

BACKSCATTER OF 16 Mc/s RADIO WAVES FROM LAND AND SEA

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Summary

Relative backscatter coefficients for 16 Mc/s backscatter from land and sea at elevation angles between 5 and 30° were obtained using a large ground-based sounder at Brisbane. For both land and sea, as the angle of elevation decreases, the backscatter coefficient at first increases smoothly and then decreases suddenly at a certain angle which has been called the knee angle. This angle is about 13° for land, and smaller for sea. For a given angle of elevation above 13°, backscatter from sea is about 10 dB stronger than from land.

The nature of the scattering irregularities is discussed in the light of the experimental evidence, and it is concluded that the main scattering agents are trees and wave crests. An explanation of the knee effect is advanced.

I. INTRODUCTION AND PREVIOUS WORK

Ground backscatter is the process by which radio waves are scattered at the ground so that some of the energy goes back along its original path to the transmitter. This process is used in oblique-incidence sounding of the ionosphere. A pulse of radio energy may undergo backscatter at the ground after one or more reflections from the ionosphere, and the time the echo takes to return is a measure of the range at which backscatter occurs. The various uses of backscatter sounding are outlined by Peterson (1957).

The strength of backscatter echoes depends on the backscatter coefficient at the echoing area of the ground. This coefficient may be expected to vary according to elevation angle and type of ground, and the interpretation of the results of backscatter soundings requires a knowledge of this behaviour.

The backscatter coefficient has been variously defined by different writers, and the definition used here is that given by Cosgriff, Peake, and Taylor (1960),

$$\gamma = \sigma_0 / \sin \Delta,$$

where γ is the backscatter coefficient, σ_0 is the radar cross section per unit area of the surface, and Δ is the angle of elevation of the rays with respect to the mean level of the terrain.

The radar cross section occurs as a factor in the radar equation (Clapp 1946; Shearman 1956; Cosgriff, Peake, and Taylor 1960; Nielson *et al.* 1960),

$$P_R = \sigma G^2 P_0 \lambda^2 / (4\pi)^3 R^4,$$

where P_0 = power transmitted,

P_R = power received,

R = range of target,

G = antenna gain, and

σ = radar cross section.

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The radar cross section per unit area of the surface, σ_0 , is a parameter commonly used in radar. The backscatter coefficient γ is related to σ_0 , and is the radar cross section per unit area normal to the direction of propagation at the scattering area (hence the $\sin \Delta$ in the definition). The choice of this definition makes the present work easily comparable with the results of Hagn (1962) and Cosgriff, Peake, and Taylor (1960).

Cosgriff, Peake, and Taylor used centimetric radar (about 30 000 Mc/s) to measure backscatter coefficients. At 16 Mc/s, the measurement is rendered more difficult by the great distances involved and the large size of the antennas required. The most direct method is to mount the antennas on an aircraft; this has been done at 32.8 Mc/s by Nielson *et al.* (1960), and the results were given by Hagn (1962). Sea echoes were found to be about 20 dB stronger than land echoes for the same angle of elevation. The disadvantages of this method include uncertainties due to the motion of the aircraft, difficulty in calibrating the antennas, and radio noise from the aircraft ignition system.

The present method is less direct, as it involves oblique ionospheric reflections between the sounder and the point of ground scatter. The main disadvantage is that the precise nature of the ionospheric reflections cannot be determined. The advantages are that a large antenna system can be used, with high azimuthal directivity and a well-known vertical radiation pattern; that large echoing areas at great ranges can be investigated; and that the fading of the backscatter echoes can be attributed to effects in the ionosphere and at the target area, and not to the motion of the sounder.

Previous observations using ground-based sounders have been qualitative, and gave conflicting results. Villard and Peterson (1952*a*, 1952*b*) working at 3–30 Mc/s, and Shearman (1956) at 10–27 Mc/s, found no noticeable difference in echo amplitude between land and sea echoes, while Ranzi and Dominici (1959) at 22.3 Mc/s estimated that sea echoes were perhaps 10 dB stronger than land echoes of comparable range.

