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VLF Phase Perturbations

associated

The very-low-frequency (VLF) region of the electromagnetic spectrum, spanning the frequency range of 3–30 kc, has in recent years acquired considerable importance as a stable transmission link for making long-range frequency comparisons. A number of VLF transmitters, with carrier frequencies held stable to within one part in 10^{10}, are now in operation throughout the world. Accurate means of comparing (and recording) the phase of the received VLF transmission with that of a local frequency standard have also been developed and made generally available in recent years. The Applied Physics Laboratory has made wide use of VLF frequency monitoring in connection with the Navy navigational satellite program, and five VLF stations are continuously monitored at the APL Howard County Laboratory. This installation has been described in a previous issue of the *Digest*.[1]

According to the VLF mode theory,[2] propagation takes place in the spherical waveguide formed by the earth's surface and the lower ionosphere. Effective ionosphere heights at VLF frequencies are of the order of 70 km during the daylight hours and 90 km during all-darkness propagation. These heights are typical of the lowest region of the ionosphere, the D-layer. The D-region behaves as though composed of two layers, which have been designated D_α and D_β. The lower layer, D_β, which is the effective layer for VLF during daylight conditions, is formed rapidly at ionospheric sunrise, dissipates at sunset, and remains substantially constant during the daylight hours. The effective dimension of the waveguide thus changes diurnally by about 20 km, and this effects a diurnal change in propagation time between transmitter and receiver. The magnitude and nature of the diurnal change in propagation time are functions of the path length between transmitter and receiver, the geometry and nature of the path on the earth's surface, the time of year, and of various perturbing factors which can change the electrical properties of the lower ionosphere.

Any sporadic geophysical event, such as the nuclear explosion of July 9, 1962, which can alter the state of the lower ionosphere can introduce perturbations which will be superimposed on the normal diurnal phase shift. Continuous phase-

[1] B. W. Shaw and C. R. Haave, "Frequency Monitoring of VLF Transmissions," *APL Technical Digest*, **1**, May–June, 1962, 7–11.

[2] J. R. Wait, "New Approach to the Mode Theory of VLF Propagation," *J. Research Nat. Bur. Standards*, **65D**, 1961, 37–46.

VLF propagation paths remote from the July 9 nuclear burst were perturbed by the effect, on the lower ionosphere, of charged particles geomagnetically deflected into the VLF path. Some of these particles attach to field lines directly accessible from the burst region, and others are geomagnetically trapped and drift longitudinally from the burst to the VLF path.

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High-Altitude Nuclear Bursts

monitoring of a stabilized VLF transmission is well-known as a sensitive indicator of such lower ionosphere irregularities associated with magnetic disturbances, meteor showers, abnormal ionization in the D-region due to cosmic ray flux enhancements, and solar flares. With the advent of the nuclear bomb, the man-made perturbation to the ionosphere caused by a high-altitude nuclear burst must be added to those resulting from natural causes. It is the purpose of this article to discuss the VLF phase perturbations associated with high-altitude nuclear bursts and also their interpretation in terms of the radiation and particles produced in the detonation.

Burst-Engendered VLF Phase Perturbations

Let us assume that the VLF path being monitored is in darkness, so that the effective ionosphere height is about 90 km. Any mechanism which can enhance the ionization below this altitude over the VLF path will then produce a "phase anomaly," in that the effective nighttime ionosphere height will be lowered toward the daytime level. This is shown in the VLF phase record as a distinct, and usually rapid, decrease in relative propagation time.

For discussion purposes the VLF perturbations resulting from high-altitude nuclear bursts may be divided into two categories, depending upon the time lapse between detonation and onset of the VLF perturbation. If the perturbation is essentially simultaneous with the detonation, it will be classed as *direct*; if there is appreciable time lag between detonation and onset of the perturbation, it is classed as *delayed*. It will be seen in what follows that the delay times observed for a number of VLF paths are most important in elucidating the specific mechanism causing the perturbation.

