BACKSCATTER ECHO FROM LAND AND SEA AT 16 MHz

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Summary

Comparison is made of absolute backscatter coefficients for land and sea measured at elevation angles between 8° and 30° at Brisbane. An explanation of the wide disparities that exist between individual measurements is given in terms of the presence or absence of various sizes of trees.

I. Introduction

A pulse of radio energy transmitted at an oblique angle may undergo backscatter at the ground (from land or sea) after one or more reflections from the ionosphere. Some of the energy returns along its original path to the transmitter and the time that the echo takes to return is a measure of an equivalent free space range at which the backscatter occurs.

The strength of the backscatter echo depends upon a parameter known as the backscatter coefficient, which varies with the elevation angle, and on the roughness and composition of the surface where backscatter takes place. The power P_{R} of a signal received by a radar after transmission of a signal of power P_{T} may be expressed for the case of a curved Earth and a curved parabolic layer of the ionosphere as (Shearman 1956)

$$P_{\mathrm{R}} = \frac{P_{\mathrm{T}} G^2 \lambda^2}{64\pi^3} R \sin(D/R) A_0\, \theta_{\mathrm{B}} \int_{D-\delta D}^{D} F^2 \,\mathrm{d}D\,, \tag{1}$$

where G is the gain of the antenna used, R is the radius of the Earth, D is the ground distance from the scattering source, F is the factor representing ionospheric focusing and absorption, θ_{B} is the beamwidth of the antenna to half power, and A_0 (often denoted σ_0) is a parameter representing the radar cross section per unit area of the ground surface. δD is the interval of ground range from which, at a given instant, echoes are arriving. (This implies that the interval of ground range corresponds to transit times lying within an interval equal to the duration δt of the emitted pulse. It has been shown that $\delta D = \frac{1}{2} c\, \delta t \sec \Delta$, where Δ is the angle of elevation.)

The backscatter coefficient γ can also be related to A_0 by the definition given by Cosgriff, Peake, and Taylor (1960)

$$\gamma = A_0 \operatorname{cosec} \Delta\,. \tag{2}$$

Work on direct backscatter at 32·8 MHz using an aircraft was done by Nielson *et al.* (1960) and was later revised by Hagn (1962). They found no variation of backscatter coefficient with elevation angle for sea at vertical polarization but found land echoes

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20 dB weaker than sea echoes for the same elevation angle. Ranzi and Dominici (1959), working at $22 \cdot 3$ MHz, and Steele (1965) at 16 MHz, used ionospheric sounders and estimated that land echoes were 10 dB weaker than sea echoes.

In this paper a method is described for measuring the absolute value of backscatter coefficient by using an ionospheric sounder. The antenna has a narrow azimuthal beam and its vertical radiation pattern on an actual site is known. The sounder is located about 40 km from the coast. The land (towards the west) and the sea (towards the east) extend for several thousands of kilometres without interruption.

II. Experimental Technique and Recording

The highly directive backscatter sounder of Thomas and McNicol (1960) transmitted at 16 MHz from Brisbane (lat. $27 \cdot 5°$ S., long. $152 \cdot 9°$ E.) using a pulse of 800 μ sec and a repetition frequency of $8 \cdot 33$ sec^{-1}. The antenna comprised an array of four three-element Yagi antennas. The beam was aimed either due east or due west. The Brisbane receiver was used to record a range–amplitude display of the signal on a film moving continuously past the trace on an oscilloscope screen displayed by brightness or blackout modulation of the time-base trace. The gain of the receiver was decreased in 12 stages of about 3 dB each (maximum gain 36 dB) over a period of 1 min. A measurement of elevation angle was made (Mir 1969) simultaneously at Amberley (lat. $27 \cdot 7°$ S., long. $152 \cdot 7°$ E.).

III. Calculation of Absolute Backscatter Coefficient

The modified radar equation from equation (1) and equation (2) may be expressed as

$$P_{\mathrm{R}} = \frac{P_{\mathrm{T}} G^2 \lambda^2}{64\pi^3} R \sin(D/R) \theta_{\mathrm{B}} \, \gamma \sin \Delta \int_{D-\delta D}^{D} F^2 \, \mathrm{d}D . \tag{3}$$

It is clear that, in order to determine γ, measurement must be made of P_{R}, P_{T}, G, D (or the equivalent range p'), and F.

