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Geophysical Effects of High Altitude Nuclear Explosions

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August 1964

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GEOPHYSICAL EFFECTS OF HIGH ALTITUDE NUCLEAR EXPLOSIONS

by

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ABSTRACT

In 1962, both the Russians and the Americans conducted a series of high altitude nuclear explosions which had widespread geophysical effects. A study of these effects is useful to the geophysicist if it will shed light on the mechanisms responsible for similar geophysical phenomena which are noted in association with normally occurring disturbances.

This paper presents a review of the effects of nuclear testing, with special emphasis on the trapped radiation, the ionosphere, and magnetic disturbances. An interpretation of these different phenomena is made.

ACKNOWLEDGMENT

We are deeply indebted to R. Meuse of the Boeing Metrology Laboratory for allowing us to use the excellent phase comparison records between WWVL reception and the Boeing Frequency Standard.

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Introduction

The detonation of high altitude nuclear devices has a profound effect upon the earth's atmosphere. Many observations of these effects have been made and various interpretations of the causative mechanisms have been attempted in the past few years. Because of the similarity of these events to the naturally occurring geophysical phenomena, considerable interest in the subject exists at this time, and there is value in the presentation of a review of some of the published articles that are of interest to the geophysicist.

It should be borne in mind throughout this review that a considerable amount of classified information may still exist.

High Altitude Tests

In recent years, a number of high altitude nuclear tests have been conducted by both the Americans and the Russians. The first series, back in 1958, yielded only a limited amount of information useful to the geophysical scientist because many details of the detonations were not made public prior to the events. In 1962, however, the American series was sufficiently well announced to allow many scientists the opportunity to set up experiments designed to investigate the details of the geophysical phenomena associated with these bursts and publish their results in the open literature. Indeed, the rapidity with which much of the classified data were made public has been quite remarkable and gratifying.

Announcements by both the United States Atomic Energy Commission and the Seismological Institute at Uppsalla also afforded scientists some information on the Russian detonations very soon after they were held. Although the exact details of the yield, altitude, and some of the other burst parameters are still not available, sufficient information has been released to allow many useful studies to be made. Table 1 gives some of the details of the announced high altitude nuclear bursts.

Table 1

Location	Time	Altitude (km)	Yield	Reference
* J.I.	Jul 9, 62 ~ 0900UT	hundreds	Megaton	Brown et al.(1963)
J.I.	Oct 20, 62 ~ 0830UT	tens	low	AEC E-382
**C.A.	Oct 22, 62 ~ 0341UT	high	few hundred kT	AEC E-384
J.I.	Oct 26, 62 ~ 1000UT	tens	submegaton	AEC E-389
C.A.	Oct 28, 62 ~ 0441UT	high	intermediate	AEC E-394
C.A.	Nov 1, 62 ~ 0910UT	high	intermediate	AEC E-404
J.I.	Nov 1, 62 ~ 1210UT	tens	submegaton	AEC E-400
J.I.	Nov 4, 62 ~ 0630UT	tens	low	AEC E-407

* J.I. = Johnston Island

**C.A. = Central Asia

Studies of naturally occurring geophysical phenomena are usually complicated by lack of knowledge of the cause of the disturbance. Although the total amount of energy contained in any one of these events is small in comparison with a solar-associated disturbance, the initiating cause is very localized and the timing is, at least in some cases, so well known that propagation times of various disturbances can be measured. This is normally not possible in the case of a solar disturbance. Consequently, extensive interest has been shown in the study of the geophysical perturbations associated with nuclear testing. Studies of the large scale displays resulting from this type of controlled stimulus may be used to shed light on the details of the mechanisms responsible for naturally occurring geophysical phenomena.

High altitude nuclear detonations, in particular, give rise to aurora, cosmic noise absorption, sporadic E [Gregory, 1962], shortwave fadeout, magnetic disturbances [Maeda et al. 1964], micropulsations [Caner and Whitman, 1962], spread-F [Heisler and Wilson, 1962], VLF anomalies [Willard and Kenney, 1963], D-layer enhancements [Obayashi et al. 1959] and other disturbances closely resemling phenomena which one notes normally in nature. Many of these disturbances can be explained in terms of debris motion and fireball expansion, others can be explained as the effects of trapped radiation, while the origin of still other disturbances is obscure.

Energy Release

Figure 1 is a schematic representation of a nuclear test published by Alpert [1962]. At the time of the explosion, a large amount of energy is released in a small volume. X-rays, γ-rays, fission fragments, electrons and neutrons are given off, and a dense hot plasma is formed in the burst area. Gamma and x-rays spray out in a 4π geometry, those headed downward will cause ionization of the upper atmosphere and ionosphere, whereas those which head outward are lost. The neutrons spray out also, travelling in a straight line, undeviated by the magnetic field, at a velocity which depends on the neutron kinetic energy. The neutrons heading outward can have some effect, since they may decay into electrons and protons before leaving the magnetosphere. The resulting charged particles will be constrained to spiral along the magnetic field lines, either entering the upper atmosphere on the first few bounces, or spending a longer period of time as trapped radiation. Energetic electrons that leak out of the blast area at the time of the burst will also spiral along the field lines, contributing to the aurora and trapped radiation.

The bulk of the plasma forms a high-temperature diamagnetic cavity, which will slowly expand and exclude the earth's magnetic field from the immediate vicinity of the explosion. If there is an appreciable atmosphere, the bubble will be buoyant, and gradually rise to higher altitudes. Charged particles

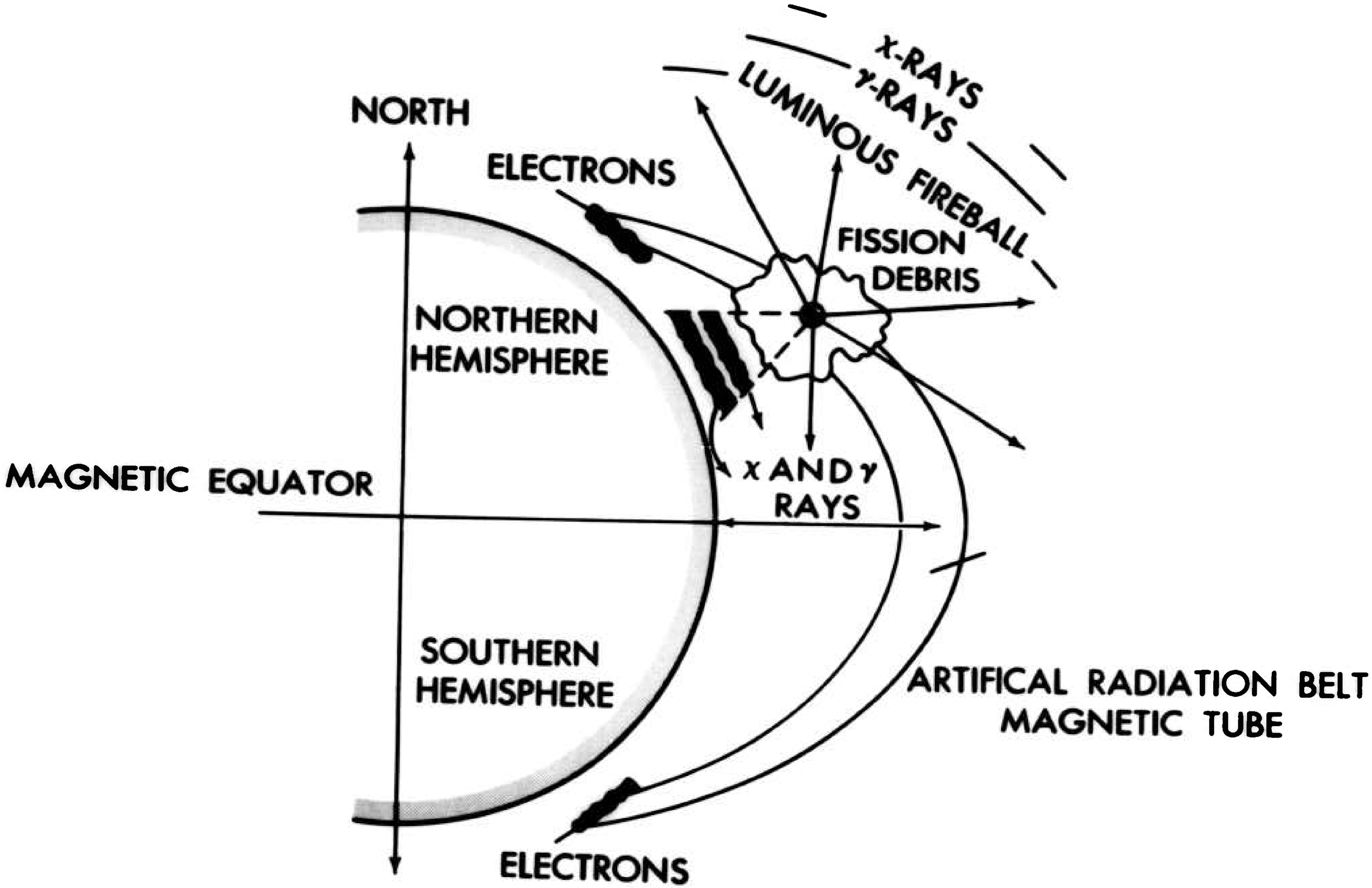


Fig. 1. Phenomenology of a high-altitude nuclear burst [Alpert, 1962].

leaking out as the bubble rises will be released into the magnetosphere at progressively larger L values. As the bubble expands, the internal energy density drops until finally the magnetic field re-enters the volume. At this time, the charged particles which have been contained are now free to leave, and the energy density drops rapidly. Using this sort of analysis on the July 9, 1962 event, Colgate [1963] arrived at the figure of two and one half seconds for the value of the time during which the magnetic field was excluded.

In the immediate vicinity of the burst area, there exists such a plethora of both prompt and delayed radiation, that it is difficult to sort out the effects that each particular constituent would have. In general, one may say that the behavior of the atmosphere and ionosphere within the line-of-sight of the burst, will, to a large extent, be controlled by the x and γ radiation, since about half of the energy released comes off in the form of x and γ radiation [Latter et al. 1961]. Without much knowledge of the burst parameters, it is difficult to do more than estimate the effect that this would have on the surroundings. The problem is complicated by any excess material that may be located in the burst vicinity, since this would change the spectrum of the x and γ radiation. There is, however, no basic lack of understanding of the energy transfer mechanisms. (As an example, see Latter and LeLevier [1963]).

On the other hand, if one confines oneself to regions remote from the burst area, it becomes possible to sort out some of the cause and effect relationships. Many of the remote effects, such as shortwave fadeout, VLF anomalies, sudden enhancement of atmospherics, etc., can be easily explained if a mechanism exists for increasing the D-region ionization in the proper fashion. The geographical extent, time behavior, and magnitude of these D-region enhancements must be sufficient to explain all the observed disturbances.

VLF Disturbances

Perhaps the best evidence for enhancements of the D-region at large distances from the burst site comes from records of VLF disturbances in both phase and amplitude following the explosion. For most VLF propagation paths, the relative phase of the received signal exhibits a diurnal variation which has a trapezoidal form. The interpretation of this is rather simple. The wave propagates in the earth-ionosphere waveguide, and the effective reflecting height for a given frequency undergoes a diurnal change. As the sun comes up, solar radiation causes a considerable increase in the ionization, such that the D-layer extends downward to some 60 km or so above the earth's surface. At night, the effective reflecting height for VLF waves increases to about 90 km. Recombination, electron attachment etc., have caused the electrons to disappear, and the strong solar ultra-violet source excitation is now absent. At night, any increase of ionization below about 90 km can be detected with surprisingly high sensitivity by the VLF techniques. When a nuclear test increases the D-region ionization, the following effects on VLF transmissions may be expected.

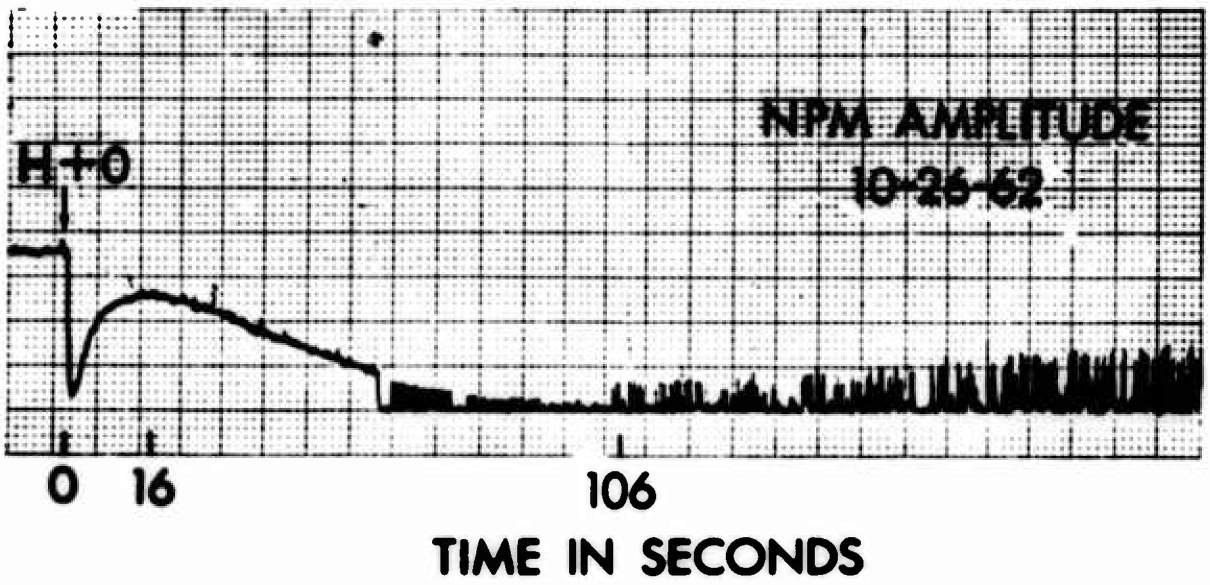
1) Phase - Since the ionization increases, the effective reflecting height is lowered, and the propagation time for the signal to go from transmitter to receiver decreases. This always causes a relative phase advance in the signal [Wait and Spies, 1961].

2) Amplitude - The amplitude of the received signal may either increase or decrease, depending on what happens to the mode of transmission. If the receiver is located near the principal minimum, the signal can either increase or decrease as the reflection height is lowered [Frisius et al. 1964]. At large distances, the signal strength usually decreases with a decrease in effective reflection height [Wait, 1957]. Nevertheless, Wait and Walters [1963] have shown a decrease in VLF reflection coefficient when a small increase in ionization is formed well below the normal reflection height. If the increased ionization is formed near the reflecting height, the apparent steepening of the ionization gradient can increase the reflection coefficient. Thus, even at large distances, the signal strength can either increase or decrease.

VLF Data

Detailed studies have been made of changes in the phase and amplitude recordings of VLF stations during the various high altitude tests of 1962 by several groups. In general, two types of effect are noted in these data. The first is a prompt effect, not noted on all the records, in which the signal characteristics change quickly. The second effect may be delayed several minutes and last much longer.

