RADIO SCIENCE Journal of Research NBS/USNC–URSI
Vol. 68D, No. 1, January 1964

VLF Anomalies Observed at State College, Pa., During the U.S. 1962 High-Altitude Nuclear Tests

C. F. Sechrist, Jr.

Contribution From HRB-Singer, Inc., State College, Pa.

During the summer and fall of 1962 the U.S. conducted five high-altitude nuclear tests near Johnston Island in the Pacific Ocean; these tests ranged in altitude from tens of kilometers to 400 km, and in yield from low to 1.4 megatons. The relative phases and field intensities of two U.S. Navy VLF stations (NPG at Jim Creek, Wash., and NBA at Balboa, Panama Canal Zone) were measured at State College, Pa., during the tests, and all except the 4 November 1962 test produced positive results.

Because of the geometry of the propagation paths and the burst point, enhanced *D*-region ionization was produced by neutron-decay beta particles on the NPG-State College path, and by geomagnetically-trapped fission-decay and/or neutron-decay beta particles on the NBA-State College path.

Concerning the NPG signal anomaly, the onset and maximum were practically instantaneous; this is consistent with the neutron-decay model of Crain and Tamarkin. The perturbations of the NBA signal were delayed by minutes, for the four tests, and by tens of minutes for the 20 October 1962 and 26 October 1962 tests; these delayed effects may be ascribed to enhanced ionization in the lower ionosphere produced by geomagnetically-trapped beta particles that originated in the radioactive decay of fission fragments and/or the decay of neutrons.

Results of preliminary computations, based on tapered- and step-ionosphere waveguide models and Wait's first-order theory for a variable height earth-ionosphere waveguide, are presented.

1. Introduction

It is known that high-altitude nuclear detonations induce VLF anomalies not only in regions which are line of sight to the burst but also in shadow regions where VLF propagation paths are shielded by the earth from the direct X and gamma radiation and particle flux. The VLF anomalies produced in the shadow regions arise from an enhancement of ionization in the lower ionosphere, caused primarily by the bombardment of beta particles which have been guided by geomagnetic field lines into the VLF propagation paths.

A prompt, shadow-zone VLF anomaly appears within a few seconds of the burst, has a lifetime of the order of seconds, and is related to the effects of neutron-decay beta particles [Crain and Tamarkin, 1961].

Delayed, shadow-zone VLF anomalies have onsets within minutes and tens of minutes of the burst, have a gradual buildup and decay, and usually have a temporal variation which correlates with the longitudinal drift times and energy spectra of the geomagnetically-trapped beta particles forming an artificial radiation belt. Generally, the first delayed effect relates to the longitudinal drift of trapped beta particles from fission fragments, and the second delayed effect relates to the trapped beta particles from neutron decay [Zmuda et al., 1963a and 1963b].

2. VLF Phase and Field Intensity Data

During the U.S. 1962 high-altitude nuclear tests the field intensities and relative phases of transmissions from NPG (18.6 kc/s) and NBA (18 kc/s) were measured at State College, Pa. The phases of these stabilized VLF transmissions were measured relative to a local reference oscillator having a frequency stability of 1 part in 10^9 per day. To avoid the slow response times of phase-tracking VLF receivers, an essentially delay-free photographic recording technique was used in conjunction with VLF receivers having bandwidths of about 200 c/s; this phase measurement technique is described by Sechrist and Felperin [1961] and by Sechrist [1962] who observed small, short-term phase perturbations during geomagnetic disturbances. The field intensity was measured simply by applying the RF amplifier outputs of the VLF receivers to peak detector circuits and recording the d-c voltage outputs on a dual-track chart recorder.

The results of the VLF measurements obtained during the nuclear tests are presented below.

2.1. Event of 9 July 1962

Concerning the 1.4-megaton and 400-km test[1]

[1] Burst information contained in the paper by Brown, Hess, and Van Allen [1963] listed in the references.

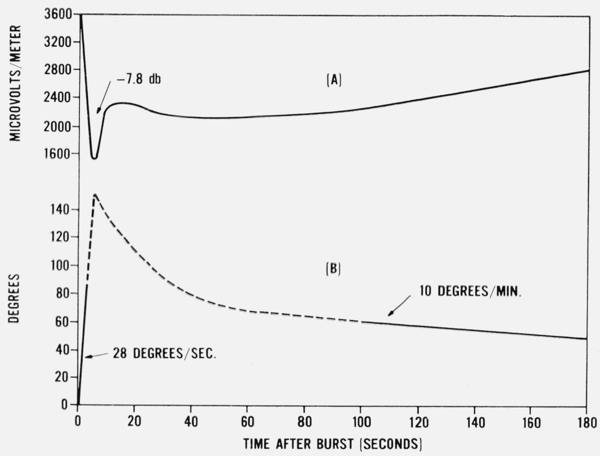

FIGURE 1. *NPG field intensity and phase—9 July 1962.*

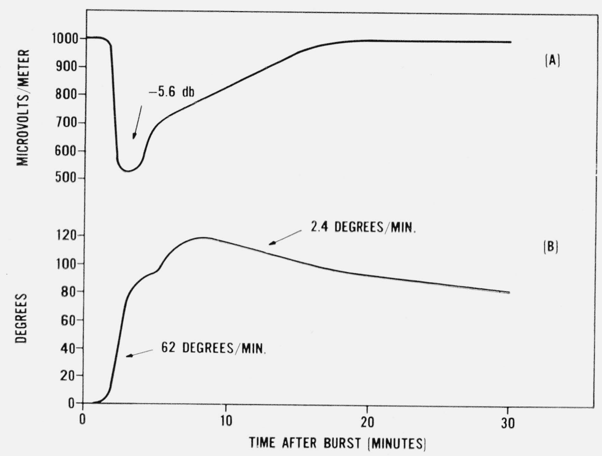

FIGURE 2. *NBA field intensity and phase—9 July 1962.*

of 9 July 1962, it should be noted that the detonation time was 0900:09 UT, layer sunrise (50 km) at State College, Pa., was 0903 UT, sunrise effects were observed in the NBA phase data commencing at about 0920 UT, and the magnetic K_p index was 2 [Lincoln, 1962]. Essentially, both paths were in darkness at the time of the detonation. The VLF data may be summarized as follows:

(1) The NPG field intensity decreased from 3600 to 1500 μv per meter less than a second after the burst, a decrease of about 7.8 db. Following a slight recovery, a nearly constant level of 2200 μv per meter was measured between 10 sec and 1 min after the burst. The field intensity recovered gradually with 2700 and 3300 μv per meter measured at H+160 sec and H+5 min, respectively. Figure 1a is a plot of the NPG field intensity for a 3-min period following the burst.

(2) The NPG phase shifted immediately after the detonation, and the maximum shift was estimated to be 100 to 200 deg. Actually, the recording oscilloscope trace went off scale for this measurement. The initial and recovery phase rates appeared to be about 28 deg per second and 10 deg per minute, respectively. The solid curves in figure 1b show the initial and recovery behavior of the NPG phase while the dashed curve is believed to be a reasonable estimate of the actual phase behavior during the off-scale period.

(3) The NBA field intensity decreased gradually from 1000 to 520 μv per meter at H+3 min, a decrease of about 5.6 db. Recovery was gradual with 720 μv per meter measured at H+6 min and 1000 μv per meter at H+20 min. Figure 2a is a plot of the NBA field intensity for a 30-min period following the burst.

(4) The NBA phase began to shift 1.5 min after the burst. The maximum phase shift of 118 deg occurred between H+6 and H+10 min. The initial and recovery phase rates were estimated to be about 62 deg per minute and 2.4 deg per minute, respectively. At H+25 min the phase shift stabilized at 80 deg and remained nearly constant until about H+45 min when the effects of the normal sunrise transition were observed. Figure 2b is a plot of the NBA phase. Note the decrease in initial phase rate near H+3 min and the fact that it coincides with the minimum in NBA field intensity and layer sunrise at State College, Pa.

2.2. Event of 20 October 1962

Regarding the low-yield and tens-of-kilometers tests [2] of 20 October 1962, it should be noted that the detonation time was near 0830 UT, layer sunrise (50 km) at State College, Pa., was 1051 UT, and the magnetic K_p index was 2− (Lincoln, 1963a). Again, both paths were in darkness. The VLF data may be summarized as follows:

(1) The NPG field intensity decreased, within seconds after the burst, from 3200 to 3060 μv per meter at H+35 sec, a decrease of about 0.4 db. The field intensity then increased steadily to 3260 μv per meter at H+100 sec. Figure 3a is a plot of the NPG field intensity.

(2) The NPG phase shifted within seconds after the burst. The maximum phase shift of 9 deg occurred at H+35 sec, and the phase recovered to its initial value at H+115 sec. The initial and recovery phase rates were estimated to be about 0.3 and 0.2 degrees per second, respectively. Figure 3b is a plot of the NPG phase. Note the plateau region near H+70 sec.

(3) The NBA field intensity decreased at H+14 min from 1100 μv per meter to 960 μv per meter at H+17.5 min, a decrease of 1.4 db. The field intensity then increased to 1100 μv per meter at H+22 min. At about H+26 min, a second field intensity decrease commenced and reached a minimum of 920 μv per meter at H+29 min, a decrease of 1.7 db below the initial level. At H+34 min the field intensity recovered to 1100 μv per meter.

[2] Burst information contained in the international AGIWARN message of 20 October 1962.

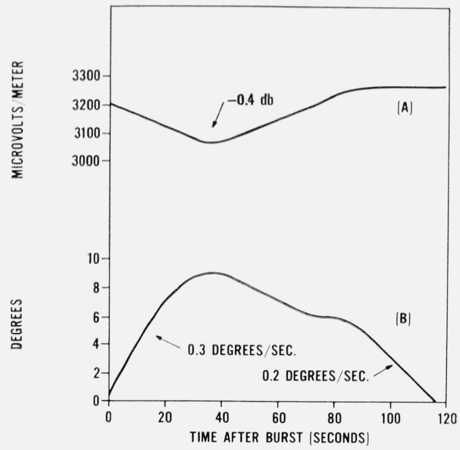

FIGURE 3. *NPG field intensity and phase—20 October 1962.*

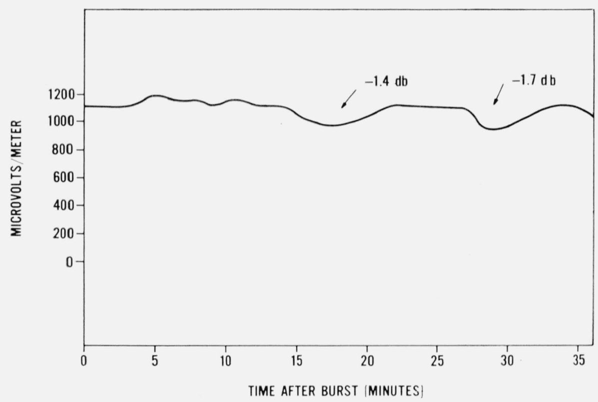

FIGURE 4. *NBA field intensity—20 October 1962.*

This was followed by a third decrease in field intensity, beginning around H+35 min, and one near H+42 min. It is believed that the observed minima are burst-related and not natural perturbations because the geomagnetic activity for this period was relatively low. Figure 4 is a plot of the NBA field intensity for a 35-min period following the burst.