II. EXPERIMENTAL TECHNIQUE

In the present investigation, the 16 Mc/s backscatter sounder at Brisbane was used. It has been described by Thomas and McNicol (1960). It employs an array of four horizontally polarized Yagi antennas mounted half a wavelength above the ground, the whole array being rotatable in azimuth. The antennas were directed to the east and to the west, to obtain echoes from the sea and the land in turn. Rectangular pulses of 600 μ s duration were transmitted, with a pulse repetition frequency of 25 pulses per second and a peak power of 5 kW. Backscatter echoes to a range of 4500 km were displayed on an oscilloscope screen by brightness modulation of the time-base trace, and were recorded on film moving continuously past the trace at $\frac{1}{2}$ in/min. An example is shown in Plate 1, Figure 1. The strong horizontal lines are at intervals of 1000 km. The range-time display thus generated was modified by the use of a swept-gain unit, by means of which the receiver gain was varied through 40 dB in a series of 12 stages. This cycle was repeated every minute, as shown in Plate 1, Figure 2.

Neglecting any variation in range during one gain sweep, we can regard each frame of the swept-gain records as a range-amplitude display, similar in format to a type A presentation of the echo pulse, with a logarithmic amplitude scale. Successive pulses are returned with different shapes as a result of fading, which makes ordinary type A presentation difficult to interpret. The present method provides a useful type of averaging of the echo shape, and some estimate of the fading rate can also be obtained.

Plate 1, Figure 2, is a record of backscatter from the sea to the east of Brisbane. The regular fading (about 0.8 c/s) is fairly typical of sea scatter. It is constant in phase across the range spread of the echo, and appears in both the $1F$ echo (leading edge at 1300 km), backscattered after one hop via the F region of the ionosphere, and the $1E_s$ echo (leading edge at 700 km), backscattered after propagation via the sporadic E layer.

Backscatter echoes from the land fade less regularly, as illustrated in Plate 1, Figure 1, where the $1F$ echo was backscattered at a range of 1300 km to the west of Brisbane.

Backscatter records for comparison with calculations were carefully selected to minimize the uncertainties due to the unknown ionospheric path of the echoes. The following criteria were adopted:

- (1) E_s -propagated echoes should not be present.
- (2) Both backscatter and vertical-incidence data should be simultaneously available and clearly recorded.
- (3) Travelling ionospheric disturbances should not be present. These could usually be detected on the records, if they were present.
- (4) Radio interference should be at a minimum.
- (5) D -region absorption should be negligible.
- (6) The F region should approximate to a simple parabolic layer.

Conditions (5) and (6) were best fulfilled in the late afternoon.

After suitable records had been selected, $1F$ echoes only were used for analysis, and the peak echo power only was considered, as this could be calculated with greater certainty than other parts of the echo pulse.

III. CALCULATION OF ECHO POWER

For comparison with the range-amplitude records, the relative peak power of a given backscatter echo was calculated using a method outlined by Shearman (1956). The backscatter coefficient was assumed to be independent of angle of elevation and type of terrain. This assumption is not true, but when the results of calculations based on this assumption were compared with the corresponding observed backscatter records, the relative backscatter coefficient, at the calculated angle of elevation and for the given terrain, could be deduced.

The calculation involves the vertical radiation pattern of the antenna array, which had been measured by means of a balloon-borne transmitter (Steele 1965).

The calculation also requires a knowledge of the base height, semi-thickness, and critical frequency of the ionospheric layer, which is assumed parabolic. The base height and critical frequency were obtained from vertical-incidence data taken at Brisbane, and extrapolated east and west along the paths of the backscatter echoes. This extrapolation was achieved by assuming that the ionospheric parameters remain fairly constant at a given subsolar point as the Earth rotates. In particular, it was assumed that the parameters at the control point of the skip ray, say 1000 km east of Brisbane, were the same as those measured by vertical-incidence sounding at Brisbane at some time up to an hour later. The actual time lag applicable was determined by superimposing a set of theoretical curves, of minimum calculated echo range versus corresponding ground range to the control point, upon a curve giving minimum observed echo range versus Eastern Australian Standard Time at Brisbane. The point of intersection of the appropriate curves identified the particular backscatter record to be paired with a given vertical-sounding record.

