ELEVATION ANGLES OF GROUND BACKSCATTER AT 16 MHz AND LARGE-SCALE IONOSPHERIC TILTS

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Summary

A technique of recording the elevation angle by a phase comparison method is described and applied to ground backscatter echoes at 16 MHz. It is shown that the results may be explained in terms of ionospheric tilts of 1° or 2° near sunset.

I. Introduction

Several methods are at present available to measure the angle of elevation of ionospheric radio waves at receiving stations (e.g. Friis, Feldman, and Sharpless 1934; Ross, Bramley, and Ashwell 1951; Miya 1954; Bain 1961). The present paper describes a phase comparison method and an electronically controlled phase changer. The aim of this project was to measure elevation angle of ground backscatter echoes and to test the extent to which the theory of Appleton and Beynon used by Shearman (1956) and later by Steele (1965*a*) is valid. The pre-sunset and post-sunset results are compared with the theory and the discrepancy is explained by involving a tilted ionosphere.

II. Experimental Technique and Recording

The transmission was carried out at 16 MHz by a highly directive backscatter sounder (Thomas and McNicol 1960) from Brisbane (lat. 27·5° S., long. 152·9° E.). A pulse of 800 μsec with a repetition frequency of $8\cdot33$ sec^{-1} was transmitted using an array of four three-element Yagi antennas. The Yagi array was aimed in a fixed direction, usually to the east or to the west. The calibration of the horizontal and vertical radiation pattern of the antenna system has been treated in detail elsewhere (Steele 1965*b*; McInnes 1966). The same antenna system is used for transmission and reception. The Brisbane receiver is used to record a range–amplitude display of the signal on a film moving continuously past the trace on an oscilloscope screen that is displayed by brightness or black-out modulation of the time-base trace. The gain of the receiver was decreased in 12 steps of 3 dB each over a period of 1 min.

Two similar Yagi antennas, located 5λ ($\lambda = 18\cdot75$ m) apart along an east–west direction on the ground, were used for the measurement of the elevation angle at Amberley (lat. 27·7° S., long. 152·7° E.) about 20 miles from Brisbane. The output of the two antennas was received as shown in the block diagram of Figure 1. In the signal path from one antenna was inserted a continuously-scanned phase changer, which changed its phase uniformly between 0° and 360° in 30 sec. The output of the other antenna and the output of the phase changer were added, amplified, and passed through a gated amplifier that selected a narrow slice (equivalent to 10 km) of the leading edge of the ground backscatter echo. The selected portion of the echo brightened the spot of a cathode ray tube, which was then photographed on a continuously

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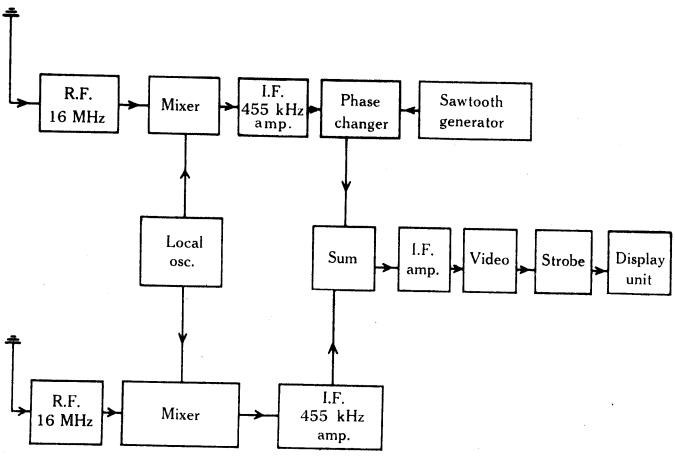
moving 35 mm film. Figure 2 shows a frame of the record that was taken with a strobe width of 10 km at 1828 hr. The echo has its leading edge at about 1810 km. The time marks on the right-hand side of Figure 2 also indicate the beginning and end of each sweep of the phase changer. The resolving power of the system was such that it enabled changes in the elevation angle of $0 \cdot 5°$ to be measured.



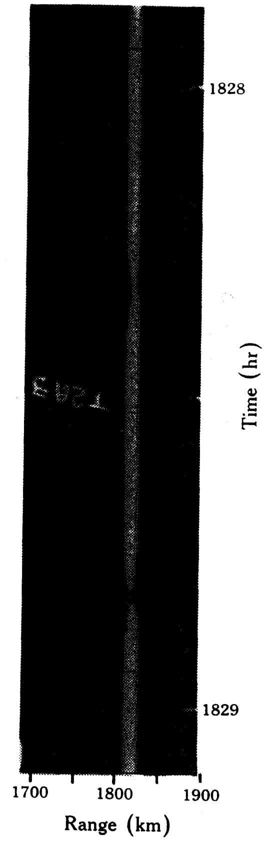


Fig. 1 (*above*).—Block diagram of the elevation angle measuring equipment.