(4) The NBA phase remained essentially constant following this burst, until the effects of the sunrise transition were observed.

2.3. Event of 26 October 1962

With regard to the submegaton, tens-of-kilometers test[3] of 26 October 1962, it should be noted that the detonation time was near 1000 UT, layer sunrise (50 km) at State College, Pa., was 1058 UT, and the magnetic K_p index was 4+ (Lincoln, 1963a). Again, both paths were in darkness. The VLF data may be summarized as follows:

(1) The NPG field intensity decreased, within a second after the burst, from 2630 to 2140 μv per meter at H+20 sec, a decrease of about 1.8 db. The field intensity then increased to 2250 μv per meter at H+60 sec. Following this, there were

[3] Burst information contained in the international AGIWARN message of 26 October 1962.

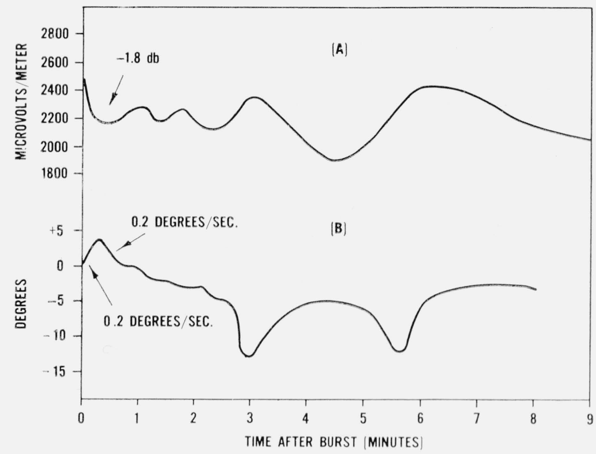

FIGURE 5. *NPG field intensity and phase—26 October 1962.*

several quasi-periodic fluctuations superimposed on the field intensity and these can be seen in figure 5a. It is probable that the fluctuations may be ascribed to the natural geomagnetic disturbance which was in progress at the time of the nuclear test.

(2) The NPG phase shifted within a second after the burst and reached a maximum phase shift of 4 deg at H+20 sec. The phase recovered temporarily to its initial value at H+1 min; then it reversed sign and became −4 deg at about H+135 sec. The initial and recovery phase rates were estimated to be about 0.2 deg per second. Following this, there were several natural quasi-periodic fluctuations superimposed on the phase and these are shown clearly in figure 5b. Note the correlation between the maxima and minima of the phase and field intensity curves near H+3 min, H+4.5 min, and H+6 min.

(3) The NBA field intensity increased at H+2 min from 920 μv per meter to 1050 μv per meter at H+7 min, an increase of 1.2 db. The field intensity then decreased and reached a minimum of 580 μv per meter at H+21 min, a decrease of 4 db below the preburst level. The field intensity then increased and reached 750 μv per meter at H+30 min. Figure 6a is a plot of the NBA field intensity.

(4) The NBA phase began to shift at about H+5 min and reached 20 deg near H+17 min at which time the phase rate increased markedly from 1.1 deg per minute to about 8.2 deg per minute. The maximum phase shift of 82 deg was reached at H+24 min and the phase remained essentially constant until the effects of the sunrise transition were observed. It should be noted that the time of minimum field intensity coincides closely with the time at which the phase reached its maximum deviation. Figure 6b is a plot of the NBA phase.

2.4. Event of 1 November 1962

Concerning the submegaton, tens-of-kilometers test[4] of 1 November 1962, it should be noted that

[4] Burst information contained in the international AGIWARN message of 1 November 1962.

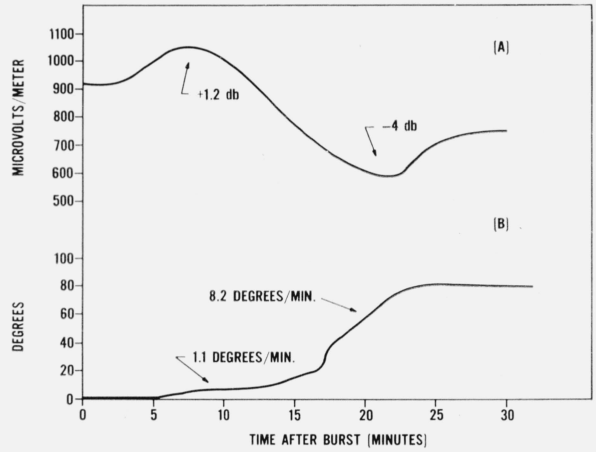

FIGURE 6. *NBA field intensity and phase—26 October 1962.*

the detonation time was near 1210 UT, layer sunrise (50 km) at State College, Pa, was 1103 UT, and the magnetic K_p index was 2+[Lincoln, 1963b]. The NBA path was sunlit while the NPG path was only partially in darkness. The VLF data may be summarized as follows:

(1) The NPG field intensity increased, within seconds after the burst, from 1530 to 1760 μv per meter at H+20 sec, an increase of about 1.4 db. The signal level then decreased to 1600 μv per meter at about H+2 min and remained essentially constant. Figure 7a is a plot of the NPG field intensity. It should be noted that solar flares generally cause an enhancement of VLF signal strength and that, therefore, the signal increase induced by the nuclear test may be attributed to the sunlit condition along a portion of the NPG path.

