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A Review of Ionospheric Disturbances Resulting from Some Naturally Occurring Events

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A REVIEW OF IONOSPHERIC DISTURBANCES RESULTING FROM SOME NATURALLY OCCURRING EVENTS

by

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ABSTRACT

Some known and some potential sources of atmospheric disturbances have been investigated in a review of scientific papers selected to illustrate the roles of naturally occurring phenomena in generating observable ionospheric effects. Reports of acoustic and ionospheric effects resulting from the Alaskan earthquake of 1964 are used as a guide to the nature of signals generated by all seisms. Scaling these effects to smaller seisms is considered. Some models for enhanced acoustic coupling between the earth and atmosphere are discussed. Investigations of signals generated within the atmosphere by meteorological events are also reviewed.

I. INTRODUCTION

This project was undertaken in support of the ionospheric monitoring program (IMP) at Los Alamos Scientific Laboratory, a program to monitor ionospheric disturbances from specific acoustical sources and to characterize those signals at several locations between the ground surface and the ionospheric F-region. The IMP effort has been concentrated on the study of acoustical disturbances using various radio-frequency (RF) monitoring techniques and, when possible, the correlation of the disturbance with a specific ground motion as its source. There are many naturally occurring disturbances in the ionospheric electron density and their presence is frequently recorded by RF sounders. The sources associated with these natural disturbances are often not known and not well understood.

This report covers a study of papers appearing in the unclassified literature on any aspect of ionospheric waves or disturbances which could confidently be attributed to natural sources. It also concentrates on experimental methodologies common to those employed by the IMP. Ionospheric effects caused by earthquakes are treated as a prime interest.

There are many interesting papers on ionospheric effects of storms, atmospheric turbulence, and atmospheric explosions. Some of these papers are discussed in Sec. III.

II. EARTHQUAKES AS A SOURCE OF IONOSPHERIC DISTURBANCES

A. Acoustic Signals

In understanding mass motions in the ionosphere that could be induced by earthquakes, it is helpful to first consider possible coupling mechanisms between a seismic energy source and the ionosphere. Published reports indicate that coupling via acoustic, infrasonic, and magnetic paths could be significant in energy transfer from the ground to the ionosphere.

For the past 50 yr there have been many credible reports of intense audible signals accompanying and presumably generated by earthquakes.[1] During the past 30 yr earthquake-related acoustic waves have been recorded by sensitive barographs[2] on several occasions, and there are a few chance recordings made on audio tape recorders.[3] Audible sounds from the New Zealand and Tibet earthquakes of 1929 and 1950, respectively, were reported from as far as 750 miles away.[1,4] Thus, very large earthquakes (that is, magnitude 8 or larger) generate acoustic energy of such a frequency and intensity that it propagates at audible levels over great distances via high-altitude acoustical ducts.[5] These facts indicate that, from near the epicenter of large earthquakes, sufficient acoustical energy can be propagated upwards at nearly vertical angles to cause significant ionospheric disturbances. Unfortunately, there are no known data from which quantitative relationships between seismic magnitude and acoustic intensity or ionospheric displacement can be established.

Perhaps because of the high level of interest in ionospheric physics or because of the experience with large atmospheric explosions in the 1950s and 60s, there are reports of several observations of ionospheric disturbances associated with the magnitude 8.3 Alaskan earthquake of March 27, 1964 (March 28, 03 36 13 UT).[6-8] Infrasonic disturbances were also observed at several distant stations.[9,10] Interpretation of the micropressure fluctuations reported in these papers on ground-coupled airwaves leads to convincing arguments that the recording instruments responded to air pressure waves generated locally by the passage of Rayleigh waves,[11] and also to a pressure wave originating near the earthquake epicenter.[12]

B. Near-Field Coupling

Following the Alaskan earthquake, unusually erratic frequency changes in the receiver signals were observed on many ionospheric sounders throughout the world. These frequency changes (Doppler effects), given by

$$\Delta f = -(f/c)(d/dt) \int n ds ,$$

apparently arise from ionospherically induced changes in the phase path length, $\int n ds$, of the RF-sounder signals. In this expression f, n, c, and ds represent the RF-sounder frequency, atmospheric index of refraction, velocity of light, and the geometric distance element, respectively. The integral is over the path of the RF-sounder wave from transmitter to receiver.