One of the best documented tests is the July 9, 1962 test held at Johnston Island, although reasonably good records exist for all the American tests and most of the Russian tests. To illustrate the prompt and delayed effects, let us start with the records of phase and amplitude for the October 26, 1962 tests at Johnston Island. These records were taken by H. R. Willard for the NPM transmission, Honolulu to Seattle, 19.8 kHz. Figure 2 shows the amplitude record on two different time scales for this event. H + O marks the detonation time. Approximately 80 ms after H + O, an extremely rapid drop in amplitude took place, followed by a very rapid recovery. At about H + 16 seconds, a second fade started and reached a minimum signal amplitude at H + 106 seconds. Recovery finally commenced and was essentially complete some 15 to 20 minutes after the burst. Figure 3 shows a comparison of the phase and amplitude records on the short time scale. The time constant of the electronics for the amplitude recording was very short, as one can see from the individual



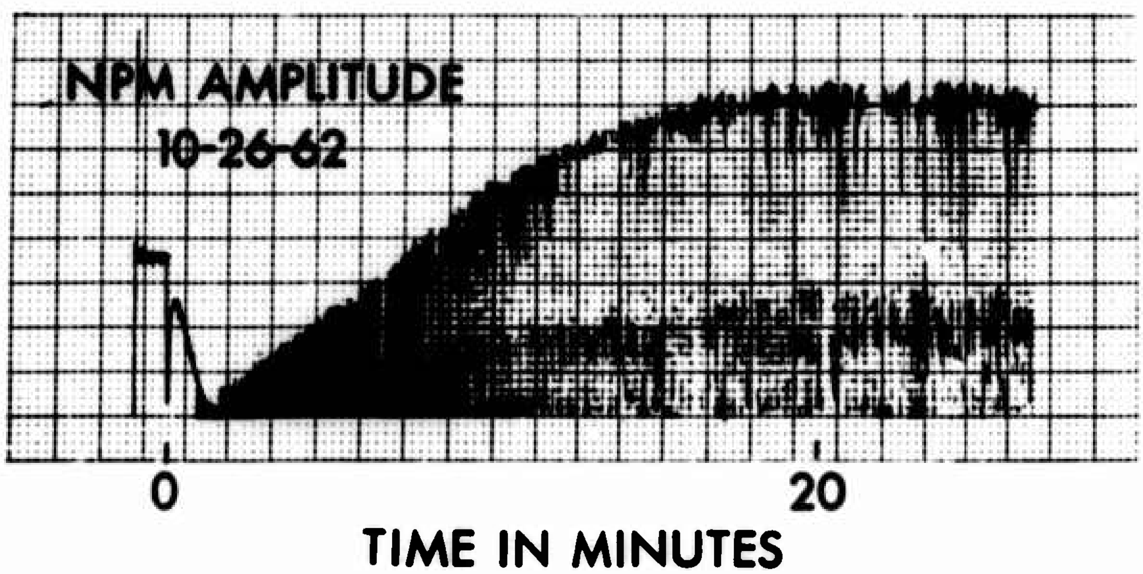


Fig. 2. NPM amplitude [Hawaii-Seattle], October 26, 1962.

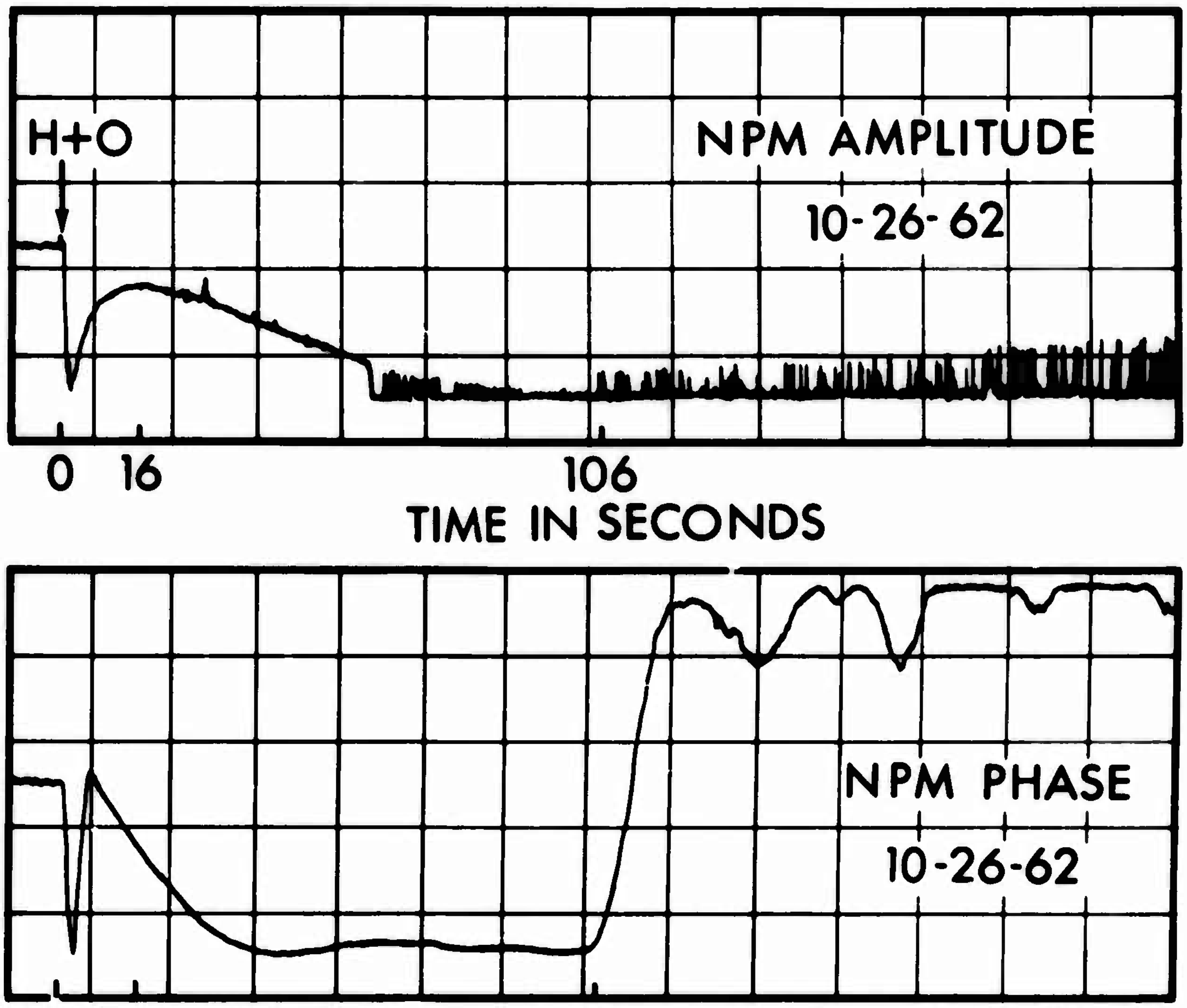


Fig. 3. NPM phase and amplitude, October 26, 1962.

dots and dashes of the code transmission. The time constant of the phase measuring device was a couple of seconds. Consequently, one may say that a prompt (i.e., 80 ms) and large effect took place on both phase and amplitude, the phase recovering first, and then starting again with another phase advance which was delayed. The rapidity with which the prompt effect recovered shows that the electron removal processes were rapid. The entire effect was consistent with excess ionization created deep in the D-region from a sudden impulsive source, followed at a later time by a delayed injection of excess ionization which lasted a much longer time. At H + 106 seconds, the transmitter went into a frequency shift keying sequence which accounts for the double envelope of amplitude in this and in the preceding figure, and the loss of phase track on this record after H + 106 seconds.

Turning now to the records of other observers, one sees in Figure 4 the data taken by Zmuda et al. [1963] on three propagation paths for the July 9 test. A prompt effect is present in the NPG-APL path, not present on the NBA-APL path, and only marginally perceptible on the WWVL-APL path. All three paths certainly have delayed effects.

The next sets of data were taken by Frisius et al. [1964] on the paths shown in Figure 5. This chain of stations is particularly useful in that it allows a very complete monitoring

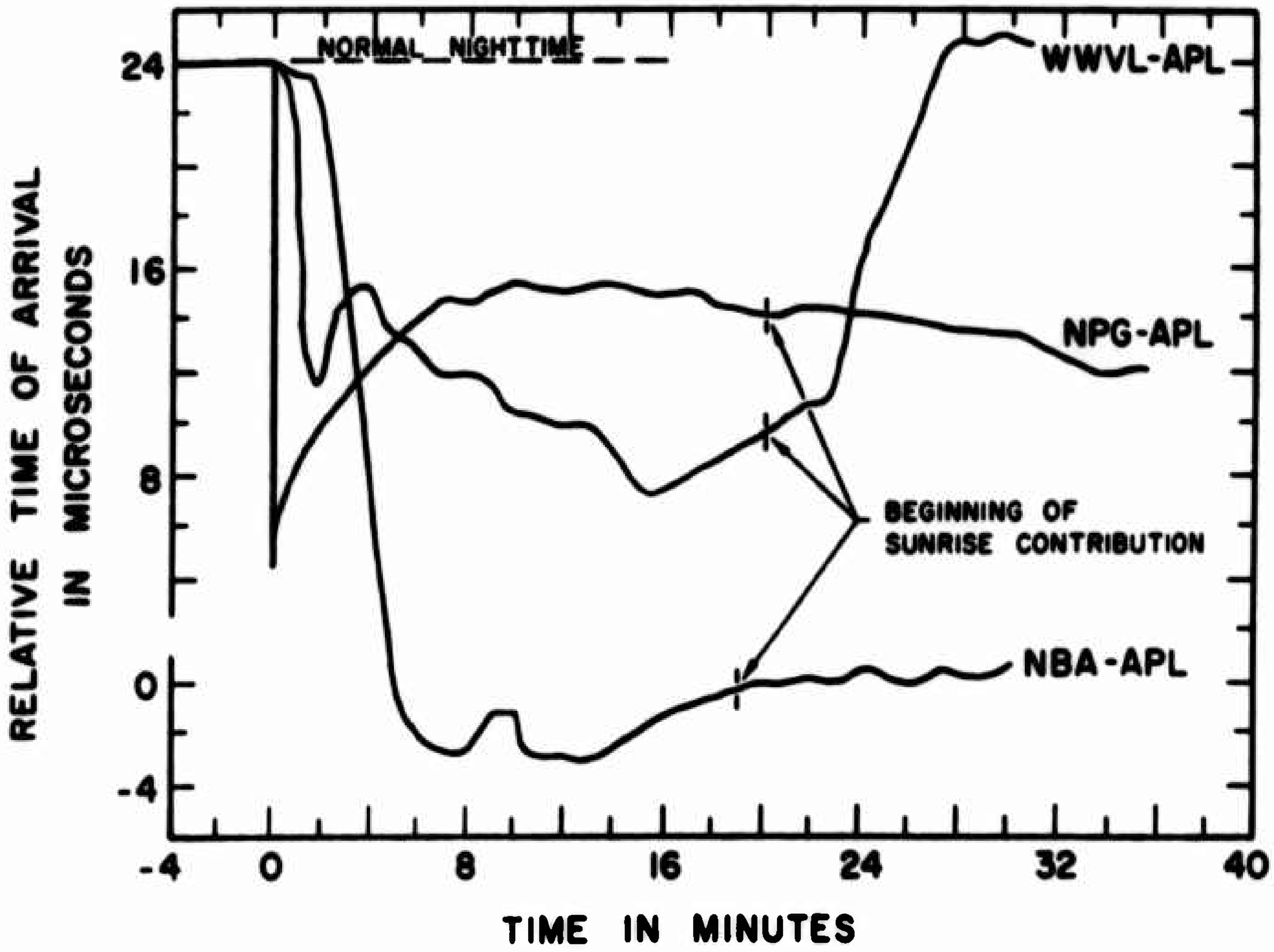


Fig. 4. VLF disturbances measured at APL, July 9, 1962 [Zmuda et al. 1963].

of changes in the mode of propagation over this region by comparing the way amplitude builds up and decreases on a station to station basis. Figure 6 shows the data taken on this network for the October 22, 1962 Russian burst around 0341UT. Again a prompt and a delayed effect are noted on these records. Figure 7 shows a similar data taken on this same network for the October 28 Russian test.

Finally, let us return to additional records taken in Seattle, Washington of the reception of a VLF station from Boulder, Colorado [R. Meuse, private communication]. Looking at Figure 8, one sees that the appearance of the WWVL reception for the October 26 event with a slow-speed response in the phase detection system has the following form. At the time of the burst, there is a very sudden advance in phase coupled with a gradual recovery. We have earlier seen from a recording with high speed resolution that a prompt and a delayed effect were both present. Because of the very slow response time of this equipment, it is impossible to resolve the two effects. However, one can see that a large and prompt increase in D-region ionization is certainly present. In Figure 9, one sees that the effect of the much larger burst on July 9 has the same shape, but a larger magnitude. Indeed, in Figure 10, again one notes that the very small effect due to the low yield burst of October 20, 1962 has the same shape. In Figure 11, note the interesting fact

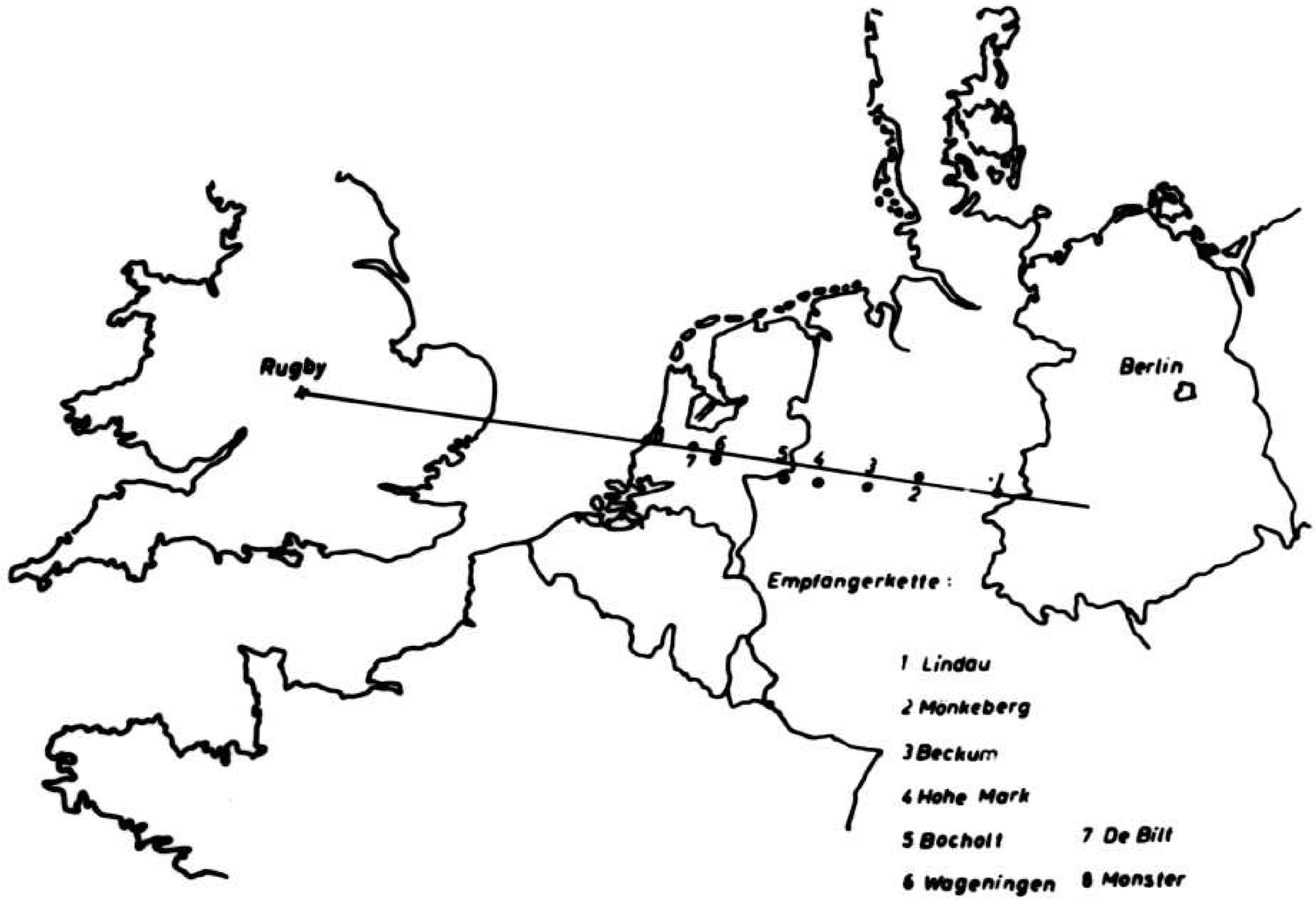


Fig. 5. Max-Planck Institute network of VLF receiving stations [Frisius et al. 1964].

