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IONOSPHERIC DISTURBANCES DUE TO UNDERGROUND NUCLEAR EXPLOSIONS
AND OTHER SOURCES: AN ELEMENTARY DISCUSSION, PART I *
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L. F. Wouters

January 15, 1971

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IONOSPHERIC DISTURBANCES DUE TO
UNDERGROUND NUCLEAR EXPLOSIONS AND OTHER SOURCES
AN ELEMENTARY DISCUSSION - PART I*

L. F. Wouters

January 15, 1971

The possible effect of vertical ground surface motion on the ionosphere, in consequence of acoustic propagation, is discussed here as an interesting scientific problem. Estimates of R.F. phase path perturbations will be developed, for several representative sources and several propagative modes (both terrestrial and atmospheric). Application possibilities include U.G. Yield measurement, U.G. test detection, Seismic discrimination. In these connections, the general concept has been conjecturally discussed in 1960, 1962 and 1967, under various auspices, as reviewed in the separate, classified, Part II (UCID-16785).

The discussion here, was prepared from the viewpoint of "an outsider looking in"; I will not pretend to be an expert on atmospheric acoustics. Correspondingly, I have borrowed ideas and methods from the several schools of thought, without discrimination. I must also emphasize that these numbers are based on analytic approximation models; I have "dodged the computer modes".

* The essential results are summarized in Section VI (page 76)
Part II is classified; it will be issued as UCID-16785.

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The Caveats. It is obligatory to understand from the start, that a quantitative attack compels the use of amplitude models for ionospheric density perturbations. Velocity/time exercises do not design definitive tests and only exacerbate conceptual controversies.

In this sense, a directly useful reference is: "H.F. Radio Measurements of High-Altitude Acoustic Waves from a Ground-Level Explosion"; Barry, Griffiths and Taenzer; JGR. 71, 17, 4173, September 1, 1966. (Hereafter referenced as BGT.) A copy is appended. This deals with the early disturbance of the ionosphere due to the 500-ton HE test: "Snowball", conducted at Suffield Test Station, Canada. In essence, those measurements made use of conventional vertical sounding techniques. The essential point which makes this work applicable to the contained underground case, is that the equivalent acoustic source pulses are similar in time structure, and much shorter than the basic period of the various ionospheric AGW modes. The "acoustic filter" model used by BGT remains valid here, with only minor scaling corrections, as will be discussed.

BGT outline a complete analytic attack on the problem - one which permits at least an immediate, semi-quantitative estimation of the observed phase effects, starting from a source model, identifying some simplifying assumptions, and avoiding procrastinative computer runs. While there are minor discrepancies within the context of their paper, nevertheless the agreement between this expeditious analysis and their experiment is firmly within a factor of two. Here I will scale predictions for some explosion examples, and for idealized seismic disturbances, using BGT as a base reference. There is a summary of estimates near the end of the paper for those who wish to avoid the Doldrums of Development. (Section VI, page 76)

Figures will be found at the end of each section.

The problem of acoustic signal synthesis and propagation from transient sources in the atmosphere, has had increasing attention since the original work by Lamb, following the Krakatoa explosion. Various pertinent references will be noted in the discussion below. However, no single, authoritative, theoretical reference exists to serve as a basis for design of experimental or applicational systems. No definitive work was found concerning acoustic/gravity wave amplitude prediction; most authors appear satisfied with identification and verification of mode velocities.

The considerations here are concerned entirely with the initial ionospheric disturbances, well before the acoustic wave can sense the possible existence of long-period, world-sized resonant modes. Virtually all the published works neglect earth curvature; they are concerned with local modes whose time constants (2 to 6 minutes) are related to the gravitational constant, viscosity, thermal conductivity, thermal and density gradients and so forth. Magnetic field splitting is omitted; this does not affect the gross behavior of the R.F. phase mechanism.

In the separate, classified Part II, I discuss certain applicational and instrumentational aspects. Here it is appropriate to provide a semi-quantitative reference frame by which to measure the numbers which I am about to develop:

"Noise" (quiet ionosphere)	.1 cycle (phase shift)
Ultimate equipment resolution	.1 cycle
Ionospheric tides (30 min. - 1 hr.)	1-100 cycles
Unidentified "acoustic" transients	1 cycle

The measurement time scale implicit here, is 1 sec. or longer; this corresponds then to exceedingly small "Doppler" shifts (at say, 5 mc), if one wishes to apply that misleading term.

Some Basic Concepts and Assumptions. The salient feature which makes interesting an acoustic wave interaction with the ionosphere, is illustrated in Fig. I.1. The electron density gradient for a representative region, is shown along with a typical (virtual) reflection boundary for a particular sounding frequency. Superimposed on this, is a sequence of pressure/density perturbations of increasing amplitude, frozen just as a positive phase reaches that virtual boundary. If we assume that such acoustic pressure changes would modulate the electron density more-or-less proportionally, then we see that there is a critical profile at which that boundary moves very rapidly with increasing acoustic amplitude. Thus, the ionosphere should act as a "toggle switch". Each sounding frequency has its switching amplitude, as sketched in Fig. I.2. The critical acoustic signal level corresponds to an energy density such that the front slope of the + (density) phase just equals the natural (-) gradient, (downward).

As depicted by BGT, acoustic waves originating from "sharp spikes"; acquire a profile at the F-layer (200-300 km) characteristic of the acoustic properties of the intervening atmosphere, with long periods and wavelengths. ($\tau \sim \frac{1}{2} - 2$ min.) The positive phase slope should not be much affected by the time structure details of relatively short surface pulse disturbances, - only by their energy content.

In order to make progress in "quantifying" the problem, I will adopt and define a number of idealized approximations in describing the principal energy sources of interest - underground explosions and earthquakes. The difficulty in acquiring useful "consensus" models for such purposes, remains one of the major mysteries of the seismic arts. Fortunately, here we need only to be able to characterize the time history of vertical surface motion due to such sources. There is a wide accumulation of data for this, which should permit a direct, semi-empirical description of the resulting surface air compression.

Also, I initially confine attention to vertical ionospheric sounding measurements, and hence to disturbances in the atmosphere and ionosphere immediately above the ground motion.

The Earth's surface can move in a number of ways (relative to a gravitationally stabilized atmosphere). An underground explosion generally causes it to move vertically up and down, over a limited area, immediately above the detonation center; there is relatively little lateral motion. An earthquake can produce a combination of vertical and lateral displacements, together with surface waves, over generally much larger areas. One suspects that purely lateral displacements (of a flat surface) would be very weakly coupled to the air above.

The weakness of such coupling for even the vertical displacement case, may be judged by the apparent neglect of air loading (other than stagnant pressure) in considerations of local surface displacement. This is probably reasonable in view of the large ratio between the shortest period of atmospheric tides ($\sim$ one hour) and the longest seismic periods ($<$ one minute). However, there may be some evidence for stronger coupling with longer-period Tsunami waves generated by sub-oceanic quakes.

I. Nuclear Explosions - Scaled Estimates:

- (1) The coupling from earth's surface to air,
- (2) The propagation from surface to ionosphere,
- (3) The effect on the ionosphere,
- (4) The consequences on a R.F. propagation path.

The Numerical Example: Syntax

For purposes of fixing the numerical range, I will use a hypothetical, nominal yield, contained event. (10 kt at 800 ft, corresponding to $375 W^{1/3}$.) Typical velocity/displacement records are available, in this range, from which the "smoothed" source model depicted in Figs. I.3a and I.3b was defined; for it:

$$d = 2.5 \times 10^4 \text{ cm. (dob)}$$

$$v_1 = 72 \text{ cm/sec (peak surface velocity)}$$

$$\tau \approx .4 \text{ sec. ("cross-over" time)}$$

Other constants:

$$\rho_o = .00125 \text{ gms/cm}^3$$

$$c = 3.4 \times 10^4 \text{ cm/sec.}$$

$$p_o = 1 \text{ bar} \approx 10^6 \text{ dynes/cm}^2$$

The Normalizing Case: Snowball/BGT

This was a 500-ton H.E. surface burst. The acoustic wave was normalized to the so-called "Brode 6%" range (r_1) beyond which it was treated as a spherically-propagating disturbance (all by BGT):

$$r_1 = 1.15 \times 10^5 \text{ cm.}$$

$$\left(\frac{\Delta p}{p} \right)_1 = .06 \quad (6\%)$$

$$\tau = .25 \text{ sec.}$$

The "input" waveform at that distance appears in BGT/Fig. 1.

1. Earth-air coupling - The Piston Model

Early rough considerations of the U.G. explosion problem depicted the air as being driven acoustically by a piston. (1960) The pressure wave turns out to have a power density so low - even right at the surface - that it can safely be treated as "acoustic". That this is reasonable might be separately concluded from the effective surface displacement velocity - a few meters/sec. - which is well below sonic velocities, and from the surface displacement proper - much less than one meter - which is very small as compared to the sound wavelengths here.

The size of the piston, and the proper way to model its acoustic coupling deserves brief discussion. One suspects that, if a piston is, say, one meter in diameter, we can move it up and down slowly without any detectable effect on the ionosphere. The air simply moves around the piston, and we have merely a local aerodynamic flow. On the other hand, if the "piston" is a large area many tens of kilometers across (as might be the case for a major, vertical, earthquake displacement), one could presume that the corresponding air disturbance would propagate upward more-or-less as a plane acoustic wave. There would be little or no "spreading", as BGT label the $\frac{1}{r^2}$ term for point sources.

In such a case, the initial source pressure is adequately described by: $p = \rho_0 cv$. This has also been shown experimentally to be a valid description for the surface air pressure immediately above an underground explosion ("on-axis"). (E.g. see: Perrett, Surface motion in the vicinity of the Boxcar Event, SC-TM-68-458, Sandia/Albuquerque, August, 1968.) Note that for our 10 kt/Syntax example here:

$$p' = \rho_0 cv = 3 \times 10^3 \text{ dynes/cm}^2$$

$$\left(\frac{\Delta p}{p} \right)' = .003 \text{ or } .3\%$$

Evidently a "piston" is an intermediate geometry, and a quantitative description for the pressure wave must include both a range term and a piston size term:

$$p \propto \left(\frac{a}{r}\right)^m \left(\frac{a}{\lambda}\right)^n$$

where a is the piston radius.

For the "textbook" piston, both exponents are unity ($m = n = 1$); this corresponds to an appropriate behavior (p^2) for the power density. The far-field pressure disturbance is given by:

$$p = (\rho_0 c v) (ka) \left(\frac{a}{r}\right) (D.F.)$$

$k = \frac{2\pi}{\lambda}$ and D.F. is the "directivity factor", which is unity along the (vertical) piston axis, and elsewhere behaves as:

$$\left\{ \frac{2 J_1(ka \sin \theta)}{(ka \sin \theta)} \right\}$$

(Cf: Stephens and Bates, Acoustics and Vibrational Physics)

By our prior restriction to the vertical region, we can omit this term. Then the axial pressure behaves essentially like that from a spherical radiator ("point source").

The applicability of this model, and its dimensioning, are based on the visual appearance of the "surface zero" displacement in surface motion photo records of typical contained underground events. These exhibit a distinctly "disk-like" appearance: The central displacement is proportionally less than that of the edge, and there is a relatively fast fall-off around that edge - viz: Fig. I.4. The diameter of the disc is of the order of the depth-of-burial (d). I estimate an uncertainty of order $\pm 30\%$ on account of the imprecision of this description. Then $a \approx \frac{1}{2} d$.

Next, I will normalize the atmospheric "source" to an upward distance equal to the dob; that also gets us far enough from the "piston" so that a spherical wave becomes a reasonable propagation model. (Next section)

So, $r = d$ and:

$$p_1 = (\rho_0 c v) \left(\frac{kd}{4} \right)$$

Finally, what about $k = \frac{2\pi}{\lambda}$? It turns out that we are going to need some sort of Fourier description to manage part of the propagation business anyway. Fortunately, the surface displacement/velocity measurements exhibit a remarkably sinusoidal character - albeit strongly damped. So it is relatively credible to assign a central wavelength as characteristic of the source, for estimates of this quality. Then $k \approx \frac{\pi}{c\tau}$, where τ is the "cross-over" time, and at last, the peak pressure at $z = d$ is:

$$p_1 = (\rho_0 c v_1) \left(\frac{\pi d}{4c\tau} \right) = \frac{\pi}{4} (\rho_0 v_1 d / \tau)$$

In numbers: $p_1 = 4.5 \times 10^3$ dynes/cm²

$$\text{and } \left(\frac{\Delta p}{p} \right)_1 \approx .0045 \text{ or } .45\%$$

This is much weaker than Snowball:

Syntax: .45% at 250 m.

Snowball: 6% at 1150 m.

Note that, by this model, the source pressure (and density) waveform will be that of the surface velocity (not the surface displacement). So Fig. I.3a also describes the acoustic source; for perspective, it is compared with Snowball in Fig. I.5. It is much less "spiky", being a quasi-sinusoid. For the same cross-over time τ , this introduces a factor or order $\pi/2$ in propagation dispersion considerations. The identification of "air displacement pulse" seems to be misleading, but it has stuck in the interests of differentiating from "air shock".

2. Atmospheric Propagation

Each source treated here will be referenced to an equivalent idealized acoustic radiator at some representative scaling distance: Plane wave, cylindrical (line), or spherical (point), source. The subsequent propagation can then be correspondingly scaled from known principles. Specifically here, we will be referencing to a spherical wave. This seems acceptable for a restricted vertical cone, because there the piston directivity factor is close to unity and very flat.

At this stage of the game, we are still dealing with the acoustic energy in terms of the classical longitudinal compression wave. It has not yet dispersed due to multiple path and density gradient effects; nor has part of it coupled into transverse propagative modes (with yet different velocities).

There are also upper limits of applicability. For BGT/Snowball, this is $\left(\frac{\Delta p}{p}\right) \sim 6\%$ at the Brode transition radius. Beyond this, linear acoustic theory applies for spherical wave propagation. Our case is well within this limit; so we match it in analytic treatment by writing $\pi_1 = \left(\frac{\Delta p}{p}\right)_1$ for the overpressure fraction at the appropriate scaling distance here.

The ratio of overpressure fractions at a second, more distant, point along the vertical axis, is then:

$$\frac{\pi_2}{\pi_1} = \frac{\gamma_2}{\gamma_1} \sqrt{\left(\frac{\rho_1}{\rho_2}\right) \left(\frac{v_1}{v_2}\right)^3 \left(\frac{P_2}{P_1}\right)}$$

It is convenient to lump the geometrical effects on power density into the single scaling term: $P_2/P_1 = L_s L_f$. Several factors are included in it:

- (1) $1/r^2$ "spreading" for (spherical) propagation in a uniform atmosphere. (Part of L_s)
- (2) An additional "non-uniform spreading factor" obtained by computed acoustic ray-tracings, related to the atmospheric density gradient. (The other part of L_s) It is expressed as a departure from $1/r^2$: $\left(\frac{\alpha_1}{\alpha_2}\right)^2$.
- (3) An attenuation factor (L_f) expressed in terms of an atmospheric "filter response" (defined in the acoustic frequency domain), $G(f)$ and in terms of the injected acoustic pressure waveform $S(t)$.

Then:
$$L_s = \left(\frac{r_1}{r_2} \right)^2 \left(\frac{\alpha_1}{\alpha_2} \right)^2$$

$$L_f = \frac{\int G(f) S(f) df}{\int S(f) df}$$

where $S(f)$ is the Fourier transform of the source waveform $S(t)$.

The use of an "overpressure fraction" depiction (rather than absolute pressure perturbation, as appears in most papers) has the merit of more directly exhibiting validity problems. When the number exceeds 10% for instance, one can still continue with linear theory in the guideline sense, recognizing the risk of serious error due to no-longer-negligible (but missing) higher-order contributions.

Note that in this propagation analysis, the attenuation consequences appear as $\sqrt{L_s L_f}$. This effectively relaxes the certainty and precision with which we need to deal with L_s and L_f ; examples of this will appear below. The derivation of this approach as described by BGT (appended) follows the convention in the literature. (E.g. Yuen et al, Seismic Coupling to the Ionosphere, JGR 74,2256, 1969.)

The Spreading factor L_s : This is scaled directly from BGT/Fig. 2. We will consider two altitudes:

$$\begin{aligned} 85 \text{ km (D-layer and 3 mc)} \quad \left(\frac{\alpha_1}{\alpha_2} \right)^2 &= 1 & L_s^{0.5} &= 8 \times 10^{-6} \\ 220 \text{ km (F-layer and 5 mc)} \quad \left(\frac{\alpha_1}{\alpha_2} \right)^2 &= 1/3 & L_s^{2.20} &= 4 \times 10^{-7} \end{aligned}$$

(These are the L_s numbers for the Syntax/10 kt example using the indicated source range of 250 m.)

The Filter factor L_f : The two altitudes behave in a radically different way. Most of the contributions which shape the high frequency cut-off come from the upper 50 km. (Note Fig. V.1) The low-frequency cut-off is determined by the lower 20 km.