For east-west propagation, magneto-ionic splitting of the echoes was not resolvable on the records, as the ordinary and extraordinary rays formed echoes at about the same range, with a sharp leading edge. The range of this leading edge enabled the semi-thickness of the layer to be deduced from the base height and critical frequency, using charts based on the equations of Appleton and Beynon (1940).

Owing to skip-distance focusing, most of the power of a backscatter echo is associated with rays very close to the skip ray. The angle of elevation of this ray at the ground, Δ_s , was obtained in the course of the calculations. The difference (in dB) between the calculated and observed peak echo powers was taken as a measure of the relative backscatter coefficient γ at the angle calculated and for the given terrain.

IV. RESULTS

As the critical frequency decreased in the late afternoon, Δ_s decreased, and γ was plotted against Δ_s . As most of the power is associated with rays at angles near Δ_s , γ was effectively plotted against Δ . Figure 1 shows two such graphs, the upper curve being for backscatter from the sea to the east of Brisbane, and the lower curve for backscatter from the land to the west. A total of 12 curves for sea and 9 for land were obtained, although not all showed such definite trends as in Figure 1.

The horizontal scale for Δ is reversed in Figure 1 because it has been conventional in the literature to plot the angle of incidence from left to right, and the angle of elevation Δ from right to left. This has the advantage that measurements at normal incidence, which may be useful for calibration purposes, can be plotted on the left. Hagn (1962) also follows this convention.

There are three main results, namely: (1) at angles of elevation near 20° , sea scatter is stronger than land scatter by about 10 dB; (2) as the angle of elevation decreases, the backscatter coefficient decreases rapidly at some angle near grazing incidence, known as the knee angle; and (3) at angles of elevation above this knee angle, the curves for both sea and land follow a law approximating to $\gamma \propto 1/\sin^2\Delta$. These three points will now be discussed in more detail.

(1) The curves above 15° are approximately parallel, but there is a 10 dB difference between land and sea. This difference is much greater than any likely errors in the antenna patterns or in the choice of the ionospheric parameters, and is therefore largely due to a difference in γ . The asymmetry of east and west propagation at sunset could have conceivably affected the result, so a sample calculation was done using morning data, when the asymmetry was reversed; sea scatter was still stronger than land scatter by about 10 dB. Morning calculations were not as reliable as those of the evening, owing to the presence of the morning F_1 layer, which rendered the Appleton and Beynon (1940) formulae not strictly applicable. Nevertheless, the morning results were sufficiently accurate to show that the difference in γ for land and sea is independent of ionospheric asymmetry.

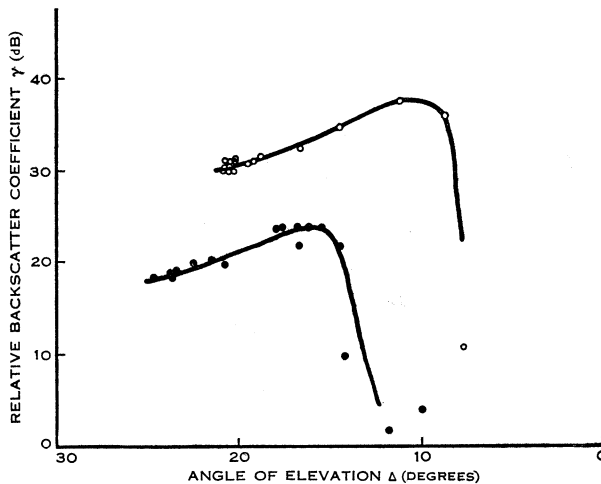


Fig. 1.—Relative backscatter coefficient as observed on two days. ○ March 23, 1963, sea; ● April 14, 1963, land.

(2) For most of the curves obtained, as Δ decreases γ decreases suddenly at some angle. This effect, also described by Hagn (1962), is called the knee effect. For land, the angle at which the knee occurs is usually between 14 and 12° . In view of the closeness of these limits, the variation is likely to be due to experimental errors, and 13° may be taken as the knee angle for the given terrain.