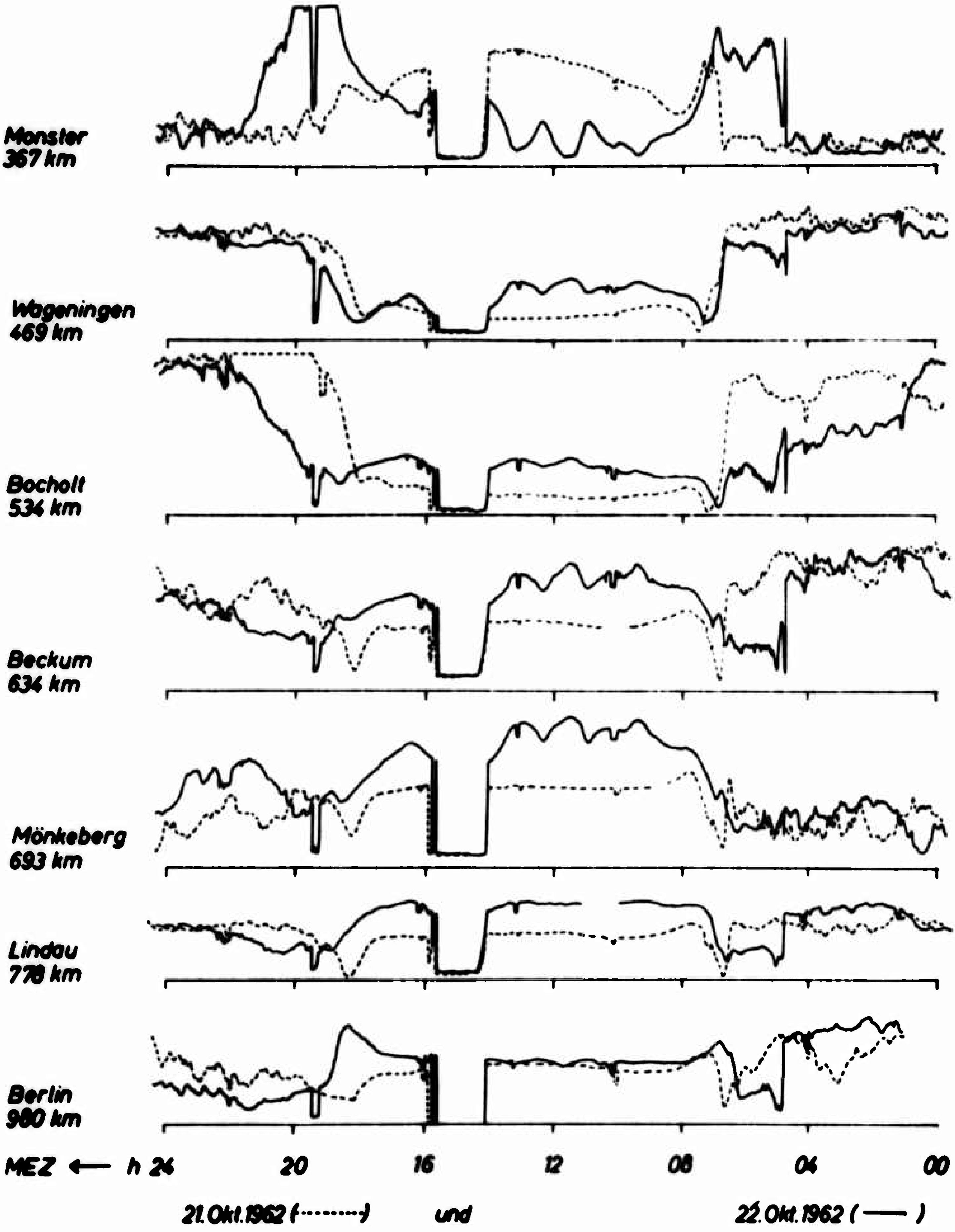


Fig. 6. VLF field-strength records [Rugby-Western Europe], October 22, 1962 [Frisius et al. 1964].

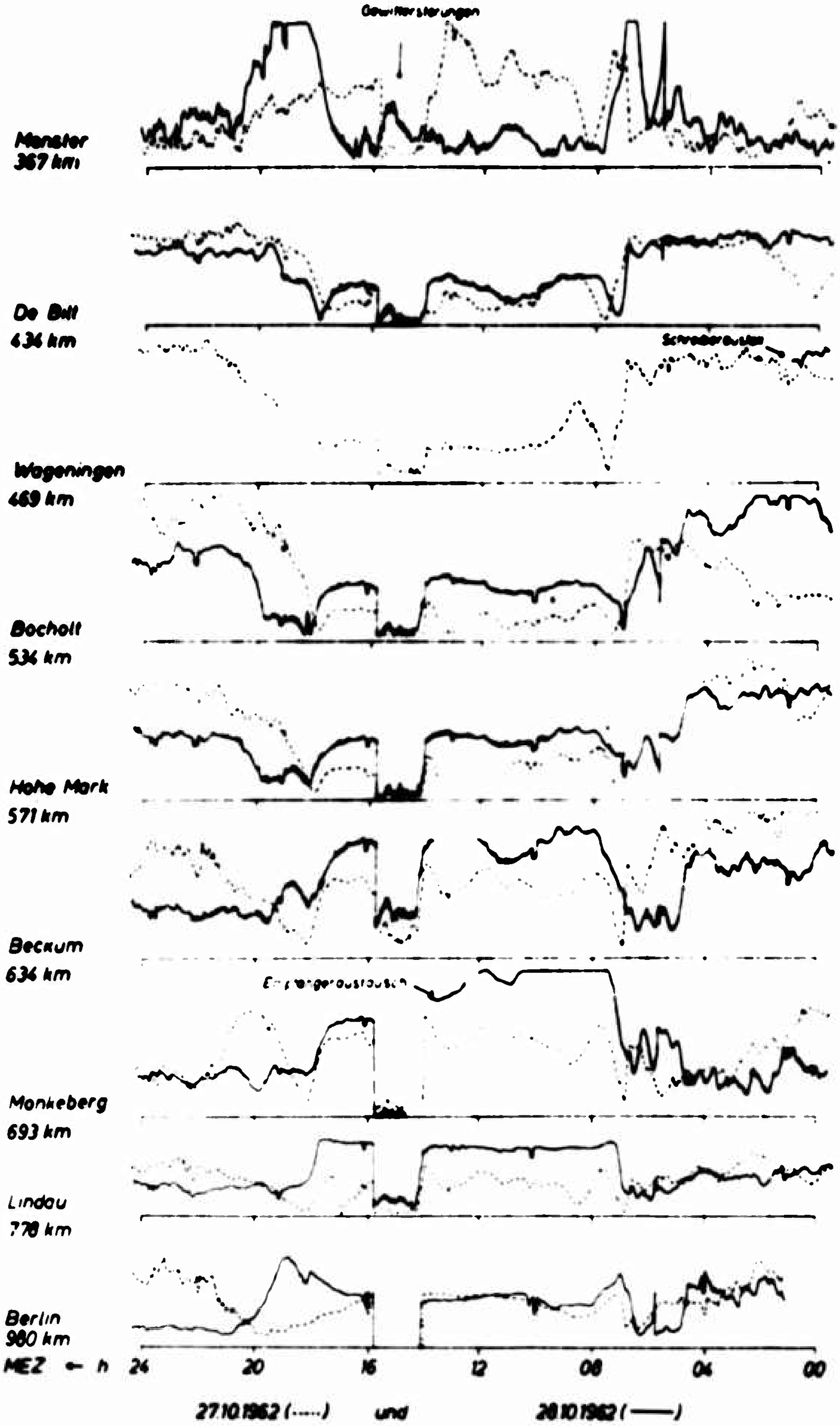


Fig. 7. VLF field-strength records [Rugby-Western Europe], October 28, 1962 [Frisius et al. 1964].

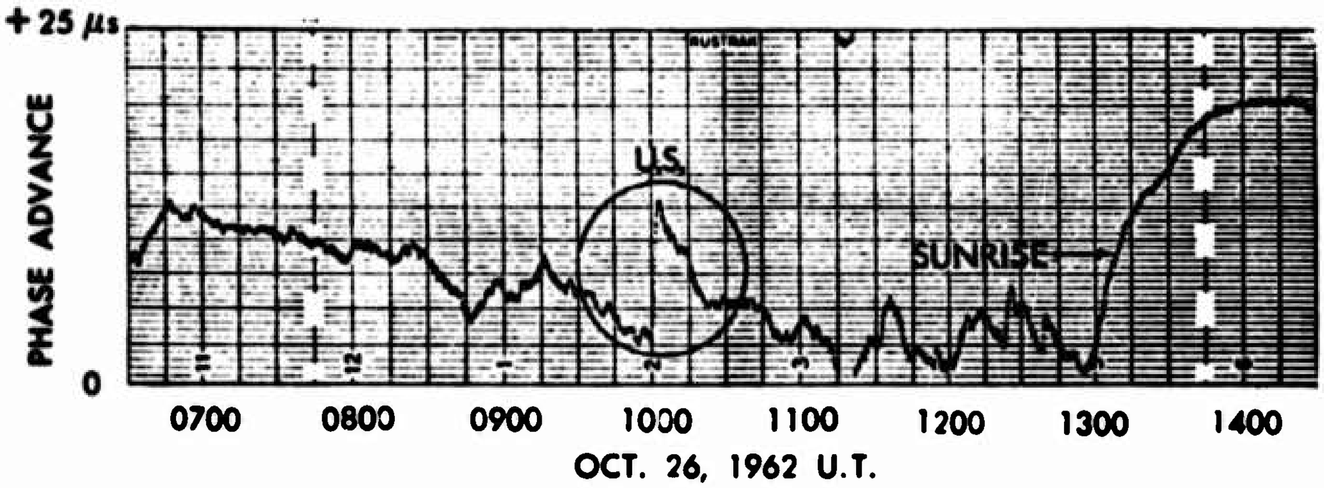


Fig. 8. WWVL phase [Boulder-Seattle] October 26, 1962.

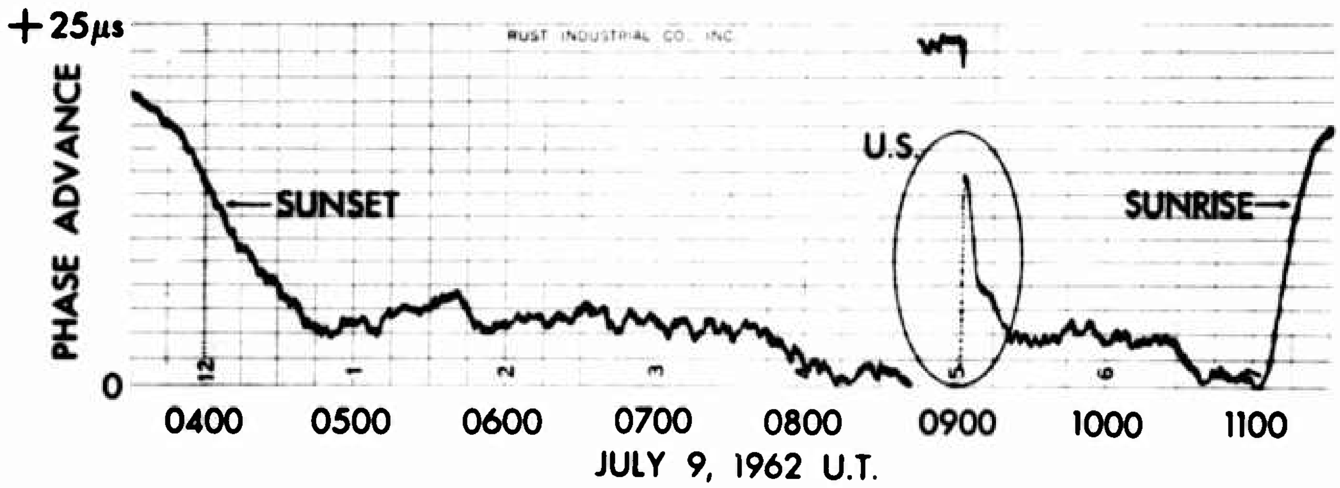


Fig. 9. WWVL phase [Boulder-Seattle] July 9, 1962.

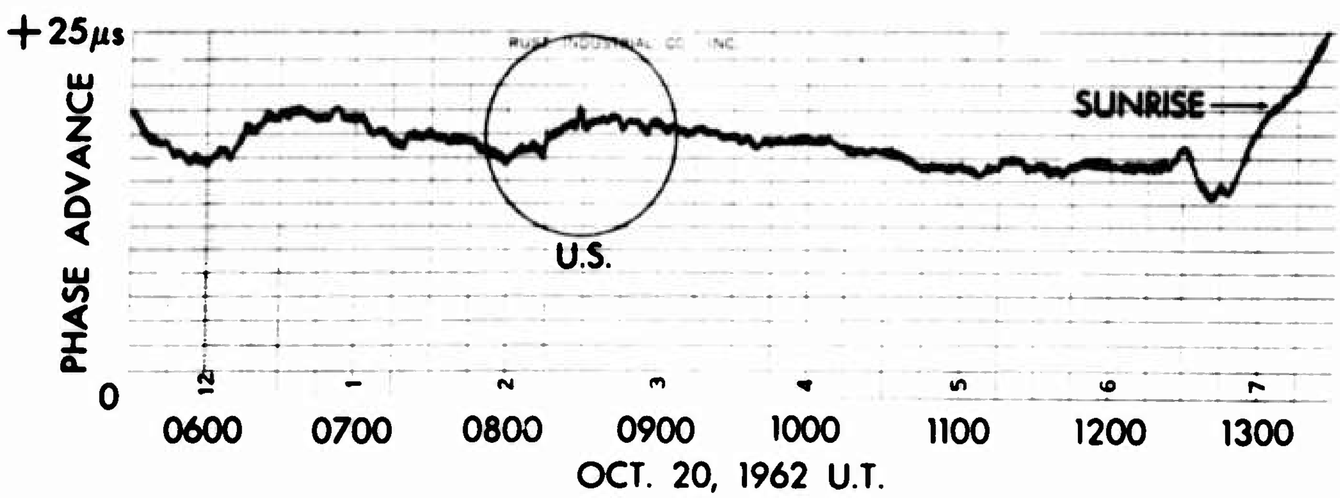


Fig. 10. WWVL phase [Boulder-Seattle] October 20, 1962.

that the American test on November 1, 1962 again produced an effect which has the same shape on the trace, but the Russian test some three hours earlier had only a delayed effect. This burst which occurred somewhere around 0910UT had no evident effect for some 20 minutes, then it reached its maximum disturbance about H + 35 minutes and was essentially recovered within an hour. In Figure 12 one notes again that the Russian burst of October 22 had no prompt effect on this propagation path; the delayed effect also had a different appearing trace on the record than that of November 1, being much larger, delayed only a few minutes, and lasting a much longer time.