85 km: The $G(f)$ integral was recomputed for this altitude; here, the final 10 km determines the upper cut-off. This turns out to be about 20 cps. The lower cut-off is unchanged, of course. The pass-band then looks like Fig. I.6. (Along with the 220 km function.) This would introduce 6 db. attenuation for a pulse half-width of about .02 sec. (Ours is $\sim .2$ sec.) In essence, the U.G. acoustic wave-form should propagate to the D-layer with virtually no distortion or attenuation. So I write $\underline{L_f^{85} \approx .8}$.

220 km: BGT Fig. 3 remains an appropriate filter description for this altitude. They performed the source-filter fold by means of an electrical pulse analog technique. An inspection of their source waveform (BGT/Fig. 1) shows why this works. The pass-band here is well outside the input pulse Fourier domain; the input pulse essentially shock-excites the atmospheric filter; what emerges is a strongly-damped ringing (BGT/Fig. 5). Many of the pulsed source cases to be considered here satisfy this analog, and I will arbitrarily use that output waveform as a characteristic one in all such cases, at 220 km. (Fig. I.7)

The Syntax input pulse (Fig. I.5) is somewhat similar to theirs. It is not as "spiky" and the "tail" is shorter. One should really re-run the analog tests using our own waveform. But to make progress in this introductory discussion, I adopt some scaled estimates based on the power response behavior of pass-band filters. It is dominated by a term of form $(f_1/f_2)^{3/2}$.

Here this only leads to factors of order unity, so that it is not a serious deception. Then $\underline{L_f^{220} = 8 \times 10^{-5}}$.

$\pi+$ factor: Finally, there is an additional π factor of .7 due to the "crossover effect" discussed later on. (This number is relatively insensitive to waveform details.) At 220 km, it is the following positive phase which counts, not the initial negative one: $\frac{\pi+}{\pi-} \approx .7$.

The Power Factors, etc.

$$(P_2/P_1)^{85} = L_S^{85} L_f^{85} = 6 \times 10^{-6}$$

$$(P_2/P_1)^{220} = L_S^{220} L_f^{220} = 3 \times 10^{-11}$$

$$(v_1/v_2) = 1.25$$

$$(\rho_1/\rho_2)^{85} = 1.5 \times 10^5$$

$$(\rho_1/\rho_2)^{220} = 6 \times 10^9$$

The Syntax Example:

$$\left(\frac{\pi_2}{\pi_1}\right)^{85} = 1.35$$

$$\left(\frac{\pi_2}{\pi_1}\right)^{220} = .4$$

(Things do not change much with altitude.) So finally:

$$\left(\frac{\Delta p}{p}\right)^{85} = .6\%$$

$$\left(\frac{\Delta p}{p}\right)^{220} = .2\%$$

The Snowball Discrepancy: The power ratio factor ($L_S L_f = 2 \times 10^{-10}$) as developed by BGT for Snowball, was verified. The corresponding (+) overpressure fraction at 220 km., then turns out to be 6%. (Not 2.2% as reported.) But later on, in recalculating the phase shifts, that higher value finds better agreement with their reported observations.

Hence a 10 kt contained explosion should result in an overpressure amplitude about 1/30 that from a 500 ton surface burst, at 220 km.

3. The Ionospheric Disturbance

In many discussions, the ionospheric plasma is treated as if it were vertically displaced by the acoustic wave. Thus a "positive pressure" pulse would seem to shift the reflection boundary upward. But such a pulse also increases the electron density, thereby moving the effective reflection layer downward. There is another difficulty with that model: At 220 km, the Snowball acoustic pulse would have moved the layer by a preposterous distance: Several tens of km.! We know that this is unrealistic, because the measured phase shifts correspond to effective distances of only a few hundred meters.

The reason seems to be related to the neglect of the gravitational field. If instead, we use the gravitational equilibrium distribution gradient, we obtain the interesting result that the physical displacement is of the same order as (but opposite to) the effective change in ionospheric height due to compression:

$$\frac{\Delta h}{\Delta z} = \frac{N}{\rho} \frac{\frac{\partial \rho}{\partial z}}{\frac{\partial N}{\partial z}} = \frac{4 \times 10^{11}}{2 \times 10^{-10}} \times \frac{(-) 10^{-11}}{10^{10}} \approx -2$$

In the Fourier domain, the density and particle velocity are in phase in an acoustic wave; the particle displacement lags by $\sim 90^\circ$. The wave is "lossy" to the extent of departure from quadrature. In the "first pulse" considerations, I will assume that the electron density perturbation is proportional to acoustic pressure.

Thus:
$$\left(\frac{\Delta N}{N} \right) = \left(\frac{\Delta \rho}{\rho} \right) = \frac{1}{\gamma} \left(\frac{\Delta p}{p} \right)$$

The vertical displacement against the gravitational field also excites another mechanical wave phenomenon - the transverse acoustic/gravity modes. This is analogous to "pond ripples" and propagates outward up to ~ 800 m/sec. The central source region is thus of dimensional order 20 km across. Constructive interference occurs with the acoustic wave, at $\sim 15^\circ$ injection angle. Inside this peripheral zone, there are cancellation effects; outside it, the incident acoustic wave is refracted so strongly as not to make further transverse (gravity) contributions. This is further discussed in Section IV.

It is instructive to compare some of the principal dimensions:

Syntax/10 kt example:

$$\underline{85 \text{ km.}} \quad \Delta h = \frac{1}{\gamma} \left(\frac{\Delta p}{p} \right) \frac{N}{dN/dz} \approx 40 \text{ m.}$$

$$\lambda_{ac} \approx 2 C_S \tau_0 \approx 240 \text{ m.}$$

$$\underline{220 \text{ km.}} \quad \Delta h = \quad \approx 55 \text{ m.}$$

$$\lambda_{ac} \approx 2 C_S \tau_{220} \approx 14 \text{ km}$$

Snowball comparison:

$$\underline{220 \text{ km.}} \quad \Delta h = \quad \approx 1700 \text{ m.}$$

The experimental scale of the Snowball disturbance is shown in BGT/Fig. 10. The long-term (30 min.) fluctuation is representative of atmospheric tidal effects. In the next section, we will identify certain non-linearities in scaling phase-shift predictions. Nevertheless, an inspection of the Snowball experiment suggests that the F-layer disturbance due to a 10 kt contained explosion would exhibit a marginal effect by that measurement technique.

For the sake of clarity, the electron density perturbation at 220 km, is thus here assumed to have the same waveform as the filtered acoustic pulse, shown in Fig. I.7 (same as BGT/Fig. 5). The peak values are to be adjusted to $\left(\frac{\Delta N}{N} \right)$ as already noted above.

4. R.F. Propagation Path Effects

The total relative phase shift along a H.F. propagation path accumulates increments due to the associated pressure-density disturbance profile. The contribution due to the effective displacement of the reflection criterion ($n = 0$ or $X = 1 - |Y_L|$ in Ratcliffe) is only a part of this. BGT construct a prediction of the phase waveform by such a path integration. It is clearly sufficient to do this for a series of instantaneous acoustic profiles (snapshots), in view of the large velocity ratio:

$$\frac{C(EM)}{C(Sound)} \sim 10^6$$

Obviously one should not expect a direct a priori resemblance between the overpressure waveform and the phase shift integral function. This is well illustrated by a comparison between BGT/Fig. 5 and BGT/Fig. 15 (theoretical). The time scale gets stretched out; in a sense, the acoustic pulse "explores" the ionosphere. Unfortunately, it does not appear to be a sufficiently "clean" interaction to help reduce the ambiguities in our present knowledge of the ionosphere. There is too much unfolding involved.

A number of avenues appear to make the problem accessible to more casual estimating. It is easy to go astray. One might guess that the most perturbing profile might be that corresponding to the arrival of the pulse front at the reflection layer. Not so. One might also suppose that we can dispense with the height dependence of electron density, provided that the acoustic wave occupies a sufficiently thin vertical region. Maybe. Let us see:

At 85 km., the case is clear-cut, since the pulse waveform comes thru with little distortion:

$$\frac{1}{2}\lambda \sim C\tau \sim 10^4 \text{ cm. or .1 km.}$$

The electron density gradient over this interval is .05%.

At 220 km., we find:

$$\frac{1}{2}\lambda \sim 6 \times 10^5 \text{ or 6 km.}$$

The corresponding electron density difference is $\sim 25\%$, and we cannot neglect it.

The relative phase path is written:

$$\beta = \frac{2\nu}{c} \left\{ \int n_1(z) dz - \int n(z) dz \right\}$$

where n^1 , n express the effective indices of refraction of the medium in the perturbed and undisturbed cases, respectively.

A linear, non-magnetic ionosphere is sufficient to exhibit the non-linear interaction complexities; it corresponds to a particular ($\Theta = 0$) and somewhat simplified version of BGT. The index of refraction is described by:

$$n^2 = 1 - \frac{X}{1 - Y_L} \quad (\text{with } Y_L \equiv 0 \text{ here})$$

$$X = \left(\frac{\omega_p}{\omega} \right)^2 \left(\frac{N}{N_p} \right)$$

The linear description of the electron density is made in terms of an inverted coordinate system: $x = Z_p - Z$

$$\begin{array}{ll} \text{so that:} & N = N_o (1 - ax) \quad \text{unperturbed} \\ & N^1 = N_o (1 - ax) \left(1 + \frac{\Delta N}{N} \right) \quad \text{acoustically perturbed} \end{array}$$

The reflection criterion ($n \equiv 0$) requires that:

$$\left(\frac{\omega_p}{\omega} \right)^2 \left(\frac{N_o}{N_p} \right) \equiv 1$$

$$\text{whence} \quad N_o = N_p \left(\frac{\omega}{\omega_p} \right)^2 \quad \text{at } Z = Z_p, \quad x = 0 \text{ necessarily.}$$

N_p , ω_p , Z_p all refer to the reflection layer, of course.

It follows at once that:

$$\begin{array}{ll} n^2 = ax & \\ n^{12} = ax - \frac{\Delta N}{N} & (\text{neglects second order product}) \end{array}$$

$$\text{and} \quad \beta = \frac{2\nu}{c} \left\{ \int_0^f \sqrt{ax - \frac{1}{\gamma} \left(\frac{\Delta p}{p} \right)} dx - \int_0^f \sqrt{ax} dx \right\}$$

Δp can acquire both negative (underpressure) and positive (overpressure) values. This representation evidently requires that $\frac{1}{\gamma} \left(\frac{\Delta p}{p} \right) < ax$ always.

(This is mainly an artifice of the description; physically it says that the reflection boundary shifts to avoid this arithmetic singularity - if the situation should come to that.) Note also that:

$$a = - \frac{1}{N} \frac{dN}{dx} \approx 2.5 \times 10^{-5} \text{ m}^{-1} \quad \text{at 220 km}$$

The 220 km. case. We mentioned that the profile of maximum relative phase was not that corresponding to the arrival of the first front at the reflection layer. The reason for this is best seen by considering the (synthetic) case of a symmetric* acoustic pulse in a uniform ionosphere. (Fig. I.8a) The two excursions (opposite sign) contribute cancelling phase contributions. Now we insert the reflection boundary (Fig. I.8b) right at the "cross-over". Only one excursion now contributes and we have a large phase effect. This is also suggested in BGT/Fig. 15. The initial (-) phase excursions appear to correspond in time, to the passage of the acoustic cross-over through the reflection layer; the peak timing of that first large (-) excursion agrees almost exactly with the cross-over time. (25 sec. - BGT/Fig. 5)

For our estimation purposes, I then assume that the pressure cross-over has just reached the layer. The initial underpressure pulse is above that boundary and is lost to the H.F. path. The subsequent overpressure pulse is modeled via a triangular approximation. (This makes the integrals "easy".) (Fig. I.7):

$$\frac{1}{\gamma} \frac{\Delta p}{p} = bx \quad \text{for the rise: } 0 \text{ to } x_1 \quad (b < a)$$

$$\frac{1}{\gamma} \frac{\Delta p}{p} = d - cx \quad \text{for the fall: } x_1 \text{ to } x_2 \quad (d = cx_2)$$

$$\text{At } x_1: \quad bx_1 = c(x_2 - x_1) \quad \text{So: } c = \frac{x_1}{x_2 - x_1} b \quad \text{and } d = \frac{x_1 x_2}{x_2 - x_1}$$

* Equal RF phase areas.

Then:

$$\beta_1 = \frac{2v}{c} \left\{ \int_0^1 \sqrt{(a-b)x} \, dx - \int_0^1 \sqrt{ax} \, dx \right\}$$

$$\beta_2 = \frac{2v}{c} \left\{ \int_1^2 \sqrt{(a+c)x-cx_2} \, dx - \int_1^2 \sqrt{ax} \, dx \right\}$$

(The total shift is $\beta_1 + \beta_2$ of course)

We will see that in many practical cases: $b \ll a$, $c \ll a$, and the obvious (and welcome) simplifications are possible. The subsequent struggle will not be reproduced here. One finds:

$$\beta_1 = -\left(\frac{2}{3} \frac{v}{c} \sqrt{a} \, x_1^{3/2}\right) \left(\frac{b}{a}\right)$$

$$\beta_2 = -\left(\frac{2}{3} \frac{v}{c} \sqrt{a} \, x_1^{3/2}\right) \left(\frac{c}{a}\right) \left\{ 1 - 3 \left(\frac{x_2}{x_1}\right) \left(1 - \frac{2}{3} \sqrt{\frac{x_2}{x_1}}\right) \right\}$$

The first enclosure evidently dimensions the problem. For BGT/Snowball (5 mc. at 220 km), this comes out:

$$\beta_0 = -\left(\frac{2}{3} \frac{v}{c} \sqrt{a} \, x_1^{3/2}\right) = \underline{\underline{-8 \text{ cycles}}}$$

At least it's in the ballpark.

There is one other detail. Since this "peak" model now associates us with the second (and positive) overpressure pulse, the appropriate amplitude factor must appear (as mentioned before):

$$\frac{\pi^+}{\pi^-} \approx .7$$

(This seems to be relatively insensitive to waveform time-scale.)

(P.S. These expressions contain two non-cancelling "c" terms.

Their origins are self-evident and non-conflicting. Sorry about this.)

Inasmuch as we have rationalized the same acoustic waveform at 220 km., for our 10 kt U.G. example as for BGT (but with different amplitudes), the common coefficients are:

$$a = 2.5 \times 10^{-5} \text{ per meter}$$

$$\tau_1 = 10 \text{ sec}$$

$$\tau_2 = 50 \text{ sec.}$$

$$X_1 = 2.7 \times 10^3 \text{ m.}$$

$$X_2 = 13.5 \times 10^3 \text{ m.}$$

$$\frac{v}{c} = \frac{5}{3} \times 10^{-2}$$

We next obtain the total phase shift for an instantaneous profile. All this is being done at the 5 mc. critical frequency for vertical reflection, neglecting magnetic field splitting.

Syntax example:

$$\left(\frac{\Delta p}{p}\right)_+ = .2\% \text{ at } 220 \text{ km.}$$

$$b = 5.3 \times 10^{-7} \text{ m}^{-1} \quad c = 1.3 \times 10^{-7} \text{ m}^{-1}$$

Find:

$$\beta_1 \approx -.17 \text{ cycle} \quad \beta_2 \approx -.35 \text{ cycle}$$

$$\underline{\beta \approx -.5 \text{ cycle}}$$

Snowball check:

$$b = 1.6 \times 10^{-5} \text{ m}^{-1} \quad c = 4 \times 10^{-6} \text{ m}^{-1}$$

$$\beta_1 \approx -5 \text{ cycles} \quad \beta_2 \approx -11 \text{ cycles}$$

$$\underline{\beta \approx -16 \text{ cycles}}$$

To the precision of the assumptions and approximations above (factor of 2), this is indistinguishable from the BGT data.

These numbers also corroborate our earlier suspicion that the interaction due to a nominal, contained, U.G. test is going to be marginally observable.

85 km. case (10 kt example only)

Since we can now set $a \equiv 0$, the integrals are a bit different:

$$\beta = \frac{2v}{c} \left\{ \int \sqrt{K} - \frac{1}{\gamma} \left(\frac{\Delta p}{p} \right) dx - \int \sqrt{K} dx \right\}$$

K plays the rôle of confining the phenomenology below the reflection boundary. By virtue of a similar treatment, one obtains:

$$\beta_1 = \frac{1}{2} \left(\frac{v}{c} \right) \frac{b}{\sqrt{K}} X_1^2$$

$$\beta_2 = \frac{1}{2} \left(\frac{v}{c} \right) \frac{c}{\sqrt{K}} (X_2 - X_1)^2$$

The origin of the phase contributions are perhaps a little more clearly exhibited here. Setting $K \equiv b$ makes the integrand just zero at reflection and avoids imaginary roots.