A direct perturbation may arise in two ways: (1) a sufficient portion of the VLF path is directly exposed to the prompt* X rays and gamma rays from the burst and to electrons produced in the radioactive decay of neutrons and fission fragments; or (2) the VLF path is shielded from direct radiation effect from the burst by the earth and its atmosphere, but the geomagnetic field lines

* *Prompt* refers to burst products produced essentially simultaneously with the burst, as distinguished from the *delayed* products that stem from the radioactive debris.

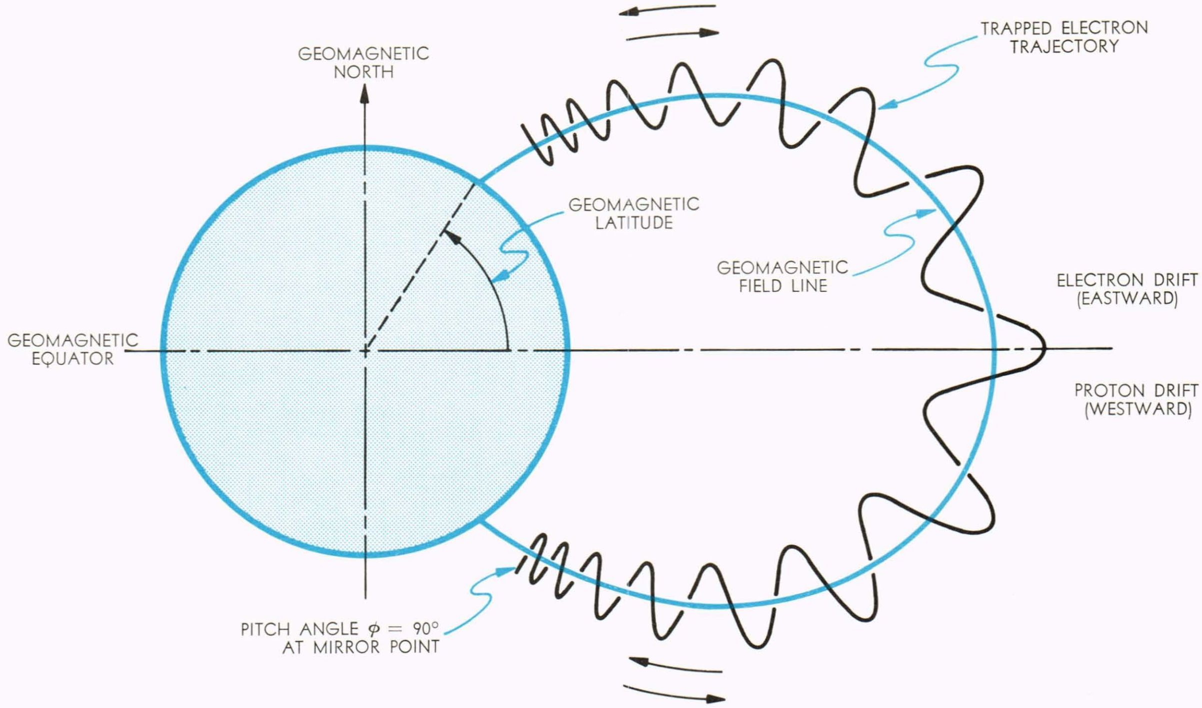

Fig. 1—Representation of particles trapped and drifting in the geomagnetic field of the earth. The particles oscillate back and forth between mirror points and drift in magnetic longitude.

passing through the VLF path are exposed to the burst in such manner that charged particles may be readily channeled geomagnetically into the VLF path. The latter type of disturbance with neutron-decay electrons has been discussed by Crain and Tamarkin.[3]

A delayed perturbation connects with the relatively slow azimuthal drift from the burst region to the VLF propagation path of geomagnetically-trapped particles formed in the radioactive decay of neutrons and of fission fragments. Since the positively-charged protons (or ions) drift westward in the geomagnetic field and the electrons drift eastward, a series of delayed perturbations on different VLF paths makes it possible to decide immediately whether the perturbation was caused by the drift of trapped protons or trapped electrons. Additional relationships result from the correlation existing between the temporal variation of the VLF perturbation and the drift rate and energy spectrum of the particles.