Without showing any more data of this kind, let us summarize what has been shown. Both prompt and delayed effects can occur in the ionosphere after a nuclear burst. For the Russian bursts, prompt effects were noted all over Western Europe, but not the Western United States. For the American tests, prompt effects were always noted in the Western United States, and only sometimes in the Eastern United States, depending on the paths involved. The time behavior of the delayed effects could also vary even though the explosion location and detection sites remained the same. Let us now attempt to explain the cause of all these effects.

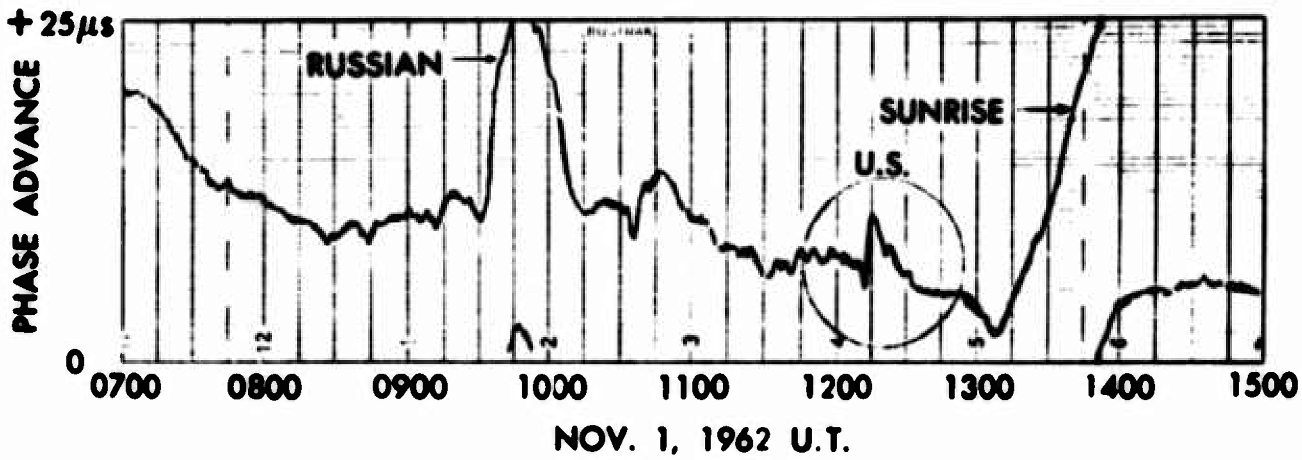


Fig. 11. WWVL phase [Boulder-Seattle] November 1, 1962.

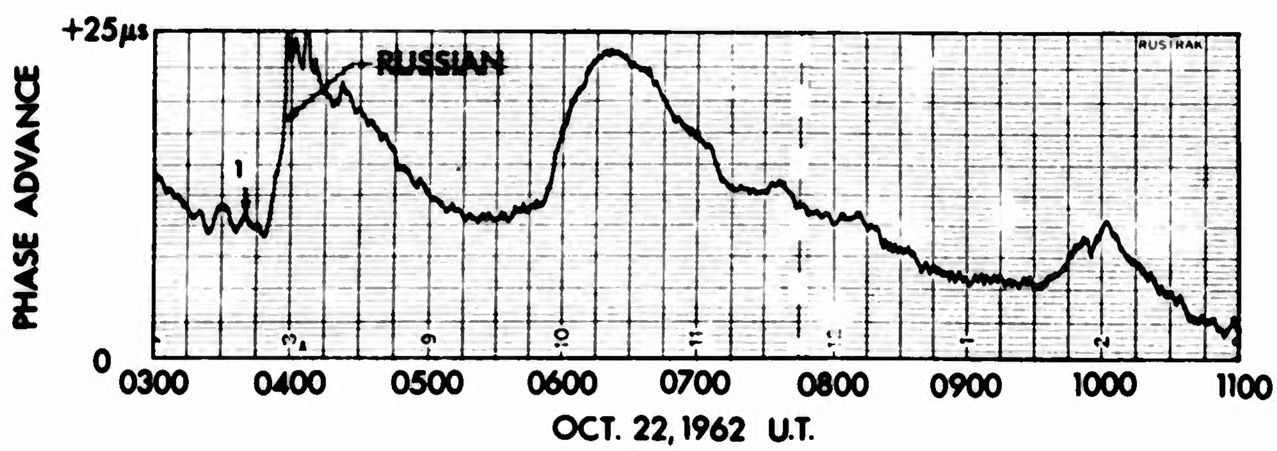


Fig. 12. WWVL phase [Boulder-Seattle] October 22, 1962.

Prompt Effects

Records taken over the United States with only half-minute time resolution saw the effects commencing "simultaneously" with the burst. X and γ radiation must be ruled out as the cause of the prompt effect because this effect was not confined to regions within the line-of-sight of the burst. We can also eliminate direct β particles and debris as the cause of the first phase advance since no charged particles can reach the NPM transmission path directly from the blast area soon enough. Dumping of trapped radiation, ionospheric enhancements due to travelling hydromagnetic waves, and similar causes must also be ruled out as the cause of the prompt effect because the temporal and spatial behavior of these sources can be shown to be unsuitable.

The answer to the prompt effect lies in the neutrons which leave the blast area. As was first suggested by Crain and Tamarkin [1961], a small fraction of the neutrons formed in the fission area (see Figure 13) will decay into protons and electrons before they leave the earth's magnetic field. Those neutron-decay products which mirror at high altitude will contribute to long lasting radiation belts; those which mirror at low altitude will be lost quickly; and finally an appreciable fraction will be lost in the earth's atmosphere on the first north-south passage. This last category will be comprised of those neutron-decay products injected into the magnetic field with pitch angles such that they

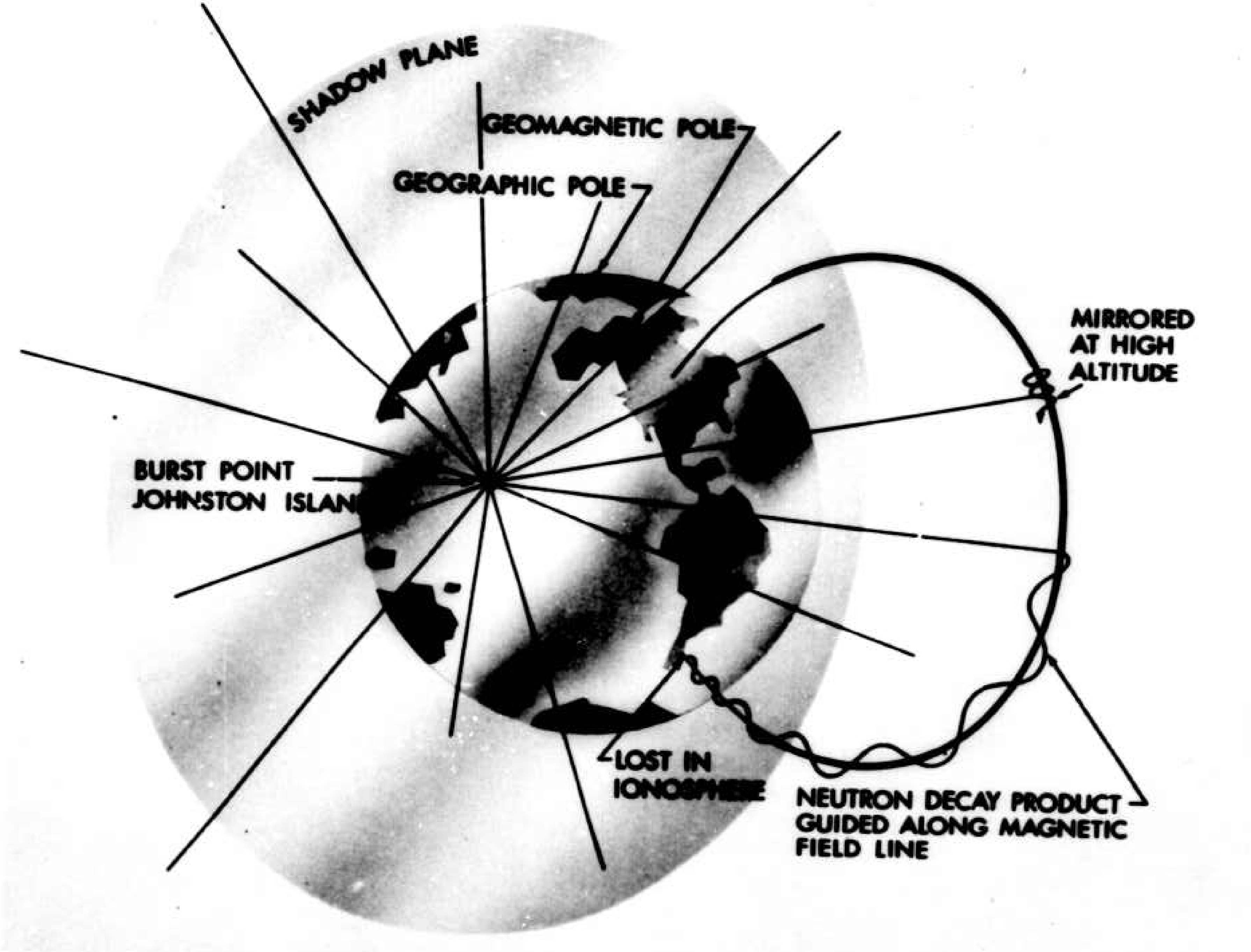


Fig. 13. Trapping and precipitation of neutron decay products in the magnetosphere.

would mirror in or below the atmosphere.

Since the neutrons are uncharged and would have energies in the low Mev region [Watt, 1952], they can travel across field lines without being deflected and decay at regions remote from the blast site within an extremely short time. Calculations have been made by the authors [Kenney and Willard, 1963] to determine if the magnitude of the neutron source is sufficient to explain the prompt D-region enhancements, and if the geographical distribution is also correct. Calculation of the contribution of this source to the trapped radiation have also been carried out. To do this, one assumes a source of neutrons at the burst point, and computes the decay density in the illuminated portions of the magnetosphere. To separate those decay products which enter the atmosphere on the first pass and cause prompt effects from those which have a longer life, the injection pitch angle distribution is important. Because of momentum and energy considerations, the decay proton comes off in essentially the same direction as the parent neutron, whereas the electrons are produced isotropically.

Looking at Figure 14, one sees that neutrons decaying in different portions of the magnetosphere will cause different injection pitch angle distributions for protons and electrons, but one can take account of these different distributions. For a

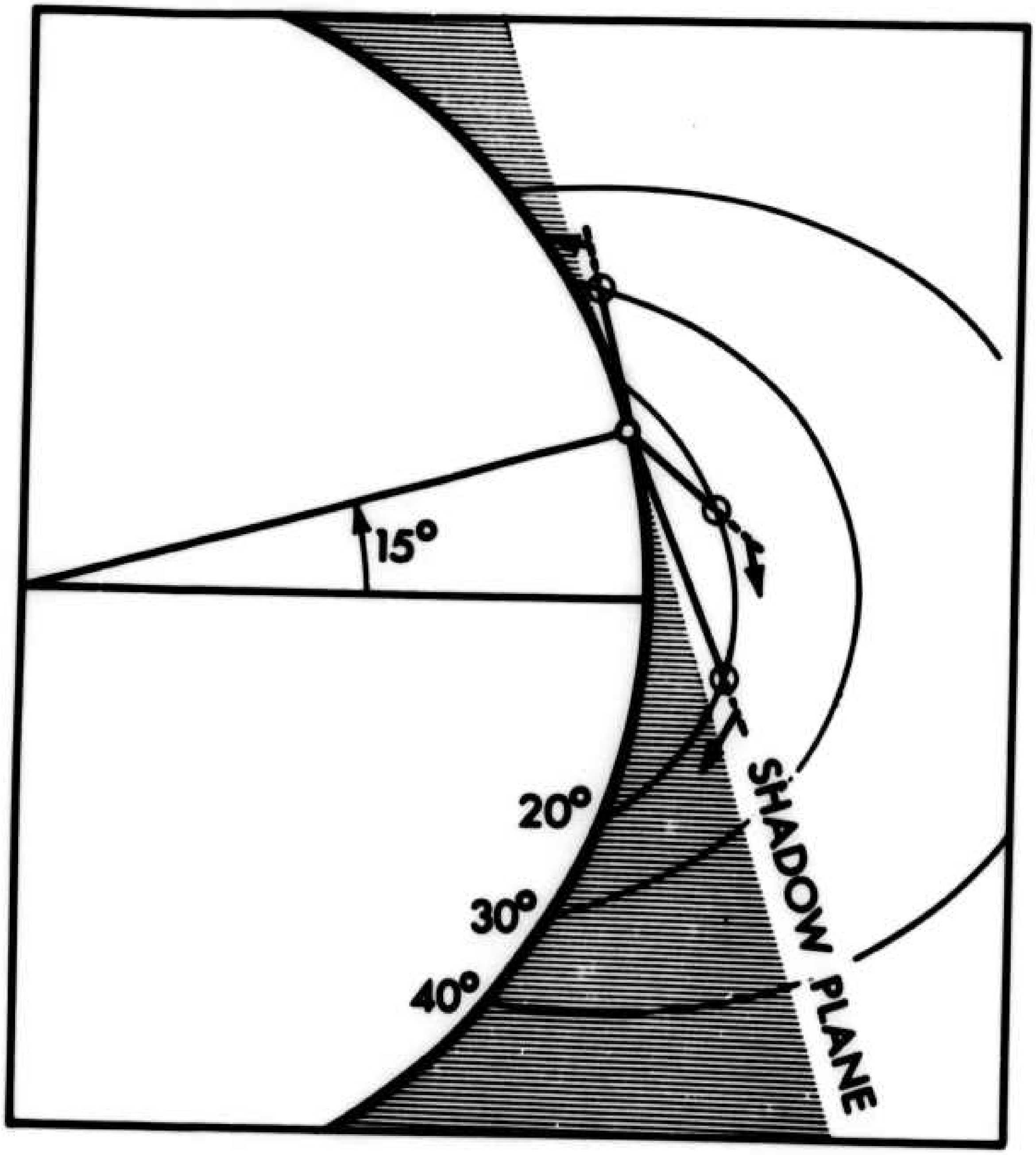


Fig. 14. Shadow plane and proton pitch angle.

given flux tube, all neutrons which decay north of a certain point will be travelling in such a direction that their protons will be dumped into the northern hemisphere. All those neutrons decaying south of a certain point in a given flux tube will produce protons that are dumped immediately into the southern hemisphere. Those in between contribute to the trapped radiation. The electron distribution can be similarly accounted for, although they are produced isotropically at the decay point. These calculations have been performed for fission bursts at the top of a slab atmosphere, and the results have been plotted on world maps.

