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The Effects of Polar-Cap Absorption on HF Oblique-Incidence Circuits

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Abstract. Data from HF oblique-incidence ionosonde circuits were studied to determine to what extent they were affected by the radio absorption events now known as polar-cap absorption (PCA). The data were recorded on three circuits terminating in Ottawa (from Churchill, Resolute Bay, and The Hague) and on a fourth circuit between Churchill and Resolute Bay. A relatively weak event caused an appreciable decrease in the range of usable frequencies on the Canadian circuits. More intense absorption resulted in blackout conditions on all circuits, including the transatlantic. The effects on these circuits could be interpreted from a consideration of the geometry of the propagation modes involved and of the pattern of PCA events that has been established with other experimental equipment, particularly riometers. The regular oblique ionosonde data on the Ottawa–Resolute Bay circuit were supplemented for a short time by amplitude measurements. These data showed that, although PCA reduced the signal strength on all frequencies received, the noise was absorbed at the same time; hence, the signal-to-noise ratio was not appreciably affected. This result is probably dependent on the location of the circuit.

Introduction. 'Polar blackouts' or radio-wave propagation failures in the HF band due to absorption have long been recognized as a serious problem in high-latitude communications. As a result of recent research, it is now possible to divide such blackouts into two main types arising from quite different physical processes and having distinctive space and time variations. The main distinguishing features of the two types, now commonly known as polar-cap absorption (PCA) and auroral absorption, respectively, are described elsewhere, e.g., *Reid and Collins* [1959], *Reid and Leinbach* [1959]. The present study is primarily concerned with polar-cap absorption. Its main characteristics are now sufficiently well known from experiments to make it possible to extrapolate the effects of this kind of absorption to operational HF circuits. It is the purpose of this investigation to examine the validity of such extrapolations for circuits lying partly within the polar cap. For this purpose, absorption measurements made by 30-Mc/s riometers are compared with data from oblique ionosondes. In addition to obtaining information on the communication problem we are interested in seeing what these data may add to the knowledge already accumulated about PCA events.

The features of PCA that are considered to be well established and that, in conjunction with the geometry of oblique circuits, will determine the attenuation on a given circuit during an absorption event can be summarized as follows: Within a few hours of certain large solar flares, particles ejected from the sun penetrate the ionosphere to form an abnormal ionized layer which is relatively uniform over the polar cap and lies within the height range of 50 to 90 km. The low-latitude boundary of the region affected is determined by the energy selection imposed on the incoming particles by the geomagnetic field; under magnetically undisturbed conditions it is defined approximately by a line of geomagnetic latitude at about 65°. In association with the main phase of the geomagnetic storm which usually follows the onset of the PCA by about a day the earth's magnetic field is distorted, allowing the particles to penetrate farther south (cf. *Ortner, Leinbach, and Sugiura*, [1961]). Superimposed on the PCA storm-time variation of the ionization is a solar-controlled variation due to the decrease in the number of free electrons at night as a result of attachment processes. Details of the processes involved have been worked out by *Bailey* [1959], *Reid* [1961], and others.

The absorption experienced by a radio wave passing through this ionized layer is expressed by magnetoionic theory in terms of k, the absorption index in decibels, where

$$k \propto N\nu/[(\omega \pm \omega_L)^2 + \nu^2]$$

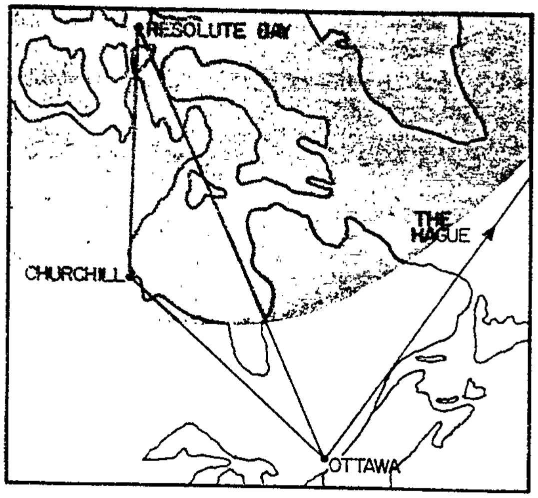

Fig. 1. Location of the HF oblique circuits. Shaded area denotes the general area affected by PCA in the absence of magnetic disturbance.

assuming that the operating frequency, $\omega/2\pi$, is much larger than the plasma frequency. N and ν are respectively the local electron density and collision frequency, and ω_L is the component of the angular gyrofrequency along the direction of propagation. For frequencies being considered here, ω_L can be neglected in comparison with ω. The relative magnitudes of ω and ν (which is very dependent on height in the atmosphere) will determine to what extent the absorption is frequency-dependent. If $\omega^2 \gg \nu^2$, the absorption will vary inversely as the frequency squared. If $\omega^2 \ll \nu^2$, the absorption will be independent of frequency. From present knowledge of collision frequency [*Ratcliffe and Weekes,* 1960], it seems likely that the variation will be somewhere between the two extremes outlined above.