Geomagnetically-Trapped Particles

As is well known from the theory of the motion of charged particles in a uniform magnetic field, the particle orbit consists of a uniform translation along the field and a superimposed circular motion in a plane perpendicular to the field. The sense of rotation is such that the magnetic field associated with the spiraling charge is in a direction so as to oppose that of the ambient field. In the geomagnetic field, when viewed along the field direction, protons rotate counterclockwise and electrons clockwise. The angular velocity of the particle, known as the gyro-frequency or cyclotron-frequency, is found to be $\omega_c = eB/m$ in electromagnetic units, where e, m, and B are the particle charge, mass, and magnetic induction, respectively. If the magnetic field is not uniform in space, a drift perpendicular to the field direction and field gradient also exists. The particle will also experience an outward (centrifugal) force $mv_{\parallel}^2/R$ (R is the radius of curvature of the field line and $v_{\parallel}$ is the velocity parallel to the field) tending to displace the particle from its curved trajectory. Just as in the case of an electric field perpendicular to the magnetic field, the net effect is not displacement in the direction of the outward force, but rather a drift at right angles to both the force and the magnetic field. The total drift due to field inhomogeneity and centrifugal force is given by $v_d = (v_{\perp}^2/2 + v_{\parallel}^2)/\omega_c R$, where $v_{\perp}$ and $v_{\parallel}$

[3] C. M. Crain and P. Tamarkin, "A Note on the Cause of Sudden Ionization Anomalies in Regions Remote from High-Altitude Nuclear Bursts," *J. Geophys. Research*, **66**, 1961, 35–39.

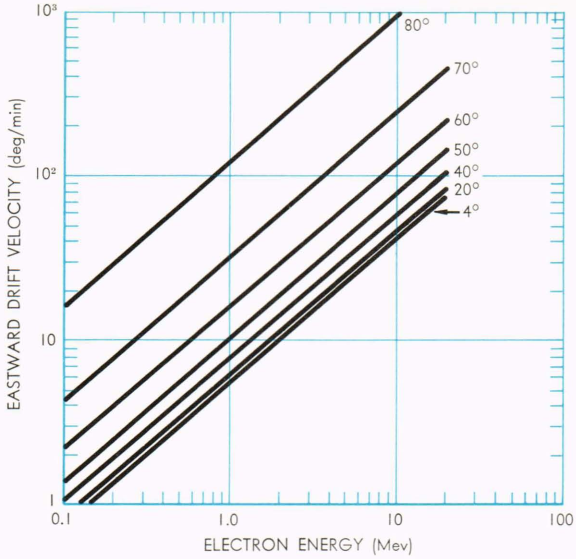

Fig. 2—Longitudinal drift of trapped electrons mirroring at 80-km altitude above the earth's surface and for various geomagnetic latitudes and electron energies.

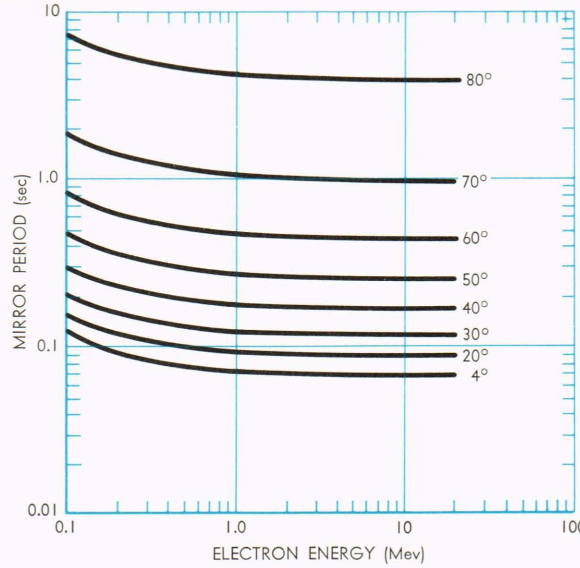

Fig. 3—Mirror period of geomagnetically-trapped electrons mirroring at 80-km altitude above the earth's surface and for various geomagnetic latitudes and electron energies.

are the velocities perpendicular to the parallel with the field direction, respectively, ω_c is the gyro-frequency, and R is the radius of curvature of the field.