Figure 15 shows the effects of a one kiloton fission burst at Johnston Island. The numbers assigned to the contour lines indicate the number of electrons or protons formed by neutron decay in a flux tube connected to one cm^2 of the surface of the earth. Figure 16 shows the effects of a similar burst at a different latitude. The USAEC has announced that the Russian high altitude bursts were held in "Central Asia", and atmospheric bursts at Semipalatinsk. For lack of more precise information, we have assumed that "Central Asia" is in the vicinity of Semipalatinsk. The contours for these different latitudes are quite similar.

Figure 17 shows the effect that this same burst would have on prompt electron deposition. The numbers attached to the contours are equal to the number of electrons dumped on the first

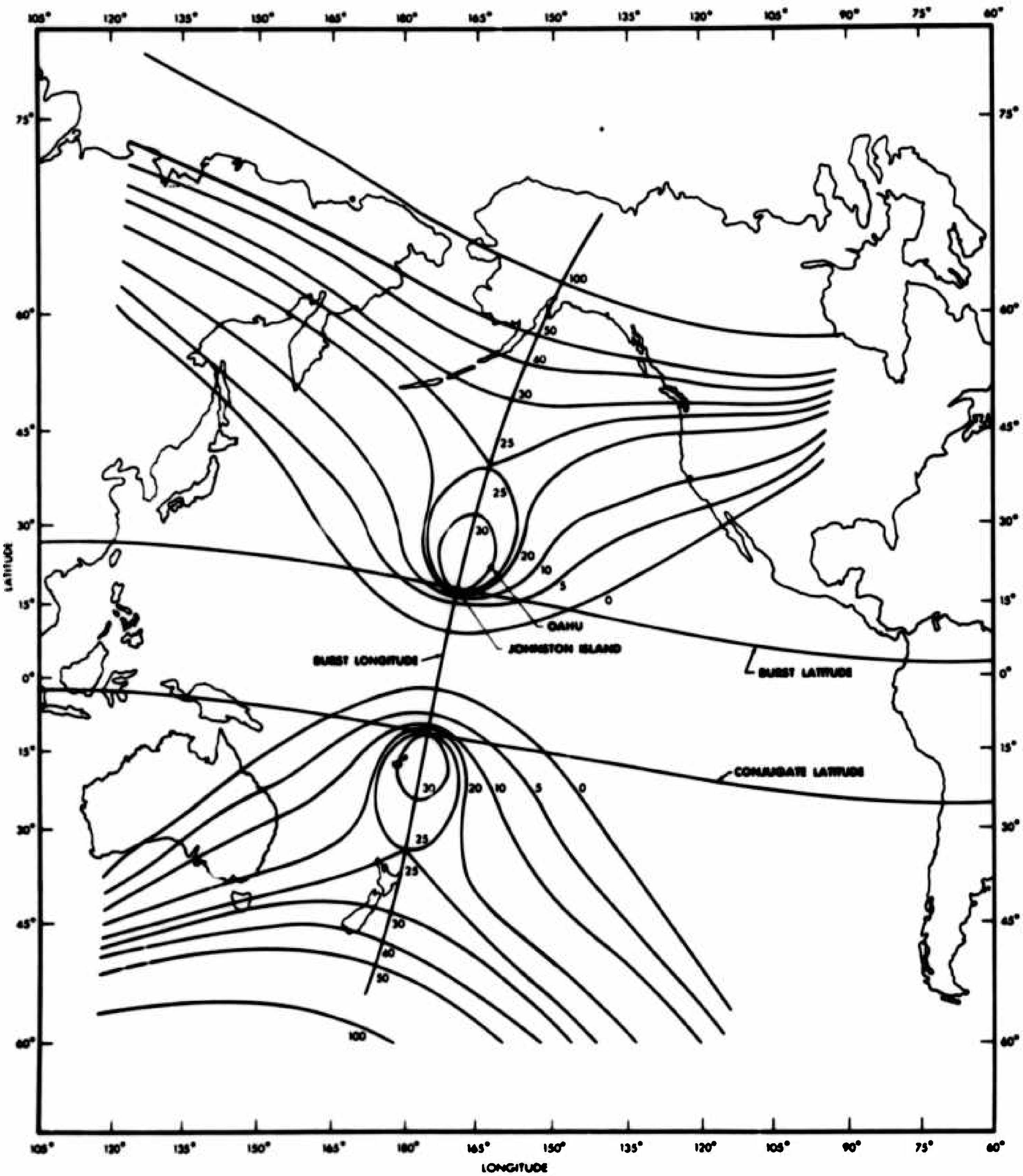


Fig. 15. Contours of neutron decay inside a flux tube of unit area at the surface of the earth for a one kiloton detonation over Johnston Island.

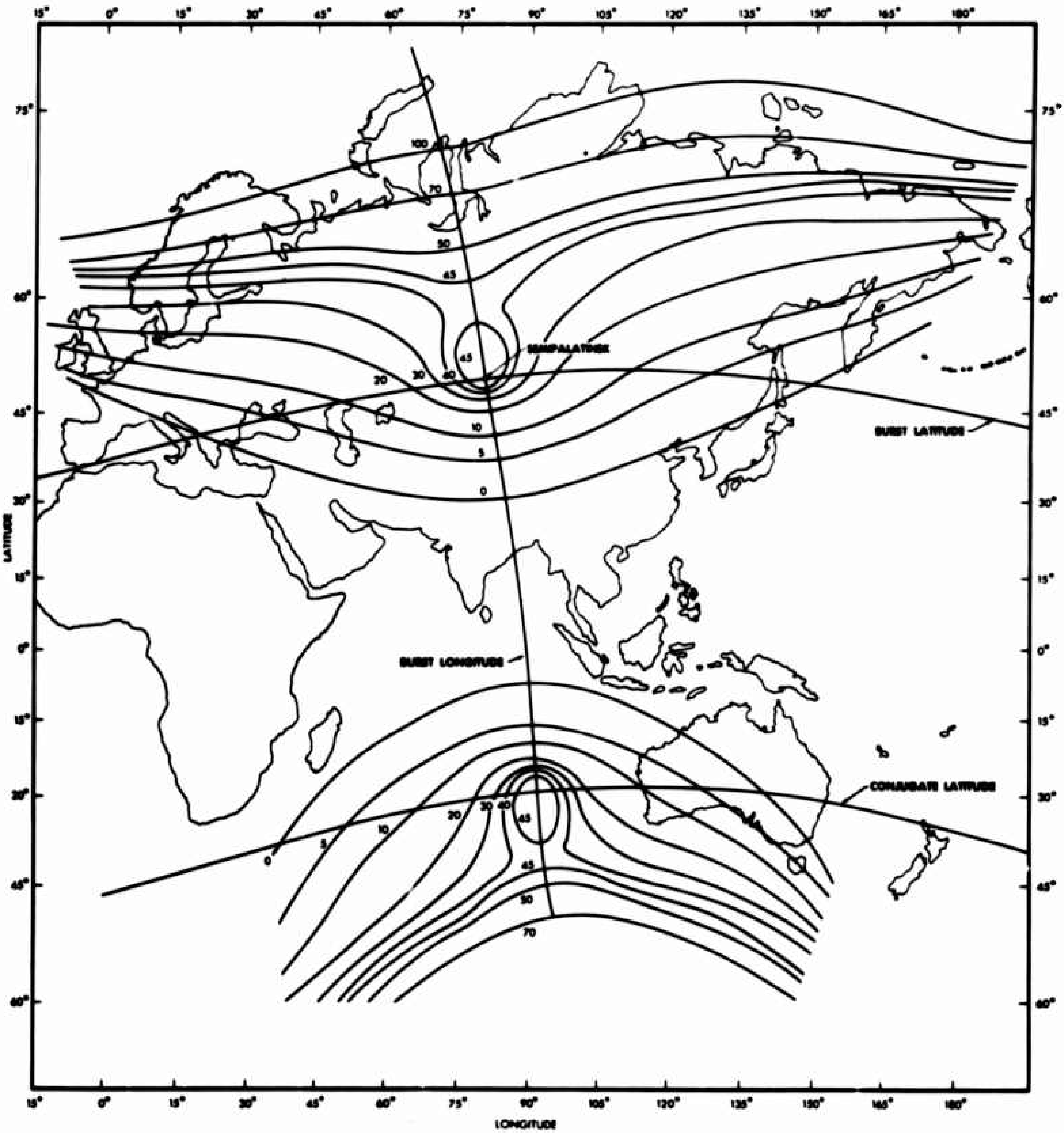


Fig. 16. Contours of neutron decay inside a flux tube of unit area at the surface of the earth for a one kiloton detonation over Semipalatinsk.

entry into the atmosphere. Since the effective energy for a neutron decay beta is about 350 kev, and it takes about 35 ev to form one ion pair in the atmosphere, each of these electrons forms about 10^4 ion pairs as it enters the atmosphere. Most of this energy loss will take place in a layer about 5 km thick, somewhere around 70 km. Figure 18 now shows the similar prompt beta deposition for this type of burst at Johnston Island. Again note that the general outline of the prompt beta deposition extends all over the western part of the United States and over to Japan, covering part of Australia, but missing Russia and Europe completely.

It is very interesting now to look at Figure 19 where the prompt deposition of protons is shown. Note that the patch is much smaller but more intense. Since the protons are more energetic, they also create more ion pairs as they enter the atmosphere. This gives a much more intense patch in the vicinity of the burst, and also in the conjugate area. Figure 20 shows the prompt proton deposition for the Semipalatinsk area.

Figure 21 shows the general outline of the prompt electron deposition for a Johnston Island burst, and also what it would have been if the burst had been held at different altitudes. Any VLF path which was discussed previously for which there was a prompt effect on a Johnston Island burst lay inside of these

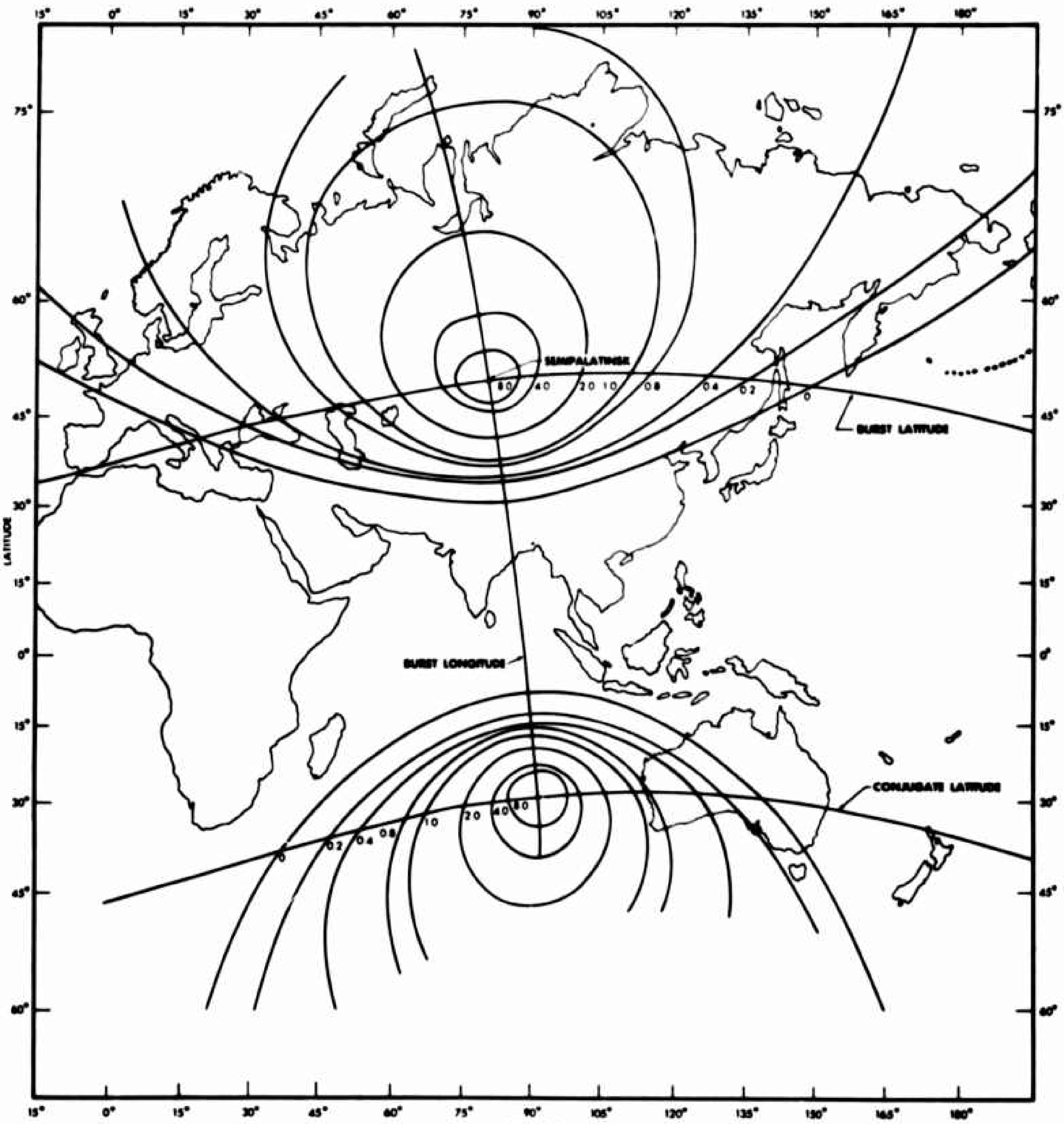


Fig. 17. Contours of prompt beta deposition above one square centimeter of the earth's surface for a one kiloton detonation over Semipalatinsk.