The acoustic pulse is essentially the original velocity waveform, so that now:

$$X_1 = 54 \text{ m.}$$

$$X_2 = 216 \text{ m.}$$

$$b = -5 \times 10^{-5}$$

$$c = -1.7 \times 10^{-6}$$

$$\text{also } a = 5 \times 10^{-5}$$

$$v = 3 \times 10^6$$

and we find:

$$\beta_1 = .015$$

$$\beta_2 = .045$$

$$\underline{\beta \approx + .06 \text{ cycle}}$$

An inspection of the profile numbers (x_1, x_2) shows at once why the phase shift is so insignificant at 85 km. For $v = 3$ mc, $\lambda = 100$ meters; the acoustic pulse interacts with very few H.F. wavelengths indeed. This suggests that there may be a "best height" and a "best frequency" for pulses of nuclear explosion origin. Presumably, also there will be different "best heights" and "best frequencies" for acoustic sources of radically different character, such as non-contained explosions and earthquakes.

The 85 km case does not appear to hold much experimental profit. It probably should have been more correctly exercised at 100 km, but the difference does not warrant reconsideration.

P.S. This arithmetic differs from BGT in that it makes no assumptions as to the dimensions of the region in which $n \approx 1$. In this respect, there are range validity questions in both this model and the BGT approach; neither traces the phase interaction "exactly".

FIG I.1
 THE SLOPE PHENOMENON
 (HYPOTHETICAL)
 ①-②-③ INCREASING
 ACOUSTIC AMPLITUDES @ 220 KM.
 ②; CRITICAL "SWITCHING"
 AMPLITUDE

FIG I.2
 ACOUSTIC "SWITCHING" FUNCTION
 TYPICAL F-LAYER
 DAYTIME CONDITIONS

(a) VELOCITY

(b) POSITION

FIG I.3

SOURCE MODEL

SURFACE MOTION WAVE FORMS

FIG. I.4

SOURCE MODEL

THE PISTON APPROXIMATION
(VERTICAL SCALE EXAGGERATED)

FIG. I.5

FILTER INPUT FUNCTIONS
COMPARED.

FIG I.6
ATMOS. ACOUSTIC FILTERS

FIG I.7
ACOUSTIC SIGNAL @ 220 KM.
(FILTER OUTPUT)
NORMALIZED

FIG. I.8

ACOUSTIC-IONOSPHERIC INTERACTION

(+) RF PHASE ADVANCE } AT f_c
(-) RF PHASE RETARD }

220 KM

II. Corollary Nuclear Considerations

One is immediately curious about a variety of related possibilities: Higher yields, non-contained explosions, earthquakes, Tsunamis; noise and neglected environmental aspects, higher altitudes and frequencies, grazing incidence; S & P waves, Rayleigh and Love waves; better theoretical representations and calculations, special "applications" and on and on. One could write a book.

Above, I considered a class of cases in which the overpressure profile resulted in a small perturbation of the normal electron density. No account was taken of the effective displacement contribution; one could expect some phase waveform modification therefrom; and a reduction in peak phase shift of possibility as much as 30%.

Many of these new cases "drive" the ionosphere much more severely - so much so, that the shift of the virtual reflection surface completely masks the electron opacity phase effect. The "switching" condition for this is:

$$\underline{b > a}$$

and here we definitely enter into some domains of hypothesis.

"Switching" Domain. There appear to be two "strong pulse" domains, as the acoustic amplitude is increased. The first of these lies just above that slope threshold, or:

$$N' = N_o(1-ax) \left(1 + \frac{\Delta N}{N}\right) = N_o$$

whence:
$$\frac{\Delta N}{N} \geq ax$$

Suppose
$$\frac{\Delta N}{N} = \frac{1}{\gamma} \frac{\Delta p(x)}{p_o} = \frac{1}{\gamma} \left(\frac{\Delta p}{p}\right) \sin 2\pi \left(\frac{x}{c\tau}\right)$$

Find:
$$\left(\frac{\Delta p}{p}\right)_{th} = \Gamma \frac{u}{\sin u} \quad u = 2\pi \left(\frac{x}{c\tau}\right)$$

where
$$\Gamma = \frac{\gamma a c \tau}{2\pi} \approx .05 \text{ typically}$$

and the critical condition corresponds to $\frac{u}{\sin u} \equiv 1$

The Γ coefficient includes $a = \frac{1}{N} \frac{dN}{dz}$; hence it is a function of altitude (among other environmental conditions), and indirectly, critical sounder frequency. Correspondingly there is a relationship between acoustic amplitude and switching frequency as typified by Fig. I.2. The elements of the "switching" mechanism are depicted in Fig. I.1. In essence, the phase shift exhibits a radical change in amplitude dependence at that critical level, per Fig. II.1.

Note that, whereas the "normal" low-amplitude phase effect appears as a retardation, this downward boundary shift results in a phase advance as also illustrated in Fig. II.2. What is more, as this (hypothetical) phenomenon grows (with amplitude), the (-) opacity contribution decreases as well. Ultimately the phase shift reaches a quasi-plateau (the "rectangular approximation"), corresponding to a downward displacement Δx of the same dimension as the overpressure phase. (We are now up to $\frac{\Delta p}{p} \sim 8\%$.) For this:

$$\beta \sim 2 \frac{c_s \tau_{ac}}{\lambda_{RF}} \sim 400 \text{ cycles}$$

There is a corresponding propagation time reduction:

$$\Delta T \sim 2 \frac{c_s}{c_{em}} \tau_{ac} \sim 80 \text{ microsec.}$$

The "Strong Pulse" Domain. A much more severe phase effect may come into evidence at still higher acoustic amplitudes. (Fig. II.2b) When $b \gg a$, the compressed electron density may exceed the critical value at an altitude substantially below the "rectangular" shift. It is exhibited by the "Iceberg effect" (near the bottom of the figure), where the acoustic peak first pokes through the critical density value, as the acoustic pulse propagates upward. This should be accentuated as the pressure pulse becomes more shock-like, with smaller (-) precursor, and sharper, steeper, (+) pressure front.

Of course, in all of these peculiar interactions, the excess electron cloud must be thick enough to support the necessary induced R.F. reflection currents. I.e., it must become opaque enough - usually several R.F. wavelengths thickness. This will tend to shade and slope the sharp-edged criteria being developed here.

The onset of this domain is defined by:

$$a\Delta z = \frac{1}{\gamma} \frac{\Delta p}{p} \gg ax_1 \approx .06$$

or $\frac{\Delta p}{p} \gtrsim 20\%$ typically

Note that $\Delta z \propto \frac{\Delta p}{p}$ once more at very high (quasi-shock) amplitudes (but now advancing in phase).

Beyond this, the rates of change enter a true Doppler-like regime, the phase shift should again reverse sign, and besides, one is no longer "acoustic".

1. Boxcar/Jorum

Contained, high-yield underground case; 220 km only:

$$\left(\frac{\Delta p}{p} \right)_+ = 6\%$$

Formally, this duplicates Snowball/BGT. The amplitude is the same, and the same waveform was rationalized at 220 km. I separately tested that the phase shift is relatively insensitive to precise waveform assumptions - as long as the area is constant. This is not surprising, considering the form of the phase shift integrals. (A marginal "switching" value, as well.)

Without further ado:

$$\beta = -16 \text{ cycles}$$

Why Jorum? There is a provisional claim of observation of an ionospheric disturbance (acoustically coupled at 4000 km) associated with that event: L. M. Libby, Detection of Nuclear Tests and Earthquakes by Doppler-Shift Ionosonde, etc., RAND, December, 1970. The observed phase shift at that distance was much smaller than this number, of course. In Section IV, I will suggest that the effective long-range acoustic source size is ~ 300 km, and that the propagation scaling is $\sim r^{-3/2}$. Thus this "local" prediction is consistent with a long-range observation above threshold.

2. Non-contained Underground Explosions

By this I mean underground explosions for which "significant" hydrodynamic effects occur in the atmosphere. (At least retarc formation results.) I will only suggest an estimation approach here, since it should become clear that a vertical sounding effect should be readily visible.

One can again use Snowball/BGT as a measure of "lower bounds" for expectations here; why is this?

First, the acoustic source pulse is likely to be "softer", in the sense that the release of hot gas takes place through much broken material, and it is presumably accompanied by accretion of cold dust. Hence one would expect a less "spiky" source pulse (than Snowball), with the consequence that a larger fraction of the hydrodynamic energy release will lie in a lower frequency domain. So more of the pressure wave will "get through the filter". But I am not presently aware of any reliable close-in air pressure waveforms (Sedan, Cabriolet, etc.) by which to quantitatively test this.

Secondly, a useful way to grossly model the source problem, would be to assign an equivalent surface explosion yield to the released gas - but with that softer input waveform, of course. While there is no a priori technical limitation to the smallest possible situation, one suspects that it might be uninteresting or unprofitable (on other grounds) to tailor a nuclear event so as to release much less energy than did Snowball.

3. Atmospheric Explosions

Obviously anything comparable to Snowball (500 tons) or larger, should result in comfortably visible effects. There exists an accumulation of evidence in this respect, and I discuss this briefly in the separate classified section on "Applications". It is almost self-evident that the business merits closer review for possible usefulness in the contexts of applicable scientific knowledge, military problems, and foreign test observation.

10 kt Surface Burst: This idealization readily demonstrates what was said above, concerning "Yield Saturation". We have:

$$\left(\frac{\Delta p}{p}\right)_+ \approx 30\%$$

Aside from evident doubts about the validity of our formalisms for overpressures this large, the number clearly speaks for an "easy" visibility in ionospheric sounding. At 220 km:

$$a \rightarrow 2.5 \times 10^{-5} \quad b \rightarrow 7.5 \times 10^{-5}$$

and we have a clear violation of conditions. As we just discussed, for this case the local electron density grossly exceeds the critical density - and, in fact, that reflection boundary now shows up well below the back edge of the pulse. We can make a rough estimate:

$$\beta \approx \frac{2v}{c} \Delta Z = \left(\frac{2v}{c}\right) \frac{1}{\gamma a} \left(\frac{\Delta p}{p}\right) \approx \underline{330 \text{ cycles}}$$

This appears as well as a directly observable propagation time advance of about 70 microseconds.

High Yields (and/or High Altitude Bursts) When the atmosphere is driven sufficiently hard to propagate a shock, the ionospheric plasma should be "swept" with it; then $v_{sh} \gg v_c$ and one experiences something approaching a true Doppler effect in the sounder measurement. (This is probably where the label came from.) Presumably this shift persists through the passage of the following rarefaction and the reestablishment of densities closer to normal. The magnitude of the effect and its arithmetic are very different, and will not be attempted here.

4. Collapse (This is a real piston!)

It is interesting to estimate the effect associated with collapse. Evidently it will be related to area and depth of the collapse zone; one might thereby develop useful deductions as to yield and DOB.

Consider again the 10 kt synthetic case; I assign the following dimensions to the collapse crater:

$$\begin{aligned} \text{Depth } D &\sim 20 \text{ m} & \text{Radius } R &\sim 80 \text{ m} \\ \text{Fall Time } T &\sim 2 \text{ sec} \\ \text{Peak velocity } v_1 &\sim 20 \text{ m/sec} \end{aligned}$$

Then one finds the surface pressure change:

$$\left(\frac{\Delta p}{p}\right)^1 = \frac{\rho_0 c v}{p} = 8\%$$

It is a "big" number, and one can see this in the collapse movies - the collapse zone acts as a giant "vacuum cleaner" for everything loose standing near the edges. (Note Fig. II.2.)

Now the piston factor:

$$\frac{kd}{4} \sim \frac{\pi d}{4c\tau} \sim .25$$

from which $\left(\frac{\Delta p}{p}\right)_1 \sim 2\% \text{ at } 200 \text{ m}$

Again we play the $L_s L_f$ game. Here the pulse width contains lower frequencies than before and one estimated $L_f \sim 10^{-3}$. Also $L_s \sim 2 \times 10^{-7}$.

Then $\pi^2/\pi_1 \sim 1.6$, so that $\left(\frac{\Delta p}{p}\right)^{2.20} \sim 3\%$

The input pulse is still short enough compared to the acoustic filter response, so as to adopt the shock-excited waveform, as before. The previous considerations all dealt with linear-theory propagation of overpressure inputs. Here it is initially an underpressure, and (by virtue of linearity) we simply invert the waveform. Then the phase change must be advancing; the R.F. phase coefficients are all the same except:

$$b = 8 \times 10^{-6} \quad c = 2 \times 10^{-6}$$

and one finds: $\beta = 8$ cycles

The collapse effect is much larger than the direct acoustic wave interaction, at 10 kt contained.

A similar exercise for Boxcar leads to higher numbers, but evidently weakly dependent on yield:

$$\left(\frac{\Delta p}{p}\right)_i \sim 2.5\% \text{ at } 350 \text{ m}$$

$$\left(\frac{\Delta p}{p}\right)^{2.20} \sim 8\%$$

$$\underline{\beta = 20 \text{ cycles}}$$

FIG. II.1
PHASE SHIFT FUNCTION
(IDEALIZED MODELS)

FIG. II.2
STRONG PULSE CASE

FIG II.3
THE COLLAPSE PISTON

III. Earthquakes

Recently, reports have appeared concerning ionosonde detection of seismic disturbances, and there has been speculation as to the possibility of discriminating between "earthquakes and bombs". As in the early days of true seismic detection, these seem to have much the flavor of "finding it when one knows where to look". Superficially, one can get lost in the maze of possible paths and travel time differences: Earthquake (or bomb) at point A, which affects the ionosphere at a (variable) location B (via several modes n), as seen by an ionosonde situated at yet a third point C. (Shades of Rube Goldberg!) We seek possible discriminants by which to more closely confine the problem.

The Local Regime. A number of features exhibited thus far by nuclear explosions carry over to the earthquake problem. Perhaps the most significant one, is the effect of the acoustic filter in determining the acoustic waveform at the F layer. The ionosphere should be a particularly sensitive sensor for mechanical disturbances which have frequency distributions in its pass-band. (Order of 4×10^{-4} to 2×10^{-2} Hz - or $\tau \sim 1$ min.) A somewhat surprising feature of ionospheric sounder records, is the paucity of fluctuations in this period domain. Despite that sensitivity, it appears to be a relatively quiet region.

This then suggests that earth motions exhibiting such long periods would couple best. But for a local source, this would imply source dimensions of order $c_s \tau \sim 500$ km! (A cataclysmic motion, indeed.) Propagated surface waves eventually exhibit such disperse components, but by then, the amplitudes have become very small. Most local sources exhibit spectra characterized by periods of order 1 second; they are not much slower than contained explosions. Hence we can reasonably again adopt the model of transient excitation of an acoustic filter.

In elementary seismic descriptions, earthquakes are modeled as central point sources at "shallow" or "deep" underground locations. I will confine this to shallow sources of medium size. (E.g., Richter 6 at 10 km depth) The surface intercept of the disturbance propagates as a circular ring of waves, with distinctions between S and P waves, and much further out, between Rayleigh and Love waves. First I ask if a piston model is still credible for dealing with ionospheric effects in the vicinity of the epicenter. Unquestionably, there will be a greater element of fiction to such an approach here (than for contained bombs).

1. The Local P-wave with "Vertical" Coupling

Obviously, the earthquake "piston" is much larger; in order to dimension it, I resort to phase difference considerations:

$$d = 2a \sim \frac{\lambda}{4} \sim \frac{c\tau}{2} \sim 2 \text{ km}$$

Here I use the P wave velocity; presumably it is this longitudinal surface motion which more closely resembles a piston. ($\tau \sim \frac{1}{2}$ sec on typical shallow, close-in P wave records.) Perhaps the most significant feature of this dimension is that it radically changes the character of the acoustic distribution:

$$ka \sim \frac{c_{\text{gnd}}}{c_{\text{air}}} \sim 25 \gg 1$$

The acoustic energy propagation is thereby strongly confined to the normal to the surface motion. Although the P-wave tends to be "messy" - even close-in - I will model its propagation as radial from a "center". The effect of the surface reflection is to make that center appear shallower. Hence we can consider the initial, close-in, acoustic pulse as a continuous radially propagated wave, originating at that shallower point (Fig. III.1). In order to dimension its amplitude, I will use the surface pressure:

$$p_1 = \rho_0 c v_1$$

(The surface is sufficiently flat for this, considering the air wavelength.)

Suppose I assume a surface velocity similar to that for contained low-yield explosions: $v_1 \approx 60 \text{ cm/sec}$.

Then: $p_1 = 2.5 \times 10^3 \text{ dynes/cm}^2$

$$\left(\frac{\Delta p}{p} \right)_1 = .0025 \text{ or } .25\%$$

Further, I assign an effective source depth of 3 km. (This will become the new r , in the propagation scaling factor.)