Two possible doubts arise concerning the reality of the knee. First, the knee may be due to failure of the propagation path. As the critical frequency falls, Δ_s approaches zero, and the echo vanishes as virtually all rays penetrate the ionosphere. This failure may appear to be a knee if the calculations erroneously give values of Δ_s that are too large. But investigations show that Δ_s would not be in error by as much as 13° . In the present work, as Δ_s decreases, the most rapidly varying ionospheric parameter is the critical frequency. Above 10° , assuming other ionospheric parameters to be constant, an error of ± 0.2 Mc/s (as is likely) would give rise to an error of only $\pm 1^\circ$ in the calculated value of Δ_s . Below 10° , the rate of change of Δ_s with critical frequency increases, and when Δ_s is 5° , an error of ± 0.2 Mc/s may introduce an error of $\pm 5^\circ$ in Δ_s .

Secondly, the terrain may not be uniform to long ranges. Perhaps at some range there is an abrupt change in the terrain, so that γ becomes very small at long ranges (corresponding to low angles of elevation); but reference to maps shows that there is no range at which the terrain in the illuminated region changes abruptly.

For sea, the knee angle is less constant than for land, and in half of the cases plotted the knee (if it existed) was at an angle below those for which data were available. When the knee was observed, it occurred at angles ranging from 14 to 9°. The presence of a knee at 14° shows that in some cases, at least, the knee is a real effect, although at angles below 10° it could possibly be due to errors in calculating Δ_s as mentioned above. Probably the knee is always present, and the knee angle varies according to the state of the sea.

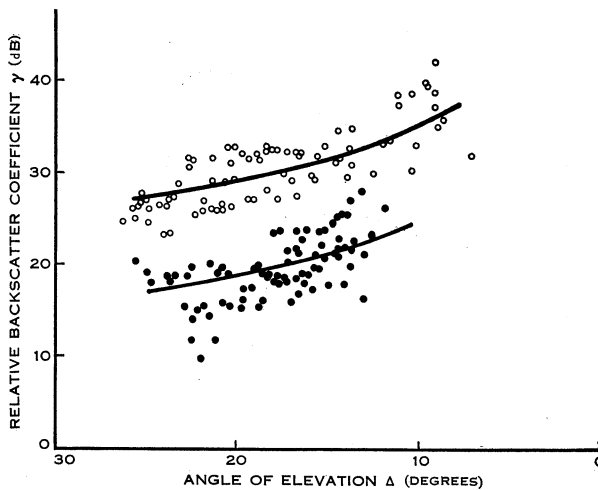


Fig. 2.—Variation of relative backscatter coefficient with elevation angles above the knee. The curves superimposed represent the function $\gamma \propto 1/\sin^2\Delta$. ○ sea; ● land.

(3) The points plotted for various days are collected in Figure 2; points which fell below the knee are omitted. The curves superimposed on the points represent the relation $\gamma \propto 1/\sin^2\Delta$. For both sea and land echoes, this fitted better than $1/\sin\Delta$ or $1/\sin^3\Delta$, although on individual days one of the latter relations sometimes fitted better. In Figure 2, the scatter of points about their respective means is not as large as may appear, as the γ scale is merely relative. Owing to day-to-day changes in transmitter output, sea roughness, receiver gain, and oscilloscope brightness, the points for various days probably have slight zero errors differing from one day to the next, and therefore can legitimately be moved up or down the γ axis for better agreement. When this was done, it was found that if indeed $\gamma \propto 1/\sin^2\Delta$, the scatter of points falls within 3 dB of the curves of Figure 2. This is about the accuracy to be expected if the probable errors are 2 dB in reading the echo power and 1 dB in calculating it.

V. THE NATURE OF THE SCATTERING IRREGULARITIES

At any range and time, the intensity of a backscatter echo depends on the density of scattering irregularities on the ground, and also on the extent to which the individual echoes from these irregularities reinforce one another on arrival at the receiver.