Davies and Baker[7] report that about an hour after the earthquake a large Doppler shift began on both the 4.0-MHz vertical sounder signal and the WWVH 10-MHz signal received by an oblique sounder at Boulder, Colorado. Initially the period was 90 min, but it grew longer with the passage of time. Row[8] attributes this effect to the disturbance being composed of a combination of acoustic and internal gravity waves. In a later more complete analysis[13] Row compares the Doppler records taken at Boulder with a compendium of measurements of atmospheric and ionospheric responses to the pressure pulses of nuclear detonations in the atmosphere. He finds that the Boulder records are a reasonably good fit to predictions of a theoretical model for the impulse response of an isothermal atmosphere. This model is also used successfully in fitting pressure data from several nuclear explosions. The great similarity between disturbances caused by distant nuclear explosions and the long-period portion of the Alaskan earthquake record from Boulder—and their agreement with the atmospheric propagation model predictions, in addition to the numerical results of Press and Harkrider[14]—show that the disturbance propagates from the source to Boulder as long-period waves via an atmospheric path. Thus, we see in the Boulder records of the Alaskan earthquake an excellent example of seismic-induced, observable ionospheric disturbances caused by both the near-field impulse propagating through the atmosphere and teleseismic Rayleigh waves coupling acoustically to the ionosphere. The first path results in the relatively long period and transit time of acoustic gravity waves, whereas the second gives oscillatory periods and arrival times characteristic of dispersed Rayleigh waves.

Vertical ground motion near an epicenter will generate atmospheric disturbances characteristic of the seismic spectrum and of the impulse due to permanent vertical ground displacements. There are fewer than 200 measurements of near-field vertical ground motion, most of which were recorded by instruments in southern California. The available data have been analyzed to determine a seismic spectral response function for vertical ground motion. Spectral curves of vertical ground velocity have been published by Agbabian Associates.[15] These curves can be used to make a statistical estimate of near-field acoustic signals. An example of a mean vertical ground velocity spectrum for seisms of Richter Magnitude (RM) 6 is shown by curve C in Fig. 1. The Richter scale for surface-wave magnitudes is used throughout this report. Large surface areas in the epicentral region are predicted to experience vertical velocities up to 0.30 m/s with periods from 0.2-4 s. The mean atmospheric pressure signal for near-field motion is then given by

$$\Delta P = \rho c v \approx (0.00123\ \text{gm/cm}^3)(3 \times 10^4\ \text{cm/s})(30\ \text{cm/s}) = 1100\ \text{dynes/cm}^2$$

where ρ, c, and v are density, sonic velocity, and vertical ground velocity, respectively. The average spectrum of seismic motion[15] is similar for all shallow earthquakes larger than RM 3; therefore, predicted surface motion pressure signals can be scaled. For example, close-in ground motion should lead to $\Delta P \approx 110$ dynes/cm^2 for RM 5 seisms.

Because humans have a normal hearing threshold of 1-10 dynes/cm^2, they should hear sounds from RM 5 earthquakes even though the major part of the seismic spectrum is below the range of human hearing. How the sound of a much larger (RM 8) earthquake would be perceived can be estimated from studies relating actual sound intensity to a quantitative estimate of loudness reported by typical listeners.[16] Loudness is approximately proportional to $\Delta P^{0.6}$; each decade of change in signal pressure corresponds to a factor of 4 in loudness. Thus, between earthquakes of magnitude 5 and 8, the loudness is predicted to increase by a factor of 64, resulting in an impressive sonic signal in keeping with observations.