During PCA the increased ionization in the D region is expected to cause a corresponding increase in the absorption of all radio waves passing through it. From the discussion above, the lower frequencies are expected to be absorbed more than the higher ones. Propagation of the lowest frequency by any mode (the lowest usable frequency, or LUF) is normally controlled either by reflection from the E layer, the so-called 'E-layer cutoff,' or absorption in the D region. Lower frequency limits have been discussed by *Fulton, Sandoz, and Warren* [1960]. During the presence of the abnormal ionization in the D region producing PCA, the LUF's are expected to be higher than normal. Increases in LUF's were used in the present work as an indication of absorption.

Standard methods of detecting PCA utilize either riometers, which record the cosmic noise level at frequencies near 30 Mc/s [*Little and Leinbach,* 1959], or vertical HF ionosondes from which either blackouts or the minimum recorded frequency (f_{min}) serve as an index of absorption [*Collins, Jelly, and Matthews,* 1961; *Jelly and Collins,* 1962]. For an estimation of the absorption on HF oblique circuits, f_{min} is of limited value because it depends on the sensitivity of the sounding equipment. On the other hand, to use riometer data as was done in this work requires an extrapolation from absorption measured at 30 Mc/s to lower frequencies and from near vertical incident to very oblique transmission angles. Because of the effect of collision frequency shown above, this requires some assumptions about the height of the layer in addition to a value for the vertical-incidence absorption. In the present work, riometer data were used to determine the presence of absorption, and on occasion f_{min} was used as a check. A quantitative determination of the effects of PCA on HF circuits would require recordings of signal strength on each of the frequencies received. By a fortunate chance some suitable signal strength measurements were made during a PCA event, and the additional information they provide is used here.

Analysis of data. The oblique-incidence equipment for recording the data has been described in detail in a report by *Southern* [1961]. In operation, the transmitter and distant receiver are simultaneously tuned in steps of 100 kc/s from 1.05 Mc/s to 48.95 Mc/s. The received signals are recorded on film as a function of frequency and time in a presentation permitting identification of modes of propagation. Sweeps are completed in 8 minutes and are repeated twice an hour. For the amplitude measurements, the signal strength received from Ottawa was recorded at Resolute Bay in decibels above 1μv. Fifteen pulses were recorded on each 100-kc/s step from 7.05 Mc/s to 25.05 Mc/s. Modes could be identified with the aid of the oblique ionograms. Runs of this type were made in 3 minutes about 5 times a day.

The locations of the circuits on which data

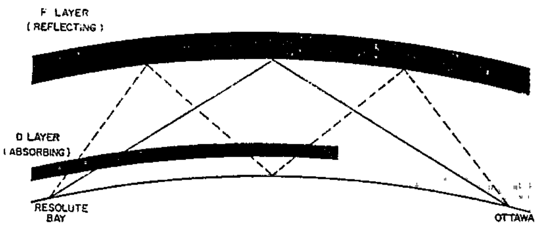

Fig. 2. Geometry of modes on the RB–OT path. A reflecting F layer and absorbing D region are represented.

were recorded are shown in Figure 1. The approximate area affected by PCA in the absence of magnetic disturbance is shaded to show where the circuits are located with respect to the absorbing region. The Resolute Bay–Churchill path lies entirely within the 'polar cap'; the Resolute Bay–Ottawa and the Churchill–Ottawa circuits both pass partly through the region, and the Ottawa–Hague circuit skirts the southern edge. Riometer and f_{min} observations of the southern extent of the absorbing layer are often too limited to determine how much of this last circuit passes through the polar cap.

Figure 2 shows the likely modes of propagation on the Resolute Bay–Ottawa path as an aid to visualizing the effects of PCA on these circuits. In the diagram (which is not drawn to scale) the absorbing ionization is pictured as a distinct layer at about 60-km height with the F layer at a height of 250 km. The one-hop mode passes once through the ionization in the D region; the two-hop mode passes two or three times through the layer but less obliquely than the one-hop. Two-hop modes are generally reflected at lower frequencies than once-reflected modes. Under certain conditions, reflections from sporadic ionization in the E region (E_s) (not shown in the diagram) may be of importance in maintaining communications during periods affected by absorption.