Fig. 2 (*right*).—Elevation angle record for April 12, 1966 at 1828 hr with the antennas directed eastward. The leading edge of the echo is at 1810 km with an elevation angle of $16 \cdot 5°$.

If equal signals arrive at the two antennas, the amplitude of the resultant signal is zero when the phase difference is 180°, but if the two signals are not of the same amplitude the resultant amplitude will be minimal but not zero when the phase difference is 180°. The amplitudes of radio waves, originating from the same source and received via the ionosphere at two antennas some distance apart, exhibit a certain amount of independent fading (Whale 1954). In the present case with antennas only 5λ apart it was expected that the position of the minimum would be a reliable indicator of the angle between the direction of propagation of the waves and the straight line joining the antennas. The elevation angle corresponding to the actual leading edge of the backscatter echo can best be measured by isolating a very narrow region, but this presented problems technically. The minimum with a 20 km strobe was broad and not well defined, while the overlap of rays with higher and lower angles of elevation gave a broad minimum. In some cases independent fading gave several apparent minima. In the case of a strobe width of 10 km the minimum was better defined and there was less independent fading. The variation of amplitude made it necessary to observe several frames to measure the average angle of elevation. The signal from a strobe width of less than 10 km was usually too weak to be recorded in the presence of noise.

Most of the records from eastern or western directions were taken between 1600 and 2100 hr local time. In some cases the elevation angle changed by 15° in 2 hr.

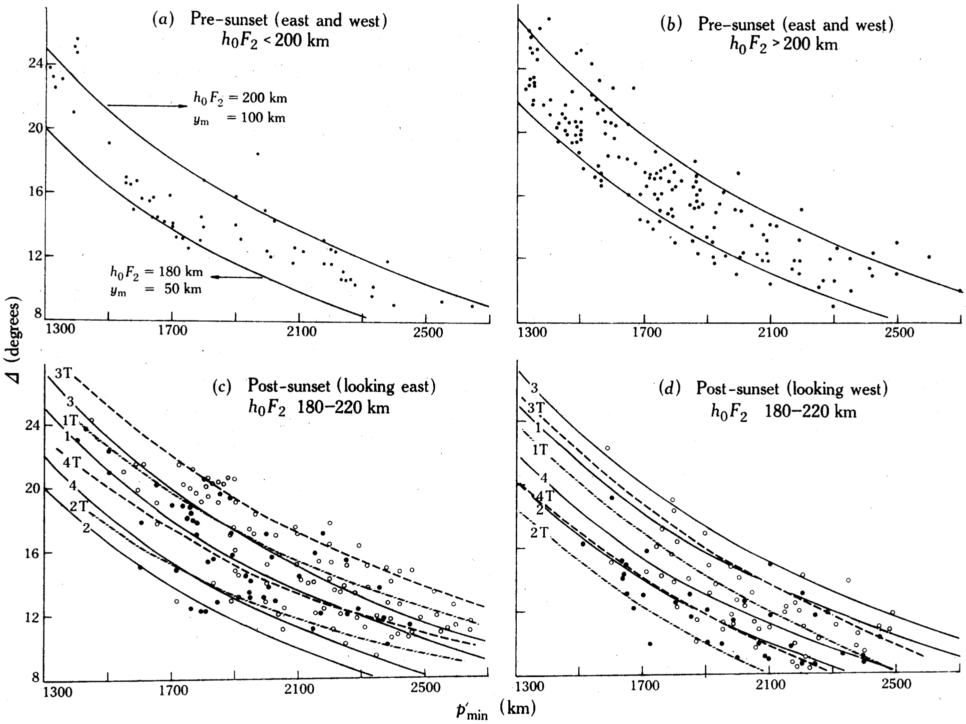


Fig. 3.—Plots of the experimental values of the equivalent free-space range of the leading edge p'_{min} versus the elevation angle Δ compared with the theoretical curves of Shearman (1956). The curves in (c) and (d) are given by the following (the tilt being positive in (c) and negative in (d)):

Curve	h_0F_2 (km)	y_m (km)	Tilt (deg)	Curve	h_0F_2 (km)	y_m (km)	Tilt (deg)
1	200	100	0	1T	200	100	1
2	180	50	0	2T	180	50	1
3	220	100	0	3T	220	100	1
4	200	50	0	4T	200	50	1

III. Calibration

In order to find the elevation angle corresponding to the position of minimum amplitude recorded on the film, the whole receiving system with the phase changer in the circuit was calibrated.