A recent study[17] using the intensity of the 557.7-mm airglow line to detect atmospheric pressure waves has found evidence for the generation of short-

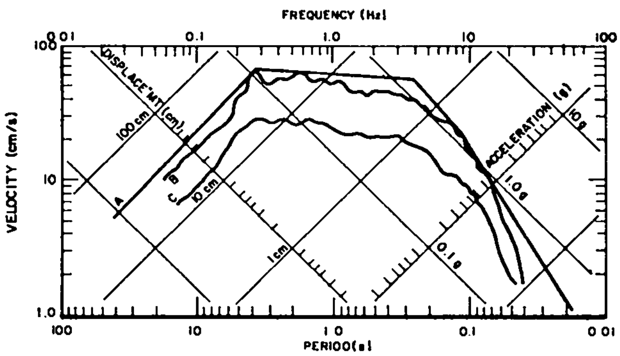

Fig. 1.
Undamped vertical seismic ground-response spectra. Curve A is from the federal regulatory guide. B is the 84th percentile curve. C is the mean spectral curve.

period (4-12 min) oscillations by instabilities on large-amplitude, long-period waves. If this is the case, a clear separation of long and short periods in far-field ionospheric records should not be expected and the periods of observed wave motion cannot be assumed to have a predictable propagation time from the primary source. This effect will tend to complicate Doppler sounder records of ionospheric waves.

One other factor worth mentioning is the seemingly supersonic propagation of long-period acoustic waves sometimes reported. Einaudi,[16] in an approximate solution to the acoustic gravity-wave equation, attempts to provide for the nonlinear effects of shock formation by large-amplitude waves propagating upward. The acoustic amplitude range considered by Einaudi was larger than is often applicable for supersonic signals reported from earthquakes, but in some instances shock formation may occur, resulting in reduced acoustic propagation time. If a shock front develops, it could account for the formation of an N-shaped pressure wave at high altitude even though that waveform was not present in the source function. Linear processes will then tend to stretch the wave.

C. Rayleigh-Wave Coupling

Following the Alaskan earthquake at 03 36 UT on March 28, 1964, the National Oceanic and Atmospheric Administration (NOAA) seismic station reported that the first Rayleigh waves from the Alaskan seism arrived in the Boulder, Colorado, area at 03 53 UT. This time coincides with the onset of pressure variations recorded on a nearby microbarograph. Both the amplitude and period of the atmospheric pressure waves were compatible with a Rayleigh wave source. The coupling of significant quantities of energy from seismic into atmospheric waves is by no means restricted to spectacular events such as the Alaskan quake, but because of its great magnitude, acoustical effects that might otherwise go unnoticed are clearly manifest. A simple extrapolation of these effects to more moderate-sized earthquakes should be undertaken with caution and certainly all available data should be used in making extrapolations.

Yuen, Weaver, Najita and others at the University of Hawaii, while working to develop a tsunami warning system,[19,20] have made direct correlations between Doppler sounder records representing vertical motions in the ionospheric F-region and seismograms of local Rayleigh waves from distant earthquakes of magnitudes 7.8 and 7.9. There seems to be little doubt that on at least two occasions they have observed Doppler shifts of approximately 1 Hz on a 5-MHz reference frequency resulting from the upward propagation of atmospheric pressure disturbances caused by Rayleigh waves on the earth's surface. Fortunately, the theory of Rayleigh wave propagation is quite well understood,[21] and reports of extensive experimental studies of Rayleigh wave propagation and detection have been published.[22-24] For the magnitude 7.9 Hachinohe, Japan, earthquake of May 16, 1968, the amplitude of Rayleigh waves of 25-s period was estimated to be about 0.15 cm at Hawaii, 5800 km away.[19] The usual expression relating vertical ground motion and peak-to-peak acoustical pressure in normal air is $\Delta P \approx \rho c v_0 = 247(2d/T) = 247(0.3/25)\mu b \approx 3\mu b$; where ρ is the density of air, c the sonic velocity, v_0 the vertical ground velocity, 2d the peak-to-peak ground displacement, and T the Rayleigh wave period. Thus, although Rayleigh wave amplitudes of 1.5 mm or more may produce an easily observable ionospheric displacement under good conditions, the predicted corresponding pressure change of about 3 μb is too small to record on many available barographs.