The other factors in π^2/π_1 do not change very much for the vertical field. The initial cycles of a P-wave record resemble the initial surface excursion of the contained explosion, repeated several times. One anticipates perhaps a narrower source frequency distribution and this may affect the L_f term unfavorably at 220 km. Find:

$$L_S^{85} \sim 1.2 \times 10^{-3} \quad L_f^{85} \sim .8 \quad \left(P_2/P_1\right)^{85} = 10^{-3}$$

$$L_S^{220} \sim 6 \times 10^{-5} \quad L_f^{220} \sim 6 \times 10^{-5} \quad \left(P_2/P_1\right)^{220} = 4 \times 10^{-9}$$

Finally: $\left(\pi_2/\pi_1\right)^{85} \approx 17$

$$\left(\pi_2/\pi_1\right)^{220} \approx 6$$

and: $\left(\frac{\Delta p}{p}\right)^{85} \approx 4\%$

$$\left(\frac{\Delta p}{p}\right)^{220} = 1.5\%$$

Phase Shifts: We continue with the nominal BGT acoustic waveform at 220 km:

220 km $b/a \rightarrow .16 \quad \beta_1 = -1.3$

$c/a \rightarrow .04 \quad \beta_2 = -2.7$

and $\beta \approx -4 \text{ c.}$

85 km: The acoustic pulse at 85 km due to an earthquake, should be longer and more "cyclic", than that from an explosion. To estimate the maximum D-layer effect, I model one pressure phase as a symmetric triangle with an acoustic length $\sim 270 \text{ m.}$

Then: $\sqrt{K} = .082 \quad X_1 = X_2 - X_1 = 135 \text{ m}$

$$b = c = 2.1 \times 10^{-4}$$

and find: $\beta \approx .5 \text{ c}$

Thus the local longitudinal (vertical) ground motion from a modestly strong earthquake should produce a visible local ionospheric effect.

2. S-wave - Also Vertical Case

However the S-wave is generated, its principle property here, is that at some distance out (let us say beyond the spherical model dimension used above), it results in a vertical wave displacement of the earth's surface per Fig. III.2. As this ring propagates radially out, a corresponding acoustic wave presumably propagates upward as a fairly flat cone (or inverted dish) with inclination angle:

$$\psi \sim \frac{c_{\text{air}}}{c_{\text{earth}}} \sim .08 \text{ rad or } \sim 5^\circ.$$

Inasmuch as the ground attenuation is small on the source scale considered thus far, the effective "piston" (as seen by the ionosphere) is large indeed - of order 100 km (for a flat, "perfect", geology). A similar model is discussed by Yuen et al (Ibid).

Suppose that the peak surface velocity is 6 cm/sec with a waveform time scale again of order $\frac{1}{2}$ second. The surface pressure is:

$$p_1 \sim 250 \text{ dynes/cm}^2$$

and: $\left(\frac{\Delta p}{p}\right)_1 \sim 2.5 \times 10^{-4} \text{ or } \underline{.025\%}$

Let us estimate the consequences at 220 km. If one does this on a strictly plane wave basis, one obtains suspiciously high scaling numbers. (Like $\pi_2/\pi_1 \sim 600!$) One can make a fragile, semi-empiric argument* for introducing an intermediate range scaling factor. (r^{-1} instead of r^{-2})

In that case: $L_s^{220} \sim .015$ $L_f^{220} \sim 7 \times 10^{-5}$ $\frac{P_2}{P_1}^{220} \sim 10^{-6}$

and: $\left(\frac{\pi_2}{\pi_1}\right)^{220} \approx 110$

So that: $\left(\frac{\Delta p}{p}\right)^{220} \approx .025$ or 2.5%

At 85 km: $\left(\frac{\pi_2}{\pi_1}\right) \approx 100$

$\left(\frac{\Delta p}{p}\right)^{85} \approx .025$ - - - 2.5% also.

These π factors are still disconcertingly large, but it is difficult to argue for a stronger range dependence, without sacrificing the "dish" model.

Phase Shifts: (Vertical sounding, continued)

At 220 km: $b/a \rightarrow 2.5$ $|\beta_1| \sim 2$

$c/a \rightarrow .065$ $|\beta_2| \sim 4$

and: $|\beta| \approx 6 c.$

At 85 km: $\sqrt{K} = .082$ $x = 135$ m.

$b = \frac{1}{\gamma x} \left(\frac{\Delta p}{p}\right) \rightarrow 1.3 \times 10^{-4}$

and: $|\beta| \approx .3 c.$

This crude S-wave coupling model predicts nothing strongly different from P-wave, at least locally.

* It agrees better with data such as it is.

3. "Slow Motion" and Tsunamis

The structure of the $L_s L_f$ factors suggests that a relatively small motion over a large area, might produce an optimum effect. There is little reliable evidence to justify such an expectation from either contained explosions or from earthquakes. In some way, such a fictional source resembles and presages the Rayleigh wave consideration below. In order to further define what one might look for, I will do the problem backwards, starting with a fiducial phase shift of one cycle.

First we choose optimum models for L_s, L_f ; we assume a vertical surface motion such that the predominant frequencies lie in the range 5×10^{-3} to 5×10^{-2} Hz. ($\tau \sim 2$ min.) One might perhaps envision this as a large-scale, small-amplitude relaxation of the earth medium, following a large transient disturbance. With some qualitative justice, this restriction permits $L_f \sim .1$.

Evidently for periods that long, phase differences will be small across relatively large areas ($\lambda \sim 500$ km) and the source-acoustic coupling may be viewed as quasi-planar. A conservative approach preserves the "curvature", albeit small. Using a reasonable source phase criterion, I adopt as the source scaling distance:

$$r_1 \sim \lambda/8 \sim 60 \text{ km.} \quad (\text{also } \frac{kd}{4} \sim .4)$$

Then find: $L_s \sim .025$

and we obtain a large acoustic multiplier: $\frac{\pi_2}{\pi_1} \sim 5 \times 10^3$

Next, I approximate the relaxation pulse as a uniform fall slope - in effect a "saw-tooth" acoustic wave from the standpoint of RF phase interaction. One finds:

$$|\beta| \approx \frac{4}{3} \left(\frac{v}{c} \right) a \quad x_1^{3/2} \left(\frac{c}{a} \right)$$

where the (second) c represents the wave slope, and:

$$x_1 = c_s \tau \sim 30 \text{ km}$$

$$c = \frac{1}{\gamma x_1} \frac{\Delta p}{p} \approx 2 \times 10^{-5} \left(\frac{\Delta p}{p} \right)^{2.20}$$

For a one cycle phase shift, this obtains:

$$\left(\frac{\Delta p}{p} \right)^{2.20} \approx .2\%$$

and working back thru the various coupling factors:

$$\left(\frac{\Delta p}{p} \right)_1 \approx \underline{10^{-4}\%} \quad \text{or} \quad \underline{1 \text{ dyne/cm}^2}$$

The corresponding fall velocity is $\sim .025 \text{ cm/sec}$
and the total "sinking" is $\sim 3 \text{ cm}$.

A clear geographical case in which surface motion of this scale is exceeded (in area, amplitude and time) is the Tsunami. It should be possible to trace the progress of a Tsunami by ionospheric monitoring.

FIG III. 1
LOCAL P-WAVE COUPLING MODEL
 SHOWING DEVELOPMENT OF
 "CONCENTRIC" ACOUSTIC WAVE
@ $R_a \gg 1$

FIG III, 2

S-WAVE COUPLING MODEL
THE "DISH"

NOTE THAT RAYLEIGH WAVE
COUPLES ANALOGOUSLY
(GREAT DISTANCES)

IV. The Remote Regime - Rayleigh Waves, "Duct Injection" and Other Topics

Everything considered so far pertains to experiments in which both the acoustic and the radio-sounder paths were assumed to be vertical (or nearly so) and within the acoustic refraction zone (i.e., 200 km or less from the source). Now, let us look at "angles" and remote effects.

Things become more ambiguous, contentious, and speculative here. A number of mechanisms and models have been set forth in the literature, and the data so far seems to confirm all of them. As I implied before, here I will only consider "first arrival" signals. Even so, this allows many possible signal paths. The observations suggest one common feature, however: There seems to be an absence of intermediate coupling routes — that is, signals which travel part way seismically, couple up to the atmosphere, and travel the rest of the way acoustically. This may simply reflect on the large velocity dispersion which the overall contribution integral would then exhibit. This coherence integral necessarily "peaks" around the source and around the sensor, and it is only at those corresponding path times that a unique signal does become visible. Conversely, the signal structure furnishes clues as to the dimensions of these central zones of in-phase contributions, and hence on energy-coupling efficiencies.

(Suffice it to say that we "fudged our way out of it" when dealing with just the local regime in the earlier sections.)

In order to assuage the presentation, I elect here a more hypothetical approach: I will start with what should be the most generally acceptable feature of the problem — namely, the ionosphere — and work backwards towards required source magnitudes for each signal path and choice of source. As a phase visibility threshold I adopt:

$$\beta = 1 \text{ cycle.}$$

Obviously, here I will need to "fudge" to the extent of assuming a density perturbation profile in the H.F. interaction region. But, we will see that even this is not as critical, nor as ambiguous as one might off-hand think. The real problems arise when one finally compares required acoustic source amplitudes with those customarily observed.

1. The Remote Rayleigh Wave

One significant feature of a Rayleigh wave at 3000 km, is that its central frequency distribution lies in the middle of the lossless acoustic pass-band for vertical propagation. A small, slow, vertical ground motion results in an air pressure wave which experiences a large amplification factor upward. Another feature is, in fact, the smallness of observed Rayleigh amplitudes: $\sim 10^{-2}$ cm with $\tau \sim 30-60$ sec.

From the H.F. interaction standpoint, the acoustic density profile is no longer that corresponding to the pulse excitation of an equivalent acoustic filter. The first-order prediction would be for a reproduction of the Rayleigh waveform. Indeed, corroboration for this is claimed in the literature - cf. Yuen et al (Ibid); Weaver et al, Nature 226, 1240 (1970).

Since the waveform approximates a continuous sinusoid, the phase path integral should be taken over a sufficient number of (acoustic) cycles to account for the partial RF phase shift cancellation between opposite acoustic phases in the ionospheric gradient. (Note Fig. IV.1) We can roughly estimate this factor in the following way:

$$n = \sqrt{ax} \qquad n^1 = \sqrt{ax - \frac{\Delta N}{N}}$$

Now: $\frac{\Delta N}{N} = \frac{1}{Y} \frac{\Delta p}{p} = \frac{\Delta_0}{Y} \sin wt = \frac{\Delta_0}{Y} \sin kx$

whence: $n = \sqrt{ax} \qquad n^1 = \sqrt{ax - b \sin kx} \qquad b = \frac{\Delta_0}{Y}$

and $\beta = 2 \left(\frac{v}{c} \right) \int (n^1 - n) dx.$

We go to the "small effect" approximation:

$$n' \rightarrow \sqrt{ax} \left(1 - \frac{b}{2a} \frac{\sin kx}{x} \right)$$

and:
$$\beta = -\left(\frac{v}{c}\right) \left(\frac{b}{\sqrt{ka}}\right) \int_0^{\infty} \frac{\sin kx}{\sqrt{kx}} d(kx)$$

The integral represents the averaging factor: $\int_0^{\infty} = \sqrt{\frac{\pi}{2}}$

Finally:
$$\beta = -\left(\frac{v}{c}\right) \sqrt{\frac{\lambda_s}{a}} \left(\frac{b}{2}\right) \quad \text{with } b = \frac{1}{\gamma} \left(\frac{\Delta p}{p}\right)_m$$

At 220 km, with $\lambda_s \sim 8$ km, $v \sim 5$ mc, find:

$$\beta = -100 \left(\frac{\Delta p}{p}\right)^{220}$$

Thus, for our 1 cycle threshold, we require:

$$\left(\frac{\Delta p}{p}\right)^{220} \approx 1\%$$

Next, consider $L_s L_f$.

For $r \gg \lambda$, the local motion distribution (or "dish") approaches a moving band source; that is, the acoustic range scaling should be taken as cylindrical, with a large effective source size: $r_1 \sim \frac{\lambda}{4} \sim \frac{c\tau}{2} \sim 60$ km. One has a quasi-plane wave propagating upward — something like Fig. III.2, but on a larger scale. I adopt the same acoustic-ray-bending as indicated in BGT/Fig. 2, so that $L_s \sim \frac{60}{220} \times \frac{1}{3} \sim .09$.

I also assign $L_f \sim .8$

Then:
$$\pi_2/\pi_1 \sim 3 \times 10^4 \quad (!)$$

This is a very large number; it hints that perhaps this particular problem falls outside the domain of applicability of this scaling method. Nevertheless, multipliers of this general size appear necessary, if the theory is to support the observational reports.

Still working backwards, we obtain the required surface pressure amplitude:

$$\left(\frac{\Delta p}{p}\right)_1 \approx 3 \times 10^{-7} \quad (\text{or } .3 \text{ dyne/cm}^2).$$

The corresponding surface velocity would be:

$$v = \frac{\Delta p}{\rho c} = 7 \times 10^{-3} \text{ cm/sec}$$

with a vertical Rayleigh amplitude component $\sim$.06 cm.

While this is a very small motion, its lateral dimensions are not: $\lambda \sim 200$ km. One might simulate it, if one could raise and lower the entire surface of Lake Tahoe by one mm within 30 seconds! (There have been other suggestions in the past for using Lake Tahoe as a simulator.)

The data references show that RF phase disturbances of threshold magnitude are indeed seen at the appropriate time. But the corresponding Rayleigh wave seismic amplitude is noticeably lower than derived here. ???

Love Waves. As I remarked way back at the beginning, one would not expect good (or poor) acoustic air coupling with purely lateral earth motion. Since Love waves have no vertical component, they are excluded from consideration by the approach adopted here. Of course, it is possible that a Love wave generates small, local, surface air turbulence, but it is difficult to envision a significant ionospheric consequence from this.

2. "Duct Injection"

Referring to BGT/Fig. 2, note that there is a band of critical ray traces (approximately 20° to 25° from vertical) which appear to inject into a horizontal plane, at approximately 170 km. Arguments have been set forth for "trapping" the acoustic energy in particular layers associated with stagnant thermal or gravitational density inversions.

It is only fair to point out that there appears to be some controversy and equivocation as to the reality and interpretation of "duct modes". A possible underlying reason for this is that one really expects much more from any mechanism to which "waveguide" or "duct" gets attached in identification. It is important to distinguish these relatively decrepit propagation modes from the more classical profile of "duct" or "waveguide". Here the propagation path is not bounded by well-defined, low-dispersion surfaces; consequently, the modes are much less defined, lossier, and phenomenologically more capricious than they are in, say, microwave conductors, or even in the classical VLF ionospheric duct.

The "duct" concept appears to be valid to the extent that the wave energy content obeys a range relationship having a somewhat lower exponent than simple spherical propagation. E.g., $r^{-3/2}$ rather than r^{-2} . (A true duct would behave as r^{-1} .) This may be a reasonable basis on which to "force" further progress here. Keep in mind that right here we will still be dealing with longitudinal compression (conventional acoustic) disturbances, with $v \sim 270$ m/sec (at altitude) and in the pass-band domain of 6×10^{-4} to 6×10^{-2} Hz (central $\tau \sim 2$ min). The propagated wave must lie in this band, or must have dispersed down into it. (This is observationally verified.) Again we start by considering the ionospheric interaction at ~ 200 km altitude.

The R.F. Phase Path. For a "ducted" acoustic wave, the instantaneous density profile in principle appears as a horizontal distribution, rather than a vertical one. Hence a vertical R.F. sounder monitors the properties of the edge of the duct, rather than the integral of the acoustic waveform. So we must adopt a model for the acoustic wave transition at its gray lower edge; for expediency, I have constructed the one shown in Fig. IV.2. This depicts the electronic density gradient as unperturbed below the transition layer, which is taken to be $\frac{\lambda}{4} \sim 8$ km thick. For simplicity, the transition is approximated as a straight line perturbation gradient. (It gives an undeservedly good prediction.)

P.S. Note that now all acoustic wave components should sequentially modulate the R.F. phase path, as a procession across the central (RF) Fresnel reflection zone (for a vertical sounder).

The effect of this assumed distribution becomes at once apparent if we consider the situation at an acoustic "peak" (Fig. IV.2). The critical electron density for reflection, which was originally at ①, has now lowered to ②, as the density gradient increased. The shift in the reflection boundary becomes competitive with the phase path integral beneath it (labeled ③) for any value of the acoustic amplitude - not just for the larger ones.

We thus need to reconstruct the analytic model in a somewhat different way. The electron density is now described by:

$$N = N_0 \left\{ 1 - ax + b(x_2 - x) \right\}$$

where
$$b = \frac{1}{\gamma x_2} \left(\frac{\Delta p}{p} \right)$$

The boundary shift is defined by $1 - ax + b(x_2 - x) = 1$,

whence
$$\Delta x = x_2 \left(\frac{1}{1 + a/b} \right) \approx \frac{b}{a} x_2 \quad (\text{for } (a/b) \gg 1)$$

Since now $x_2 = 8$ km, as determined by the ionosphere, we write:

$$\psi = 2 \left(\frac{v}{c} \right) \Delta x = \left(\frac{2vx_2}{c} \right) \left(\frac{b}{a} \right) \approx 600 \left(\frac{b}{a} \right) \quad (\text{cycles}).$$

This expresses the apparent phase shift due to the effective change in ionospheric height associated with $\left(\frac{\Delta p}{p} \right)$.