The range of frequencies received on the four circuits was plotted for several of the events detected on the Resolute Bay and Churchill riometers. We shall discuss representative examples of weak, moderate, and intense PCA events, viz., September 28, September 10, and July 1961. Although these events were chosen to be representative of different absorption intensities, each has features which are not typical and which will be discussed in connection with the event.

The lowest usable frequencies are affected most by absorption and will therefore be mainly used in the discussion. To emphasize the absorption variation from undisturbed conditions, $\triangle$LUF will be used, where $\triangle$LUF is defined to be the difference between the LUF at a given hour on a disturbed day and an undisturbed day. $\triangle$LUF then serves as an index of absorption, like $\triangle f_{min}$ in studies of vertical-incidence data (cf. *Jelly and Collins* [1962]).

Results and discussion. Since interpretation is generally easier for weak events than for more intense ones, data from the September 28 event will be presented first, and the other events will be compared with it. In Figure 3, the frequency range received over the RB–OT path is plotted on a universal time scale for September 28–30, 1961. The maximum usable frequency (MUF) plotted in the diagram is the one-hop F mode recorded on the ionogram. The LUF plotted may be determined by one- or two-hop F or by sporadic E. September 28 is typical of an undisturbed day; both MUF's and LUF's show only the normal diurnal variation, which in general is more pronounced in the MUF and more regular in the LUF. A weak PCA event (about 1.5 db on the Resolute Bay 30-Mc/s riometer) is initiated by a flare of importance 3 at 2208 UT. Flare times are taken from the CRPL F-Series. On September 29 the midday LUF's show an increase of about 5 Mc/s over the corresponding values of the previous day. The two-hop mode which passes several times through the absorbing region was not received at all, nor was the sporadic E mode, which passes very obliquely through the D region. Amplitude measurements made at 2208 UT on September 28 and 29 will be discussed later.

In Figure 4, $\triangle$LUF's from the four circuits are compared with the cosmic noise absorption observed on the 30-Mc/s riometer at Churchill. Although there are many random fluctuations typical of oblique ionograms, the systematic diurnal variation can clearly be seen in the data from the three Canadian circuits. Heavy bars at the upper limit of the $\triangle$LUF range represent absorption blackouts. Where there was doubt about the cause of no reception, the curves are not joined; thus, discontinuities in the curves may be caused by blackouts due to absorption

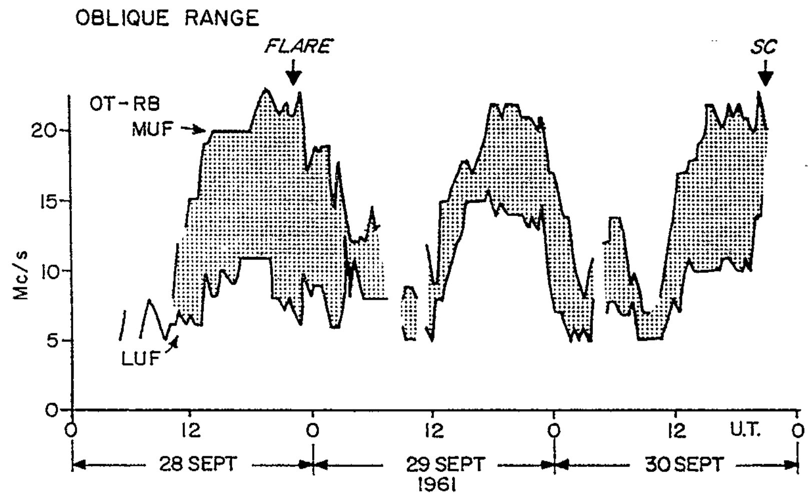

Fig. 3. Range of frequencies received on the RB–OT path during the early part of the PCA event of September 28, 1961.

or to lack of ionization sufficient to support reflections, or they may be a result of equipment malfunctions. After the flare on September 28 the northernmost circuit RB–CH, and possibly RB–OT, shows increases in △LUF corresponding to the slight increase in the cosmic noise absorption. The absorption recovered at night (local midnight about 0600 UT), and all but the OT–HA circuit showed an increase the following morning which continued as a regular diurnal variation throughout September 29 and 30. The OT–HA circuit did not experience absorption in passing through the ionosphere at very nearly the same geomagnetic latitude as the CH–OT circuit, which was absorbed. Two interpretations are possible: either the southern cutoff of the ionization was very abrupt and lay between the *D*-region penetrations of the two circuits, or the lines of equal magnetic cutoff do not follow exactly the lines of geomagnetic latitude but are distorted southward over central Canada similarly to isochasms of auroral occurrence suggested by *Hultqvist* [1959].