Rayleigh waves from the Alaskan earthquake reached the Boulder area in approximately 17 min and, although I do not have records of the "enhanced infrasonic waves beginning around 03 53 UT" which Davies and Baker[7] refer to in their report, the timing leaves little doubt that they were induced by Rayleigh waves. Davies and Baker also report that "...the beginning of a disturbance was observed on the Boulder 4-MHz and WWVH 10-MHz signals at about 03 52 UT," and "Shortly before 04 00 UT, a major disturbance occurred on all three frequencies." Although the authors do not discuss details of the major ionospheric disturbance at 04 00 UT, they are confident that its source was Rayleigh waves generated by the 03 36 UT seism arriving in the Boulder area 3900 km from the epicenter approximately 16.7 min later. The associated acoustic disturbance observed at 03 53 UT then required about 7 additional min to propagate up to the ionospheric F-region and be recorded by the phase sounders.

The "beginning of a disturbance . . . at 03 52 UT" reported by Davies and Baker is not explained by Rayleigh waves because of inadequate propagation time. Although it is probably not applicable to these small-amplitude waves, the possibility of supersonic wave propagation should not be dismissed.

D. Less Common Modes of Acoustic Coupling

The possibility of uncommon and even unknown modes of energy coupling and propagation should never be ruled out. For example Benioff, Ewing, and Press[25] have recorded infrasonic signals at Pasadena that were generated approximately 265 km away by very short period Rayleigh waves from an earthquake of magnitude 5.6, equivalent to an energy release of only about 2.5 kt. They attribute the generation of this long-range acoustic signal to unusually close coupling predicted to exist between ground and air when soil conditions are such that seismic group velocities approach the local acoustic velocity. Under these conditions, the pressure formula is given by $\Delta P = \rho c v_0 \beta/(\beta^2-1)^{1/2}$, where β = (seismic velocity, v_s)/(acoustic velocity, v_a). Then as $v_s \rightarrow v_a$, the factor $\beta/(\beta^2-1)^{1/2}$ can become arbitrarily large.[26] This situation can be realized in the deep layers of loosely compacted low-density sediments found in the Imperial Valley of southern California, which was determined to be the infrasound source.

Vertical motion of the surface of water is potentially one of the most significant sources of enhanced infrasonic signals. Source areas are often extremely large, and there are many known cases where bodies of water move with natural periods that are well suited for the generation of atmospheric pressure changes that propagate with very little attenuation. These factors, together with the resonant oscillatory nature of liquid moving in closed or partially closed basins, make this an important source of infrasound and the associated ionospheric disturbances.

Stationary waves resulting from free oscillations of water in closed basins are known as seiches. The size, shape, and depth of the water mass, together with the wave mode, determine the period of oscillation. Lakes, canals, and partially enclosed bodies of water such as bays and estuaries are known to exhibit seiche-generated changes in the water surface level. Seiche oscillations were observed in Lake Geneva as early as the 18th century. Only much later in the 19th century did the behavior of water waves subject to restrictive boundary counditions receive extensive study. Easily solvable general wave equations were found, but they proved to be of little practical value because of unknown or highly complex boundary conditions. More recently, large quantities of reliable data on water surface levels have been recorded from many locations throughout the world. The availability of reliable data so stimulated computational efforts that today there is good agreement between the calculated and observed periods of seiche waves for several of the earth's lakes and narrow seas. There are, of course, many more bodies of water for which seiche calculations have never been performed. A general treatment of this topic, in addition to a discussion of some periods and damping factors for seiches in European lakes, is given by Defant.[27]