There is an additional phase shift due to the "little piece" ③; it is attacked by a "triangular approximation" somewhat similar to that used earlier for the vertical acoustic wave:

$$\beta_3 = \frac{2v}{c} \left\{ \int_1^2 \sqrt{cu-d} \, du - \int_0^2 \sqrt{au} \, du \right\}$$

where $c = a + b \quad d = cx$

After a suitable arithmetic episode, one obtains:

$$\beta_3 = -\frac{2}{3} \left(\frac{v}{c} \right) \left(\frac{b}{a} \right) \sqrt{a} \, x_2^{3/2}$$

Whence the total phase shift:

$$|\beta| = 2 \left(\frac{v}{c} \right) \left(\frac{b}{a} \right) x_2 \left\{ 1 \pm \sqrt{\frac{ax_2}{3}} \right\}$$

Again, a and x_2 characterize the ionosphere, rather than the acoustic wave. One finds:

$$\sqrt[3]{a x_2} \sim .2$$

The gradient contribution is here only 20% of the effective height change.

Finally: $\beta \approx 720 \frac{b}{a}$ (max. value)

Also: $\frac{b}{a} \approx 4 \left(\frac{\Delta p}{p} \right)$ and $\beta \sim 3000 \left(\frac{\Delta p}{p} \right)$

For the phase threshold of 1 cycle, it follows that

$$\left(\frac{\Delta p}{p} \right)^d \sim .03\%$$

Duct Propagation Factors. I confine the problem to the "duct input" due to either a contained explosion or a local P-wave. Without great error, I can then match this to the earlier acoustic prediction for the ionospheric environment. The remaining unknown is the duct propagation itself.

For both those cases, I earlier adopted the shock-excited acoustic filter output (Fig. IV.3a) as the waveform convention; this becomes the input to the duct. We know (by observation) that the "output" must be a "teardrop", dispersed wavetrain envelope containing several cycles of 2-minute periodicity. (E.g., Fig. IV.3b.) This problem also deserves better analog testing, but since the "stretching ratio" is only something like two, I will simply redistribute the wave energy via:

$$L_f^d \sim \frac{\tau_2 n_2}{\tau_3 n_3} \sim .15$$

Also, by our prior scaling argument:

$$L_s^d = \left(\frac{r_2}{r_3} \right)^{3/2} \sim .02$$

We find:
$$\left(\frac{\pi_3}{\pi_2} \right) = .055$$

Correspondingly, the threshold "duct input" must be:

$$\left(\frac{\Delta p}{p} \right)^{170} \approx .6\%$$

There is also a "matching" π factor, of order:

$$\left(\frac{\pi^d}{\pi^{220}} \right) \sim \sqrt{\frac{\rho_{170}}{\rho_{220}}} \times \frac{220}{170} \times \frac{L_f^{170}}{L_f^{220}} \sim 2.5$$

In the absence of a detailed propagation calculation, this is ambiguous to a factor of about 2. It permits referencing to the 220 km cases estimated earlier.

Evidently this equivalent threshold would be:

$$\left(\frac{\Delta p}{p} \right)_{eq.}^{220} \approx .25\%$$

Earlier, for the 10 kt contained nuclear case, we deduced that $\left(\frac{\Delta p}{p} \right)^{220} \approx .2\%$. Thus this source case should result in a marginally visible phase signal at 3000 km. Recalling that the effect scales weakly with yield (for 1 mt Boxcar, $\left(\frac{\Delta p}{p} \right)^{220} \approx 6\%$), one would then anticipate a comfortably visible signal at high yields. Collapse should also generate a remotely visible effect.

For the local P-wave earthquake example, we predicted $\left(\frac{\Delta p}{p}\right)^{220} \approx 1.5\%$; it too should be clearly visible via the "duct".

This serves to show that the acoustically-propagated ionospheric effects may approach in sensitivity, those observed locally. If anything, it corroborates the published observations of the acoustic component by this mechanism.

3. "Gravity Waves" or "AGW"

The complete AGW propagation problem is typically described by:

$$c^2 \frac{\partial^2 X}{\partial z^2} + \left\{ \frac{\partial c^2}{\partial z} + \gamma g \right\} \frac{\partial X}{\partial z} + \left\{ \omega^2 - k^2 \left(\frac{Q^2}{\omega^2} \right) \right\} X = 0$$

where $Q^2 = g \frac{\partial c^2}{\partial z} + \{\omega^2 c^2 - (\gamma-1)g^2\}$

and $X = \text{div } \bar{v}$, the dilatation

A multiplier $e^{i\omega t} J_0(kr)$ is factored in the derivation. The pressure and density are integrable from the solutions for $X(z,r,t)$, as for instance at the surface, simply:

$$i\sigma p(o) = -\gamma p_o X(o)$$

In the older classical treatments (Lamb, Pekeris), the "pulse" is considered to be a small pressure-density variation in the stagnant atmosphere. The atmospheric properties were approximated by analytically manageable models of the pressure-density - temperature-velocity profiles. A more elaborate multilayer matrix formulation was developed by Press-Harkrider, and Pfeffer-Zarichny, which permits the use of measured atmospheric properties.

The earlier works (e.g., Pekeris) suffice to exhibit the major features of acoustic-gravitational wave propagation. One recognizes at once that the propagation may be dispersive and possibly strongly so - note the terms in $\frac{\partial c^2}{\partial z}$. It may be dissipative, as witnessed by the central term in $\frac{\partial X}{\partial z}$, according to whether the coefficient has real components. Finally, the complexity of the third coefficient suggests "many" modes; standing waves are also permitted in certain regions of the ionosphere, according to the sign of the brackets: $\{\omega^2 - k^2 \left(\frac{Q^2}{\omega^2} \right)\}$.

The modern "solutions" of these equations are generally carried to the point of exhibiting the "root behavior". That is, producing the mode dispersion function: Group velocity versus component period. There are many comparable representations of this, using the " v_g vs. τ_m " format - see e.g.: Baker and Davies, JGR 73,448 (1968) - reproduced here as Fig. IV.4. The original work was done by Pfeffer-Zarichny, and Press-Harkrider; most of the "authoritative papers" listed in the bibliography display their (or similar) dispersion functions.

It is obligatory in a comprehensive program, to integrate these expressions "completely", with realistic environmental representations. This is not a trivial exercise. One should obtain all of the various "prompt" modes discussed before, plus many more longer-period ones. The various references are generally addressed in detail to one or another class of these modes. Only a few authors (such as Harkrider, Pierce, and Wickersham) attempt a more extensive survey of the complete problem. The field appears to be clear for comprehensive waveform/amplitude cataloging by computational methods. Of course, one can hardly approach this by the casual estimation which I have adopted, and it should be evident that there is no such pretense intended.

The only AGW mode which is reasonably subject to the estimation approach used here, is the so-called "Gravity Wave". It is the direct result of vertical displacement of the atmospheric medium by the (vertical) acoustic wave above a source; it is analogous to "pond ripples". Let us see what we get by primitive application of: Energy conservation principles, qualitative dynamical descriptions, and constraints demanded by observational data.

The effective height is taken as ~ 150 km. In a first-order model, the likely source region is that including a 15° acoustic ray incidence, corresponding to the first Fresnel zone of constructive interference between the vertical acoustic driver and the faster gravity wave. This sets $r_2 \sim 60$ km (as used below).

The peak displacement is estimated as a perturbation of the equilibrium gradient:

$$(\Delta Z)_1 = \left(\frac{\Delta p}{\rho} \right) \frac{\rho}{\partial \rho / \partial z} = \frac{1}{\gamma} \left(\frac{\Delta p}{p} \right)^{1.50} \frac{\rho}{\partial \rho / \partial z}$$

Yuen et al provide a guide (their Fig. 7) to propagation definition. This suggests a self-consistent attenuation of order: $L_f \sim .07$ (The same number may be estimated by constructing a bell-shaped filter approximation and shock-exciting it by a synthetic displacement input waveform.) The contestable point in this argument is that the filter factor is not strongly sensitive to propagation mode. Nevertheless, let us plow on.

There is no reason to adopt a radial law strongly different from r^{-1} , so that

$$L_s \sim .02$$

Then $(\Delta Z)_2 = L_s L_f (\Delta Z)_1 = .035 (\Delta Z)_1$

Finally:
$$(\Delta Z)_2 = L_s L_f \frac{1}{\gamma} \frac{\rho}{\partial \rho / \partial z} \left(\frac{\pi_{220}}{\pi_2} \right) \left(\frac{\Delta p}{p} \right)_{eq}^{2.20}$$

$$= 150 \frac{\Delta p}{p}_{eq}^{2.20}$$

The principal R.F. phase effect of the gravity wave will be to change the virtual reflection boundary for a particular frequency.

Then:
$$\beta = \frac{2v}{c} (\Delta Z)_2 = .033 (\Delta Z)_2 = 50 \left(\frac{\Delta p}{p} \right)_{eq}^{220}$$

A one cycle threshold corresponds to $(\Delta Z)_2 \sim 30$ meters and a (vertical) local displacement $(\Delta Z)_1 \sim 900$ meters. Normalizing to the equivalent 220 km acoustic pulse, this produces a case threshold of:

$$\left(\frac{\Delta p}{p} \right)_{eq}^{220} \sim 2\%$$

Thus a significant gravity wave effect requires fairly strong sources: Something between Syntax and Boxcar for contained explosions; the assumed P-wave example is marginal. More materially, note the ratio of the remote phase effects:

$$\beta_{Ac}/\beta_{Grav} \sim 8$$

This again "agrees" (incredibly!) with some reported observations: Weaver et al (Ibid) (The Rayleigh followed by the AGW).

Standing Waves. There should be a longer period mode (order of 20-30 minutes) which is not propagative, but stationary. Presumably it would be excited by a propagative field, but with even weaker coupling. Its detection would be verified by virtue of its period and its geometric structure; it might be peculiarly useful in "location" problems.

4. Grazing Incidence

Rather self-evidently, a grazing incidence H.F. path "spends more time" in the marginal density region just under the reflection boundary. One would suppose that this might be especially worthwhile (from a sensitivity standpoint) for a path tangent to a ducted acoustic wave. There is a difference, but it is not as attractive as one might think.

The basic reason for this appears in Fig. IV.5. The geometry for the most-grazing surface path (and really not a realistic one) limits the grazing angle to $\sim 12^\circ$, at 2000 km. This enters as $\frac{1}{\sin 12^\circ} \sim 5$, a phase path multiplier. It also enters separately as $\sin 12^\circ \sim \frac{1}{5}$, a multiplier for the phase consequence of the effective height change.

For instance, in the duct example above, we have:

$$\beta = 2 \left(\frac{v}{c} \right) \left(\frac{b}{a} \right) x_2 \left\{ \sin \theta + \frac{\sqrt{ax_2}}{3 \sin \theta} \right\}$$

For the vertical sounder { } ≈ 1.2

For the grazing sounder { } ≈ 1.2 also!

In-between, it is actually a shallow saddle.

Similar considerations apply to the earlier cases of vertical acoustics with grazing H.F. paths. The principle differences should be to alter the phase waveforms and to shift the domains of sensitivity, without a useful improvement in sensitivity.

Polarization Effects. The instantaneous acoustic profile may exhibit a R.F. polarization sensitivity quite apart from magnetic field effects. For instance, a vertical sounder using a simple dipole may sense a different relative phase path when oriented tangentially to an acoustic duct field, than orthogonally.

FIG IV.1

MANY-CYCLE (ACOUSTIC) CASE

Scales exaggerated
to illustrate contribution cancellation($\pm$)

CONDITIONS AT PRESSURE PEAK

FIG IV.2

ACOUSTIC DUCT INTERACTION
DUCTED WAVE PROPAGATING
NORMAL TO EXHIBIT PLANE.

(a)
ACOUSTIC DUCT
INPUT

(b)
PROPAGATED DISPERSED PULSE
(RANGE FACTOR OMITTED)

FIG IV. 3

DUCT DISPERSION EXAMPLE

FIG. IV. + " v_g vs. T_m "
MODE DISPERSION FUNCTIONS

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FIG. II.5
GRAZING INCIDENCE
 VS.
VERTICAL SOUNDING

V. Acoustic Properties and Noise

Some Detailed Properties of the Extended Atmosphere

There are a number of features of acoustic propagation of the real atmosphere which tend to get "run over roughshod" in the various attempts to explain, predict and experiment.

1. The Acoustic Skew Filter

The use of a single pass-band filter model for the Fourier characteristic of the atmosphere is acceptable, as long as the upper and lower frequency limits continue to converge with altitude (or at least remain unchanged). If either one "turns around" and diverges, then we have to take another look. In fact that is exactly what does happen, by the classical model used in BGT. Fig. V.1 plots the frequency behavior of the -10 db attenuation levels as function of altitude; it is a skewed tunnel. Note also that much of the middle atmosphere exhibits a broader pass-band than either the source or the interaction regions.

A possible approach would be to approximate the problem as two series filters. In effect, the waveform seen at ~ 120 km would be reinjected into the second and higher domain, as if it were a quasi-source pulse.

2. Acoustic Focussing

I refer again to BGT/Fig. 2. Note that there is also a band of acoustic ray-traces which returns to the surface in the range 250-500 km. This is a well-known phenomenon, of course, and it was of much concern during the days of NTS atmospheric testing. Now note the concentration of ray traces at 85 km altitude and ~ 200 km range. Here the non-uniform factor is greater than one. It is also the D-layer regime and suggests that one might observe a stronger ionospheric effect in this focal zone. But it is likely to be a "mixed bag of pulses", on account of the path travel time differences. Because of the basic weakness of the D-layer interaction, this intensification could probably only be observed on atmospheric nuclear events.

"Noise": Lighting and "Supersonic Dimples". An inspection of typical ionosonde data shows noise "signals" whose character is suggestive of singular non-ionospheric source origins. Among such possible sources, one might consider:

Lightning
Supersonic A/C
(True) Gravitational waves

3. Lightning

One can get lost in "source definition" here: Cloud-cloud, cloud-ground, 10^8 to 10^9 joules, leader and main strokes, etc. etc. A useful equivalent is to think of it as 100 lb HE simultaneously detonated on a line ~ 2 km long. (It is thus not a "central" source, and locally scales less severely than $1/r^2$.) I adopt a mean observational model: 100 dynes/cm² at 10 km with $\tau \sim .2$ sec.

Then: $\left(\frac{\Delta p}{p}\right)_1 \sim .01\%$

I will omit further details of choice, since this is a relatively undefineable business anyway:

$$L_f \sim 3 \times 10^{-5}$$

$$L_s - \left(\frac{\alpha_1}{\alpha_2}\right)^2 \left(\frac{r_1}{r_2}\right)^2 \sim 7 \times 10^{-4}$$

$$\text{and } (P_2/P)^{220} = 2 \times 10^{-8}$$

Then find $\left(\frac{\pi_2/\pi_1}{\pi_1}\right)^{220} \sim 20$

and finally $\left(\frac{\Delta p}{p}\right)^{220} \rightarrow .2\%$

Resorting to the "Spike excitation" argument, I scale directly from Syntax (or Snowball) to find

$$|\beta| \sim .5 \text{ cycle}$$

A lightning stroke looks like a small contained nuclear explosion, at least locally. There are no obvious, a priori arguments for expecting reliable discrimination for duct injection, so I will not redo that exercise. Presumably, the absence of an (earlier) Rayleigh wave response should provide a discriminant.

4. Supersonic A/C

These acoustic sources may have the peculiar feature of coupling especially well to certain duct modes. Assuming the optimum vertical injection angle of $\sim 25^\circ$, then for a particular Mach number, the normal to the bow wave makes the same angle:

$$M = \frac{C_a}{C_s} = \frac{1}{\tan 25^\circ} = \underline{2.2}$$

(This is about the cruising value for the Concorde, for instance.)
Again I choose a heuristic source description, based on effects observations:
 2×10^4 dynes/cm² at 300 m, with $\tau \sim \frac{1}{4}$ sec. (This typically "blows out
windows".) I scale this to cruise level (20 km) by $\sqrt{\frac{\rho_1}{\rho_2}} \sim 3.5$.

Then $\left(\frac{\Delta p}{p}\right)_1 \sim 7\%$

(The sound velocity effect is small)

This is "spiky" business, so that the BGT acoustic filter number should be reasonably valid here: $L_f \sim 2.7 \times 10^{-5}$. L_s scales a bit different, since we have a quasi-line source:

$$L_s \sim \left(\frac{\alpha_1}{\alpha_2} \right)^2 \cdot \left(\frac{r_1}{r_2} \right) = 1.5 \times 10^{-4}$$

Then $\left(P_2/P_1\right)^{2.20} = 4 \times 10^{-9}$ and $\left(\pi_2/\pi_1\right)^{2.20} = 1.5$

This has the consequence: $\left(\frac{\Delta p}{p}\right)^{220} \sim 10\%$ (!)