A portable pulsed transmitter and a half-wave dipole mounted on a pole fixed to a truck were used for the calibration. The two Yagi antennas were situated at a distance of 5λ apart and mounted at a height of $0\cdot5\lambda$ above the ground. They were located on an east–west line and directed east (or west). Starting at a distance about 1540 m from the antennas and in line with them, the truck was driven northwards until the direction from the truck to the antennas was at an angle of 8° from their east–west line. Following this, the truck was stopped at positions calculated to give 1° increments in this angle. The distance between the dipole and the antennas (1540 m) was sufficiently large to consider that parallel rays were reaching the antennas. The signal received from the two Yagi antennas thus recorded a minimum position on the film.

Once the position from which a calibration corresponding to an 8° elevation angle had been obtained and marked on the ground, this calibration was checked by operating the oscillator and recording on the film each day before taking records. Any change in position of the minimum was used to correct the calibration for that particular day.

IV. Results

The simultaneous measurements of elevation angle Δ of the rays in the leading edge of the echo received at Amberley and the equivalent range p' corresponding to those angles were plotted (Fig. 3) for records of about 60 hr taken from eastern and western directions during the summer and winter months of 1964 and 1966. The data collected were divided into six groups. Figures 3(*a*) and 3(*b*) show a plot of Δ versus p'_{min} for the pre-sunset period, and Figures 3(*c*) and 3(*d*) for the post-sunset period looking east and west respectively. The cases where the height of the F_2 region lay between 180–200 and 200–220 km indicate different behaviour before and after ground sunset.

V. Comparison with Theory

In the case of a curved Earth and a parabolic ionospheric layer Shearman (1956) expressed the Appleton and Beynon equation for the oblique range p' (i.e. the equivalent free-space path length to the scatter source) as

$$p' = 2xy_{\mathrm{m}}\tan^{-1}h\left(\frac{x\cos i_0}{1-\{x^2y_{\mathrm{m}}/(R+h_0)\}\sin^2 i_0}\right)+\frac{2R\cos(\Delta+i_0)}{\sin i_0}, \tag{1}$$

where

$$\Delta = \cos^{-1}[\{(R+h_0)/R\}\sin i_0],$$

i_0 is the angle of incidence of rays on the base of the ionosphere, x is the ratio of the transmitted frequency to the critical frequency, R is the radius of the Earth ($\sim$ 6371 km), y_{m} is the semithickness of the parabolic layer, and h_0 is the true base height of the ionosphere.

In order to determine the skip range (p'_{min}) we have to find the values of Δ and p' that give the minimum value of p' using i_0 as the independent variable, i.e. we have to find where $\mathrm{d}p'/\mathrm{d}i_0 = 0$. This can in principle be done explicitly (though the expressions derived are extremely inconvenient) but the expression (1) for p' can be computed for any set of values of h_0F_2, f_0F_2, and y_{m}. By changing i_0 in steps of

$0 \cdot 5°$, p'_{min} may be found sufficiently accurately. The angle i_0 corresponding to p'_{min} is used to calculate Δ, which is the elevation angle corresponding to p'_{min}. In the present case, data were selected for h_0F_2 between 180–200 and 200–220 km. The maximum and minimum limits of Δ for a certain p' were calculated for these values of h_0F_2 using values of x of $3 \cdot 0$, $2 \cdot 7$, $2 \cdot 4$, $2 \cdot 1$, and $1 \cdot 8$ and values of y_{m} of 50 and 100 km. The solid curves shown in Figure 3 give the maximum and minimum limits of Δ for a particular p' in the absence of any tilt in the ionosphere. For the pre-sunset period (Figs 3(*a*) and 3(*b*)) most of the points fall within the limits calculated by using Shearman's equation in the absence of any tilt. Most of the points for the post-sunset period (Figs 3(*c*) and 3(*d*)) are outside the curves, thus showing disagreement with the Appleton–Beynon theory. This discrepancy may be attributed to

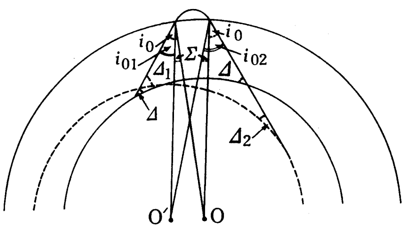


Fig. 4.—The geometry of a tilted Earth.