A good example for consideration is a large canal in which a seiche can be generated by simply changing the rate at which water is allowed to flow in or out. Canal and lake seiches are also generated by strong steady winds or by impulses of local storms. The natural period for a long, deep, rectangular basin is $T = 2\ell/n(gh)^{1/2}$, where n is the number of wave nodes, $n \geq 1$, ℓ the length of the basin, g the acceleration due to gravity, and h the depth. The predominant seiche motion results from a superposition of waves propagating in the positive and negative directions along the long axis of the basin. The oscillatory period is longest for $n = 1$ and $\lambda = 2\ell$. For example, the fundamental mode in a 10-km long, 10-m deep ship canal is about 30 min, and the distribution of existing modes will depend on the exciting function. The damping factor for seiches, $\xi = \lambda/T$, is also highly dependent on the geometry of the body.[28] Apparently, damping factors can vary widely; therefore, a seiche on a highly damped canal might give rise to an ionospheric disturbance characteristic of a single-impulse source, whereas on a deep open lake a seiche source would resemble a slowly decaying periodic driving function.

Measured periods and damping factors for some lake seiches are reported by Defant.[28] These numbers show that seiche periods span the entire infrasound spectrum, and damping factors can be exceedingly small.

Amplitudes of seiches will depend on their sources, but for lakes that have been studied and for estuaries of the Baltic and Adriatic Seas, seiche amplitudes of several centimeters do not seem unusual. When winds and storms create seiches that result in detectable ionospheric disturbances, a monitoring system would probably be unable to confirm that the disturbance was in fact caused by a seiche.

There is a high probability that the differential vertical motion on bodies of water in the near-field region of any earthquake will result in seiches. The existence of characteristically low damping factors could then result in much stronger coupling to the ionosphere than would occur from the seism alone. An estimate of the coupling enhancement can be made[16] using the mean undamped vertical ground-response spectral curve representing California earthquakes of magnitude 6.4. The mean response curves from this report include data from seisms of several different magnitudes, but they are so heavily weighted to magnitude 6.4 that this assumption is quite good. The maximum mean vertical displacement of about 15 cm occurs for periods of 4-16 s or more. Long-period displacement results in a predictable tilt in local bodies of water according to the model of Press.[29] The resultant water-surface displacement amplitude will be affected by an amplification factor that may range from 1 to quite large values, depending on existing boundaries. The natural seiche period, being proportional to the ratio $\ell/\sqrt{h}$, will be in the range of small atmospheric attenuation for most bodies of water with linear surface dimensions exceeding approximately 100 m. Energy coupled from seiches to the ionosphere will also depend on the damping coefficient of the wave.

The long duration of moderately damped seiches could result in a factor of 10 increase in net ionospheric coupling.

Seiches on rivers, lakes, and harbors at teleseismic distances are not uncommon for large earthquakes. Richter has found that many seiches were generated throughout Western Europe and Scandinavia by the Lisbon earthquake of 1755; the magnitude of that quake is estimated to have been 8.5. Large seiches at such great distances indicate the existence of resonant coupling with Rayleigh waves.

The superposition of reflected or multiply refracted Rayleigh waves to form stationary or slowly moving surface waves may be an important factor in Rayleigh wave generation of both infrasound and seiches. Reports of easily visible seismic waves moving slowly along the ground surface imply the existence of nearly stationary short-wavelength disturbances[2] resulting from superposition of waves. Primary seismic waves sweeping past a fixed point with velocities in excess of 9 000 km/h and wavelengths of 60 km or more can hardly be the cause of such reports. It is more likely that the strong infrasonic coupling reported by Benioff et al.[24] resulted from a slowly moving superposition wave instead of greatly retarded primary Rayleigh waves.