An increase in absorption associated with an increase in the incoming particle flux appears on the riometer record starting about an hour before the sudden commencement of the magnetic storm (SC) at 2109 UT. The absorption peak, which has been omitted in the diagram, rose to about 8 db on the Churchill riometer. A corresponding increase occurred in the △LUF's before the SC, although it is not apparent in the diagram because of the compressed time scale. On the CH–OT circuit the effect is most pronounced. The increase in absorption and blackouts that began before the SC is an unusual effect, which has recently been discussed by *Axford and Reid* [1962]. The OT–HA circuit blacked out during the absorption peak. During the recovery of the absorption peak and the onset of the magnetic storm, signals were received on frequencies above 15 Mc/s by strong sporadic-*E* reflection on the RB–CH and RB–OT paths accounting for the high LUF's during the early hours of October 1. During the rest of that day discrepancies between LUF's and riometer measurements are due to a general disturbance in the ionosphere associated with the magnetic storm: sporadic *E*, auroral absorption, and a lowering of the electron density in the *F* region. These effects have been described by *Hill* [1960], *Little and Leinbach* [1958], and *Meek* [1952], respectively. These discrepancies may be due in part to propagation failures resulting from the difficulty in synchronizing the equipment after interruption of contact by blackout.

The second event to be discussed is of medium intensity (3 db on the RB riometer). Figure 5 shows the variations in a manner similar to Figure 4 with the Resolute Bay riometer record shown at the top and △LUF's for the four oblique circuits below. Most probably this event was initiated by a flare listed as importance 1