(2) The NPG phase began to change within seconds after the detonation with a phase rate of about 1 deg per second. The maximum phase shift was 20 deg at H+20 sec. The phase recovered to its initial value with a recovery rate of roughly 0.3

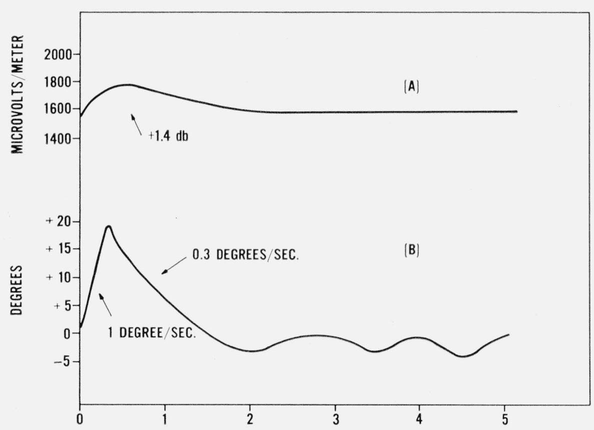

FIGURE 7. *NPG field intensity and phase—1 November 1962.*

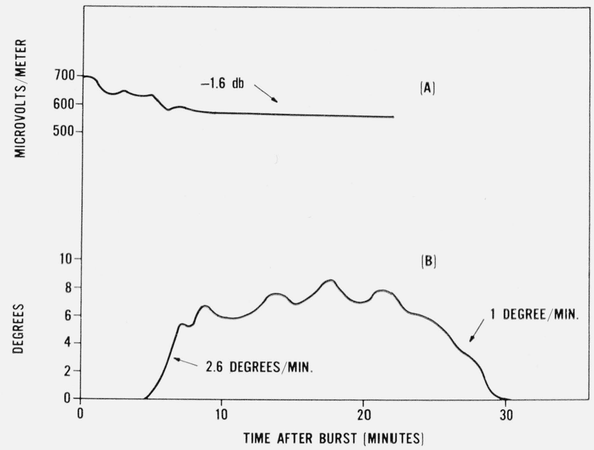

FIGURE 8. *NBA field intensity and phase—1 November 1962.*

deg per second at H+1.5 min. Following this, the phase appeared to oscillate slightly about an average phase value of −2.5 deg. It is probable that these quasi-periodic fluctuations were induced by the abnormal geomagnetic activity which was in progress during this period. Refer to figure 7b for a plot of the NPG phase for a 5-min period following the burst.

(3) The NBA field intensity decreased slowly from an initial level of 700 μv per meter to 570 μv per meter at H+10 min, a decrease of about 1.6 db. Small fluctuations were superimposed on the field intensity curve during the decrease, as illustrated in figure 8a. After H+10 min the signal level was essentially constant at a value of 560 μv per meter.

(4) The NBA phase began to shift at about H+5 min with a phase rate of 2.6 deg per minute. A rather broad maximum deviation of 9 degs was reached near H+18 min. As shown in figure 8b, small quasi-periodic fluctuations were superimposed on the NBA phase curve, and these may be ascribed to the natural geomagnetic disturbance in progress during this period. The phase recovered, with a rate of 1 deg per minute, to its initial value near H+30 min.

2.5. NPG and NBA Data Summaries

Tables 1 and 2 contain some of the important parameters with regard to the VLF field intensity and phase anomalies observed on the NPG and NBA signals during the high-altitude nuclear tests.

3. Interpretation of VLF Data

On the basis of the foregoing data summaries contained in tables 1 and 2, it is apparent that at least three different VLF effects may be induced in the shadow regions by high-altitude nuclear detonations. First, the prompt VLF anomaly observed only on the NPG signal appeared in varying degrees of severity on the four bursts, and recovery was well under way minutes after the burst. Second, the VLF anomaly delayed by minutes, observed only on

TABLE 1. *NPG data summary*

	9 July 1962	20 October 1962	26 October 1962	1 November 1962
Burst time	0900:09UT	0830 UT	1000 UT	1210 UT
LSR (50 km at State College)	0903	1051	1058	1103
K_p index	2	2−	4+	2+
ΔE onset	<1 sec	> 1 sec	<1 sec	>1 sec
ΔE max	−7.8 db	−0.4 db	−1.8 db	+1.4 db
Time of ΔE max	H+5 sec	H+35 sec	H+20 sec	H+20 sec
$\Delta\phi$ onset	<1 sec	>1 sec	<1 sec	>1 sec
Initial $\Delta\phi/\Delta t$	28°/sec	0.3°/sec	0.2°/sec	1°/sec
$\Delta\phi$ max	100°–200°	9°	4°	20°
Time of $\Delta\phi$ max	H+5 sec	H+35 sec	H+20 sec	H+20 sec
Recovery $\Delta\phi/\Delta t$	0.16°/sec	0.2°/sec	0.2°/sec	0.3°/sec
Recovery time	H+5 min	H+2 min	H+1 min	H+2 min

TABLE 2. *NBA data summary*

	9 July 1962	20 October 1962	26 October 1962	1 November 1962
Burst time	0900:09 UT	0830 UT	1000 UT	1210 UT
LSR (50 km at State College)	0903	1051	1058	1103
K_p index	2	2−	4+	2+
ΔE onset	H+1.5 min	H+14 min H+26 min	H+2 min H+15 min	H+5 min
ΔE max	−5.6 db	−1.4 db −1.7 db	+1.2 db −4 db	−1.6 db
Time of ΔE max	H+3 min	H+17.5 min H+29 min	H+7 min H+21 min	H+10 min
$\Delta\phi$ onset	H+1.5 min	----------	H+5 min H+17 min	H+5 min
Initial $\Delta\phi/\Delta t$	62°/min	----------	1.1°/min 8.2°/min	2.6°/min
$\Delta\phi$ max	118°	----------	82°	9°
Time of $\Delta\phi$ max	H+8 min	----------	H+24 min	H+18 min
Recovery $\Delta\phi/\Delta t$	2.4°/min	----------	----------	1°/min
Recovery time	H+30 min	H+30 min	H+30 min	H+30 min

the NBA signal, appeared significant on the 9 July 1962 test, but subsequent tests revealed secondary VLF effects commencing within minutes after the burst. Third, the VLF anomalies delayed by 15 to 25 min for the 20 October and 26 October 1962 tests were observed only on the NBA signal; they were absent in the 9 July 1962 and 1 November 1962 data probably because of sunrise and daytime effects, respectively.