Another possible mode of enhanced seismic-ionospheric coupling is the tsunami wave. Displacement waves surely accompany all marine and coastal seisms, but they are usually of such small magnitude that they go unnoticed even by recording instrumentation. Small seismic displacement waves will be amplified significantly, however, when moving into shallow waters of coastal regions or submarine banks. Millimeter-high waves in the ocean become centimeter-high waves when depth decreases by a factor of 100. The ionospheric coupling from this source will depend on the area of shallow-water regions. Meteorological tsunamis and tidal bores should be considered in the same category as seismic tsunamis. Ionospheric disturbances clearly attributable to these events are expected to occur rarely, if ever, but they should remain on the list of potential natural sources.

E. Piezomagnetic Disturbances

Davies and Baker[7] point out that the Boulder, Colorado, sounder records began to show pulsations at 02 32 UT on March 28, approximately an hour before the Alaskan earthquake occurred. In seeking to determine the significance of this observation, one finds that an ionogram taken by Leonard and Barnes[6] from Adak at 03 30 UT, 6 min prior to the seism, shows the existence of unusual ionospheric turbulence up to a virtual height in excess of 250 km. The ionogram taken at 03 15 UT, however, is undisturbed. Some unpublished phase-sounder records taken from Adak[30] on the day of the quake also show definite strong disturbances at 03 15 UT and probably as early as 02 50 UT. These three observations may prove nothing, but they certainly force one to consider the possibility that unusual widespread ionospheric disturbances were generated long before the seism actually occurred.

By chance, a magnetometer record was taken at Kodiak covering the period prior to the Alaskan earthquake. Moore[31] has reported the circumstances surrounding the magnetic field measurement and reproduces a portion of the record showing a brief magnetic field increase of 100 γ (1 mOe or 1/4 π A/m) and two smaller positive pulses at approximately 03 33 UT. It is only possible for Moore to say that these positive disturbances are "believed" to have been associated with the earthquake, and that no other positive fluctuations nearly as large as 100 γ have been seen.

There is good reason to posit a correlation between this magnetic disturbance and the impending earthquake based on the piezomagnetic properties of local rock. The possibility of piezomagnetic phenomena being manifested during the changing stress conditioning along earth fault zones has long been considered.[32] Stacy[33] has computed piezomagnetic field changes from movement along a fault perpendicular to the geomagnetic field, and found results similar to the actual geomagnetic field changes observed after earthquakes in Japan. *In situ* measurements of geomagnetic changes occurring simultaneously with small earthquakes are reported by Breiner.[34] There is little doubt that the piezomagnetic effect exists in surface rock and gives rise to observable changes in local geomagnetic fields.

While geomagnetic field changes probably accompany or precede earthquakes, details of the nature and magnitude of these changes are unknown. Calculations provide only rough estimates of the magnitude and extent of field changes. From this basis it is not possible to calculate the amount of energy involved in the field change or how much might be coupled to the ionosphere as a detectable disturbance. Changes in the Boulder Doppler-sounder records that are seen shortly after 02 30 UT could possibly be the result of piezomagnetic pulses coupling to the ionosphere. An apparent ionospheric disturbance that preceded a magnitude 6 earthquake on April 26, 1973, might also be due to piezomagnetic effects.[35] Details of the ionospheric disturbance were not recorded nor were any geomagnetic field changes, but reported events fit the same pattern as the Alaskan quake. While piezomagnetic phenomena have long been associated with earthquakes, it does not appear that they have been previously associated with ionospheric disturbances. Evidence for significant piezomagnetic effects appears strong enough that the entire phenomenon should be investigated.

III. IONOSPHERIC DISTURBANCES RESULTING FROM METEOROLOGICAL EVENTS

Relationships between ionospheric phenomena and local weather conditions have been studied for at least 50 yr.[36] Gherzi,[37] in 1950, reported a correlation between the RF-signal reflection height for a 6-MHz fixed-frequency ionospheric sounder and the dominating local air mass. Related effects were reported by Beynon and Brown[38] and Colwell[39] after studies of E- and F-layer critical frequencies and RF skywave attenuation showed correlations with local barometric pressure. These early studies concentrated on normal meteorological conditions, but in the 1960s, as measurements of short-period ionospheric motions improved, correlations between ionospheric disturbances and intense local storms were discovered. Ionospheric Doppler soundings often found disturbances within 200 km of thunderstorms having cloud tops above 12 km.