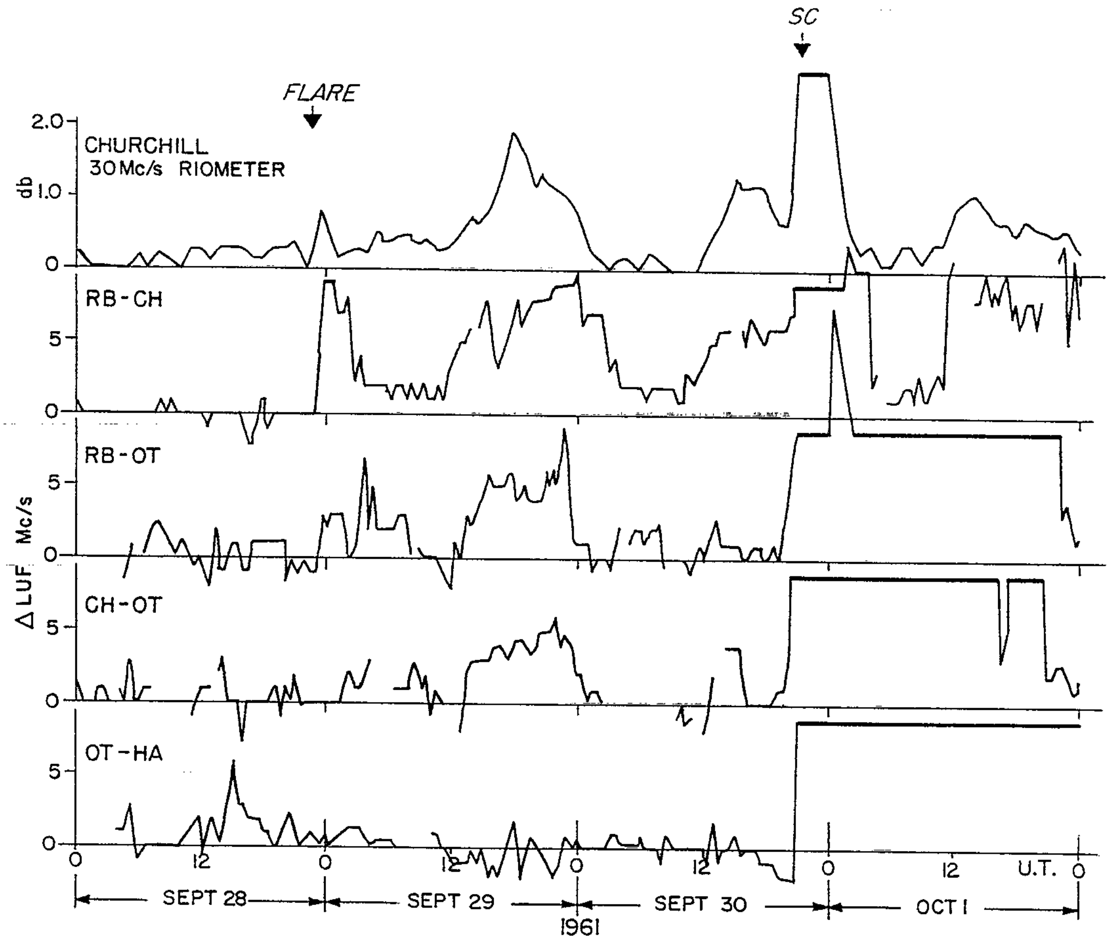

Fig. 4. Polar-cap absorption event of September 28, 1961, on (*a*) 30-Mc/s riometer at Churchill, (*b*) lowest usable frequency on the RB–CH path, (*c*) the RB–OT path, (*d*) CH–OT path, (*e*) OT–HA path.

which occurred at 1950 UT, September 10, at NO8 W90 heliographic coordinates. This absorption event is unusual; it is similar to an earlier event in April 1958 in that it was not followed by a magnetic storm. A sudden magnetic impulse did occur, however, at 1525 UT on September 11. In this example, as in the previous one, the absorption on the RB–CH circuit (as represented by △LUF's) is most closely correlated with the absorption measured by the riometers. The RB–OT circuit shows less absorption, possibly because it passes only once through the absorbing layer and at higher frequencies; i.e., the median noon LUF on the RB–CH circuit was about 5 Mc/s compared with 10 Mc/s on the RB–OT circuit. CH–OT shows irregular absorption, perhaps partly mixed with auroral absorption. On September 10 the OT–HA circuit is affected by a peculiar absorption which although of interest in itself is probably not associated with PCA since it began before the PCA-initiating flare. Thereafter the fluctuations appear to be random except for the increase at 0600 UT on September 12, which occurred at the same time as a maximum in absorption on the CH–OT circuit. The circuits were not completely blacked out for any extended period during the recovery of the PCA, a result in agreement with what would be expected in the absence of a magnetic storm and the associated ionospheric disturbances. The lack of data on the circuits terminating in Churchill

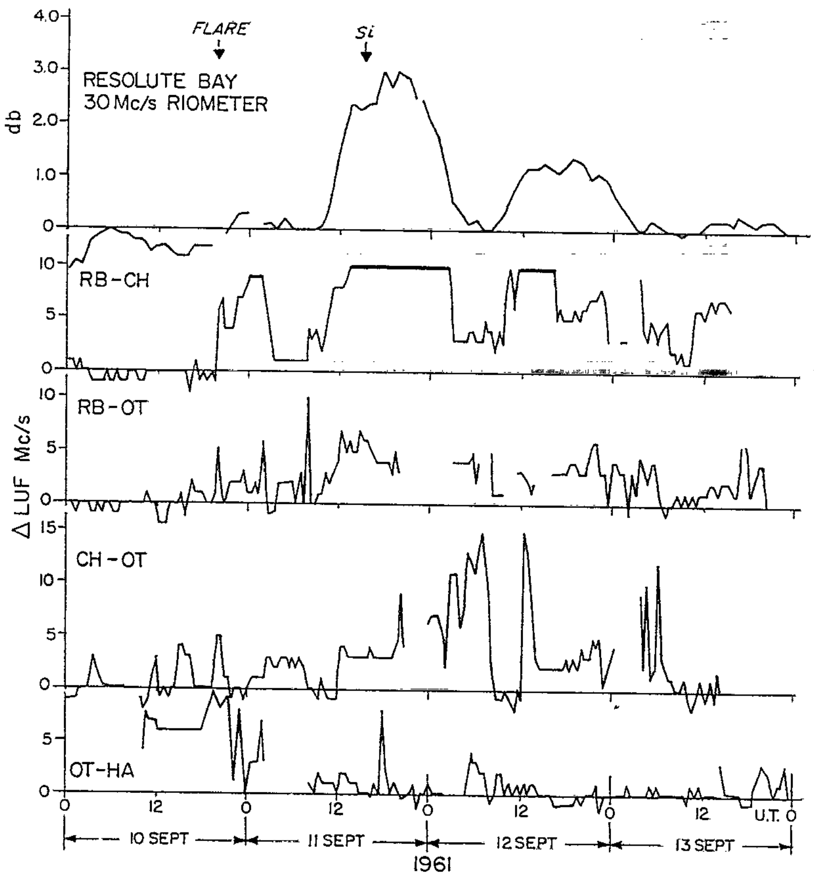

Fig. 5. Polar-cap absorption event of September 10 on (*a*) 30-Mc/s riometer at Resolute Bay: LUF's on (*b*) RB–CH, (*c*) RB–OT, (*d*) CH–OT, (*e*) OT–HA circuits.

on the latter part of September 13 is probably caused by equipment malfunction.