(a) *Power Received Back at Antenna Terminals* P_{R}

To obtain the absolute value of P_{R} it is necessary to calibrate the receiver, including the transmit–receive (TR) switch. For this purpose, a signal generator was first connected to the TR switch input and, using a known output power, the output of the TR switch, i.e. at the receiver input terminals, was measured with an oscilloscope. The signal generator was then connected to the receiver input terminals with its output adjusted to furnish the same power to the receiver as in the previous measurement. With the swept-gain unit in operation and with a film moving at normal recording speed, a film record was then made using either (1) positive intensity modulation or (2) reverse intensity modulation (blackout), according to which was subsequently to be used in recording backscatter. In addition, a direct measurement was made of the respective attenuations introduced by the 12 stages of the swept-gain unit. The processed film was then examined to determine at which stage of the swept-gain unit this calibration trace was only just visible. Subsequently recordings of backscatter could then provide absolute measurements of received power by comparing the stage on the backscatter record at which the trace was again just visible. As the stages were approximately 3 dB, this procedure allowed a determination within a margin of about ± 1 dB.

(b) *Transmitted Power Measured at Antenna Terminals* P_T

The measurement of P_T was accomplished using an r.f. ammeter and a known dummy load. The duration and shape of the transmitted pulse were measured using a Tektronix oscilloscope to observe the output of a diode sampler in the transmitter output. The pulse was fairly rectangular and it was safe to assume that P_T was constant during the period of the pulse and zero at all other times. The determination of peak transmitted power P_T requires the average power $\langle P \rangle$ and the duty cycle ω, which are related by $P_T = \langle P \rangle / \omega$. In order to calculate $\langle P \rangle$ the r.f. ammeter was connected in series with the transmission line to check that it had no effect on the intensity of the ground backscatter echoes observed on an oscilloscope. The transmission line was then replaced with a known dummy load (50 Ω) connected across the transmitter, and the ammeter reading was found to be quite close to the previous reading. This showed that the dummy load was matched with the output impedance of the transmitter and had the same impedance as that of the transmission line. The average power RI^2 could then be determined from the reading I of the ammeter and the known dummy load R. This measurement was further checked by measuring the potential difference across the dummy load with an oscilloscope of suitable bandwidth. The absolute accuracy of P_T was about $\pm 8\%$. In order to check any change in P_T during recording, the r.f. ammeter was left connected and its reading was regularly checked.

(c) *Antenna Gain* G

The experimental arrangements to find the gain G of the array were the same as those used by Steele (1965) with the exception that a standard half-wave dipole at a distance of 10 wavelengths from the array was used. A tethered balloon carrying a 16 MHz crystal-controlled oscillator modulated by a 130 Hz signal was used to radiate energy and the same receiver was used to detect the resulting signal from the array and the dipole. Losses introduced by the dipole antenna, which was of different impedance from that of the array, and by the ~ 180 m long transmission line connecting the dipole were taken into consideration. The level of the signal was read using a Tektronix oscilloscope. The height of the balloon and theodolite readings were used to calculate the elevation angle of the pilot transmitter with respect to the array and the dipole. The array and the dipole were also faced in two different directions, 80° and 260° magnetic, in order to calibrate the array from geographical east and west respectively. These are the directions from which all the records used in finding the absolute backscatter coefficient from land and sea were taken.

The gain of the array at a particular elevation angle G_Δ may be expressed as

$$G_\Delta = G_A + G_S,$$

where G_A is the gain of the array with respect to the standard in decibels and G_S is the gain of the standard in decibels. The antenna gain is plotted against elevation angle in Figure 1 for eastern and western directions. The difference in patterns may be attributed to the different ground profiles between the array and the pilot transmitter.

