shock front and \( \alpha_0 \) is the undisturbed density (Lundquist, 1952). In the absence of detailed information about the explosion characteristics, we can arrive at limiting (maximum) values of \( M \) by considering a strong shock. For this case \( \alpha/\alpha_0 = (\gamma + 1)/(\gamma - 1) \) where \( \gamma \) is the ratio of the specific heats. The correct value of \( \gamma \) is not known – an acceptable range for this region is \( \gamma = 1.4 \) to \( \gamma = 2 \). The low values of \( \gamma \) used by Caner and Whitham (1962) to explain the possibility of very high Mach numbers are not justified, since the medium is by no means fully ionized (1-2% only), and since the shock direction is normal to the direction of the field. For shocks normal to the field direction in a medium where the magnetic pressure is much higher than the hydrodynamic pressure, \( \gamma = 2 \) can be used (Montgomery, 1959) and \( M = 2.45 \). At the other extreme, the ratio of the specific heats up to an altitude of 90 km is normally defined to be 1.4 (Minzner, Champion and Pond, 1959). For \( \gamma = 1.4 \), \( M = 4.6 \). Applying this maximum value of \( M \) to \( T_{\text{min}} \), we arrive at an extreme value for \( T_{\text{min}} = 2.2-2.8 \) seconds.
It would appear therefore that for bomb temperatures up to 2 kev a 2 second time delay is not impossible, although not very likely. In particular the low x-ray yield and high Mach number are rather extreme assumptions. For temperatures in excess of 2 kev a 2 second time delay is quite reasonable.
REFERENCES


Jacobs, J.A. and T. Watanabe (1962). Propagation of hydro-
magnetic waves in the lower exosphere and the origin of 
short period geomagnetic pulsations. J. Atmos. Terr. 
Phys. 24, 413-434.

(Ed. Johnson, F.S.), Stanford University Press.

Kahalas, S.L. (1962). Magnetohydrodynamic wave propagation 

Kenney, J.F. and H.R. Willard (1963). Trapped radiation and 
ionospheric perturbations due to an impulsive neutron 

Latter, R. and R.E. LeLevier (1963). Detection of ion-
ization effects from nuclear explosions in space. 
J. Geophys. Res. 68, 1643-1666.


Investigations during 1962 of the Alert anomaly in geo-

effects resulting from two high-altitude explosions. 
Nature 184, BA 34-52.

Arkiv f. Fysik 5, 297-347.

Maeda, H., A.J. Shirgaokar, M. Yasuhara and S. Matsushita 
(1964). On the geomagnetic effect of the Starfish high-
alitude nuclear explosion. To be published J. Geophys. 

ARDC model atmosphere. Air Force Surv. Geophys. 115, 