In the geomagnetic field, the magnetic moment of a charged particle ($= mv_\perp^2/2B$) is practically constant, with important consequences for the reflection of trapped particles. As the particles spiral down the field lines toward the earth's surface, they encounter larger values of B. Because of the constancy of the moment, the quantity $v_\perp^2$ starts increasing as B increases, and since the total kinetic energy of the particle is also constant, the augmentation of $v_\perp^2$ is at the expense of $v_\parallel^2$, the square of the velocity component along the field line. Ultimately, at the so-called mirror point, the particle has no motion in the field direction and all the particle's kinetic energy is in the gyration around the field line. Because there exists a field gradient across the particle orbit at the mirror point, the particle is then reflected back along the field line. The particles thus oscillate back and forth along the field line between the magnetic mirror points, and at the same time drift in longitude (magnetic). A pictorial representation of geomagnetically-trapped particles is shown in Fig. 1.[4]

Figure 2 shows the drift rate for electrons of different energies, for various geomagnetic latitudes, and for a mirror-point altitude of 80 km above the earth's surface.

The mirror period of electrons mirroring at an altitude of 80 km for various magnetic latitudes and energies is shown in Fig. 3. The particles mirroring at high altitudes remain trapped to form a relatively stable artificial radiation belt. The particles mirroring (or simply penetrating) low in the atmosphere lose energy rapidly by collisions and are not trapped for an extensive period of time. It is these particles, however, which cause ionization at altitudes low enough (70 to 90 km) to effect a VLF phase perturbation. The data in Figs. 2 and 3 were computed using the expressions derived by Hamlin, Karplus, Vik, and Watson[5] for the dipole field. To describe the particle motion to a higher order of approximation, it is best to use the coordinate system proposed by McIlwain.[6]

VLF Perturbations from the July 9 Nuclear Event

We shall use as examples of nuclear-burst-engendered VLF phase perturbations some observations made at APL in connection with the high-altitude nuclear event of July 9, 1962. At 09:00:08 UT (Universal Time) on this date, a 1.4-megaton device was exploded at an altitude of about

[4] See also J. A. Van Allen, "Dynamics, Composition, and Origin of the Geomagnetically Trapped Corpuscular Radiation," *Intern. Astron. Union Trans.*, in press, 1962.

[5] D. A. Hamlin, R. Karplus, R. C. Vik, and K. M Watson, "Mirror and Azimuthal Drift Frequencies for Geomagnetically Trapped Particles," *J. Geophys. Research*, **66**, 1961, 1–4.

[6] C. E. McIlwain, "Coordinates for Mapping the Distribution of Magnetically Trapped Particles," *J. Geophys. Research*, **66**, 1961, 3681–3692.

Table I

VLF STATION DATA

Station		*Freq. (kc)*	*Distance from APL/JHU (km)*	*Distance from Johnston Island (km)*	*Geographic Coordinates*		*Geomagnetic Coordinates*	
Call	*Location*				*N. Lat. (deg)*	*W. Long. (deg)*	*N. Lat. (deg)*	*W. Long. (deg)*
NPG	Jim Creek, Wash.	18.6	3700	5500	47	122.5	53	66
NBA	Balboa, Panama	18	3300	9600	9	80	21	12
NPM	Hawaii	19.8	7700	1400	21	158	21	93.5
APL/JHU	Howard County, Md.	—	—	9100	39	77	51	10
JOHNSTON ISLAND		—	9100	—	17	169.5	14	104

400 km above Johnston Island. This burst produced an array of geophysical phenomena, including, as is now well known, the formation of an artificial radiation belt composed of electrons produced in the radioactive decay of fission fragments.[7, 8, 9] The VLF perturbations noted for the Hawaii (NPM)-to-Howard County, Jim Creek (NPG)-to-Howard County, and Balboa (NBA)-to-Howard County paths are representative of the two classes of perturbations noted above, and have been studied in some detail. Pertinent data on these VLF paths and their coordinates are compiled in Table I.