Before discussing the various physical phenomena which may induce VLF anomalies in the shadow regions, it is of interest to examine the two propagation paths with respect to the burst.

3.1. Propagation Paths

Table 3 presents the propagation path distances and geomagnetic coordinates which are pertinent to the interpretation of the VLF data. Note that the McIlwain [1961] L-values are given for Johnston Island, State College, NPG and NBA. It is interesting to note several fortuitous relationships, namely:

(1) The propagation path lengths from State College, Pa., to NPG and NBA are equidistant (3500 km).

(2) The geomagnetic latitudes of NPG and State College are practically equal.

(3) The geomagnetic longitudes of NBA and State College are practically equal.

(4) The difference in geomagnetic longitude between Johnston Island and the NBA-State College path is approximately 90 deg.

TABLE 3. *Propagation paths and geomagnetic coordinates*

Station	Distance from State College	Geom. lat.	Geom. long.	L
	km			
State College, Pa.	----------	52° N	10° W	2.6
NPG	3500	53° N	66° W	2.6
NBA	3500	21° N	12° W	1.2
Johnston Island	9000	14° N	104° W	[a] 1.12

[a] This is the L value for the burst of 9 July 1962 (Van Allen et al., 1963).

3.2. Prompt VLF Effects

The prompt VLF effects observed only on the NPG signal occurred within seconds after the detonations. Because the NPG-State College path is shielded by the earth from direct ionizing radiation such as X-rays and γ-rays created in the detonation, it is suggested that the Crain and Tamarkin [1961] theory be invoked to explain the large phase and amplitude excursions observed within seconds after the detonations. In this theory, it is asserted that prompt neutrons from the burst decay into protons and beta particles, with a half-life of about 13 min; the betas then spiral down the geomagnetic field lines into the D-region of the ionosphere where they enhance the ionization and cause increased absorption and decreased propagation times of VLF radio waves propagating in the earth-ionosphere waveguide. Of course, the geometry of the detonation point and VLF propagation path must be such that the geomagnetic field lines which intersect the propagation path are within line of sight of the burst.

The neutron-decay betas are assumed to be ejected isotropically, with an electron energy per unit energy interval peaking at about 400 kev and an end-point energy per unit energy interval of 780 kev. The neutron-decay betas must also be energetic enough to penetrate through the upper atmosphere and to produce ionization by Coulomb-scattering, collisional detachment, bremsstrahlung, etc., in the 70- to 90-km altitude region. Bailey [1959] published curves for the vertical penetration of charged particles and showed that in the 70- to 90-km height region the relevant energy range for protons was 1 to 8 Mev, and 50 to 300 kev and above for electrons. Electrons are primarily responsible for the abnormal ionization causing the VLF perturbation, because only the electrons have sufficient energy and injection angles permitting ionization over large volumes. Crain and Tamarkin [1961] state that each neutron-decay beta causes multiple ionization and thus several ambient electrons; for example, a 300 kev beta will produce some 10^4 ion-pairs on the average because the energy required to produce one ion-pair is about 36 ev [Bailey, 1959].

In addition to the neutron-decay betas, Zmuda [1963a] has suggested that betas from the radioactive decay of fission products in the bomb debris may also have been geomagnetically deflected into the NPG-State College path; this would contribute to the essentially instantaneous ionization enhancement causing the NPG phase and field intensity anomalies.

3.3. Delayed VLF Effects (1.5 to 5 Minutes)

A simple geometrical construction shows that the NBA-State College propagation path will not be influenced by the prompt neutron-decay beta effects of the 1962 tests, because the geomagnetic field lines which intersect this path lie below the shadow cone which is tangent to the earth's surface and whose apex is at the detonation point.

The VLF anomalies on the NBA signal, delayed by minutes (1.5 to 5 min, approximately), are explicable in terms of the eastward drift and energy spectrum of the electrons comprising the bomb-induced radiation belts which form in the geomagnetic meridian through the burst point. The trapped radiation is composed largely of electrons produced in the radioactive decay of fission fragments. Heller [1961] has computed the energy and time beta ray spectra of fission products of U^{235} by fission neutrons. Referring to the spectrum for the burst time, the electron energy per fission per unit energy interval has a maximum around 3 to 3.6 Mev. Also, Carter et al. [1959] have measured spectral data for fission fragment electrons in the energy range 1 to 7 Mev.

Assuming the geomagnetic field is approximated by the field of a centered dipole, table 4 shows the eastward drift velocity and drift times of trapped electrons for geomagnetic latitudes near NBA and State College, Pa. These velocities may be computed using the equations of Hamlin et al. [1961]. Note that the drift time from Johnston Island to NBA for 3.0 Mev electrons is 6 min which is comparable to the time of maximum phase shift observed on the NBA signal during the 9 July 1962 test.