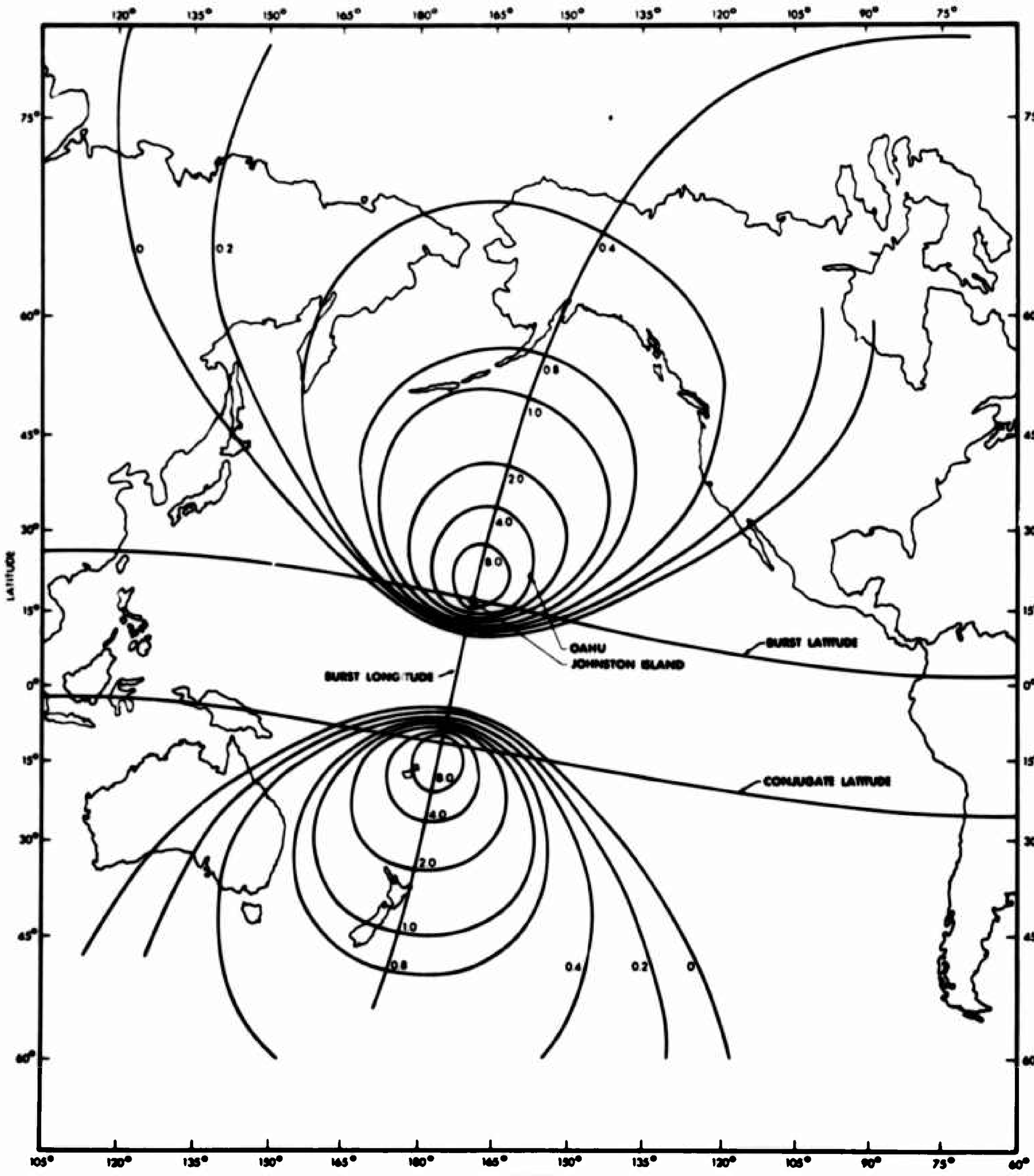


Fig. 18. Contours of prompt beta deposition above one square centimeter of the earth's surface for a one kiloton detonation over Johnston Island.

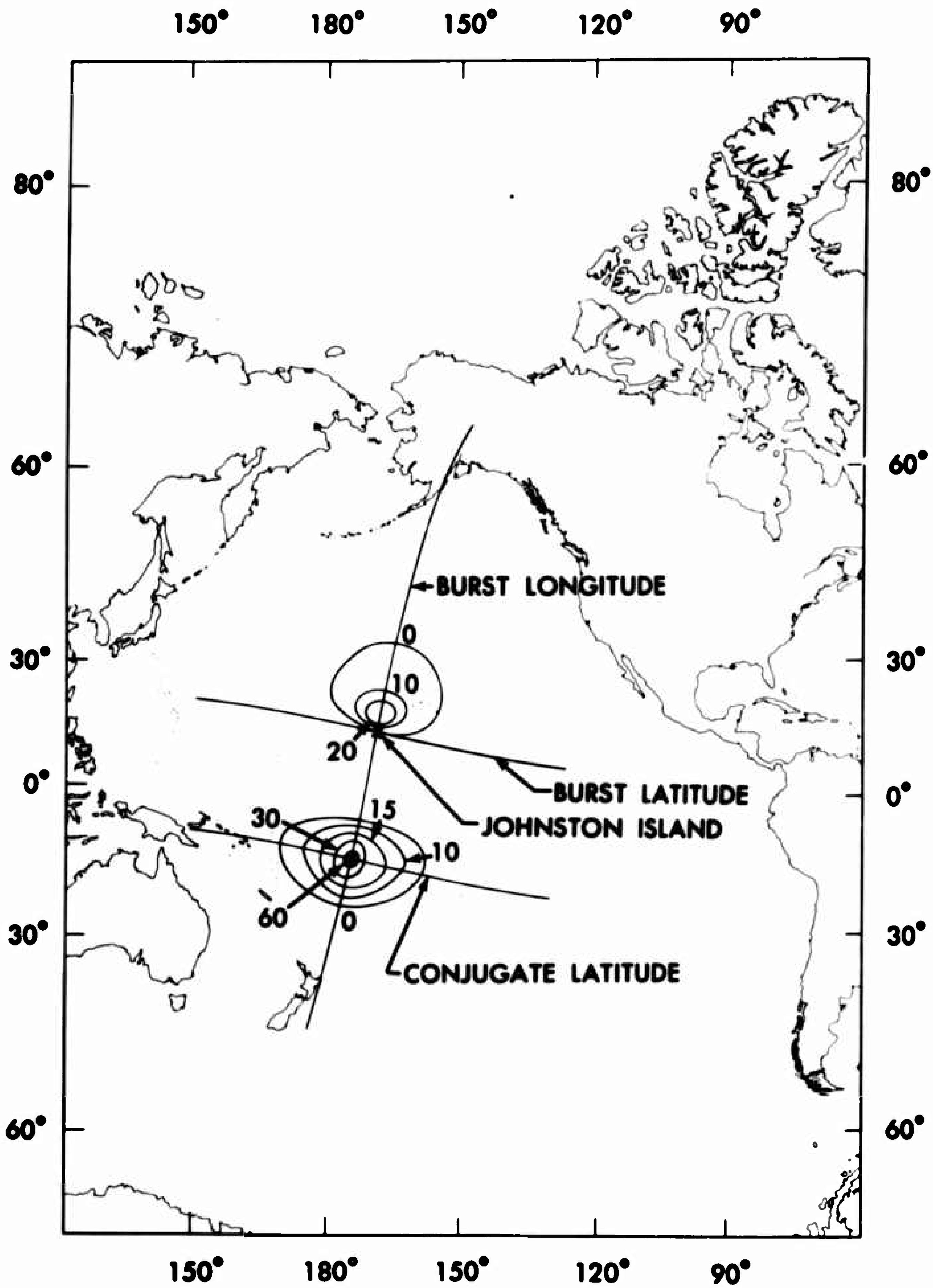


Fig. 19. Contours of prompt proton deposition above one square centimeter of the earth's surface for a one kiloton detonation over Johnston Island.

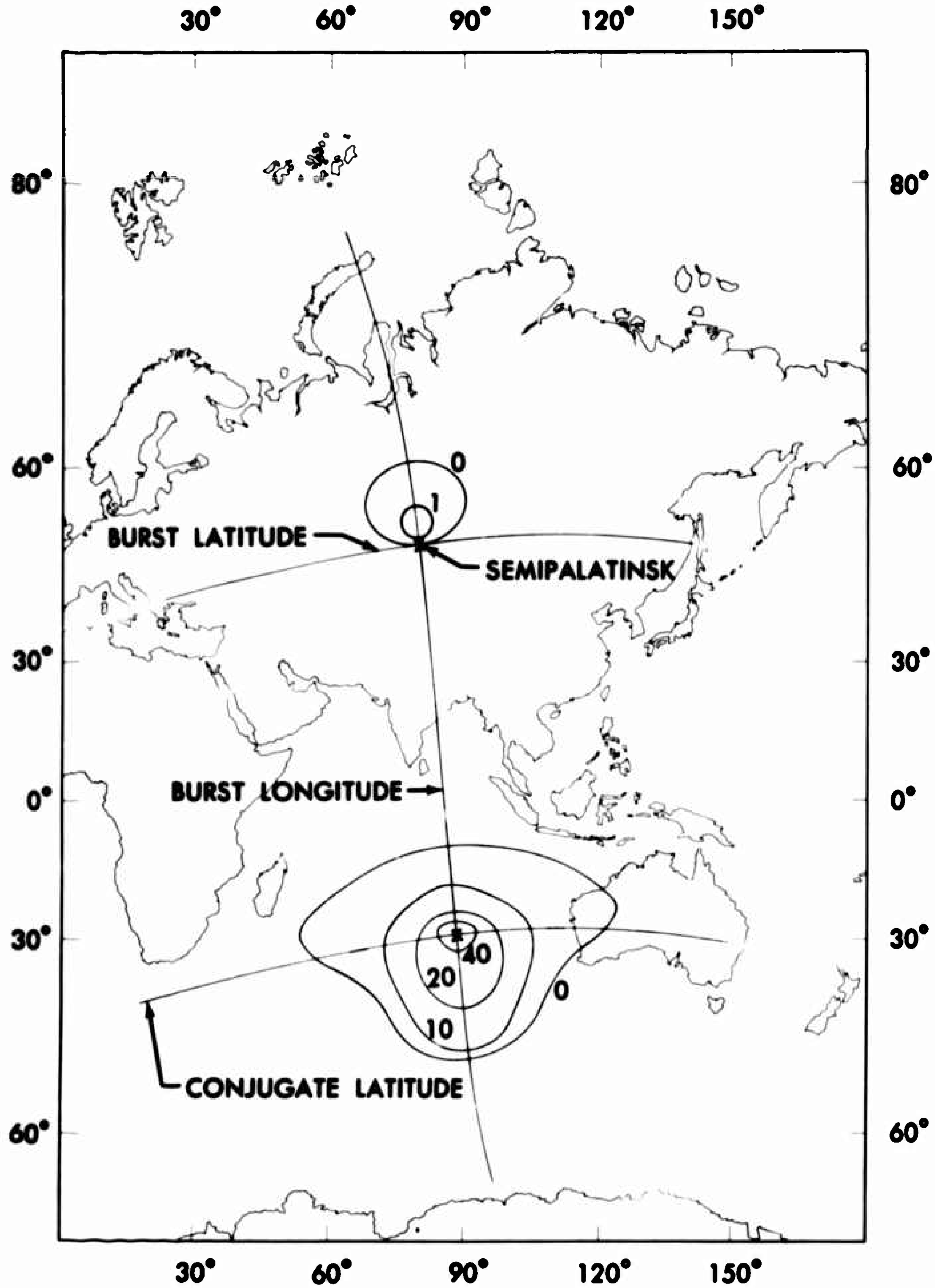


Fig. 20. Contours of prompt proton deposition above one square centimeter of the earth's surface for a one kiloton detonation over Semipalatinsk.

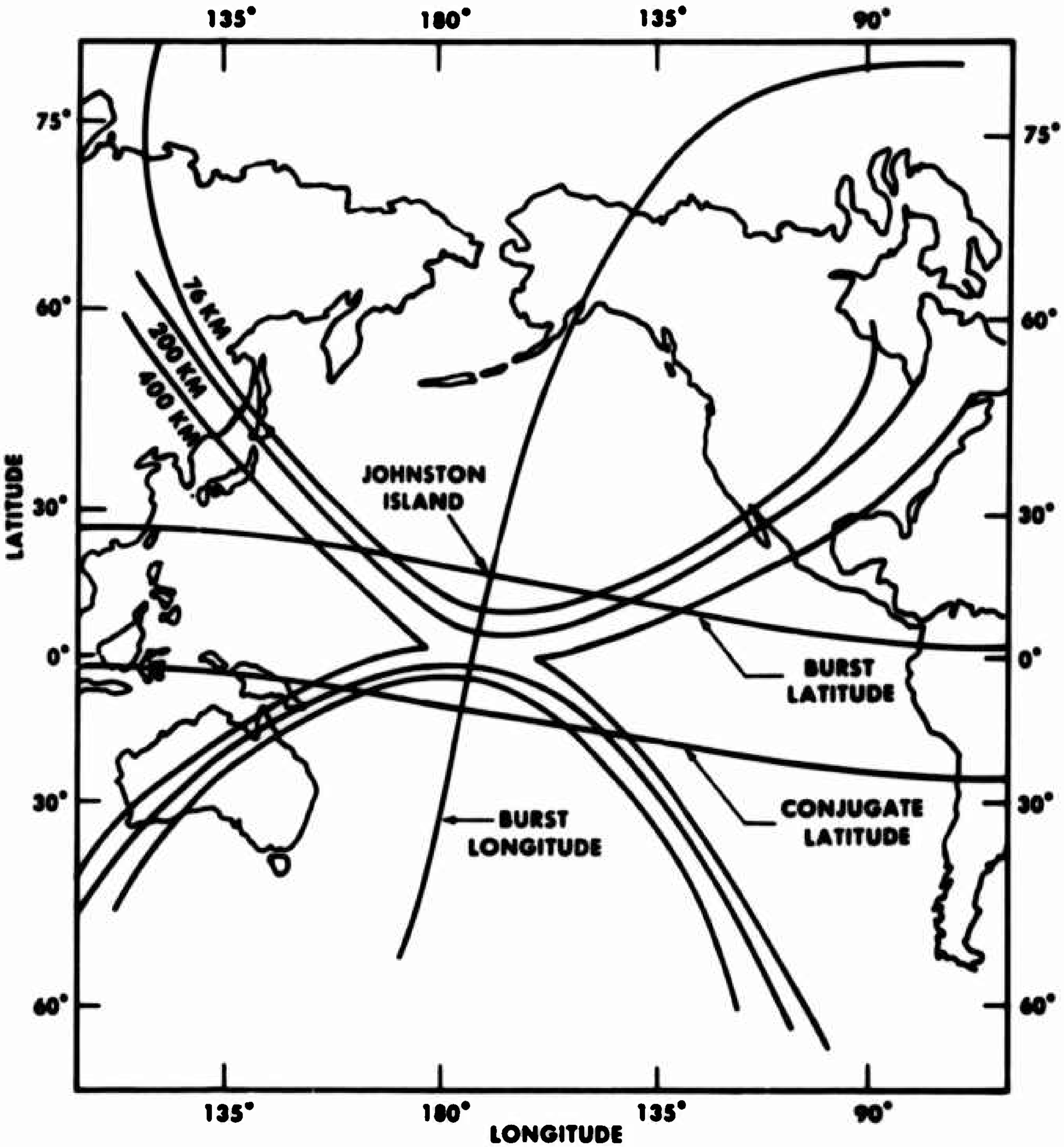


Fig. 21. Outline of extreme neutron decay injection showing effects of increased burst altitude.

prompt areas. Those for which no prompt effect was noted lay outside of these areas. Those which were borderline were right on the fringes of these areas. An example of this good agreement can be seen in the data published by Zmuda et al. [1964] for the October 20, 1962 shot (see Figure 22) in which prompt effects were noted on the NPM-APL, NPM-Anchorage, and NPG-APL paths, but not on the NBA-APL path. The same sort of good agreement is indicated by the Japanese records [Takenoshita et al. 1963] taken of the July 9, 1962 test.