ionospheric tilt. It is possible to calculate the maximum and minimum limits of Δ for a certain p' in the presence of ionospheric tilt if the ionosphere is taken to be unaltered and the Earth is tilted (Fig. 4). In the presence of tilt Shearman's equation should thus be modified to read

$$p' = 2xy_{\mathrm{m}} \tan^{-1}h\left(\frac{x\cos i_0}{1-\{x^2y_{\mathrm{m}}/(R+h_0)\}\sin^2 i_0}\right)+\frac{R\cos(\Delta_1+i_{01})}{\sin i_{01}}+\frac{R\cos(\Delta_2+i_{02})}{\sin i_{02}}, \tag{2}$$

where

$$i_{01} = i_0-\epsilon \qquad \text{and} \qquad i_{02} = i_0+\epsilon,$$

with ϵ the tilt angle, which is taken as positive when the ionosphere increases in height from west to east.

The expression for p' from equation (2) was computed for a tilt of 1° and the same set of values of h_0F_2, f_0F_2, and y_{m} as for a nontilted ionosphere by changing i_0 in steps of $0 \cdot 5°$. The corresponding values of i_{01} and i_{02} were used to calculate the second and third terms of equation (2). The value of i_{01} corresponding to p'_{min} was used to calculate Δ_1, which is then the elevation angle corresponding to p'_{min}. The maximum and minimum limits of Δ_1 calculated in this way for a 1° tilt are plotted in Figures 3(*c*) and 3(*d*) (T curves).

A comparison of the experimental points in Figures 3(*a*)–3(*d*) with the theoretical curves (and making minor extrapolations to obtain results for other tilts) suggests that satisfactory agreement between experiment and theory can be obtained on the following basis.

(1) Prior to sunset all results (Figs 3(*a*) and 3(*b*)) can be accounted for by postulating ionospheric tilts lying between about $\pm 0\cdot 5°$.

(2) After sunset, when the sounder is looking eastward (scatter from the sea), the results (Fig. 3(*c*)) can be fitted for tilts between 0° and $+1\cdot 5°$.

(3) After sunset, when the sounder is looking westward (scatter from land), the results (Fig. 3(*d*)) can be fitted for tilts between 0° and $-1\cdot 5°$.

In order to determine whether systematic tilts (i.e. tilts over a belt of the order of 100–500 km wide) of this order are plausible, an examination was made of the variation of $h'F_2$ with time after sunset on four nights of January 1966 (a month in which many of the backscatter results were obtained). If it is assumed that as the sunset line moves west a certain configuration of electron densities moves with it, without perturbation, then it is possible to convert the dependence of $\Delta h'$ (change of $h'F_2$) on time to a dependence on displacement x from the sunset line. The plots of $\Delta h'$ versus x are shown in Figure 5. The average tilt varies from 1° to 3°. Thus in so far as the reflecting layer responsible for ground backscatter is correctly represented by the $h'F_2$ results, tilts of the required magnitude do in fact occur.

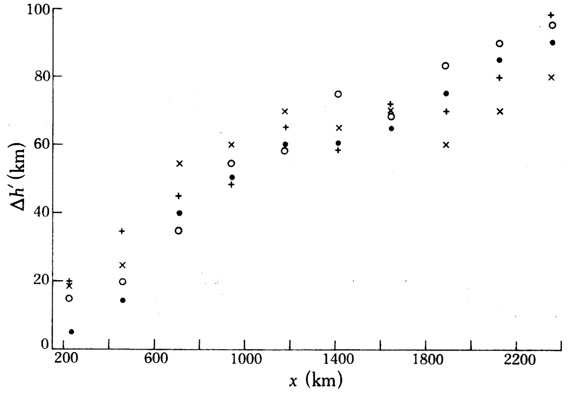


Fig. 5.—Plots of the vertical movement $\Delta h'$ versus the horizontal displacement x show the systematic tilt that was derived from the vertical incidence data.

VI. Conclusions

The following conclusions therefore appear valid for the ionosphere in these latitudes.

(1) Shearman's (1956) formula fits well the experimental data for ground backscatter eastward or westward when the ionosphere is in sunlight.

(2) A modified formula, assuming that the ionosphere has the same shape but is tilted (in the east–west vertical plane), fits the post-sunset results using tilts of up to $1\cdot 5°$, tilts of this magnitude being consistent with ionogram analyses.

VII. Acknowledgments

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