It is indeed a large effect on the Ionosphere.

We can do two things with this:

- Vertical Sound
- Duct Inject

Vertical Sounding. The acoustic wave here "saturates" the Ionosphere, just as did the 10 kt atmospheric explosion. (I.e., it violates our early condition: $b < a$.) So we go to the rectangular approximation, as before, and this is now mainly sensitive to acoustic pulse length (rather than amplitude). It does not differentiate well among sources. (Unless one goes to sounder arrays.) We write at once:

$$\underline{\beta \approx 360 \text{ c. (at 5 mc)}}$$

Duct Mode. The "injection factor" turns out to be larger than before, partly because of the favorable coupling geometry discussed above:

$$\left(\pi_2/\pi_1\right)^{170} \sim 3$$

One then gets an "enormous" effective duct input: $\left(\frac{\Delta p}{p}\right) \sim 30\%$.

Using the same propagation factor as before, the signal at our reference distance (3000 km) then becomes:

$$\underline{\left(\frac{\Delta p}{p}\right)^d \sim 2\%}$$

The corresponding local sounder phase excursion should be:

$$|\beta| \sim 600 \left(b/a\right) \sim \underline{24c.}$$

The acoustic wave from an SST (or a B-1) thus modulates the ionosphere (from the HF refraction standpoint), in the form of a coma-shaped dimple (or ripple segment) per Fig. 2. This dimple is dragged along ~ 300 km behind the A/C; further back, there should be a low-amplitude pattern of dispersed waves corresponding to the characteristic duct wavelength. When the A/C goes subsonic, the dimple should likewise disperse down to that duct mode, which will then continue propagating as an extension of the final flight line.

One might suspect that a large number of supersonic trails (randomly oriented) could thus "roughen up" the ionosphere. Whether this might have military, ecologic or communication significance, I leave to the activist and the politician.

FIG. II.1
 THE SKEW FILTER
 ATMOS. ACOUSTIC PASS-BAND

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FIG. V.2

SUPERSONIC "DIMPLE" HYPOTHESIS

ACOUSTIC SHOCK PERTURBS

F-LAYER ELECTRON DENSITY

VI. Summary

These tables outline the analytic logic and the treated cases (Table VI.1); also the essential estimation results (Table VI.2).

Some entries are "self-fulfilling", in the sense that the choice of relevant calculational parameters was guided more by known data, than by basic theoretical structure, or physical knowledge. Of course, the point is that these semi-empiric parametric choices were also acceptably within the expectation range.

There are some self-evident environmental idealizations not mentioned in the Introduction. These were implicit throughout the development and included such assumptions as:

- Infinitely flat, uniform, earth medium
- "Ideal", uniformly graded ionosphere (not "mottled")
- No magnetic field

In the course of the exercise, there were many false leads and just plain mistakes. (Not all have been located.) A surprising feature of these "involuntary tests" was the high degree to which the "results" were insensitive to such errors, as well as to the specific model details. This might be ascribed to several characteristics:

1. The phase path effect is described as a difference between perturbed and unperturbed cases; environmental idealizations and departures thus enter into the results in second (or higher) order.
2. The phase path integrals depend on the second root of the environmental assumptions.
3. The use of semi-empiric source/propagation models (data-adjusted) makes the non-linear response compression of the media (Earth, atmosphere) implicit in the energy scaling.

There are some unresolved ambiguities in the longer-range time-of-arrival (TOA) numbers. They are exhibited principally for purposes of orientation. It is here especially that one finds equivocation between data, theory, authors and authorities. ("You can find it if you know where to look"- - "Which mode is it?"- - - "There's work left to be done".....)

TABLE VI.1 - TOPIC OUTLINE

Introduction

The Caveats

Basic Concepts and Assumptions

I. Nuclear Explosions

The Numerical Example: Syntax

The Normalizing Case: Snowball/BGT

1. Earth-Air Coupling - Piston Model
2. Atmospheric Propagation
Spreading and Filter Factors
3. The Ionospheric Disturbance
4. Propagation Path Effects (RF)
220 and 85 km Cases

II. Corollary Nuclear Considerations

"Switching" Domain

"Strong Pulse" Domain

1. Boxcar/Jorum
2. Non-contained U.G. Explosions
3. Atmospheric Explosions
10 kt - - - Hi Yield
4. Collapse

III. Earthquakes

The Local Regime

1. The Local P-wave - - "Vertical" coupling
2. S-wave - - also vertical
3. Slow Motion and Tsunamis

IV. The Remote Regime - Rayleigh Waves, Duct Injection, etc.

1. The Remote Rayleigh Wave; Love Waves
2. "Duct Injection"
 - The RF Phase Path
 - Duct Propagation Factors
3. Gravity Waves; Standing Waves
4. Grazing Incidence; Polarization Effects

V. Acoustic Properties and Noise

Some Detailed Properties of the Extended Atmosphere

1. The Acoustic Skew Filter
 2. Acoustic Focussing
- "Noise": Lightning and "Supersonic Dimples"
3. Lightning
 4. Supersonic A/C
 - Vertical Sounding; Duct Mode

TABLE VI.2 - SUMMARY OF ESTIMATES

<u>"Local" Acoustic Cases</u>				
<u>Source</u>	$\frac{\Delta p}{p}$ max.	<u>Phase Shift*</u> F layer, 5 MHz		
500 T HE, Surface	6%	-16 C.		
10 kt Nuclear, Surface	(30%)	+330 C.		
10 kt U.G. Contained	.2%	-.5 C.		
1 mt U.G. Contained	6%	-16 C.		
U.G. Collapse, 10 kt	3%	+8 C.		
U.G. Collapse, 1 mt	8%	+20 C.		
Earthquake, Richter 6 Epicenter ~ 10 km down.				
P-wave (local)	1.5%	-4 C.		
S-wave (~ 100 km)	2.5%	±6 C.		
Lightning ("Average Stroke")	.2%	±.5 C.		
SST (~ 300 km)	10% (!)	~±360 C		
<u>"Remote" Cases</u> (at ~ 3000 km)				
<u>Source</u>	<u>Propag/Coupling</u>	$\frac{\Delta p}{p}$ max.	<u>Phase Shift*</u>	<u>Approx. TOA</u>
Earthquake	Rayleigh + acoustic	1%	± 1 C.	30 min
	P-wave + ac. duct	1.5%	± 6 C.	3 hrs 15 min
	P-wave + Gravity wave	1.5%	±.8 C.	1 hr 15 min
				{ 3 hrs
U.G. Nuclear, Contained				
10 kt	Acoustic duct	.2%	± 1 C.	3 hrs 15 min
1 mt	Acoustic duct	6%	±25 C.	
	Gravity wave	6%	± 3 C.	{ 1 hr 15 min 3 hrs

* First main excursion peak.

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APPENDIX A

HF Radio Measurements of High-Altitude Acoustic Waves
from a Ground-Level Explosion

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Linear acoustic theory predicts that a large ground-level explosion—several hundred tons of TNT—should produce a pressure wave amounting to several per cent of ambient in the atmosphere 200 km above the explosion. Analysis of the interaction of such a pressure disturbance with the ionosphere implies that the passage of the wave should be readily measurable by means of vertical-incidence radio phase-path soundings. Radio measurements made at the time of a 500-ton explosion have confirmed the hypothesis. The shape of the observed phase disturbance agrees well with that predicted, and the observed onset times check to within 10 seconds with acoustic ground-to-ionosphere travel times. The amplitude and duration of the disturbances were approximately 100 radians and 2 minutes, respectively. The amplitude is slightly smaller than predicted; however, the observed duration is approximately twice that calculated. Refining and fitting the model to obtain better agreement—especially in disturbance onset time, shape, and duration—may represent a technique for improving present estimates of the upper-atmosphere density molecular weight and temperature.

1. INTRODUCTION

The neutral acoustic wave that traverses the ionosphere as the result of a ground-level explosion may be readily calculated. If this is done, one discovers that the explosion of several hundred tons of TNT produces a pressure disturbance of several per cent of ambient in the ionosphere directly overhead. Such a disturbance should be readily measurable by vertical-incidence radio soundings since the neutral disturbance must produce corresponding electron number-density fluctuations. If sound waves in the upper atmosphere can, indeed, be measured in this fashion, the results may improve our knowledge of the upper atmosphere, especially its mean molecular weight, density, and temperature.

An opportunity to test the possibility of radio measurement of upper-atmosphere acoustic waves occurred in July 1964, when an explosion of 500 tons of TNT was detonated at the Suffield (Alberta) Experimental Station of the Canadian Defence Research Board. Two vertical-incidence radio sounders were installed near Suffield (at Bow Island and at Arneson) by the Stanford Radioscience Laboratory. It was planned, through sounding measurements made at these sites—located at equal distances magnetically north and south of the blast—to

measure the time, shape, and intensity of upper-atmosphere acoustic waves and to check the expected influence of the earth's magnetic field on the radio measurements. Unfortunately, winds at the time of the blast distorted the hoped-for geometry and prevented a confirmation of the magnetic field dependence. The experiment was successful, however, in measuring the characteristics of the upper-atmosphere pressure wave.

2. THEORY

The following is a brief outline of the method used to predict the radio phase-path disturbance observed near the explosion. The theory is presented in two parts: (1) a calculation of the size and shape of the neutral pressure wave produced in the ionosphere by the blast and (2) a prediction of the effect of such a pressure disturbance on ionospherically reflected HF radio waves.

A. Neutral pressure wave. The description of acoustic waves generated by explosions in the atmosphere is facilitated by considering separately the near- and far-field effects. The shock wave traveling in the near field must be described by a set of nonlinear differential equations. The blast-wave computations of Brode [1959] were used to describe near-field

Fig. 1. Pressure versus distance from source for spherical shock wave at 6% overpressure.

effects. Brode's results extend from the surface of the explosive to a point at which the maximum shock overpressure has been reduced to 6%. Figure 1 shows the 6% waveshape for a 500-ton blast.

To simplify calculations, an approximation to Brode's waveform (Figure 1) was assumed to be uniformly distributed over a hemispherical wavefront 1150 meters from the source. From this point outward, the disturbance was treated as a linear acoustic wave. The following discussion summarizes the linear acoustic theory used to describe propagation in the far-field regions.

The power density carried by a linear, plane, harmonic acoustic wave is given by the equation [Rayleigh, 1894]:

$$P = \frac{\rho a^3}{2\gamma^2} \left(\frac{p_{\max} - p_0}{p_0} \right)^2 \quad (1)$$

where

- ρ = atmospheric density.
- a = velocity of sound.
- γ = ratio of specific heats C_p/C_v .
- $p_{\max}$ = maximum pressure in the wave.
- p_0 = ambient atmospheric pressure.

For a wave propagating from point 1 to point 2, one may therefore relate the overpressure at each point by the simple ratio

$$\frac{\Pi_2}{\Pi_1} = \frac{\gamma_2}{\gamma_1} \left(\frac{\rho_1}{\rho_2} \right)^{1/2} \left(\frac{a_1}{a_2} \right)^{3/2} \left(\frac{P_2}{P_1} \right)^{1/2} \quad (2)$$

where Π is the peak normalized overpressure $(p_{\max} - p_0)/p_0$.

Point 1 is taken as the 6% wavefront with its associated linearized waveshape shown in Figure 2. The wave intensity at point 2—the ionosphere directly above the blast—is then calculated by using equation 2.

All terms on the right-hand side of equation

2 are defined by the properties of the atmosphere except the maximum power-density ratio p_2/p_1 , which would be unity for a lossless plane wave. As a wave propagates upward in the atmosphere, the power density will be decreased by two separate mechanisms, spreading and attenuation. The two losses will be considered independently;

$$\frac{P_2}{P_1} = L_s L_f \quad (3)$$

where

- L_s = power-density loss factor caused by spreading.
- L_f = power-density loss factor caused by atmospheric filtering.

Waves generated by explosions in a uniform atmosphere are spherical, and the power density is inversely proportional to the area of the front. Thus, for a disturbance propagating from the Brode 6% radius (1150 meters from the source) to the upper ionosphere (the F layer at 220-km altitude), the spreading loss factor L_s in a homogeneous atmosphere would be $L_s = (1.15/220)^2 = 25 \times 10^{-6}$.

For the real atmosphere, the increased loss caused by nonuniform spreading was estimated (through the use of acoustic raytracing, Figure 2) to be about three times that for a homogeneous atmosphere. Thus,

$$L_s \cong 8 \times 10^{-6} \quad (4)$$

The atmospheric-filter response $G(f)$ at high frequencies may be obtained by integrating the attenuation as a function of frequency be-

Fig. 2. Acoustic raytracing for ground-level explosion (rays at 10° increments).

tween two points x_1 and x_2 ;

$$G(f) = \exp \left[-2 \int_{x_1}^{x_2} \alpha(f, h) dx \right]$$

or, expressed in decibels,

$$G(f) = -8.68 \int_{x_1}^{x_2} \alpha(f, h) dx \quad (5)$$

The pressure attenuation α (in nepers/meter) is a function of frequency and altitude and was shown by *Rayleigh* [1894] to be

$$\alpha(f, h) = \frac{4\pi^2 f^2}{a^3} \left(\frac{2\eta}{3} + \frac{\gamma - 1}{\gamma} k \right) \quad (6)$$

where

η = kinematic viscosity.

k = thermal conductivity.

γ = ratio of specific heats C_p/C_v .

The viscosity may be written as:

$$\eta = 0.499 \frac{v^2}{\nu} = \frac{1.497 a^2}{\gamma \nu}$$

where

v = mean particle velocity.

ν = collision rate.

Ignoring the generally much smaller conductivity then yields

$$\alpha(f, h) = \frac{4\pi^2 f^2}{\gamma \nu a} \quad (7)$$

Substituting this value in equation 5 gives

$$G(f) = -f^2 \times 3.42 \times 10^2 \int_{x_1}^{x_2} \frac{dx}{\gamma \nu a} \quad (8)$$

in decibels, or

$$G(f) = -K_{1-2} f^2$$

where

$$K_{1-2} = 3.42 \times 10^2 \int_{x_1}^{x_2} \frac{dx}{\gamma \nu a}$$

The value of K_{1-2} was evaluated graphically with the point x_1 taken at ground level and x_2 directly above, at 220-km altitude. The resulting value of K_{1-2} was $6.01 \times 10^3 \text{ sec}^{-2}$.

Equation 8 describes the attenuation of high acoustic frequencies. Propagation of low frequencies is limited by a cutoff frequency, which

is caused by the variation in atmospheric density with altitude. The value of the lower limit may be obtained by observing that, to a vertically traveling sound wave, the atmosphere has the appearance of an exponentially tapered transmission line. The acoustic impedance is [*Rayleigh*, 1894]

$$z = a\rho \quad (9)$$

where a is the speed of sound, and ρ is the atmospheric density. Although both vary with altitude, variations in the density are much more pronounced, being approximately exponential;

$$\rho = \rho_0 \exp [-h/H_s]$$

where

h = altitude.

H_s = scale height.

ρ_0 = a reference density.

Substituting this in equation 9 gives

$$z = a\rho_0 \exp [-h/H_s]$$

The cutoff frequency for such an exponentially tapered transmission line is [*Skilling*, 1951]

$$f_{co} = \frac{a}{4\pi H_s} \quad (10)$$

Since both the speed of sound and the scale height vary with height in a similar manner, the lowest useful frequency is not strongly height dependent. An average value of 0.004 cps, taken from equation 10 and the atmospheric characteristics given in *U. S. Standard Atmosphere* [1962], is appropriate. Figure 3

Fig. 3. Atmospheric filter response of path from ground level to 220-km altitude as a function of frequency. Low-frequency cutoff at $f_{co} = a/4\pi H_s \approx 0.004$ cps. High-frequency response from equation 8, $G(f) = -6 \times 10^3 f^2$.

summarizes the atmospheric-attenuation characteristics for a sound wave traveling vertically from ground level to 220-km altitude.

The effect of atmospheric filtering on the particular acoustic wave of interest—i.e., Brode's 6% waveform—was determined by analog means. An electrical filter, having the attenuation characteristics of Figure 3, was constructed. When excited by a voltage waveform identical to that of the approximated Brode shockwave for 6% overpressure, the output signal represented the neutral acoustic disturbance in the *F* layer directly above the blast. The total acoustic power loss factor caused by atmospheric filtering— L_f , of equation 3—is the square of the ratio of maximum-output to maximum-input voltage (Figure 4). The value obtained in this manner was

$$L_f = 2.7 \times 10^{-5} \quad (11)$$

Substituting the values from equations 4 and 11 into equation 3, to obtain the power-density ratio, yields

$$\begin{aligned} P_2/P_1 &= L_f L_r \\ &= 8 \times 10^{-6} \times 2.7 \times 10^{-5} \\ &= 2 \times 10^{-10} \end{aligned}$$

The value of *F*-layer overpressure may now be determined from equation 2 with $\Pi_1 = 6\%$ and the appropriate values of γ , a , and ρ taken from *U. S. Standard Atmosphere* [1962]. The predicted maximum *F*-layer overpressure for a 500-ton explosion is then found to be

$$\Pi_2 = 2.2\%$$

Fig. 4. Analog technique used to determine power loss due to spectral filtering.