TABLE 4. *Longitudinal drift velocities and times of trapped electrons*

Electron energy	Drift veloc. (20° lat.)	Drift veloc. (50° lat.)	J.I. to NBA drift time (20° lat.)	J.I. to S.C. drift time (50° lat.)
0.3 Mev	2.1°/min	3.6°/min	43 min	25 min
0.4	2.7	4.6	33	19.5
0.5	3.2	5.6	28	16
0.78	4.8	8	18.8	11.2
3.0	15	26	6	3.5
3.3	17	29	5.3	3.1
3.6	18	31	5	2.9
10	45	80	2	1.1
14	60	100	1.5	0.9

Because the NBA-State College path lies approximately along a geomagnetic meridian (10°–12°W), it forms a natural boundary to observe indirectly the passage of the drifting, trapped electrons through monitoring of the VLF perturbations induced by betas mirroring below 90 km. Because the perturbations in the NBA signal, for the 9 July 1962 test, commenced at H+1.5 min, it is suggested that electrons having energies near 14 Mev must have caused the onset of the anomaly.

Thus, for the 9 July 1962 test, there is good qualitative agreement between the temporal variation of the VLF phase anomaly over the NBA-State College path and the change of energy with time of the trapped electrons drifting over NBA. Any displacements in time of the respective VLF anomaly and electron energy maxima could be caused by the lag in the response of the ionosphere to the ionizing mechanism, analogous to the relaxation time between the maximum electron production rate and the maximum electron density observed near noon in the normal, undisturbed ionosphere.

The above time correlation between the electron energy and the VLF anomaly maxima for the 9 July 1962 test suggests that the enhanced *D*-region ionization responsible for the VLF anomaly over the NBA-State College path was the result of ionization produced in regions closer to NBA than State College. Also, it should be noted that no delayed effects were observed on the NPG-State College path; this supports further the contention that regions closer to NBA were perturbed by the abnormal ionization.

It is apparent from examination of table 2—NBA data summary—that onset times of H+2 min and H+5 min were observed for the field intensity and phase anomalies for the 26 October 1962 test, and that onset times of H+5 min were observed for the field intensity and phase anomalies for the 1 November 1962 test. Comparison of these times with those in table 4 suggests further that a time correlation exists between the VLF anomaly onset times and the energies of fission-decay electrons. For example, 10 Mev electrons have drift times from Johnston Island to NBA of 2 min, 3.3 Mev electrons have drift times of 5.3 min, and a drift time of 5 min corresponds to an electron energy of 3.6 Mev.

3.4. Delayed VLF Effects (15 to 40 Minutes)

VLF anomalies delayed by tens of minutes (14 to 35 min, approximately) were observed on the NBA signal for the 20 October 1962 and 26 October 1962 tests. It is believed that these delayed anomalies are explicable in terms of the eastward drift and energy spectrum of trapped radiation composed largely of neutron-decay electrons. Again, it is assumed that the radiation belt forms in the geomagnetic meridian through the burse point. Referring to the spectrum of neutron-decay electrons [Zmuda et al., 1963b], the electron energy per unit energy interval has an end-point value of 780 kev and a maximum around 400 kev. Table 4 presents the eastward drift velocity and drift times of trapped electrons for geomagnetic latitudes near NBA and State College, Pa. Note that the drift times from Johnston Island to NBA for 780 and 400 kev electrons are 18.8 min and 33 min, respectively. Also, the drift times from Johnston Island to State College for 780 and 400 kev electrons are 11.2 and 19.5 min, respectively. It is interesting to note that these times are comparable to the onset times and times of maximum VLF disturbance for the 20 October 1962 and 26 October 1962 tests. The correlations between onset times and times of maximum VLF disturbance and neutron-decay electron drift times are not as marked as those for the 9 July 1962 test. Nevertheless, it is believed that at least portions of the observed VLF anomalies may be attribued to the effects of neutron-decay electrons which drifted eastward from the burst point and mirrored at heights below 90 km along the NBA-State College propagation path. For the 20 October 1962 test, it is possible that some of the field intensity minima observed may be attributed to trapped neutron decay electrons which drifted several times around the world.

3.5. Quasi-Periodic VLF Fluctuations

The quasi-periodic fluctuations observed in the VLF field intensity and phase data for the 26 October 1962 and 1 November 1962 tests may be ascribed to the natural geomagnetic disturbances which were in progress at the times of these tests [Sechrist, 1962]. An examination of geomagnetic micropulsation data for the above dates revealed that quasi-periods of 20 sec and 1 min were present at State College during the tests of 26 October 1962 and 1 November 1962, respectively.

4. Theoretical VLF Field Intensity and Phase Anomalies

It is beyond the scope of this paper to compute the electron production rate as a function of height, time, and geographical location and to determine the electron density-height profiles along a given VLF propagation path. However, it is interesting to assume plausible perturbed models of the earth-ionosphere waveguide for the NPG and NBA paths, and then compute the theoretical maximum VLF phase and field intensity anomalies $\Delta\phi$ and ΔE, respectively, for the 9 July 1962 test.

4.1. NPG-State College Path

If one considers a burst altitude of 400 km for the 9 July 1962 nuclear test, it can be shown that the geomagnetic field lines which intersect about 85 percent of the NPG-State College path are line of sight to the burst point, assuming a dipole model of the geomagnetic field. The remaining field lines lie below the shadow cone which is tangent to the earth with its apex at the burst point. Therefore, assuming that neutron-decay betas produce enhanced *D*-region ionization along 85 percent of this path, a first approximation to the earth-ionosphere waveguide is a sharply bounded model having a step ionosphere. That is, for the 9 July 1962 test, the undisturbed nighttime ionosphere height is about 90 km over 15 percent of the NPG-State College path, while the perturbed 85 percent of the path is assumed to be lowered uniformly by Δh to a constant height. A more realistic model would probably have a tapered-step ionosphere because the number of neutrons reaching relevant field lines decreases with distance from the burst point.