In the work described here, the instantaneous echoing area was a portion of a circular annulus about 100 km wide, and about 15° in azimuthal extent, corresponding to a length of about 250 km at a range of 1000 km. This represents quite a large sample of the terrain, much larger than that sampled by Nielson *et al.* (1960). In their work, any large irregularities such as mountains had a marked effect on the echo strengths, and for the sake of clarity only comparatively smooth surfaces were selected when deriving the backscatter coefficient. In the present work, that restriction is not necessary and, in fact, not possible. The echoes received contained components from both large and small irregularities. This may explain why the backscatter coefficient for land here, and in Ranzi and Dominici (1959), was only 10 dB below that for sea, whereas in Hagn (1962) it was 20 dB below.

The individual scatterers may be assumed to be upright objects such as trees and wave crests (Goldstein 1951; Katz and Spetner 1958). This assumption is supported by the following observations:

(1) The observed relationship $\gamma \propto 1/\sin^2 \Delta$ shown in Figure 2 is consistent with a theory of backscatter from vertical cylinders proposed by Katz and Spetner (1958). The theory, as quoted by Cosgriff, Peake, and Taylor (1960), is of the form

$$\gamma \propto 1/\sin \Delta (A + \sin^2 \Delta),$$

which, depending on the value of A , will be between $1/\sin \Delta$ and $1/\sin^3 \Delta$. Shearman (1956) predicted the equivalent of $1/\sin \Delta$ for a model consisting of hemispherical bosses on a flat conducting plane. The observed relationship therefore suggests that the scatterers are more rugged than hemispheres. Trees, which approximate to vertical cylinders, and wave crests, which are roughly conical, would seem to fulfil this requirement.

(2) The results in Figure 2, in which γ increased as Δ decreases, are similar to Hagn's (1962) results for vertical polarization, but quite different from his results for horizontal polarization, which show the opposite trend. In the present work, the polarization of the outgoing waves is initially horizontal, but becomes elliptical at the echoing area after propagation through the ionosphere. It seems probable that the backscatter echoes are due largely to the vertical component of the waves at the scattering area. This would be true if the scattering irregularities were vertically polarized.

(3) The fading of backscatter echoes may be attributed largely to the movement of the scattering irregularities. For land, the random fading can be explained in terms of the wind in the trees, as mentioned by Clapp (1946); the phase relationships between the various components of the backscatter echo are continually changing in a random fashion.

For the sea, the regular fading observed is due to the fact, observed by Crombie (1955), that backscatter echoes are most effectively returned by sea waves moving radially with respect to the sounder and of length about half the radio wavelength. Such waves will always exist as components of the complex structure of the sea. A train of such waves behaves as an array, returning echo components in phase with one another.

Sea waves of a given length have characteristic velocities, causing characteristic Doppler shifting of the radio frequency of the echoes, and the fading rate represents the beat between the resulting frequencies. Dowden (1957) observed the regular fading of backscatter echoes from the sea, but his explanation, based on the beat between Doppler-shifted echoes from opposite directions, will not suffice here as the sea is viewed in only one direction. The explanation is probably that, in a Fourier analysis of the sea surface, there will be two components with a wavelength $L = \frac{1}{2}\lambda$. These will have velocities $\pm v$, where

$$v = (gL/2\pi)^{\frac{1}{2}},$$

and g is the acceleration due to gravity. Doppler shifts will be

$$\begin{aligned}\Delta f &= 2v/\lambda \\ &= \pm 0.41 \text{ c/s}\end{aligned}$$

for radio waves of 16 Mc/s. The fading rate would therefore be 0.82 c/s, which agrees with the observed rate.

Such an explanation is in accord with the observations of Ingalls and Stone (1957), who measured the Doppler power spectrum of sea echoes at 18 and 24 Mc/s and found spectrum peaks at the carrier frequency and two narrow sidebands shifted by the appropriate value of Δf . In the present work the carrier frequency component appears to be small, as the fading rate is $2\Delta f$ and not Δf .

VI. AN INTERPRETATION OF THE KNEE EFFECT

It may be possible to explain the knee in the curve for the backscatter coefficient, assuming that the scattering irregularities are upright objects such as trees and wave crests, and that the polarization is effectively vertical at the echoing area.