Fig. 5. Overpressure waveform at 220 km determined from analog model.

The above calculation has ignored the effect of ground reflection. For the case of perfect reflection, twice as much energy as considered above would be directed upward. Since overpressure is proportional to the square root of energy density, this effect could increase the predicted *F*-layer overpressure to 3.1%. The magnitude and waveshape of the predicted ionospheric pressure disturbance are shown in Figure 5.

B. Interaction between acoustic and radio waves. Owing to ion-neutral collisions, neutral acoustic density fluctuations in the upper atmosphere will impose corresponding fluctuations in the local ion and electron number densities. Since the radio-wave index of refraction is a function of the local electron number density, the phase path of a radio signal traversing the disturbed region should be sensitive to the existence of predominantly neutral acoustic waves.

The exact phase perturbation imposed upon an HF radio wave, incident vertically on the ionosphere, depends upon a large number of variables. The calculation must take into account the acoustic waveshape and intensity as well as its direction relative to both the geomagnetic field and the radio ray everywhere along the radio signal path. Further, one must include the radio ray direction relative to the magnetic field and, of course, the undisturbed electron number density everywhere along this raypath. The situation is further complicated by splitting of the radio-wave energy into its ordinary-, *O*, and extraordinary-wave, *X*, components as a consequence of the magnetic field.

Several assumptions were made to simplify the calculation. Only the *X* component was considered, and ray bending was ignored (Figure 6). The ray was assumed to be perpendicularly incident on a parabolic layer and per-

Fig. 6. Actual and approximated acoustic- and radio-wave conditions for vertical-incidence reflection.

turbed by a plane acoustic wave moving at an angle Φ with respect to the vertical ray.

The electron number density N in an undisturbed parabolic layer is described by

$$N = N_{\max} \left(\frac{2h}{H_T} - \frac{h^2}{H_T^2} \right) \quad (12)$$

where H_T is the layer half-thickness, and h is measured from H_0 . At high altitudes where the magnetic pressure exceeds the neutral pressure (above roughly 140 km), the presence of a pressure wave in the ionosphere changes the electron number density by an amount [Holloway et al., 1963]:

$$\frac{\Delta N}{N} = \frac{(p - p_0)}{p_0} \frac{\cos^2 \varphi}{\gamma} \quad (13)$$

where φ is the angle between the magnetic field and the direction of acoustic-wave travel. The overpressure $(p - p_0)/p_0$ is a function of both h and time, defined by the acoustic waveshape and angle Φ . The resulting new density profile is

$$\begin{aligned} N'(h) &= N + \Delta N(h) \\ &= N_{\max} \left(\frac{2h}{H_T} - \frac{h^2}{H_T^2} \right) \\ &\quad \cdot \left[1 + \frac{(p - p_0)}{p_0} \frac{\cos^2 \varphi}{\gamma} \right] \end{aligned} \quad (14)$$

The phase path of a vertically reflected radio wave is found from the integrated index of refraction,

$$h_p = \int_0^{h_1} \mu \, dh \quad (15)$$

For a longitudinal propagation of the extraordinary component, the index of refraction μ is given by [Ratcliffe, 1959]

$$\mu^2 = 1 - \frac{X}{1 - |Y_L|} \quad (16)$$

where

$$X = \frac{f_{N'}^2}{f^2} = \frac{f_{N_{\max}}^2}{f^2} \frac{N'}{N_{\max}}$$

and

$$Y_L = \frac{f_H \cos \theta}{f}$$

in which

$f_{N_{\max}}$ = plasma frequency at the layer maximum.

f_H = cyclotron frequency.

θ = angle between magnetic field and HF path.

f = radio frequency.

Substituting the density profile of equation 14 into equation 15 yields the expression for phase path

$$h_p = \int_0^{h_1} \left[\frac{h^2}{CH_T^2} - \frac{2h}{CH_T} + 1 \right]^{1/2} dh \quad (17)$$

where

$$C = \frac{f(f - f_H \cos \theta)}{f_{N_{\max}}^2 \left\{ 1 + \left[\frac{(p - p_0)}{p_0} \right] \frac{1}{\gamma} \cos^2 \varphi \right\}} \quad (18)$$

The upper limit h_1 of equation 17 is the true reflection height and is found by setting the index of refraction to 0—i. e., $X = 1 - |Y_L|$. Or, substituting for X and Y_L , one obtains

$$h_1 = H_T[1 - (1 - C)^{1/2}] \quad (19)$$

Since the value of C is defined as a function of time for a given radio signal blast site geometry (Figure 6), the radio-wave phase path, as a function of time, may be found by substituting equation 19 into equation 17: the round-trip phase path β , in cycles, is

$$\beta(t) = \frac{2h_p f}{c} \quad (20)$$

where c is the speed of light, and f is the radio-signal frequency.

Equations 17–20 allow one to compute β as a function of time for the given neutral pressure wave (Figure 6). The approximations involved are the assumptions of (1) parabolic ionospheric density, (2) an undeflected extraordinary ray, and (3) a pressure disturbance whose physical size is much larger than the region in which the index of refraction differs appreciably from unity—i.e., much larger than the pressure-sensitive portion of the radio path. The theoretical phase-path disturbance expected at the Arneson and Bow Island sites, near Suffield, were calculated with the aid of a digital computer and equations 17–20. The results of these calculations are given in section 5 of this paper.

Fig. 7. Experiment location.

3. EXPERIMENTAL EQUIPMENT

Four vertical-incidence sounders were employed. Two were located near Arneson, Alberta, 85 km magnetic north of the Suffield Experimental Station, and the remaining two were installed at Bow Island, Alberta, 85 km magnetic south of the blast (Figure 7).

To obtain the highest sensitivity to density disturbances, the pulse transmitters were operated at frequencies near the F -layer ordinary- and extraordinary-wave critical frequencies. These were measured about 15 minutes before the blast, and operating frequencies selected at that time were used throughout the test.

Each sounder operated with a peak-pulse power of about 1 kw. The pulsewidth was 200 μ sec, and a 60 pps repetition rate was used. Signals were transmitted and received on separate, horizontal, three-wire, broadband, dipole antennas, located about 25 feet above ground level.

The output of each receiver was translated down to 25 kc/s and recorded on magnetic tape. WWV signals were simultaneously recorded on an adjacent channel for timing purposes. The data were recorded continuously from 90 minutes before detonation until 45 minutes afterward. The magnetic tapes were later processed to produce range-versus-time film records showing the phase of the received signal.

Film records were generated in the following manner. An oscilloscope sweep was triggered on a positive zero crossing of the 25-kc/s IF signal derived from the transmitted pulse, and the sweep was intensity modulated with the recorded waveform. The result was an oscilloscope trace containing a series of dots corresponding to the peaks of the waveform shown in Figure 8. By slowly moving a 35-mm film strip perpendicular to the sweep, the dots from each successive oscilloscope trace were recorded as lines or stripes.

Fig. 8. Idealized receiver output waveform.

Fig. 9. Stripe recording taken at Bow Island during disturbed period.

Figure 9 shows a 'stripe' recording taken at the peak of the ionospheric disturbance on the 5.4-Mc/s Bow Island record. The transmitted pulses may be seen at the lower edge of the recording as several parallel lines. The received pulses appear farther up on the record as the band of diagonal lines. Phase changes introduced by ionospheric fluctuations may be obtained by counting the number of stripes that cross a given horizontal line drawn through the received pulses. As each stripe crossing represents a phase-path change of 2π radians, the phase path, as a function of time, may be plotted directly from these records.

4. RESULTS

At the time of the Snowball test, which occurred at 10:58 MST on July 17, 1964, the two Arneson transmitters were placed on 5.6 and 5.7 Mc/s, while those at Bow Island operated on 5.2 and 5.4 Mc/s. These frequencies were chosen by the operators in an attempt to receive only extraordinary-wave components (see section 2).

Clear, explosion-induced disturbances were seen about $9\frac{1}{2}$ minutes after detonation on all frequencies except 5.2 Mc/s. Because this frequency was well below the critical frequency, both ordinary and extraordinary waves were reflected from the ionosphere with nearly the same delay. As a result, the two echoes overlapped and produced a record in which no *F*-layer perturbation was discernible.

The 5.4-Mc/s Bow Island record (Figure 9) shows *O* and *X* echo components separated enough so that they may be independently scaled. The disturbance onset manifested itself as an abrupt change in stripe slope, which may be seen at +10 minutes 4 seconds and 10 minutes 13 seconds on the *X* and *O* echoes, respectively. Similar disturbances were meas-

ured at the Arneson site, except for the absence of ordinary components; the transmitters were operating above the *O*-wave critical frequency.

The *X*-wave-phase-versus-time record taken from the 5.4-Mc/s Bow Island stripe recording is shown in Figure 10. The effect due to the explosion was estimated by drawing, on the phase plot, a curve that was considered to be a best guess of the undisturbed ionospheric-echo phase. The difference between the two curves then represents the phase disturbance. All records were reduced in the above manner; the results are summarized in Figure 15.

5. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

This section compares the experimental results summarized in section 4 with the predictions, using the linear acoustic theory presented in section 2. Two sets of on-site data—the ionospheric electron number-density profile and the atmospheric-wind profile—were used in calculating the theoretical waveforms.

The nearest measured electron number-density profile at the time of the test was taken at the Canadian Defence Research Board experimental station at Kenora (near Winnipeg),

Fig. 10. Phase versus time from Bow Island 5.4-Mc/s stripe recording.

Fig. 11. Vertical-incidence ionogram taken at Kenora, Manitoba (1100 MST).

Manitoba. Figure 11 shows the ionogram from this station. The ordinary-wave critical frequency is seen to be about 5.0 Mc/s. To obtain a better estimate of electron number density above the blast site at Suffield, Alberta, this record was scaled up in frequency so that the ordinary-ray critical frequency corresponded to the estimated 5.5 Mc/s obtained from the Stanford sounders at Bow Island and Arneson.

The estimated horizontal wind component in the Bow Island-Arneson direction is shown in Figure 12. Data for this curve were compiled

Fig. 12. Estimated wind profile.

Fig. 13. Radio-wave raytracings based on Kenora experimental electron number-density profile, adjusted to fit observed local critical frequencies.

from several sources. The 0-20-km altitude winds were measured with a weather balloon released at the test site approximately one hour before T_0 . Sounding rockets fired at Cold Lake, Alberta (about 300 miles north of Suffield), about one hour after the blast, provided data to an altitude of 80 km. No measurements

Fig. 14. Acoustic raytracing over Suffield based on *U. S. Standard Atmosphere* [1962] and experimental wind profile. Rays at 2° increments, travel time ticks at 50-second intervals.

above this height were taken during the test; the winds shown in Figure 12 above 80 km were estimated on the basis of high-altitude wind data contained in *Manring et al.* [1959], *Stroud et al.* [1956, 1960], and *Kellogg and Schilling* [1951].

Radio-wave and acoustic raytracings (Figures 13 and 14), based on the experimental wind and electron number-density profiles described above, were generated using digital raytracing capabilities developed by Dr. Tom Croft at the Stanford Radioscience Laboratory. The two figures were superimposed to obtain

the onset time of the disturbance and the angles φ and Φ , the angles between the direction of acoustic-wave propagation and the magnetic field and the radio raypath, respectively.

The theoretical radio-wave frequency disturbances were then calculated with the appropriate values of φ , θ , and Φ and the methods given in section 2, part B. A parabolic ionosphere, fitted to the true height profile of Figure 11, (adjusted to 5.5-Mc/s O-wave critical frequency) was assumed. A comparison between the waveforms obtained in this manner and the experimental results is shown in Figure 15.

Fig. 15. Comparison of experimental and theoretical phase-disturbance records.

6. CONCLUSIONS

The general agreement between observation and theory demonstrates the effectiveness of using simple linear acoustic theory to describe the propagation of explosion-induced disturbances to large distances. Inspection of Figure 15 shows that the period of the predicted disturbance is somewhat shorter than that observed, but the onset time, strength, and shape of the predicted phase disturbances compare well with the experimental results.

This comparison strengthens the confidence in the sound-velocity profile used in the model and suggests that the assumed atmospheric-filter characteristics (Figure 3) may be in error—i.e., the real atmosphere appears to have a narrower bandpass than calculated. Since the shape of the filter is a critical function of the atmospheric molecular weight and collision rate near the radio wave reflection point, it may be possible to obtain some information about the high-altitude atmosphere by fitting a filter to match the observed waveform.

Some refinement of the model will probably be necessary since the effect of acoustic 'convection' was neglected in the analysis. Convection is a second-order effect but is not necessarily negligible at acoustic intensities of several per cent. Its inclusion would lengthen the predicted disturbance and thus improve the agreement with experiment.

No conclusion regarding the effect of the earth's magnetic field on acoustic-wave propagation or neutral-ion interaction can be drawn from the results. The degree to which a neutral acoustic wave produces a corresponding charged-particle disturbance is expected to be dependent on the angle between the direction of the acoustic wave and that of the magnetic field. Sounders were placed 85 km magnetic north and south of the blast in an attempt to verify this dependence. This arrangement should have provided $\alpha \approx 30^\circ$ over the south site and $\alpha \approx 60^\circ$ at the north site and should have produced a 3:1 ratio in measured phase amplitude. However, winds at the time of the blast (Figures 12 and 14) changed these angles

to about 37° and 41° , respectively, and this difference is equivalent to an amplitude ratio of only 1.1:1. While a smaller disturbance was observed at the northern site, the differences are within experimental error.

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REFERENCES

- Brode, H. L., Blast wave from a spherical charge, *Phys. Fluids*, **2**, 217-229, 1959.
- Holway, Lowell, Jr., D. Kahn, and E. Rolfe, Investigation of traveling waves in the ionosphere and their effects, *Final Rept., Contract no. AF19(628)-2802*, Raytheon Co., Res. Div., Waltham, Massachusetts, 12-14, December 1963.
- Kellogg, W. W., and G. F. Schilling, A proposed model of the circulation in the upper stratosphere, *J. Meteorol.*, **8**, 222-230, 1951.
- Manring, E., J. F. Bedinger, and H. B. Pettit, Some wind determinations in the upper atmosphere using artificially generated sodium clouds, *J. Geophys. Res.*, **64**, 587-591, 1959.
- Ratcliffe, J. A., *The Magneto-Ionic Theory and Its Applications to the Ionosphere*, Cambridge University Press, Cambridge, England, 1959.
- Rayleigh, J. W. S., *The Theory of Sound*, The Macmillan Company, London, 1894.
- Skilling, H. H., *Electric Transmission Lines*, pp. 353-354, McGraw-Hill Book Company, New York, 1951.
- Stroud, W. G., W. Nordberg, and J. R. Walsh, Atmospheric temperatures and winds between 30 and 80 km, *J. Geophys. Res.*, **61**, 45-56, 1956.
- Stroud, W. G., W. Nordberg, W. R. Bandeen, F. L. Bartman, and P. Titus, Rocket grenade measurements of temperatures and winds in the ionosphere over Churchill, Canada, *J. Geophys. Res.*, **65**, 2307-2323, 1960.
- U. S. Standard Atmosphere, NASA, U. S. Air Force, U. S. Weather Bureau, 1962.

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Bibliography on "Ionospheric Disturbances"

Included hereunder are references pertinent to three major information categories:

1. Papers specifically addressed to the matter of measurable ionospheric disturbances, due to acoustic sources of contemporary interest: Underground explosions, earthquakes, etc.
2. Papers dealing with the general theory:
 - Ground-atmosphere acoustic coupling
 - Atmosphere/Ionosphere acoustic propagation
 - R.F. phase path perturbation
3. Papers related to significant peripheral data:
 - Ionospheric perturbations due to:
 - a. High altitude explosions
 - b. Surface explosions

Second-level referencing was confined principally to the first set. Specifically excluded were papers dealing with entirely surface acoustic phenomenology. The literature here can only be described as "enormous".

Major resources references included the "Bibliography of open and unclassified literature pertaining to the Effects of HANE", (DASA 1795-1,-2,-3,-4) prepared by Nuclear Research Associates, and the Weapon Data Index for pertinent classified literature.