4.2. NBA-State College Path

Again considering the 9 July 1962 test, the burst occurred on the $L=1.12$ shell which at the earth's surface has a magnetic latitude less than that of NBA. No delayed effects were observed on the NPG signal; there was a decrease in trapped electron flux in going from the latitude of NBA to that of State College [Hess, 1963]; and there was a good correlation between the temporal variation of the NBA signal anomalies and the energy contained in the trapped electron drifting over NBA. Therefore, it is reasonable to assume that a first approximation to the earth-ionosphere waveguide between NBA and State College is a sharply bounded model having a tapered ionosphere. Thus, the height of the ionosphere is assumed to increase linearly with distance from h_t at NBA to h_r at State College, Pa., where h_r is about 90 km for the 9 July 1962 test.

4.3. Waveguide Mode Theory for Variable Ionosphere Height

Wait [1961] carried out an approximate analysis for mode propagation in the earth-ionosphere waveguide with the height $z=h(x)$ of the boundary varying with distance. He assumed that the ionosphere is a sharply bounded ionized medium, and that the rate of change of height with distance (dh/dx) is always small compared with unity. Following Wait's derivation, the vertical electric field is proportional to

$$\left[\frac{1}{h(x)}\right]^{1/2} \sum_n A_n \exp\left[-ik\int_0^x S_n(x)dx\right] \cos\left[kC_n(x)Z\right] \tag{1}$$

where A_n are coefficients independent of x and z, $k=2\pi/\lambda$, and $S_n(x)$ and $C_n(x)$ are dimensional factors analogous to the S_n and C_n occurring in the conventional mode theory for a constant height of the ionosphere.

The important quantity which determines the phase and amplitude of the nth mode is the exponential term in (1). That is

$$\exp\left[-ik\int_0^x S_n(x)dx\right]=\exp\left[-ik\int_0^x \mathrm{Re}\ S_n(x)dx\right] \exp\left[k\int_0^x \mathrm{Im}\ S_n(x)dx\right]. \tag{2}$$

Therefore, the attenuation of a mode n for propagation from 0 to x is given by

$$P_n=-k\int_0^x \mathrm{Im}\ S_n(x)dx \qquad \text{(nepers)} \tag{3}$$

and the phase, for mode n, rom 0 to x is given by

$$\phi_n=k\int_0^x \mathrm{Re}\ S_n(x)dx \qquad \text{(radians)}. \tag{4}$$

The Re $S_n(x)$ and Im $S_n(x)$ were computed for given normal and perturbed models of $z=h(x)$, and the differences between normal and perturbed P_n and ϕ_n were ΔE and $\Delta\phi$, respectively. Only the dominant mode $n=1$ was considered in the preliminary computations and the influence of earth curvature was included in the manner of Wait [1961].

4.4. Results for Step-Ionosphere Model

Using the equations presented above, ΔE and $\Delta\phi$ were computed for a step-ionosphere model and a propagation path length of 3500 km, corresponding to the NGP-State College case. The results of these computations are presented in figures 9 and 10 which are plots of $\Delta\phi$ and ΔE, respectively, versus percent of path perturbed, and the parameter Δh ranges from 10 to 40 km.

As an example, the 9 July 1962 test perturbed about 85 percent of the NPG-State College path because of neutron-decay beta effects, and the maximum phase anomaly observed was in the 100- to 200-deg range. Referring to figure 9, this would suggest a Δh value of roughly 20 km which compares favorably with the diurnal height change of the reflecting layer for VLF waves.

However, referring to figure 10, a ΔE value of -1.5 db is indicated for the change in field intensity, and this differs markedly from the 7 to 8 db of maximum attenuation observed in the NPG signal for the 9 July 1962 test.

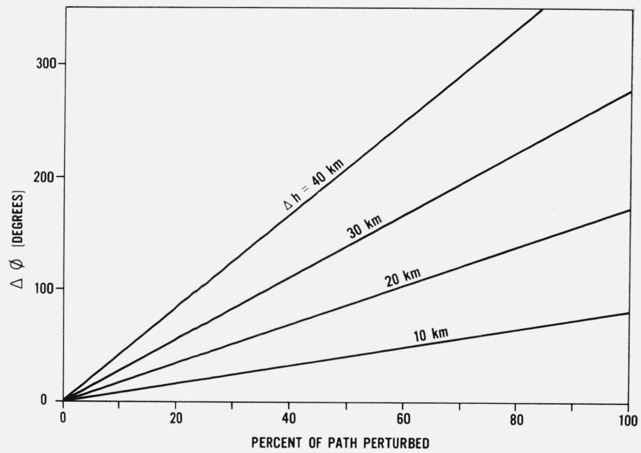

FIGURE 9. $\Delta\emptyset$ *for a step ionosphere model.*

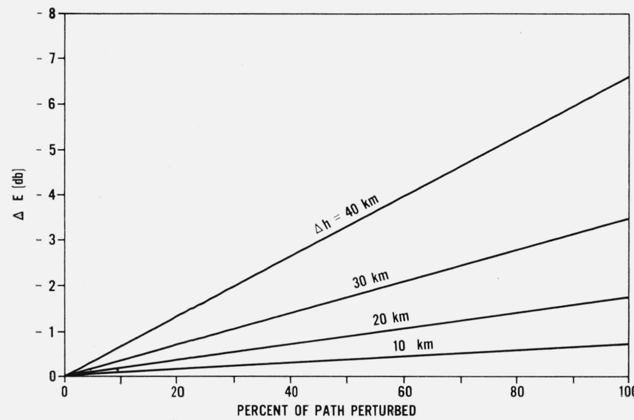

FIGURE 10. ΔE *for a step ionosphere model.*

4.5. Results for Tapered-Ionosphere Model

ΔE and $\Delta\phi$ were computed for a tapered ionosphere model and a path length of 3500 km, corresponding to the NBA-State College case. The results of these computations are presented in figures 11 and 12 which are plots of $\Delta\phi$ and ΔE, respectively, versus (h_r-h_t), and the parameter h_r ranges from 70 to 90 km.