(*d*) *Relation between Ground Distance D and Measured Equivalent Range p'*

The distance D is not measurable direct but must be computed using the measured equivalent range p' and the ionospheric parameters in the reflecting region. For this purpose the formula of Shearman (1956, equation 12) based on that of Appleton and Beynon (1940) was used. This neglects the geomagnetic field and assumes a parabolic relation between electron density and height and a horizontally stratified ionosphere. Around sunset the ionosphere is tilted (Mir 1969) and the formula must be modified. From the measurements of elevation angle and equivalent range, the tilt angle was estimated and the necessary corrections applied.

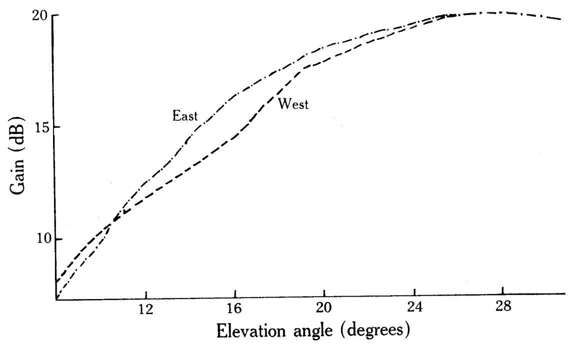

Fig. 1.—Gain of array measured from eastern and western directions.

In applying Shearman's formula, three ionospheric parameters are required: h_0F_2, the equivalent base height, in which the electron density is to be taken as zero, f_0F_2, the critical frequency, and y_m, the semi-thickness of the layer. The first two parameters can be obtained from vertical incidence ionograms. Such ionograms were available only for Brisbane but values for points due east and west of Brisbane were estimated by assuming the ionospheric configuration to travel unchanged from east to west with the speed of the sunset line ($\sim$ 1479 km hr^{-1}). In estimating parameters for the reflection point the fact that its distance is not known presents a difficulty. However, this can be determined with sufficient accuracy using Shearman's method (1956, Fig. 10) which involves the calculation of a correction term to be subtracted from p'. The error in timing due to this approximation is unlikely to exceed 2 min and ionograms are available only at intervals of 2 min or greater.

The third parameter y_m was estimated by the method of Booker and Seaton (1940) and also by that of Steele (1965), which depends on the trial and error selection of a value of y_m that will yield the measured value of p' using the approximate values of h_0F_2 and f_0F_2. The two methods were found to give consistent results, within about 10%, and a weighted mean was used in the final computations. It is estimated that an error of ± 5% would result in an error of ± 1 dB in the calculated backscatter coefficient.

(e) *Focusing Factor F*

In long distance propagation via the F layer an important factor is the focusing of the rays as a result of the convergence or divergence (defocusing) of the originally neighbouring rays. A ray from T (Fig. 2) and the neighbouring rays may form a rectangular pencil of vertical width $\mathrm{d}\Delta$ and horizontal width $\mathrm{d}\phi\cos\Delta$ at unit distance from T. The fraction of the energy contained at a unit distance is $\mathrm{d}\Delta\,\mathrm{d}\phi\cos\Delta$ of the total energy radiated. This energy when reflected from the ionosphere, returns to ground at a distance D and, assuming equal arrival and departure angles, the vertical

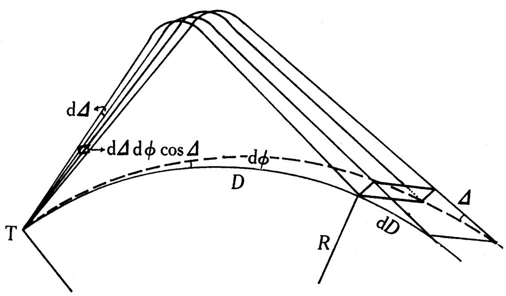

Fig. 2.—Ray paths for a curved Earth and a thick curved ionospheric layer.