Explanations have been offered by Hagn (1962) and at u.h.f., by Katzin (1957) and Spizzichino (Beckmann and Spizzichino 1963).

(1) Hagn's first suggestion was that the knee is caused by the absorption of the signal by the ground. He suggested that for vertical polarization, which he found to be more important than horizontal near grazing incidence, absorption could be a Brewster-angle effect. For land, the Brewster angle is about 17° for dry land or rocky soil, and for sea the pseudo Brewster angle for 16 Mc/s is about 0.5° (Burrows and Attwood 1949). At the Brewster angle, all the energy is absorbed and the reflection coefficient is zero (or nearly zero in the case of the pseudo Brewster angle). In the present work, however, these angles respectively are too high and too low to explain the knee. The Brewster angle is defined for smooth surfaces, but here we

have a situation where the irregularities cannot be neglected and, in fact, appear to be essential to the backscattering mechanism.

(2) Hagn's second suggestion was that there is some critical angle below which the energy is practically all reflected in the forward direction and so is not observed in the back direction.

(3) Katzin's suggestion, slightly modified by Spizzichino, is that, if H is the height of the scattering irregularities above the mean horizontal plane, the knee angle Δ_k could be defined as $\Delta_k = \lambda/4H$. For Δ less than Δ_k there would always be destructive interference between the direct field and that reflected by the surface surrounding the scatterer.

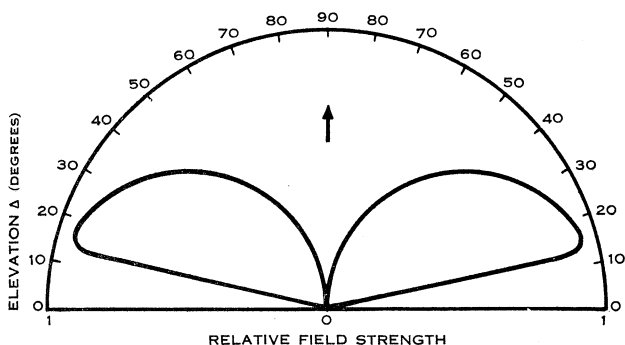


Fig. 3.—Vertical-plane radiation pattern of a short vertical cylinder standing on a smooth horizontal surface for which the Brewster angle is 17° . The arrow indicates the polarization of the cylinder.

In the present work, destructive interference is a possibility, as vertically polarized waves can exhibit phase reversal on reflection at low angles. But the formula given for Δ_k does not satisfactorily predict the knee angle. To make Δ_k equal to 13° , H would have to be about 17 m, which is too large for the trees in the area considered. To make Δ_k less than 10° , as for backscatter from the sea, H would have to be impossibly large. In contrast, Katzin (1957) concluded from his observations that H had to be much less than the measured wave height to account for Δ_k .

The suggestion made here is a combination of (1), (2), and (3). For the land, the scatterers may be regarded as vertical cylinders standing on a smooth horizontal plane. Consider the cylinders first as receiving antennas. The energy reaching a scatterer is a combination of direct and ground-reflected rays. For vertical polarization, the ground-reflected component is small above the Brewster angle and falls to zero at the Brewster angle, so the energy received is largely due to the vertical component of the direct rays. The reception pattern in the vertical plane will be similar to that of an elementary dipole in free space, provided that H is small compared with λ . Below the Brewster angle there is a phase reversal on reflection and the amplitude of the reflected wave increases. The resultant electric field close to the surface is then small. This may account for the sharpness of the knee and the fact that the knee angle occurs some degrees below the Brewster angle. Allowing for the

Brewster-angle effect, the reception pattern of a vertical cylinder will be like that shown in Figure 3.

Now consider the cylinders as transmitting antennas. The radiation pattern for transmission will be the same as that for reception. As backscatter echoes require both reception and transmission by the scatterers, they are doubly affected by the radiation pattern of the scatterers.

On this view, the knee angle would not greatly depend on the height of the trees. All that is required is that H should be appreciably less than $\lambda/4\Delta_k$, that is, less than 17 m when $\Delta_k = 13^\circ$, and this is true of the vegetation in central Australia.