Similar observations hold for the Russian bursts, and for other geophysical phenomena which depend on D-region enhancements, such as shortwave fadeout and SEA. The extremely good agreement with experiment as far as geographical distribution is concerned leads one to the conclusion that prompt D-region enhancements outside of the line-of-sight can be accounted for by the neutron decay. As far as the magnitude of the effect is concerned, things are not as encouraging since the calculations indicate that the amount of ionization produced is far too small to account for all the effects. In looking back at the approximations we have made, we find that every approximation has caused us to underestimate the magnitude of the effect. We are at present refining the approximations and repeating the calculations to see if

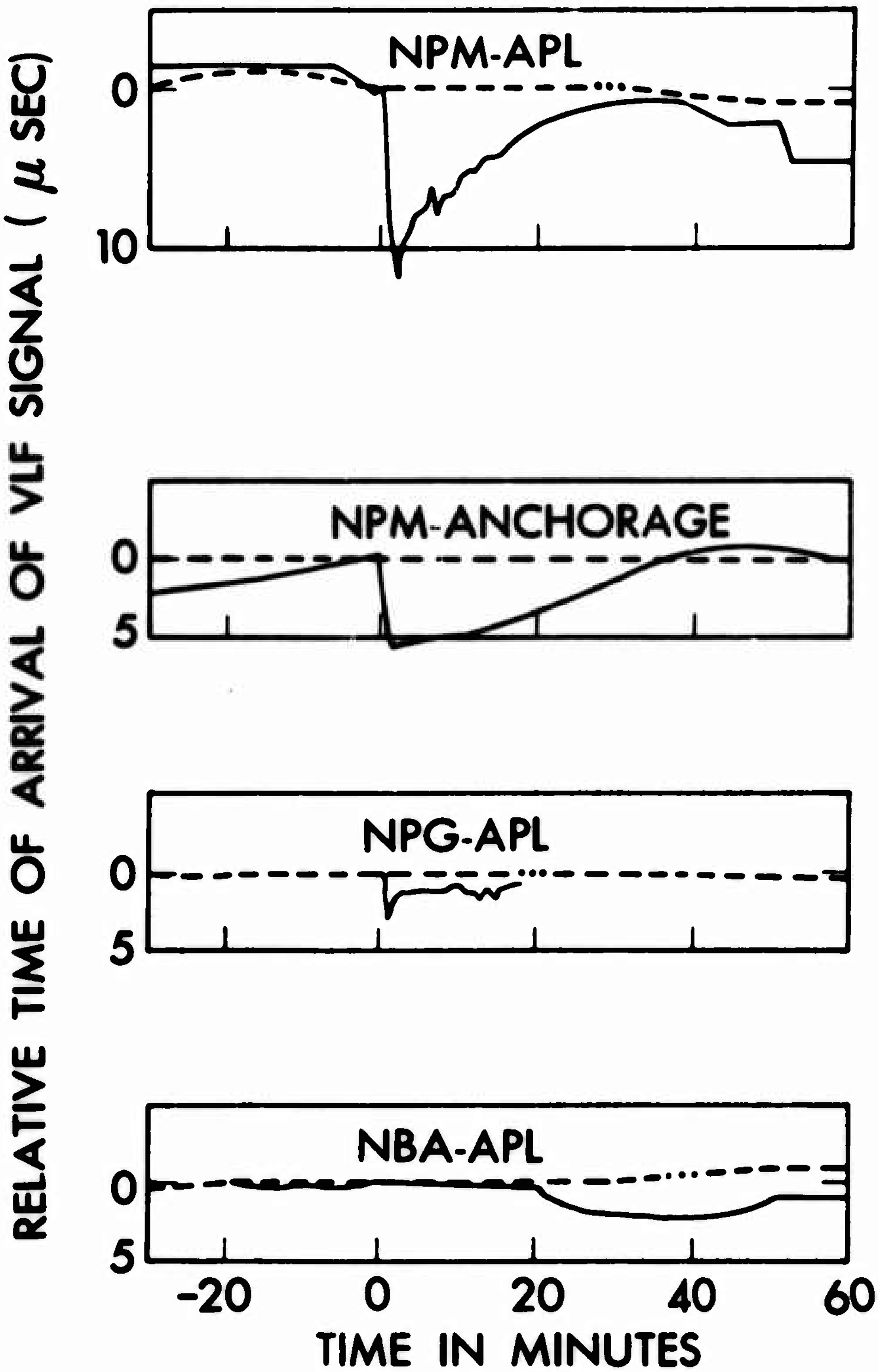


Fig. 22. VLF records, October 20, 1962 [Zmuda et al. 1964].

agreement in magnitude can also be reached. Consideration of the following effects must be made.

1. Different altitudes must be allowed for the burst. This will change the geographical outline somewhat as shown in Figure 21 and affect rather considerably the prompt proton deposition.

2. Consideration must be given to a fusion reaction. This will increase the number of neutrons, and also give them more energy, thus making the protons more effective for causing ionospheric disturbances.

3. The presence of any material, such as rocket housings, in the burst area will have a moderating effect on the neutrons. This will cause the velocity to decrease and therefore increase the decay density in the ionosphere. Without a knowledge of the burst parameters, it is impossible to estimate the magnitude of this effect.

4. Killeen et al. [1963] have pointed out that, if the burst is held above the atmosphere, about 80% of the neutrons headed downwards will be reflected from the atmosphere and also be slowed down. This will again increase the decay density.

To explain the delayed effects, we must now consider trapped radiation and its precipitation into the ionosphere.

Trapped Radiation

Several excellent papers have been published on the trapped radiation injected into the magnetosphere from nuclear bursts, and Dr. Hess [1964] has just given an excellent review paper on the topic. Let us therefore limit our discussion of this topic to consideration of the injection distribution. When the device is detonated, the magnetic field is excluded from the immediate vicinity of the rising and expanding ball of plasma because of the high conductivity. The fission fragments continually decay as they are contained in this diamagnetic cavity and form high energy electrons which are injected at progressively larger L values as the bubble rises. This will be the general control for the spatial distribution of most of the trapped radiation. The β rays injected with low pitch angles will be seen primarily as auroral electrons in the two conjugate regions. Those which undergo scattering and change their pitch angles will not be lost so quickly. This component will remain as trapped radiation, and must subsequently bounce back and forth from hemisphere to hemisphere as it slowly drifts around the world. The bounce time depends on the velocity of the particle, and the drift time on the energy of the particle.

The other principal source of trapped radiation beside fission decay is neutron decay which we just described. Although many more fission electrons will be formed than neutron decay electrons, the fission electrons must be injected into the magnetosphere only near the burst point. This then gives a large quantity of high energy electrons from fission decay at L shells near the burst, and also some neutron decay electrons scattered all over the remaining illuminated L shells. Since the spectrum of the fission electrons is harder than the natural trapped radiation, it is possible to detect these electrons over the background of the natural trapped radiation. The neutron decay electrons will have a spectrum very similar to that of the natural trapped radiation and will be very hard to detect in small quantities.

Data on the spatial distribution of these electrons has been presented by Katz et al. [1963] for the Russian burst on October 28. One notices in Figure 23 the omnidirectional flux of electrons of E > 1 Mev, showing a double humped enhancement after the Russian burst. Going to more energetic electrons in Figure 24, one sees the same double humped curve, and one is able to follow out the shape of this curve for the next few days. In Figure 25, the same sort of thing is noticed again. Additional injection on November 1 due to another Russian burst can be seen.

Walt et al. [1963] have calculated the lifetime of these particles on a theoretical basis and obtained rather good agreement with the flux measurements of Van Allen [1963] for the Starfish burst, as one can see from Figure 26. In general, most of the electrons are lost very quickly because they are mirroring at low altitudes in the dense atmosphere. As time passes, the lifetime increases and eventually stabilizes at a very large value. At this time, a state of quasi-equilibrium has come about, in which the principal source of the particles which are being lost comes from those which previously were mirroring at very high altitudes, near the equator. By a series of small-angle coulomb scattering, the pitch angles gradually change until the particles mirror in the lower atmosphere and then lose their energy rapidly. This pitch angle diffusion is valid only on low L shells. At larger L values, other loss processes predominate.

Additional experimental evidence for the detection of the short-lived trapped radiation can be seen from the VLF records which were presented earlier. Returning back to Figure 11, one sees that a good explanation of D-region enhancements is provided if one has a time profile of precipitated trapped radiation which would start overhead at about H + 20 minutes, reach its maximum value at H + 35 minutes, and be essentially undetectable at H + 50 minutes. Note that another phase advance follows about an hour later. This could possibly be the second trip around the world of the remaining trapped radiation. The neutron decay

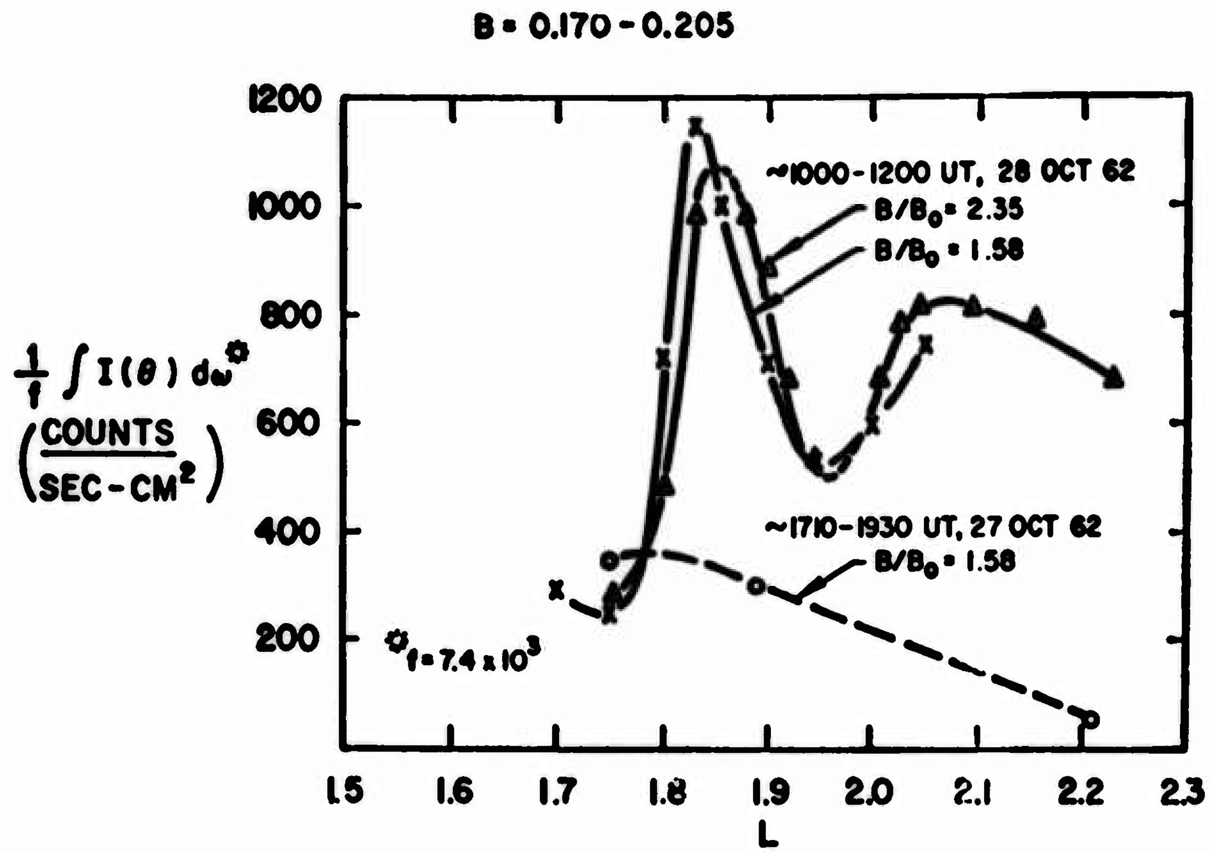


Fig. 23. Omni-directional flux, electrons of E > 1 Mev, Satellite 1962βK. [Katz et al. 1963].

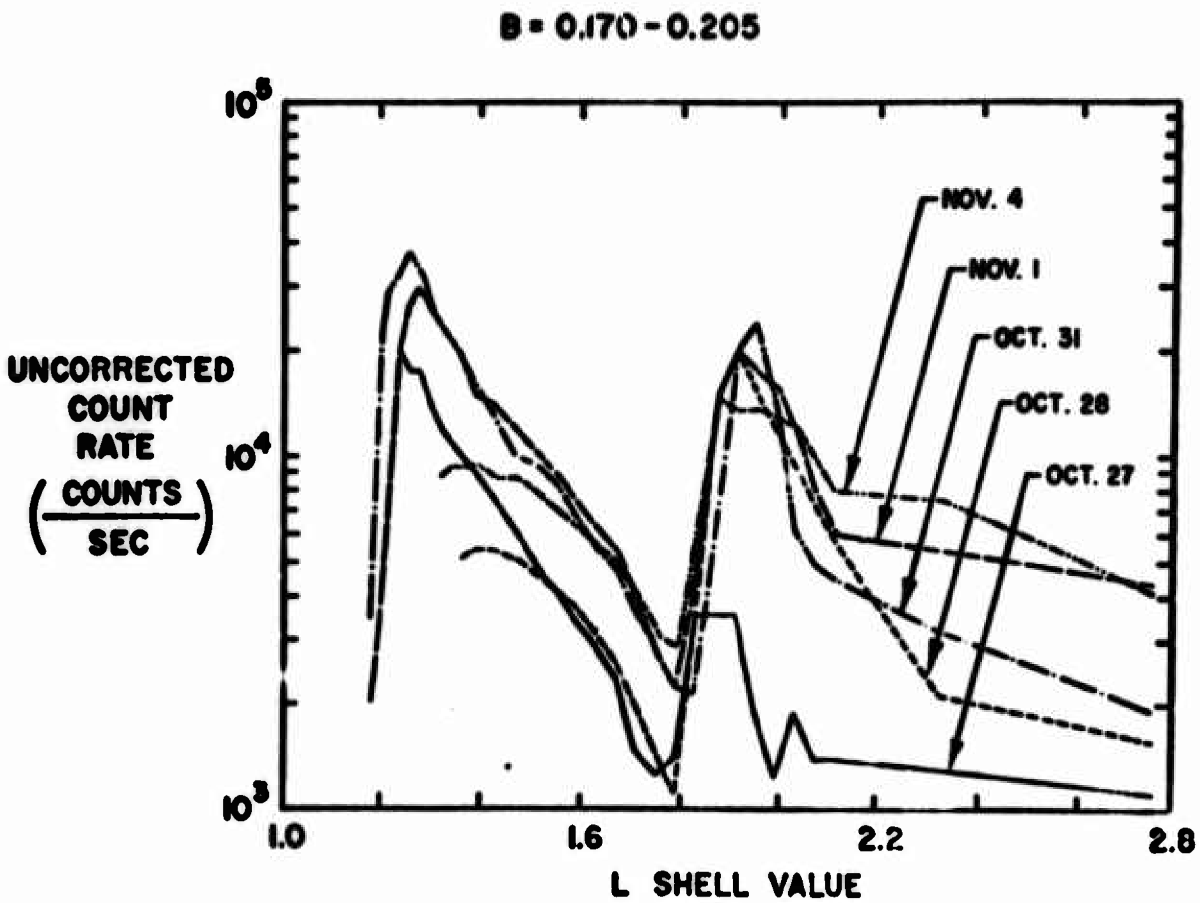


Fig. 24. High energy electrons (E > 4 Mev), Satellite 1962βK. [Katz et al. 1963].