The VLF perturbations for the NPM-to-APL path and for the NPG-to-APL path were both direct, onset of the perturbation in each case being essentially simultaneous with the burst. This would be expected for the NPM path, in view of its geometry with respect to the burst point, with one terminal point (Hawaii) close to Johnston Island and directly exposed to X rays, gamma rays, and charged particles from the high-altitude explosion.

The NPG perturbation shown in Fig. 4 is more interesting, however, in that the VLF path in this case is far enough removed from Johnston Island so that no portion of it is directly exposed to the prompt radiation from the burst. However, the geomagnetic field line that terminates at NPG and which arches upward to about 11,000 km over the geomagnetic equator, is exposed to the burst up to geomagnetic latitude 50°N where its altitude is about 1000 km. Thus, charged particles created in, say, radioactive decay of neutrons from the burst can attach to the field lines and cause the essentially direct perturbation to the VLF path, as observed. A rapid digital system was used to record phase measurements on the NPG carrier at the rate of one per second during the period of locked-key (continuous-wave) transmission immediately before and after the burst. These measurements show that the perturbation began essentially at the instant of burst and reached a peak value of 20 μsec in 10 sec.

The NPG perturbation fits generally the burst-related neutron-decay model of Crain and Tamarkin, a model which, however, does not apply to the NBA-to-APL perturbation. The perturbation for the latter path, shown in Fig. 5, is most interesting in that neither the path nor the geomagnetic field lines terminating over the path are directly exposed to the burst. Also, it is seen that the onset of the perturbation does not occur until 1.5 min after the time of burst. The peak deviation is reached at 7 to 8 min after burst, after which, in general, recovery toward normal proceeds until

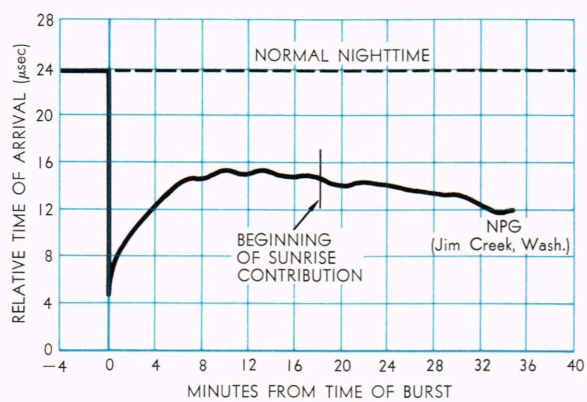

Fig. 4—VLF perturbation associated with the July 9 high-altitude nuclear burst, as observed for the NPG-to-APL path.

[7] B. J. O'Brien, C. D. Laughlin, and J. A. Van Allen, "Preliminary Study of the Geomagnetically Trapped Radiation Produced by a High-Altitude Nuclear Explosion on July 9, 1962," *Nature*, **195**, 1962, 939–943.

[8] G. F. Pieper, "A Second Radiation Belt from the July 9, 1962 Nuclear Detonation," *J. Geophys. Research*, in press, 1963.

[9] W. N. Hess and P. Nakada, "Artificial Radiation Belt Discussed at Symposium at Goddard Space Center," *Science*, **138**, 1962, 53–54.