beamwidth at the receiver is $\mathrm{d}D\sin\Delta$ and horizontal width $R\sin(D/R)\,\mathrm{d}\phi$. The cross section area of the beam at the receiver is $\mathrm{d}D\sin\Delta\, R\sin(D/R)\,\mathrm{d}\phi$. Theoretically no energy is lost from a beam and the relative energy density received at distance D is the fraction of the energy radiated between Δ and $\Delta+\mathrm{d}\Delta$ divided by this area. For a single-hop ray the focusing factor F is the ratio of the power received per unit area to the power transmitted. Thus

$$F=\frac{\mathrm{d}\Delta\,\mathrm{d}\phi\cos\Delta}{R\sin(D/R)\,\mathrm{d}\phi\,\mathrm{d}D\sin\Delta}=\frac{1}{R\sin(D/R)\tan\Delta\,\mathrm{d}D/\mathrm{d}\Delta}. \tag{4}$$

This expression, although differently arranged, is identical with that given by Davies (1965). However, equation (4) is not valid at the skip distance since, for minimum D, $\mathrm{d}D/\mathrm{d}\Delta$ is zero. In order to calculate the focusing factor at skip distance and considering only one-hop propagation, Bixby's (1953) expression for the magnitude of the electric field at the skip distance for a short vertical antenna radiating at a rate of 1 kW may be expressed as power density Pr

$$Pr=\frac{9\cdot185\times10^{-7}\cos\Delta}{4\pi\lambda^{\frac{1}{3}}\sin(D/R)\{\sin\Delta\,(\partial^2D/\partial\Delta^2)\}^{\frac{2}{3}}}\qquad \mathrm{W\,m^{-2}}.$$

For radiating power of 1 kW, the focusing factor at the skip distance F_{s} may be expressed as

$$F_{\mathrm{s}}=\frac{9\cdot185\times10^{-10}\cos\Delta}{\lambda^{\frac{1}{3}}\sin(D/R)\{\sin\Delta\,(\partial^2D/\partial\Delta^2)\}^{\frac{2}{3}}}. \tag{5}$$

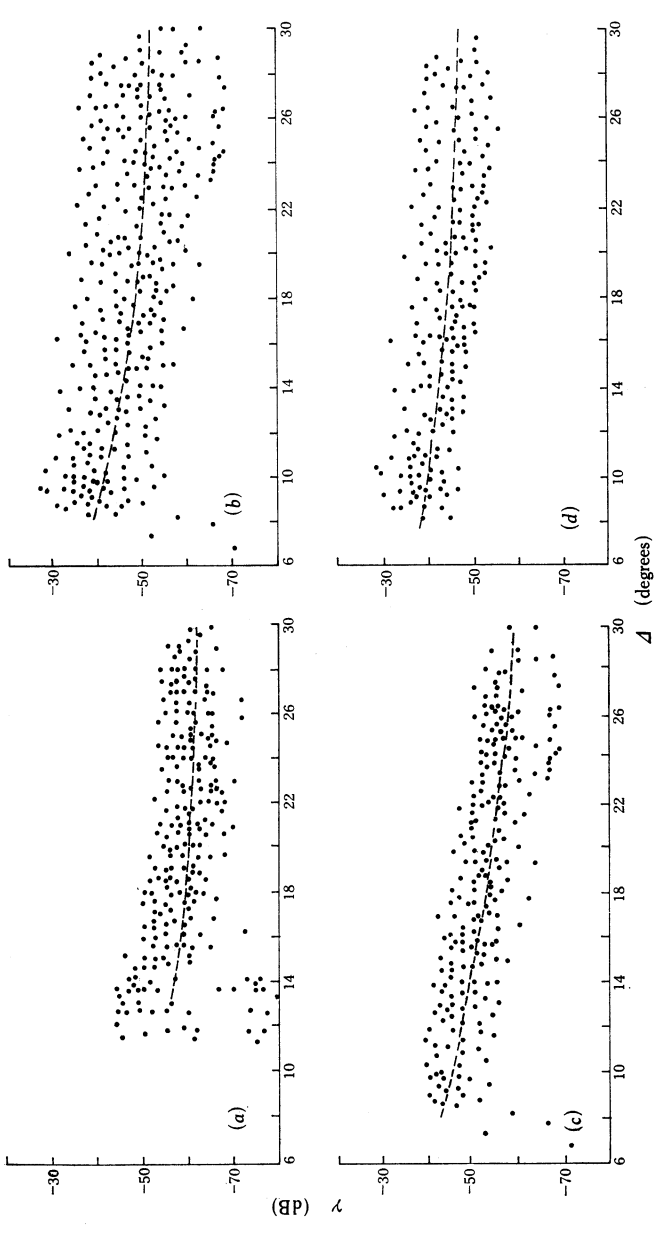

Fig. 4.—Dependence of the backscatter coefficient γ on the elevation angle Δ for (a) land, (b) sea, (c) calm sea, and (d) rough sea.