As an example, the 9 July 1962 test perturbed the NBA-State College path in regions near NBA, and the maximum phase anomaly observed was about 118 deg. Referring to figure 11, this would suggest an (h_r-h_t) value of about 25 km, assuming h_r equals the normal nighttime value of 90 km.

Referring to figure 12, a ΔE value of only -1 to -2 db is indicated for the field intensity change, and this is about 4 to 5 db less than the maximum attenuation observed in the NBA signal for the 9 July 1962 test.

More accurate and detailed computations of the theoretical field intensity and phase anomalies, including the effects of higher-order waveguide modes and a nonsharp ionosphere boundary, will be carried out and reported in a future paper.

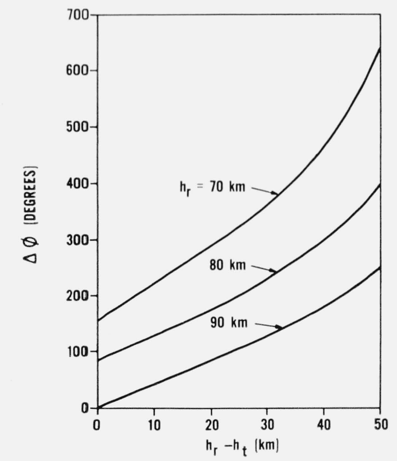

FIGURE 11. $\Delta\emptyset$ *for a tapered ionosphere model.*

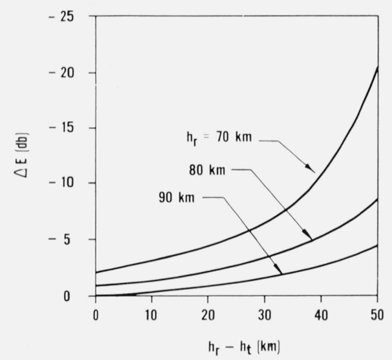

FIGURE 12. ΔE *for a tapered ionosphere model.*

The work in this paper was supported by the Office of Naval Research under Contract No. NOnr–3851(00).

Also, the author acknowledges the work of A. R. Vetter and C. Volz, Jr., who assisted with the collection of VLF data, and J. M. Musser who performed the computations concerning the theoretical VLF anomalies.

5. References

Bailey, D. K. (1959), Abnormal ionization in the lower ionosphere associated with cosmic-ray flux enhancements, Proc. IRE **47,** 255–266.

Brown, W. L., W. N. Hess, and J. A. Van Allen (1963), Introduction to the collected papers on the artificial radiation belt from the July 9, 1962 nuclear detonation, J. Geophys. Res. **68,** 605–606.

Carter, R. E., F. Reines, J. J. Wagner, and M. E. Wyman (1959), Free antineutrino absorption cross section 2. Expected cross section from measurements of fission fragment electron spectrum, Phys. Rev. **113,** 280–286.

Crain, C. M., and P. Tamarkin (1961), A note on the cause of sudden ionization anomalies in regions remote from high-altitude nuclear bursts, J. Geophys. Res. **66,** 35–39.

Hamlin, D. A., R. Karplus, R. C. Vik, and K. M. Watson (1961), Mirror and azimuthal drift frequencies for geomagnetically trapped particles, J. Geophys. Res. **66,** 1–4.

Heller, R. B. (Feb. 1961), Energy and time beta ray spectra of fission products of U^{235} by fission neutrons and U^{238} by 14 mev neutrons, WSEG Res. Mem. 19.

Hess, W. N. (1963), The artificial radiation belt made on July 9, 1962, J. Geophys. Res. **68,** 667–683.

Lincoln, J. V. (1962), Geomagnetic and solar data, J. Geophys. Res. **67,** 4875–4877.

Lincoln, J. V. (1963a), Geomagnetic and solar data, J. Geophys. Res. **68,** 1155–1156.

Lincoln, J. V. (1963b), Geomagnetic and solar data, J. Geophys. Res. **68,** 1767–1768.

McIlwain, C. E. (1961), Coordinates for mapping the distribution of magnetically trapped particles, J. Geophys. Res. **66,** 3681–3692.

Sechrist, C. F., and K. D. Felperin (1961), Short-term phase perturbations observed at 18 kc/s, J. Geophys. Res. **66,** 3601–3602.

Sechrist, C. F. (1962), VLF phase perturbations observed during geomagnetic storms, J. Geophys. Res. **67,** 1685–1686.

Van Allen, J. A., L. A. Frank, and B. J. O'Brien (1963), Satellite observations of the artificial radiation belt of July 1962, J. Geophys. Res. **68,** 619–627.

Wait, J. R. (1961), Expected influence of a localized change of ionosphere height on VLF propagation, J. Geophys. Res. **66,** 3119–3123.

Zmuda, A. J., B. W. Shaw, and C. R. Haave (1963a), VLF disturbances and the high-altitude nuclear explosion on July 9, 1962, J. Geophys. Res. **68,** 745–758.

Zmuda, A. J., B. W. Shaw, and C. R. Haave (1963b), VLF disturbances caused by the nuclear detonation of October 26, 1962, J. Geophys. Res. **68,** 4105–4114.

(Paper 68D1–326)