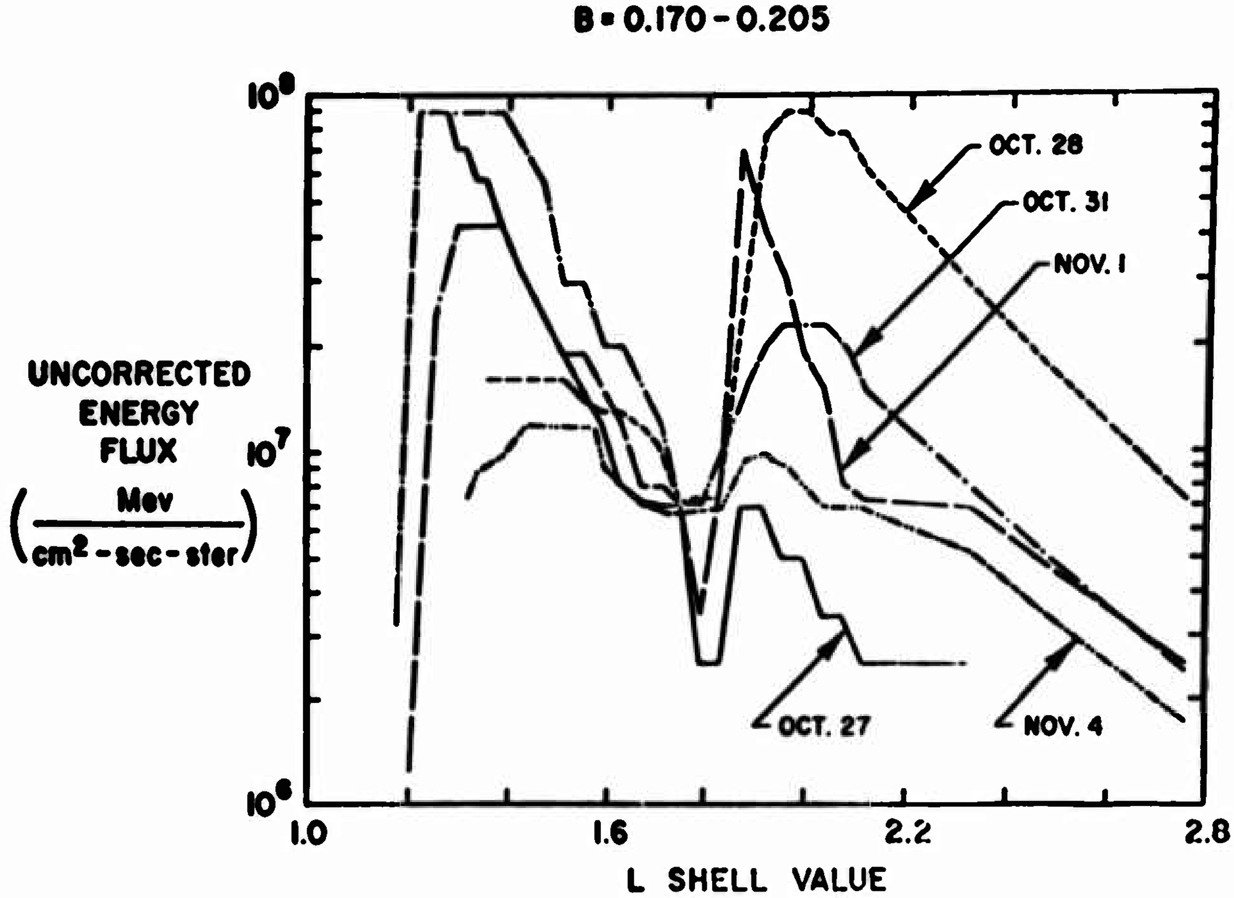


Fig. 25. Integral energy flux (E > 50 kev), Satellite 1962βK. [Katz et al. 1963].

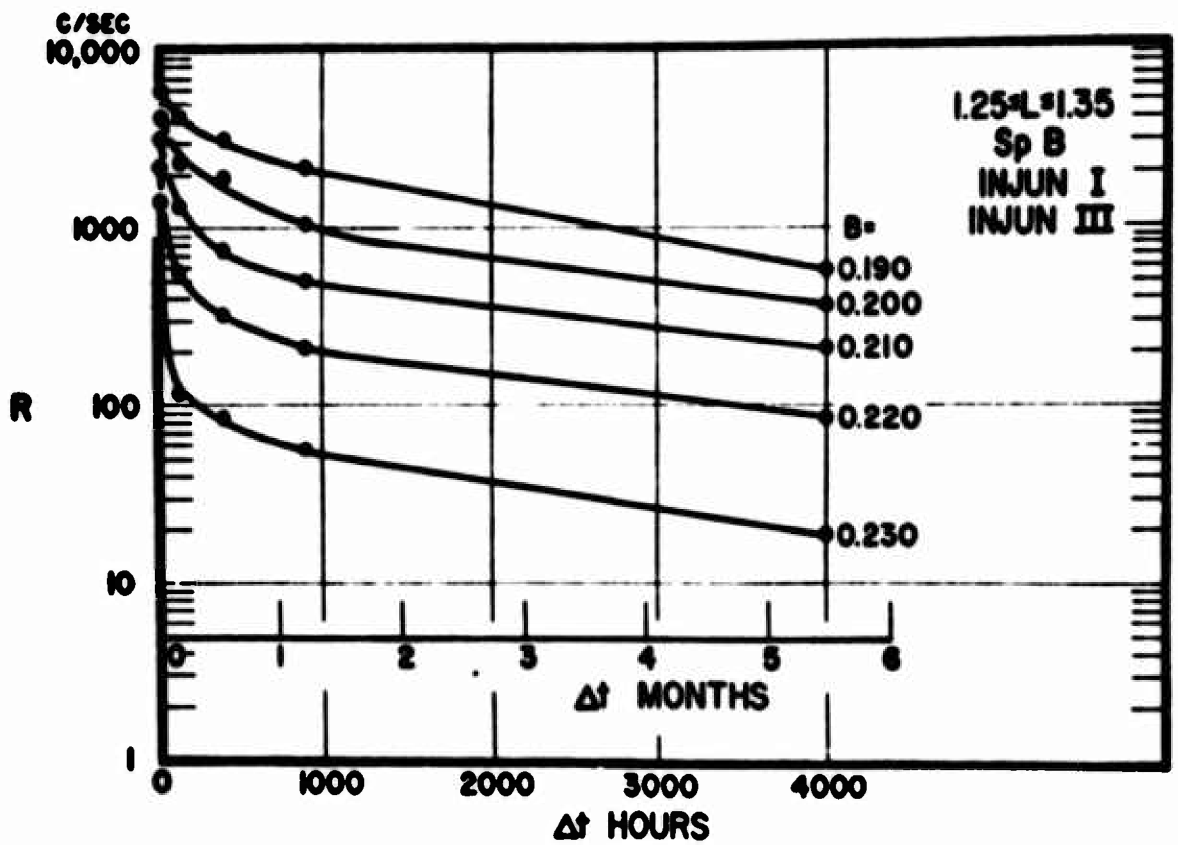


Fig. 26. Decay of artificial trapped radiation [Van Allen, 1963].

spectrum fits this drift time behavior very well. Looking back at Figure 12, however, we see a completely different behavior. This drift time behavior is, however, consistent with a fission electron source. It then becomes clear that, at large L values, the October 22 shot injected fission decay betas, but the November 1 burst did not. The November 1 burst, did, however, inject a considerable amount of neutron decay betas. These data can be used to speculate on the burst size and altitude of these two events.

We have thus far shown that the trapped radiation and D-region behavior can probably be explained by the two sources, fission decay and neutron decay. The observation of synchrotron radiation at Jicamarca and Huancayo [Ochs et al. 1963] with no absorption in cosmic noise, coupled with the delayed absorption at the Maipu Observatory [Jusick et al. 1964] and the data taken on the USNS Eltanin [Basler 1963] off the Chilean coast 23°S geomagnetic, also lend considerable credence to these ideas. Depending on the location and type of experiment either of these sources can be relatively more or less effective than the other. These D-region enhancements can be used to explain many of the observed geophysical effects, such as SSWF, SCNA, SEA, etc..

Magnetic Effects

There seems to have been three separate magnetic effects, I, one "instantaneous", II, a second effect which was delayed a few seconds, and finally, III, a main effect.

I. An instantaneous pulse with high frequency ($f > 2$ cps) was noted simultaneously at H + 0 seconds on many stations. The accuracy of determining simultaneity varies from milliseconds to tenths of seconds, depending on the timing resolution of the various stations. The most likely explanation for this is that a spheric was excited near the burst by x and γ ray emission. This, like a lightning stroke, would travel with the velocity of light in a vacuum and have high frequency components, including Schumann resonances [Balser and Wagner, 1963]. Since most magnetic stations do not have sufficiently high frequency response, this instantaneous signal may be present at all stations, but remain undetected because of instrumental limitations.

II. At H + a few seconds, a world-wide effect was noted. This consisted of an oscillatory signal with an initial period of about four seconds which probably decreased to about two seconds within a few oscillations. The signal was very highly damped. Many people have reported on these disturbances, such as Wilson and Sugiura [1963], Bomke et al. [1960], and Berthold et al. [1960] and have interpreted this as the result of travelling hydromagnetic waves with possibly two velocities, the modified Alfven (or fast) and generalized Alfven (or slow) modes. Ideally, one could then take a network of stations located at different distances, and measure these propagation velocities. The trouble with this is that confusing results are obtained because of the very wide difference in velocity calculations. Indeed, Caner [1964] has recently looked at this problem and attempted to determine the accuracy of the various station delay times that have been reported. The result of his study is quite surprising; since he finds that the stations which he believes to have the best timing accuracy all report that the onset of the rapid fluctuations disturbance is delayed about 2 seconds after the burst, independent of the location of the station.

If Caner is right, then, one rules out hydromagnetic waves as the cause and looks for a delayed electromagnetic wave. Of the many suggestions which he has advanced for this mechanism, one of the most plausible is that a broad band packet of energy is released from the burst site and travels via a hydromagnetic wave to the southern conjugate region, taking 2 seconds to get there. Some of the energy is then coupled into electromagnetic radiation, but the bulk is transferred back to the northern region. No coupling takes place there due to the high degree of ionization at that end. The packet returns to the southern region where the process is repeated. The ionization along the path changes rapidly, so the propagation velocity changes and one can explain all the detailed features of this rapidly oscillating signal via this mechanism.

It is clear that the way out of this problem is to have the various experimenters put realistic limits on their timing accuracy and report these limits at the time they report the disturbances on their data. Analysis of data from other tests would also quickly point out which approach is the correct one.

III. Finally a general or main magnetic disturbance was reported by many stations. These slow variations were different at each station, but world-wide in character. Maeda [1964] has attempted a treatment of this topic, and has computed the effect due to:

1. Diamagnetic plasma at the burst site,
2. ring current of trapped particles, and
3. augmentation of the S_q currents, associated with an anomalous ionization in the ionosphere created by x and γ radiation.

After computing these effects, a world-wide map was constructed to compare with the experimental values, and reasonable, but not perfect agreement was attained.

This general approach to the problem is quite probably correct, although there are so many uncertainties involved in the parameters, that it would be surprising if perfect agreement did exist. Perhaps further work along similar lines will enhance this agreement. As further information on anomalous ionization becomes available, refinements on these calculations will be possible.

F-Region Disturbances

Observations of changes of f_oF_2 and spread-F leave little doubt that the F-region also becomes disturbed by high altitude nuclear bursts. The mechanisms used to explain D-region enhancements simply do not fit the F-region. Changes in the F-region do not occur simultaneously on a world-wide basis. Measurement of the delay time for onset of the disturbances detected at different stations gives multiple values for the velocity of propagation ranging from a hundred meters sec^{-1} to thousands of meters sec^{-1} [Berthold et al. 1960; Obayashi, 1962]. Hydromagnetic waves and gravity waves seem to be necessary and sufficient to explain these disturbances in remote regions.

E-Region Disturbances

Davis and Headrick [1964] have recently described short period fluctuations in the E-region over the United States following a high altitude nuclear burst, and point out the striking resemblance that these fluctuations bear to the magnetic disturbances. This is interesting because it again demonstrates the intimate connection between changes in the earth's magnetic field intensity and ionospheric currents at E-layer heights.

D-Region Parameters

Because of the impulsive nature of the ionization source in the nighttime ionosphere, it was hoped that additional information on some of the D-region electron removal processes could be obtained. Along this line Le Levier [1964] has recently published an analysis of the transient effect on the D-region due to the prompt x and γ radiation and has arrived at a new estimation for the D-region dissociative recombination coefficient. This has been estimated to be between 3×10^{-7} and 7×10^{-7} $cm^3 sec^{-1}$ for 70 km altitude. Perhaps better values for the electron attachment coefficient can also be obtained.

Outstanding Problems

Although a great deal of information was obtained, all the phenomena associated with high altitude bursts has not yet been clarified. A partial listing of some of the unexplained phenomena is given below.

1. As pointed out earlier, the magnetic effects are not completely understood.
2. Approximately a 1% increase in equatorial neutron monitor rates was reported by Casaverde et al. [1963] for the July 9, 1962 event. The reason for this is not clear.

3. Filz et al. [1963] has reported a sharp increase in the loss of high energy protons (~ 55 Mev) from the inner belt over quite a long period subsequent to the Russian bursts.

4. High latitude auroras, well above the burst conjugate, were observed over New Zealand [Neff, 1963] at the time of the July 9, 1962 test.

5. Similarly, high latitude riometer absorption was noted in Alaska [Basler et al. 1963] in synchronism with the test on July 9, 1962.

6. The July 9 increase in counting rates [Durney et al. 1963] delay by approximately 20 seconds that was detected by Ariel satellite at high L values still remains unexplained.

Many of the principal outstanding problems can perhaps be solved if more data are forthcoming from different experimenters. In this line, we would particularly request three things.

1. That experimenters put, where possible, limits on accuracy of their data, particularly as far as timing is concerned.

2. That the results of other tests be published. A great deal of information has been released about the July 9, 1962 test but relatively little about the others, particularly the Russian tests.

3. That negative results also be reported if negative results are found. Quite frequently, these negative results are just as important as positive results when one is attempting

to evaluate the validity of a particular theory.

Note Added in Proof

After this paper was given, we were pleased to note that part of the controversy over the magnetic effects may have been resolved by a later publication of Bomke et al. [1964]. These authors report on the results of a network of high-time-resolution magnetometers in the Pacific area, and indicate that a strong oscillatory signal was detected simultaneously at all stations 1.9 seconds after the burst. This confirmation of Caner's analysis is interesting and leads one to look for the delayed emission of radiation.

A possible connection between this delayed electromagnetic emission, and the rapid re-entry of the magnetic field into the diamagnetic cavity at the burst site [Colgate, 1963] should not be overlooked, although a rigorous mathematical treatment is needed to evaluate this suggestion.

Recently, an alternate explanation of the prompt D-region effects has appeared in the literature. Foderaro [1964] has proposed a model in which a neutron diffusion mechanism produces the D-region ionization by neutron-air molecule collisions. The shape of the affected regions differs significantly from that given by the neutron decay model and data may be available to distinguish between that model and the one of Crain and Tamarkin [1961].

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