Figure 6 shows the intense event of July 12, 1961, which has been described in detail by *Leinbach* [1962] on the basis of riometer data. Following the flare of importance 3 at 1654 UT on July 11, which was marked by a SID on the oblique circuits, some absorption appears on the RB–CH circuit, and although it does not show on the Resolute riometer record Leinbach reports PCA at this time. After the importance-3 flare at 1000 UT on July 12 (also accompanied by a SID) absorption on all the Canadian circuits increased to blackout between 0600 and 0800 UT on July 13. By then the riometer absorption was greater than 5 db at Resolute. This PCA event, classified by Leinbach as a SC maximum event, increased slowly to a maximum at the time of the SC (1113 UT, July 13), then recovered slowly. At the time of the SC the higher-latitude circuits were blacked out, and they did not recover until late on July 15, whereas the medium-latitude OT–CH circuit recovered at night on July 14 and 15. The transatlantic circuit (OT–HA) was not affected, except by the SID's, until 1700 UT on July 13, well after the SC but coincident with the onset of the main phase of the magnetic storm, in agreement with other absorption observations.

From these examples the following patterns emerge: the three circuits RB–CH, RB–OT, and CH–OT, which enter the polar-cap region, all show absorption effects consistent with absorption measured by 30-Mc/s riometers within the region. The lowest frequencies received are considerably increased during the daytime during even the weakest events. More intense ionization absorbs all frequencies on these circuits. The

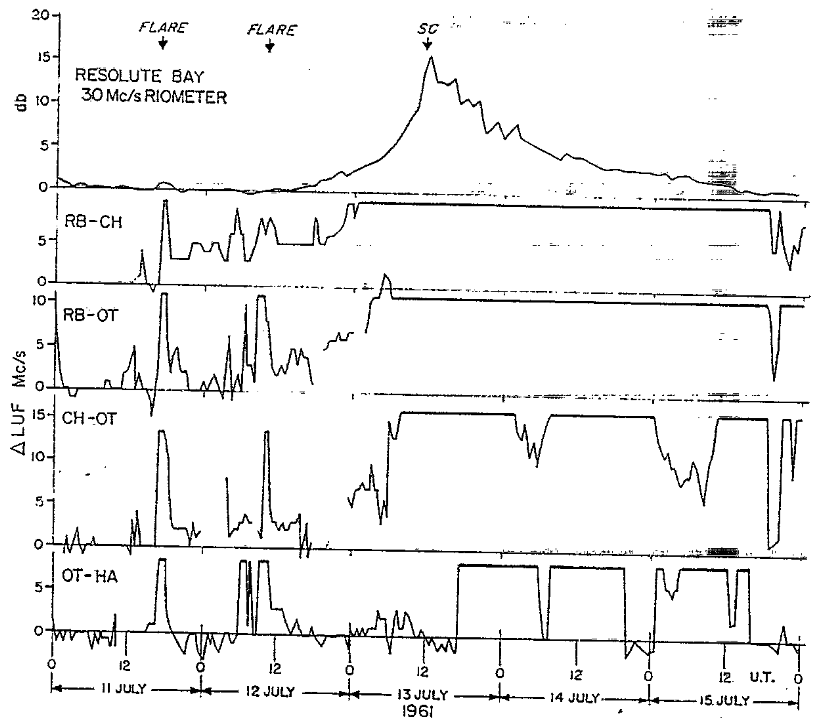

Fig. 6. Polar-cap absorption event of July 12, 1961, on (*a*) 30-Mc/s riometer at Resolute Bay; LUF's on (*b*) RB–CH, (*c*) RB–OT, (*d*) CH–OT, (*e*) OT–HA circuits.

transatlantic circuit is not affected by PCA until magnetic disturbance allows the particles to penetrate farther south. All the circuits are badly disrupted by ionospheric disturbances associated with magnetic storms. The most northerly circuit, RB–CH, is affected more by PCA and less by magnetic disturbances.