The effects of meteorological disturbances on the ionosphere can be quite important to an ionospheric monitoring program, and the use of storm-generated ionospheric waves for the development and testing of monitoring systems has great potential value. Signals from this natural source occur frequently in the US during a large fraction of the year. The storm source can be monitored by weather radar so that the spatial and temporal extent of the storm, in addition to its relative intensity, can be determined. Tests could be performed to determine signal characteristics for meteorological sources using different types of monitoring systems. Any prototype system should be tested with this signal source. Severe storms generate both ionospheric and infrasonic signals in a broad spectral range, so they provide a particularly good source for testing a combined acoustic-ionospheric monitoring system.

Because of the relatively long duration of convective storms, it is unlikely that their effects, recorded on either barographs or ionospheric sounders, would be confused with those from other sources. A much greater problem would be the reduced sensitivity of the system for short-duration signals that might coincide with storm-generated disturbances. How severe the sensitivity degradation might be would depend on the design of the system.

Davies and Jones[40] have found that the power in storm-generated ionospheric waves is concentrated in the frequency range of 3-6 mHz; that is, 3- to 5.5-min periods. This power density distribution must be attributed solely to atmospheric filtering, for in a review article on infrasound signals generated by convective storms, Georges[41] states that "observed wave periods range between extremes of about 6-300 s with 12-60 s being typical. Frequency spectra are generally broad but occasionally exhibit sharp peaks. No distinguishing waveform characteristics identify severe-weather infrasound. As a result it is difficult to identify severe-weather waves in the presence of other infrasonic signals." Fortunately this is not the case for ionospheric waves. After being filtered through the atmosphere, the severe-storm power density spectrum is concentrated in periods of 3-5 min. A representative spectrum from Davies and Jones is shown as curve D in Fig. 2. Davies, Jones, and Weaver[42] give a sample power spectrum for a high-frequency portion of natural ionospheric waves, which shows very little energy in periods shorter than 5 min. This spectrum is reproduced as curve C in Fig. 2. Curves C and D are well separated so that storm-generated ionospheric waves can be identified and probably could be used to aid in identifying infrasonic signals from the same source.

Doppler systems designed for the detection of ionospheric waves near the high-frequency end of the acoustic region (that is, periods of approximately 1 min or less) should avoid most of the interference from the longer period storm-generated waves, but

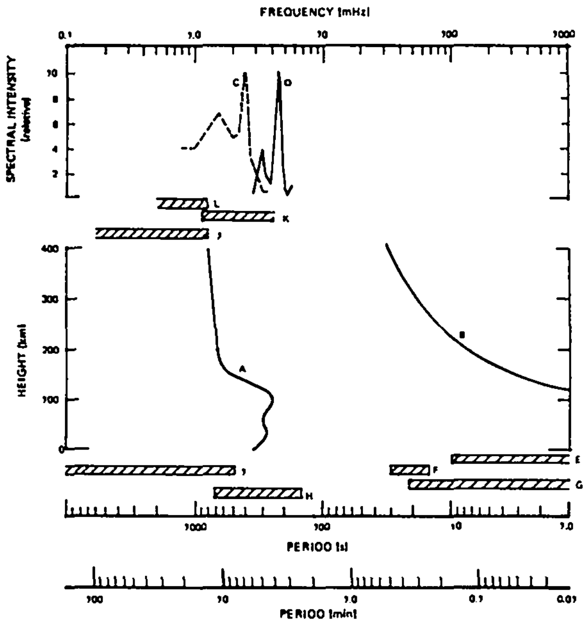

Fig. 2.
Frequency range of some natural sources of acoustic gravity waves. A is the acoustic cutoff frequency as a function of height. B is the region of acoustic attenuation greater than 1 db/km. C is the spectrum of natural ionospheric disturbances. D is the spectrum of storm-generated ionospheric disturbances. Shaded bars show the approximate spectral region of ocean wave noise (E), seismic Rayleigh wave signals (F), near-field seismic signals (G), storm-generated disturbances (H), seiche and tsunami waves (I), impulse response of the atmosphere (J), instability-generated disturbances (K), long-period traveling ionospheric disturbances (L).