DIRECT REFERENCES

Weaver and Yuen
 Detection of Ionospheric Instabilities, etc./Doppler Technique
 Proc. Symp./EM Wave Propag. Advisory Group
 NATO October, 1967

Yuen et al (Univ./Hawaii)
 Seismic Coupling/Ionosphere (Japan Earthquake)
 JGR 74,2256 (1969)

Weaver et al (Univ./Hawaii)
 Ionosonde Detection/Kurile EQ
 Nature 226, 1240 (1970)

Tolstoy et al (Hudson Labs, Teledyne-Isotopes) ARPA, etc. Ionosonde Array
 Apollo Launches
 JGR 75,5621 (1970)

L. M. Libby
 Detection of Nuclear Tests and Earthquakes, etc.
 RAND - Private Communic.

Davies
 Doppler Studies/Ionosphere/Vertical Incidence
 Proc. IRE 50, 94 (1962)

Davies
 Measurements/Ionospheric Drifts/Doppler Shift
 JGR 67,4909 (1962)

Tveten
 Some Theoretical Aspects of Phase Path Studies
 NBS 7928 (August, 1963) AD414524

Petrie and Schlak
 Exptal. MF/HF Phase Path Studies
 NBS 7935 (August, 1963) AD416335
 NBS 8204 (January, 1964) AD428330

Dyce et al (SRI)
 Cosmic Noise and Ionos. Studies/VELA
 AF(638) (December 1963) AD444659

Leonard and Barnes
Observation/Ionospheric Disturbances/Alaskan Earthquake
JGR 70,1250 (1965)

Davies and Baker (NBS-Boulder)
Ionospheric Effects/Alaskan Earthquake
JGR 70,9, page 2251 (May, 1965)

Cook and Baker
Ionospheric Motions/Rayleigh Waves
Proc. AGU, June, 1965

Row (Sylvania)
Evidence/AGW/Alaskan Earthquake
JGR 71,343 (1966)

Row (CRPL)
AGW --- due to Nuc. Det. and EQ
JGR 72,5, page 1599 (March, 1967)

Barry et al (BGT) (SEL-Stanford Univ.)
HF Radio Meas./HA Acoustic Waves, etc.
JGR 71,17, page 4173 (September 1, 1966)

Perret
Surface Motion/Boxcar Event
SC-TM-68-458 (August, 1968)

Cole
Acoustic Calc/Ground-Shock-Induced Air Blast
SC-RR-70-734 (Class.) November, 1970)

Fehr and McGahan
Use of Explosives to Study Upper Atmosphere
Corporate Report - Lamont Geological Obs., Palisades, N.Y.

Fehr and McGahan
Energy Propag., etc.
JGR 74,3, page 868 (February, 1969)

T. M. Georges
Ionos. Disturb. due to Atmos. Waves/Ionosonde
Thesis - Univ. of Michigan (1968)

Rao et al (Urbana)
Acoustic Waves, etc.
J. Atmos. and Terrest Phys. 31, page 539 (1969)

Schmoys
Multi-path Effects
JGR 74,2265 (1969)

Holway, Kahn and Rolfe AD 351 952
Investig./TW/Ionos. and Effects (U)
Final Rpt. AF 19(628)-2802 (Class.) (December, 1963)
Raytheon Corp. Res. Dio., Waltham, Mass. #S622

Project VELA HF Study (Peterson and Kanellakos)
Final Report/Contract Nour 4913(00), SRI (U)
SRI-8-113 (December, 1967) (Classified)

Gotto et al
Effects Simulation Program (U)
Raytheon Final Report F 33657-67-C-1195 (4/30/68) (Classified)

Kanellakos - Detection of Short-period Acoustic Waves, etc.
Gotto et al - Description of ESP (Raytheon Corp.)
Project VELA System Study 1968 and App. A (U)
SRI-9-0891 (Classified)

Presnell et al (SRI)
Electron Backscatter Radar (DASA Project 6.17)

Auditory Discrimination of Seismic Signals
due to Earthquakes and Explosions
VESIAC-4595-14-F

✓

GENERAL CONCEPTS AND THEORY - "Authoritative" Papers

The Krakatoa Committee (1888)
The Eruption of Krakatoa, etc. (Book)

H. Lamb
Phil. Trans. 203, Page 13 (1904)
Also "Hydrodynamics", 6th Edition (1932)

Pekeris
Free Oscillation Modes of the Atmosphere
Proc. Roy. Soc. A 158, Page 650 (1937)

Pekeris
Propag. of a Pulse in the Atmos. (I)
Proc. Roy. Soc. A 171, Page 434 (1939)

Pekeris
Propag. of a Pulse in the Atmos. (II)
Phys. Rev. 73,2, Page 145 (January 15, 1948)

Martyn
Ionospheric AGW
Proc. Roy. Soc. 201,216 (1950)

Hines
Internal Atmos. Gravity Waves/Ionosphere
Can J. Phys. 38,1441 (1960)

Reed (Sandia)
Shock Propag./Large Distances
SC-DC-2342 (May, 1961)

Pfeffer and Zarichny
AGW Propagation/Nuc. Exp./Atmos.
J. Atmos. Sci. 19,3, page 256 (May, 1962)

Pfeffer and Zarichny
AGW Propagation/Atmos./Two Sound Channels
Geofis. Pura Appl. 55,2, page 175 (1963)

Press and Harkrider
Propag. of AGW in the Atmosphere
JGR 67,10, Page 3889 (September, 1962)

2

Harkrider
Theor. and Obs./AGW, etc.
JGR 69,24, page 5295 (December 15, 1964)

Harkrider and Press
Krakatoa Air-Sea Waves
Geophy. J./Royal Astron. Soc. 13, #1-3, page 149 (July, 1967)

Pierce
Propag. of AGW, etc.
RAND RM-3596 (May, 1963) AD 405460

Pierce
Propag. of AGW
J. Acoust. Soc. Amer. 35, page 1798 (November, 1963)

Pierce
Comments on Harkrider
JGR 70,10, page 2463 (May 15, 1965)

Pierce
Theor. Study/Propag./AGW, etc.
AVCO Corp. Contract - Final Report AD 650 752

Pierce
Guided Infrasonic Modes
J. Acoust. Soc. Amer. 41,3, page 597 (March, 1967)

Kantor and Pierce
Acoustic Waves, etc.
J. Atmos. and Terrest. Phys. 30, page 1497 (1968)

Whitaker et al
Theoretical Calc./Phenomenology
AFWL-TR-66-141 (Several Vols.) (November, 1966) (Unclassified)

Greifinger
Theory of Hydromagnetic Propag.
RAND RM-5616 (June, 1968) AD 672 252

Cole & Greifinger
AGW produced by Energy Release (2 papers)
RAND RM 5738-ARPA/AFT (September, 1968) AD 678 507
RAND RM 5828-ARPA (December, 1968) AD 681 379

GENERAL CONCEPTS AND THEORY - Other Papers and Publications

Rocard (French AEC)

Long Range Atmos. Propag.

from Comptes Rendus 248, Page 3131 (June 1, 1959)

also ref. 247, Page 1973 (1958)

NRA 68-1 (Trans) in Part V

Weston

Gravity and Acoustic Waves

Can. J. Phys. 40,3, Page 446 (March, 1962)

Meecham

Simplified Treatment/AGW

Proc. IEEE 53-12, Page 2079 (December, 1965)

Van Hulsteyn

Theor. Study/Atmos. Pressure Pulse Propag.

Final Rpt. AFCRL 64-424, 5033-1-F (March, 1964) Univ. of Michigan

AD 601 386

Van Hulsteyn

Atmos. Pressure Wave, etc.

Thesis - Univ. of Michigan (1964)

Van Hulsteyn

Atmos. Pressure Wave, etc. (Parts I and II)

JGR 70 #2, Page 257 - 70 #2, Page 271 (January, 1965)

Donn and Shaw

Exploring/Atmos/Nuc. Exp. (AGW Data)

Rev. Geophys. 5,1, Page 53 (February, 1967)

Pierce et al

Biblio./Unclass. Lit./Ionospheric Effects

SRI Bibliography (1965)

Pierce

Nuc. Exp. Phenomena

Proc. IEEE 53,12, Page 1994 (December, 1965)

T. M. Georges
Ionospheric Effects of Atmospheric Waves
ESSA Tech. Rpt. IER 57-ITSA 54 (1967)

T. M. Georges, (Ed)
Proceedings/Symposium on AGW AD 686 152
ESSA Res. Labs (July, 1968)

Rostov U. (USSR) (April, 1960)
Proceedings/Scientific Symposium on Ionosphere
NRA 65-22 (Trans.) In "Part III"

North-Holland Pub. Co./Wiley and Sons (1964)
Includes: Kohl (Page 160), AGW, etc.
Book: Electron Density Distribution in the Ionosphere

Global Hydromagnetic Wave Ducts, Etc.
Nature 185,299 (January 30, 1960)

Theory of AGW Propag. from Explosive Sources
SRI-6549

IONOSPHERIC SOUNDER MEASUREMENTS AND INTERPRETATIONS

Surface and Atmospheric Nuclear Explosion Sources

Lepechinsky and Davoust

Some Effects of Nuc. Exp. on Vertical Ionos. Soundings

(Comptes Rendus 248,8, page 1203 (January, 1959))

NRS 65-16 (Trans.) in "Part III"

Hunt et al

Atmos. Waves/Nuc. Exp.

Phil. Trans./Roy.Soc. London A 252, Page 275 (February, 1960)

Rose et al

Oksman and Kataja

Round-the-World Sound Waves/Nuc. Exp./Ionosphere

Nature, 192 4808, 1173 (1961)

Chan and Villard

Observ./Ionos Disturb/HF Measurements

JGR 67,3, page 973 (1962)

Dieminger and Kohl

Effects/Nuc. Exp/Ionos.

Nautre, 193, page 963 (March 10, 1962)

Beynon and Jones

Ionospheric Effects/Nuc. Exp.

Nature 196, 253 (1962)

Lichtman and Andersen

Ionos. Effects, etc.

Hughes A/D Commnic. Dio. Rpt. #OP-36 (July, 1962)

Bowman

Some Effects of Nuc. Exp., etc.

Australian J. Phys. 15, page 405 (September, 1962)

Saha et al

Ions. Effects, etc. I and II

J. Atmos. and Terrest. Phys. 25, page 212 (April, 1963)

also 26, page 618 (May, 1964)

Webb and Daniels

Ionospheric Oscillations/Nuc. Exp.

JGR 69,545 (1964)

Davidson and Gallant (DECO Electronics, Cambridge)
Investig./Ionos. Oblique Sounder Data
AFCRL-64-408 (April, 1964) AD 602407

Mitra and Sengupta
Effects/Nuc.Exp./Ionos.
J. Instit. Telecom. Engrs. 10,8, page 323 (1964)

Hahn (Dissertation, Phillips Univ.)
Fluctuations of F-layer f_c , etc.
NRA 66-3 (Trans.) in "Part III"

Murayama
Pressure Waves (due to Nuc. Exp.) 1952-1958
NRA 67-1 (Trans) in "Part IV"
(KKJ 17, page 105 (February, 1965))

Oksman and Kivinen
Ionospheric Gravity Waves, etc.
Geophysica 9,2, page 119 (1965)

Kotadia
Effects of Nuc. Exp. - I
Ann. Geophys. 23,1, page 1 (January-March, 1967)

Kotadia
Ionos. Effects - II
Ann. Geophys. 24,1, Page 91 (1968)

McCrary
Atmos. Pressure Waves, etc.
J. Atmos. Sci. 24,4, page 443 (July, 1967)

Kanellakos
Response of Ionosphere, etc.
JGR 72,17, page 4559 (September, 1967)

Albee and Kanellakos
Spatial Model of F-region
JGR 73,3, page 1039 (February, 1968)

Wickersham
Identification/Ionospheric Motions/Back-Scattering
JGR 69,3, page 457 (1964)

Hines
Comments on Wickersham
JGR 69,11, page 2395 (1964)

Wickersham
Reply to Hines
JGR 69,11, page 2397 (1964)

Wickersham
Analysis of Large-scale/Ionospheric Disturbances
JGR 69,15, page 3235 (1964)

Heisler
Discussion of Wickersham
JGR 69, page 5105 (1964)

Wickersham
Ducted Gravity Wave Interpretation, etc.
JGR 70,7, page 1729 (April, 1965)

Wickersham
Comparison of Velocity Distributions/AGW, etc.
JGR 70, page 4875 (1965)

Wickersham
Identific./AGW/Back-Scatter
JGR 71,19, page 4551 (October, 1966)

Hines
On the Nature of Ducted AGW, etc. (Response to Wickersham)
JGR 72,7, page 1877 (April, 1967)

Wickersham
Identific. of AGW Modes, etc.
Nature 218,5137, page 156 (April, 1968)

Baker and Davies (NBS-Boulder)
Waves in Ionosphere/Nuc. Exp.
JGR 73,1, page 448 (January, 1968) AD 665921

Baker et al (ESSA/Boulder Rpt.)
Review of Ionos. Studies, etc./Nuc. Exp.
ERL-78-SDL-1 (July, 1968) AD 675 061

Baker (ESSA/Boulder Rpt.)
Observ. of Acoustic Waves/Nuc. Exp.
ERL-89-SDL-5 (October 1968) AD 678 877

Tumbler-Snapper (1952)
Effects of Explosions on Ionosphere
WT 547

Operation Ivy (1952)
Effect of Atomic Explosions on the Ionosphere
WT 642

Operation Castle (1954)
Effects of Nuc. Det. on Ionosphere
WT 929

Operation Redwing (1956)
Ionospheric Effects of Nuc. Det.
WT 1337

Operation Dominic
Ionospheric Soundings, etc.
POR-2020

Operation Dominic
Vertical Ionospheric Soundings
POR-2022

IONOSPHERIC SOUNDER MEASUREMENTS AND INTERPRETATIONS

High Altitude Nuclear Explosion Sources

Utlaut
Ionos. Effects/HANE
NBS 6050 (1959)

Cummack and King
Disturb./Ionos. F-region, etc./HANE
N.Z.J. Geol/Geophys. 2,3, page 634 (August, 1959)
Nature, 184, page 32 (September 5, 1959)

N.Z. Scientific Community
"Papers Presented" (August 23, 1962) (Misc.-1962-390)
Christchurch Symposium: Obs. and Meas.---HANE

Christchurch Geophys. Obs. (N.Z.)
Ionos. Effects of HANE
J. Atmos. and Terrest Phys. 25, page 99 (Sept., 1962)
Also: N.Z. J. Geol./Geophys. 5,6, page 1009 (December, 1962)
Note: N.Z. J. Geol/Geophys. 5,6, page 917 (December, 1962) Collins

Heisler and Wilson
Spread-F Development, etc./HANE
Nature, 196, page 258 (October 20, 1962)

HANE/Disturbances in the Ionosphere
UCRL-Trans-890(L) November, 1962

Obayashi
Wide-spread Ionos. Disturb., etc./HANE
Nature, 196, page 24 (October 6, 1962)

Obayashi
Upper Atmos. Disturb./HANE
Planetary Space Sci. 10, page 47 (1963)

Armstrong and Wharton (NBS, Jamaica)
Effects of HA TN Exp., etc.
JGR 68,6, page 1779 (March, 1963)

Baker and Gledhill
Possible Ionos. Effect, etc./HANE
JGR 68,23, page 6359 (December, 1963)

Elkins and Egeland
Ionos. Effects, etc./HANE
Kiruna Geophys. Obs. Kiruna, Sweden
SGO-63-2 (March, 1963)

Ionospheric Research Committee Mtg. #8
Athens, Greece, July, 1963
Proceedings, Arctic Communications: NATO, AGARD
Also note Translation NRA 65-20 in "Part III"

Anastassiades et al
Halley et al
Observations made by the Ionospheric Institute, etc.

Schminder and Junge
On Determination of Sound Velocity, etc./HANE
NRA 65-6 (Trans.) in "Part III"

Sengupta
Ionos. Effects of HANE
J. Atmos. and Terrest. Phys. 26,9, page 919 (September, 1964)

Bowman and Mainstone
Geomagnetic and Ionos. Effects, etc./HANE
Australian J. Phys. 17, page 409 (September, 1964)

Morlet
Geophysical Phenomena, etc./HANE
NRA 66-2 (Trans.) in "Part III"

Geophysical Effects Assoc. with HANE
Kyoto Univ. Japan
5 parts - NRA Ref. Nos: 402, 352, 471, 648, 333
(Includes Acoustic and Seismic Waves and Ionos. Disturb.)

H.F. Doppler Shifts Assoc. with US HANE (U)
NBS IQB 122 (May, 1965) (S-DI)

Breitling et al
Traveling Ionospheric Disturbances, etc./HANE
JGR 72,1, page 307 (January, 1967)

Breitling and Kupferman
h'F Variations, etc./HANE
JGR 72,9, page 2456 (May, 1967)

Kanellakos
Discussion of Breitling et al
JGR 72,21, page 5579 (November, 1967)

Breitling et al
Reply to Kanellakos (Page 5579)
JGR 72,21, page 5582 (November, 1967)

Riometers for Detection of Nuc. Exp. in Space
RAND-RM-4760-ARPA

HF Communic. and Ionospheric Effects/Nuc. Exp.
SRI-3670-F-6508 Several Vols.

Effects on and Response of Ionosphere/HANE
SRI-5481-FR Several Vols.

HF Backscatter Observations, etc.
ACF/EPL-DIPOLE 6 and 7 }
ACF-EPL-CN-40-43 } Many Vols. and Parts
ACF-EPL-5310 }

HANE Effects on Ionosphere
AVCO-RAD-SR-66 }
AVSSD-0018-67-RR } Several Vols.
AVSSD-0178-66-CR }

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