Amplitude. The data presented so far show how much the lowest frequency received on a circuit is increased by absorption. The amount by which the frequencies that are received are attenuated cannot be determined from regular oblique records. Amplitude recordings suitable for measuring absorption on the oblique path were made on the RB–OT path for a period in September overlapping the PCA on September 28. Two usable runs were made during the 3 minutes beginning at 2208 UT on September 28 and at the same time on September 29. The reflecting properties of the F layer as seen from the Churchill vertical-incidence ionosonde were very similar at these times. The record on September 28 was completed before the onset of any ionospheric effects of the flare that started near that time. We can assume that the run represents the quiet-day level for that hour, and the difference between this record and the one of the following day represents the change in absorption over that path. Figure 7 shows the curves of received signal strength and the difference between them which gives the absorption. Values were obtained by averaging the amplitudes for the 15 pulses on each frequency and smoothing over 10 frequency increments. Care was taken to select only the one-hop mode and frequencies not too close to the LUF and MUF, where focusing may be of more importance than absorption in determining the received signal strength, according to *Warren and Muldrew* [1961]. The frequency range from about 15 to 22 Mc/s is probably relatively free from focusing effects. In Figure 8 the absorption on this circuit is compared with a simple extrapolation of the absorption measured by the 30-Mc/s riometer at Churchill. Assuming an inverse frequency-squared relation, the absorption at frequency f is given in decibels by

$$A_{obl} = A_{30\,Mc/s} \times (30/f)^2 \times \text{obliquity factor}$$

The obliquity factor was calculated on the as-

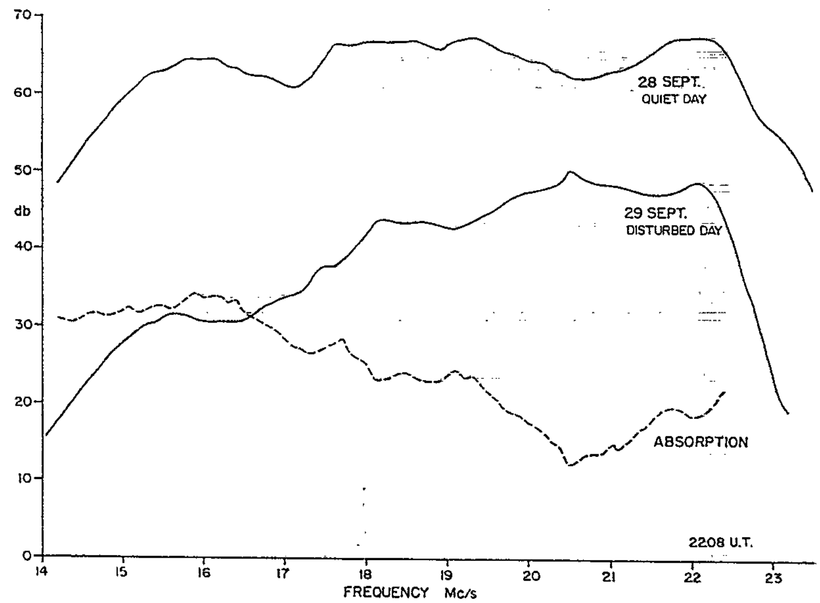

Fig. 7. Signal strength as a function of frequency received at Resolute Bay from Ottawa at 2208 UT on September 28 and 29, 1961. The dotted curve, the difference between the other two curves, represents the absorption on September 29 as a function of frequency.

sumption that the height of the absorbing region was close to 60 km. From Figure 8 there is seen to be reasonable agreement between absorption extrapolated from 30-Mc/s vertical absorption and that deduced from the amplitude measurements on frequencies between 15 and 22 Mc/s on the oblique path.

Figures 7 and 8 refer only to the amplitude of the received signal. In Figure 9 the signal-to-noise ratio is shown during the same runs (again with 10-point smoothing). Although the signal level and the range of frequencies received are reduced considerably by the absorption event, the signal-to-noise ratio remains about the same, a result to be expected if most of the noise being received at Resolute Bay is man-made and propagated from the south. Amplitude measurements at the Ottawa end of the circuit would be interesting for comparison, but so far none have been recorded. Amplitude recordings on fixed frequencies have been reported by *Egan and Peterson* [1960] and *Egan* [1961]. One of the transmissions they studied was on a 12-Mc/s circuit from Thule, Greenland, to College, Alaska, which would normally lie entirely within the polar cap, comparable to the RB–CH path. During the PCA events of April 29 and May 6, 1960, they recorded a reduction of signal strength of the order of 40 db at the same time as the 27.6-Mc/s riometer absorption increased to 12 db. Extrapolation of the riometer absorption leads to an expected value of 500 to 600 db for the absorption on that particular oblique path. Although no amplitude measurements were available for periods of high absorption for comparison, the fact that no signals were received by the regular equipment on any of the paths during similar intense events suggests that the absorption was greater than they measured. This inconsistency between the two experiments is difficult to explain; further amplitude measurements are needed to resolve it.