the system sensitivity will still be reduced because of increased line width of the received RF signal. Doppler resolution of 0.1 Hz is attainable for oblique sounders operating at 10 MHz. These instruments produce Doppler records that, for turbulent ionospheres, often contain S-shaped patterns indicating that both positive and negative frequency shifts occur simultaneously. Davies and Jones[48] show how this pattern can result from RF signals traveling from transmitter to receiver by three different paths. Their model requires only that the ionospheric reflecting surface be corrugated in a quasisinusoidal shape and be moving horizontally over the sounder. Actual Doppler records[40,43,44] often show these S-shaped patterns where the peak values of Δf exceed 1 Hz. If a backscatter radar sounder is used, the S-shaped patterns will appear as frequency splitting or as an extremely broad return signal; the system will then be quite insensitive to the detection of additional disturbances in adjacent spatial regions within ~200 km of the meteorological disturbance.

IV. SUMMARY

This report is based on a survey of the unclassified literature on ionospheric disturbances resulting from identifiable natural phenomena. Special attention is given to the potential for coupling seismic energy to the ionosphere. The Alaskan earthquake of March 28, 1964, caused atmospheric disturbances that were recorded on microbarographs and ionospheric sounders throughout the world. Effects observed from this magnitude 8.5 earthquake can be scaled to smaller seisms, but the scaling generally cannot include all geologic and atmospheric factors and is therefore quite uncertain.

The most significant mode of coupling seismic energy to the ionosphere at great distance from an earthquake is by a combination of seismic surface waves and atmospheric acoustic waves. As Rayleigh waves propagate radially outward from the epicentral region, part of their energy is coupled to acoustic waves in air. A portion of this acoustic signal propagates vertically upward to the ionosphere giving rise to a periodic disturbance characterized by the Rayleigh wave period, usually 20-30 s. This coupling mode is further identified by the delay in signal onset, which is equal to the Rayleigh wave travel time plus 5-7 min required for acoustic signals to travel from the surface to ionospheric heights. Rayleigh waves from earthquakes of magnitude 6 or greater give rise to ionospheric oscillations that are easily detectable but difficult to discriminate from atmospheric impulse signals, such as those caused by low-altitude explosions. Acoustic signals generated by Rayleigh waves are also detectable at the earth's surface at ranges in excess of 1000 km via ray paths reflected in the thermospheric region.

Ionospheric disturbances at great distances from earthquakes also result from coupling energy into the ionosphere directly above the epicenter. These perturbations can then create propagating ionospheric disturbances that contribute to ionospheric motion at distant points. Long-range propagation paths of either atmospheric or ionospheric signals generated in the strong-motion region of earthquakes are quite complex, and very few good measurements exist.

Earthquake signals recorded by either ionospheric or infrasonic detection systems can often be assigned to a specific seismic source with the aid of seismic detection instruments. In the absence of corroborating information, ionospheric signals are often so modified by atmospheric filtering that their origin cannot be positively identified.

Strong ionospheric disturbances from seismic sources, such as the Alaskan earthquake, can completely obscure signals from other sources for several hours. Smaller earthquakes and convective storms can result in periods of reduced effectiveness for ionospheric monitoring equipment.

Experience shows that diurnal tides and solar radiation, being the predominant sources of ionospheric disturbances, will determine the background noise level of an ionospheric monitoring system. The spurious signals from sources considered in this report could never have a large net effect on the usefulness of such a system, but there may be brief periods when disturbances from these sources will be detrimental to the system sensitivity. There may also be some cases when signals from earth seisms or storms are recorded but the source cannot be positively identified.

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