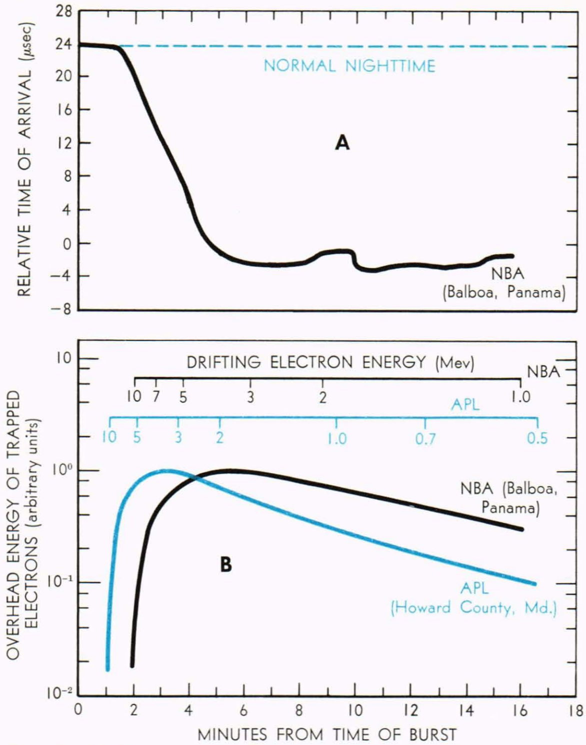

Fig. 5—VLF perturbation associated with the July 9 high-altitude nuclear burst, as observed for the NBA-to-APL propagation path: (A) VLF perturbation; (B) temporal energy variation of drifting electrons over NBA and APL/JHU.

the sunrise transition sets in at $t = 16$ min to obscure any further burst-engendered perturbations which might be present. This perturbation is explicable in terms of the drift in longitude of the trapped electrons forming the artificial radiation belt created by the burst. The NBA-to-APL path, which very nearly coincides with the 11°W magnetic meridian thus forms a well-defined north-south boundary to mark the passage of the drifting particles.

As the trapped electrons drift eastward from the burst point, an energy separation takes place, with the more energetic electrons having the higher drift rate. Also, electrons having the same energy will drift more rapidly at the higher geomagnetic latitudes. The temporal variation of the total energy of the trapped radiation over the NBA-to-APL path thus depends on location along the path. Over NBA (geomagnetic latitude 20°N) in the time interval $0 < t < 2$ min, the total overhead energy is negligibly small and pertains to electrons of energy greater than 10 Mev. The energies increase rapidly for $2 < t < 3$ (at $t = 3$, electrons of energy ~7 Mev are over NBA) and then more slowly to a maximum at $5 < t < 6$ min (at $t = 6$, electrons of energy ~3.5 Mev are overhead). After $t = 6$, the overhead energy of the trapped electrons decreases steadily.

The energy changes over the APL end of the path have a sequence much like that for NBA but with a displacement toward earlier times as a consequence of the increased drift rate at the higher magnetic latitude of APL (51°N). Regarding Fig. 5A, which shows the NBA path VLF perturbation, we first mention that a *decrease* in signal arrival time is a measure of *increasing* VLF disturbance. Applying this association, we note that there is good qualitative agreement between the temporal variation of the VLF disturbance and the temporal variation in particle energy over the NBA end of the path. Both the VLF phase perturbation and the overhead energy are increasing in the interval $1.5 < t < 5$ min and decreasing between $8 < t < 10$ and $11 < t < 16$ min. The peak VLF perturbation at $7 < t < 8$ min lags by about one minute the energy peak that occurs at $5 < t < 6$ min, as noted above. This lag may stem from a delay in the response of the ionosphere to the ionizing radiation. All in all, however, and in view of the complexities involved in the nuclear burst, in the motion of trapped particles, and in the lower ionosphere itself, the agreement is considered to be quite good.*

Since the observed VLF anomaly is more closely correlated with temporal energy changes over NBA than over APL, we conclude that the VLF perturbation is ascribable to ionization in regions of the VLF propagation path lying nearer to NBA. Independent arguments that this is the case can also be made from the spatial distribution of electrons in the artificial radiation belt and from the differences in the VLF disturbances along paths having a common terminal, APL/JHU.

A detailed account of these and other VLF perturbations associated with the high-altitude nuclear burst of July 9 has been prepared.[10]

The general picture of the delayed VLF perturbations associated with high-altitude nuclear bursts is, then, that they are correlated, in time and magnitude, with the temporal energy variation of geomagnetically-trapped particles drifting over the path. Precise VLF monitoring techniques that permit more accurate definition of VLF perturbations in time and magnitude are the key to even more detailed investigations of geophysical phenomena involving interactions between particle radiation and the lower ionosphere.

* The phase perturbation at $t = 10$ min on the VLF record cannot be described in terms of trapped electron energy changes.

[10] See also A. J. Zmuda, B. W. Shaw, and C. R. Haave, "VLF Disturbances and the High-Altitude Nuclear Explosion of July 9, 1962," paper submitted to *J. Geophys. Research.*