Conclusions. From the examples given here it is apparent that the effects of PCA on HF circuits passing through the polar region are consistent with the picture of the phenomenon derived from 30-Mc/s riometer measurements. Although it cannot be determined from the regular oblique ionograms to what extent the inverse-square law holds, the absorption does appear to be frequency-dependent in the HF band in that the lowest usable frequencies are increased during the events. The reduction in amplitude recorded during the weak event is in reasonable agreement with absorption calculated from riometer measurements, assuming the inverse-square law and a height of 60 km for the absorbing region. For communication purposes it is of practical interest that the useful frequency range is reduced during PCA, especially during the daytime, as would be expected. The signal strength is reduced, but the actual signal-to-noise ratio may not be appreciably altered, particularly on circuits terminating within the polar cap.

The absence of absorption on the transatlantic circuit before the onset of the magnetic storm suggests that the polar cap itself does not follow lines of geomagnetic latitude but may be distorted southward over southern Canada.

Acknowledgments. I wish to express my gratitude to Mr. C. Collins for his guidance in connection with this work, to my colleagues for many helpful discussions, and to Mr. W. Campbell for assisting with the analysis of the July event. The oblique-incidence equipment is operated by the

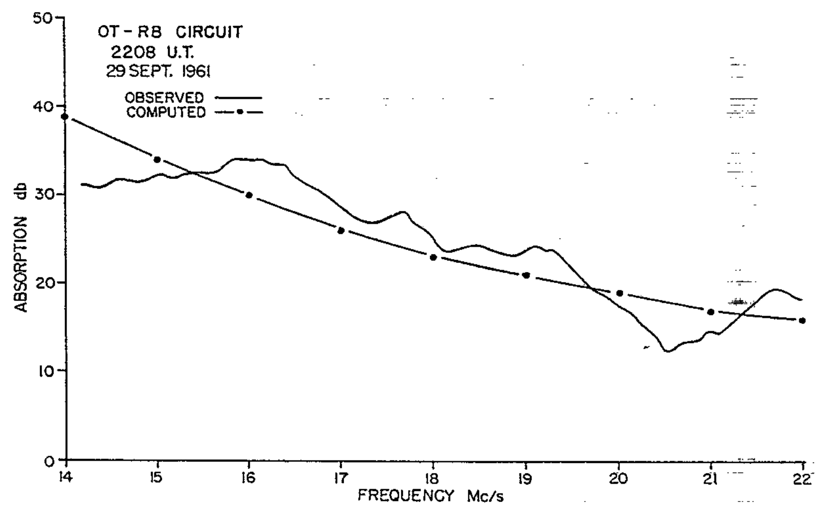

Fig. 8. Absorption measured on September 29 on the RB–OT path compared with absorption extrapolated from 30-Mc/s riometer at Churchill.

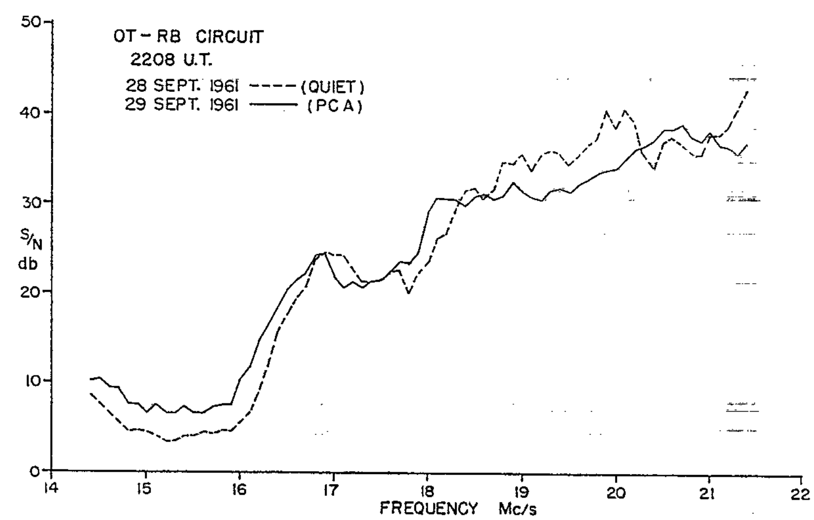

Fig. 9. Signal-to-noise ratio on RB–OT path on a quiet day (September 28) and a disturbed day (September 29).

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