Equations (4) and (5) were computed to find the focusing factors beyond skip distance and at skip distance which were further used to find the total power received for a backscatter coefficient $\gamma = 1$.

Various authors (Shearman 1956; Steele 1965) when calculating the power backscattered from the ground have neglected deviative absorption in the ionosphere. In order to investigate this absorption, an equation due to Bixby (1953, equation 4—12) was evaluated for a typical case of $y_m = 100$ km, $h_0F_2 = 200$ km. Figure 3 is a plot of the energy absorbed at various elevation angles. About 23% of the energy is absorbed from low angle rays and about 42% from high angle rays. In the present work, Bixby's method of correcting for this absorption has been used.

The difference between the measured power and the calculated power (in dB) is the backscatter coefficient γ (dB).

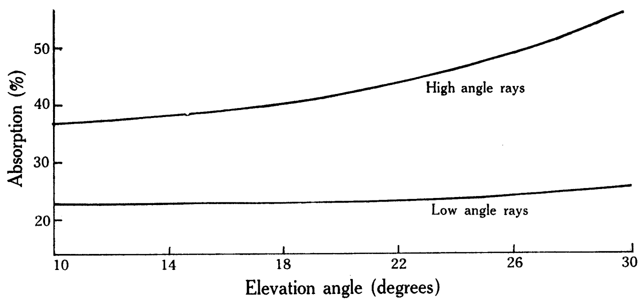

Fig. 3.—Percentage of deviative absorption at various elevation angles.

IV. Results

The results of some 100 hr of observations during 1964–6 are presented in Figures 4(*a*) and 4(*b*). Figure 4(*a*) shows the absolute backscatter coefficient γ as a function of elevation angle Δ for the westerly direction (land backscatter) and Figure 4(*b*) for the easterly direction (sea backscatter). The Commonwealth Bureau of Meteorology at Brisbane supplied data on the condition of the sea and the windspeed at sea level at Norfolk Island and New Caledonia. The area between these islands was the main source of backscatter for the easterly direction (sea). The latter group of observations based on the information provided by the Bureau of Meteorology was roughly divided into two groups "calm conditions" (Fig. 4(*c*)) and "rough conditions" (Fig. 4(*d*)) taking 10 knots wind speed as the criterion of determination between the groups.

Comparison of Figures 4(*c*) and 4(*d*) suggests that the 30 dB spread in values of backscatter coefficient for a given elevation angle, as shown in Figure 4(*b*), is at least partly due to variation in the character of the sea surface. In spite of this spread, there is evidence of a systematic trend with elevation angle, the mean value (Fig. 4(*b*)) decreasing from about −40 dB at 8° to about −50 dB at 30°, with an increase of 5 dB on all values for a rough sea (Fig. 4(*d*)) and a decrease of 5 dB for a smooth sea (Fig. 4(*c*)). It should be noted that there is a considerable spread of values also for land backscatter, with a mean of about −60 dB. There is no clear indication of dependence on elevation angle but there may be a slight fall (5 dB) between 12° and 30°. The increased spread of values at low angles is of interest.

V. Discussion

The overall results just presented are generally consistent with those obtained by Steele (1965) with the same equipment. Steele reported a difference of 10 dB in γ between calm sea and land; and of 20 dB between rough sea and land. The occurrence of a knee in the relationship between elevation angle and γ for sea, which was reported by Steele at an angle between 9° and 14°, was not confirmed by the present observations. It is possible that the exceptionally small values of γ obtained for some low elevations for land backscatter might be evidence for the knee, while the higher values obtained in other cases (sea) could be due to the effect of ionospheric tilts near sunset (Mir 1969).