For backscatter from the sea, the pseudo Brewster angle is too small to account for the knee if a smooth horizontal reflecting plane is assumed. But, as noted above, in backscatter the radio waves effectively "see" only those sea waves with crests $\frac{1}{2}\lambda$ apart. It seems likely that between these crests, the radio waves "see" only the broad trough of a "pure" sea wave of length $\frac{1}{2}\lambda$. We should therefore consider the scatterers to be sharp wave crests rising out of a smooth, curved reflecting surface. It is possible that rays of elevation, say 10° , undergo reflections in the wave troughs and reach the wave crests after reflection at angles below the pseudo Brewster angle, causing destructive interference at the crests. In this case the knee angle would depend on the theoretical wave profile between crests, which would be a function of H and λ .

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BACKSCATTER FROM LAND AND SEA

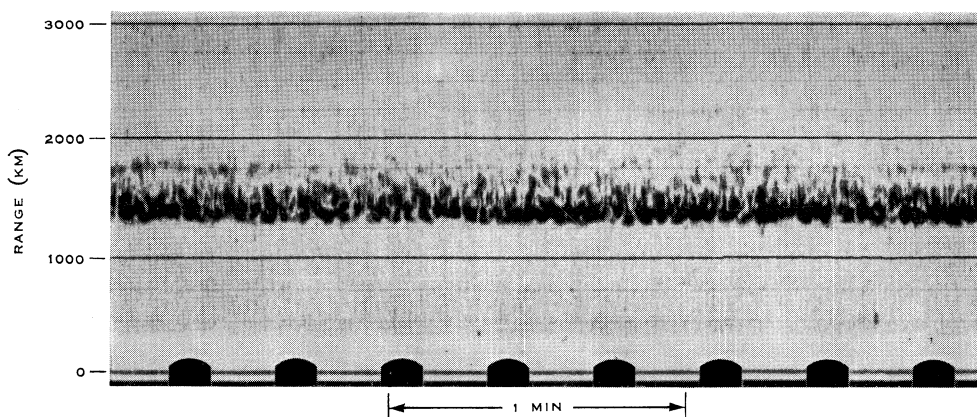


Fig. 1.—Backscatter echoes from land, April 9, 1963, at 1800 hr, with antennas directed westwards. The leading edge is at 1300 km, and propagation is by one hop in the F region ($1F$).

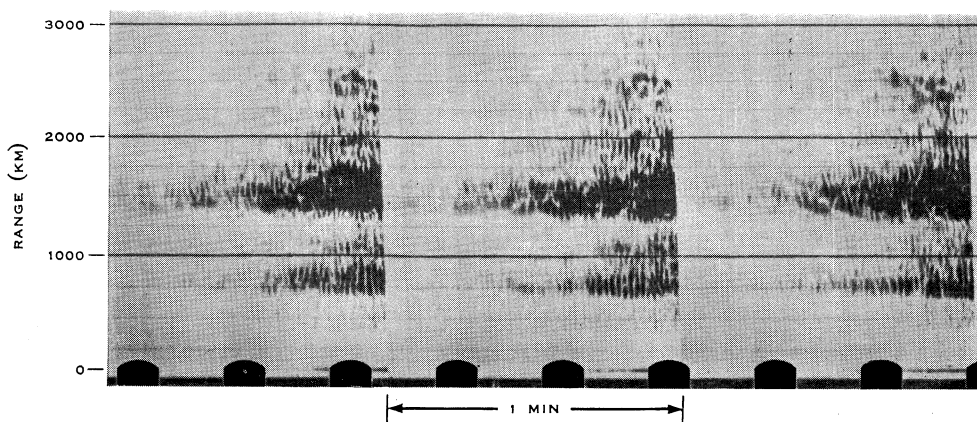


Fig. 2.—Backscatter echoes from sea, April 5, 1963, at 1620 hr, with antennas directed eastwards. The duration of each gain sweep is 1 min, and the fading rate is about 48 cycles/min. The echoes with leading edge at 700 km are $1E_s$, and those at 1300 km are $1F$.

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