Ranzi's (1962) results are not inconsistent with those presented here. At 4 MHz he found a coefficient 29 dB higher for a very rough sea than for a calm sea, while at 28 MHz the difference had decreased to 12 dB. This effect of frequency may well be related to the saturation effect reported by Davies and Macfarlane (1946) for still higher frequencies. They found that the sea backscatter coefficient ceases to increase with increasing roughness once the wave height reaches about 1 m (corresponding to a wind speed of about 10 knots). In general, conformity with this result is the indication in Figures 4(*c*) and 4(*d*) that the variation with angle of elevation is only about 5 dB for a rough sea, as against 13 dB for a calm sea.

Hagn's (1962) airborne measurements of backscatter at 32·8 MHz relate to vertically polarized waves, in contrast to the horizontal polarization considered here. The results are consistent in order of magnitude; thus Hagn obtained, for land, values between -50 and -70 dB and, for sea, about -40 dB. However, Hagn did not find any dependence on elevation angle in the case of sea backscatter.

Some consideration has been given to an explanation of the wide disparities between individual measurements of ground backscatter in terms of the presence or absence of trees. It is well known that vertical objects scatter well at microwave frequencies. Steele (1966) has investigated the radar cross section of an individual tree at 26 MHz. Steele's measurements refer to a tree on smooth ground. In order to investigate the effect due to the presence or absence of a tree, an expression of the backscatter coefficient γ in terms of a tree on rough ground is derived. The energy coming back to the receiver is scattered from trees as well as from the rough ground. In the general case of rough ground Eaglesfield (1962) has shown that if the effective cross section of a tree on smooth ground is σ_{K}, then on rough ground it could have an effective cross section σ_{T} given by

$$\sigma_{\mathrm{T}} = \sigma_{\mathrm{K}}\, f, \tag{6}$$

where

$$f = \mu_0 \lambda / 2\pi a_0 \sin \varDelta\,,$$

in which μ_0 is the horizontal scale dimension and a_0 the vertical scale dimension of the roughness. Eaglesfield's equation (8) for the cross section of a rough ground in the absence of a tree may be expressed as

$$\sigma_{\mathrm{g}} = \mu_0 \lambda \left\{ 2\pi a_0 \sin \varDelta \left(1 + \frac{\mu_0^2 \cot^2 \varDelta}{a_0^2} \right) \right\}^{-1}. \tag{7}$$

The radar cross section per unit area A_0 may be related to σ_T and σ_g as

$$A_0 = (\sigma_T + \sigma_g)/A_s\,, \tag{8}$$

where A_s, the total area of the ground illuminated, is expressed as

$$A_s = R\sin(D/R)\,\theta_B\,\tfrac{1}{2}c\,\delta t\sec\Delta\,.$$

The ratio D/R being small, $\sin D/R \approx D/R$ and

$$A_s \approx D\,\theta_B\,\tfrac{1}{2}c\,\delta t\sec\Delta\,.$$

From equations (2) and (8)

$$\gamma = (\sigma_T + \sigma_g)/A_s\sin\Delta\,. \tag{9}$$

There is a difference of about 30 dB between γ computed by equation (9) for a tree comparable to that selected by Steele and the value in the absence of a tree. The difference in size of the trees, and hence the difference in radar cross section, may also give rise to a spread of about 30 dB in γ. These factors could explain the major part of the wide spread ($\sim$ 30 dB) in the measurements.

An estimate of the density of the trees may be made to explain the absolute backscatter coefficient measured in the present case. The backscatter coefficient γ for land at 20° is 10^{-6} and A_0 ($= \gamma\sin\Delta$) is about $3\cdot4\times10^{-7}$. The area ($= \sigma_K/A_0$, with $\sigma_K = 15\cdot75$ at 16 MHz) is about $46\cdot3\times10^6\,\mathrm{m}^2$. Trees of cross section σ_K proposed in the present case with a spacing of about 6·8 km apart would give rise to a backscatter coefficient of the order of -60 dB as measured.

It is suggested that the low backscatter coefficient is due to scarcity of trees and that, as the scattering area shifts from vegetated to sand hill country, the coefficient decreases.

VI. Acknowledgments

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