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SIMULTANEOUS MEASUREMENTS OF IONOSPHERIC AND MAGNETOSPHERIC ELECTRIC FIELDS IN THE OUTER PLASMASPHERE

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Abstract. The eastward component of the electric field was measured simultaneously at ionospheric heights and in the equatorial plane of the magnetosphere by using the incoherent scatter radar at Millstone Hill and whistler data from Siple, Antarctica, respectively. The locations of the two data sets correspond to approximately magnetically conjugate areas within the outer plasmaphere, and thus a unique opportunity arises for testing the electric field mapping hypothesis and for intercomparing the measurement techniques. The whistler results are averaged for L = 3.5-4.7, while the radar data correspond to L = 4.4. The measurements represent time averages over about 20 minutes. There is excellent correlation during most of the 12 hour period of simultaneous data on 10 July 1978. The period was one of moderate disturbance (K_p = 2-3). A 500 gamma substorm developed around 0830 UT (0330 LT). During this substorm, both of the electric field measurements showed a large westward perturbation, in agreement with previous observations. The meridional component of the electric field was also measured at Millstone Hill. Taken together, these data indicate an enhanced flow with components inward and towards dawn during the substorm. Except for a time near magnetic midnight the magnitude of the zonal field scales from the ionosphere to the equator in direct ratio with the spreading of magnetic field lines in the IGRF 1975 model. The whistler data clearly show that the measurements were obtained inside the plasmasphere. The middle latitude substorm perturbations appeared to be related to a reconfiguration of the magnetospheric current system.

Introduction

Two well established experimental techniques used for measuring electric fields are the incoherent radar scatter from electron thermal irregularities in the ionosphere (Farley, 1970) and the tracking of plasma ducts which guide whistler mode waves in the Earth's middle magnetosphere (Carpenter et al., 1972). In the former technique, the line-of-sight Doppler shift is measured. The shift occurs due to the $\underline{ExB}$ drift of electron irregularities in the F region. Thus, an individual measurement yields the ionospheric electric field perpendicular to $\underline{B}$ and to the radar beam (assuming that the beam is perpendicular to $\underline{B}$ itself). If several look directions are used, both components of the perpendicular electric field can be determined. In the whistler technique, the radial drift of enhanced ionization ducts is determined from the time rate of change of the value of the Earth's magnetic field at which the wave packet crosses the equatorial plane. Thus, its results are representatiave of the east-west electric field present in the magnetospheric equatorial plane. If the electric field is curl-free and the magnetic field lines are equipotentials, the measurements by these two techniques should be related by a simple scale factor (Mozer, 1970). This mapping relationship is often tacitly assumed to be applicable in the outer plasmasphere, but has never been experimentally verified on the scale of the present data set.

The average daytime behavior of the eastward component of the ionospheric electric field determined by radar has been compared in the past with a corresponding component measured by the whistler technique (Carpenter and Seely, 1976). Even though the agreement during magnetically quiet times appears reasonable, nighttime and simultaneous comparisons are lacking.

Conjugate comparisons between balloon electric field measurements and whistlers at middle latitudes have been few and inconclusive. Balloon measurements in both hemispheres near L = 4 were compared with whistler radial drift data near L = 4, 2.7 and, 2 during a 1-1/2 hour postmidnight quiet period (Mozer et al., 1974). There was general agreement between the balloons and whistlers in the direction of the zonal field component (eastward), but the fields inferred from whistlers, when mapped downward, were a factor of 2 less than those found by the balloon technique. On the other hand, high latitude comparisons between balloon detectors and ionospheric measurements on a rocket in one case and with the Chatanika radar in another, yielded a good agreement (Kelley and Mozer, 1975).

We report here simultaneous nighttime data obtained by the radar and whistler techniques at approximately the same L value and at approximately magnetically conjugate areas within the outer plasmasphere. These conditions provide an opportunity not only for intercomparing the measurement techniques, but also for testing the mapping hypothesis and learning more about plasmaspheric electric fields during substorms.

Experimental Data

The radar data were obtained at Millstone Hill by alternating the antenna in two different azimuthal positions, as illustrated in Figure 1. The assumptions are made that the electric field is uniform over the volume covered by these two positions and that the beams are perpendicular to the Earth's magnetic field. The first assumption is a better approximation at the lower L values and deteriorates with increasing L. In addition, the decreasing signal-to-noise ratio contributes

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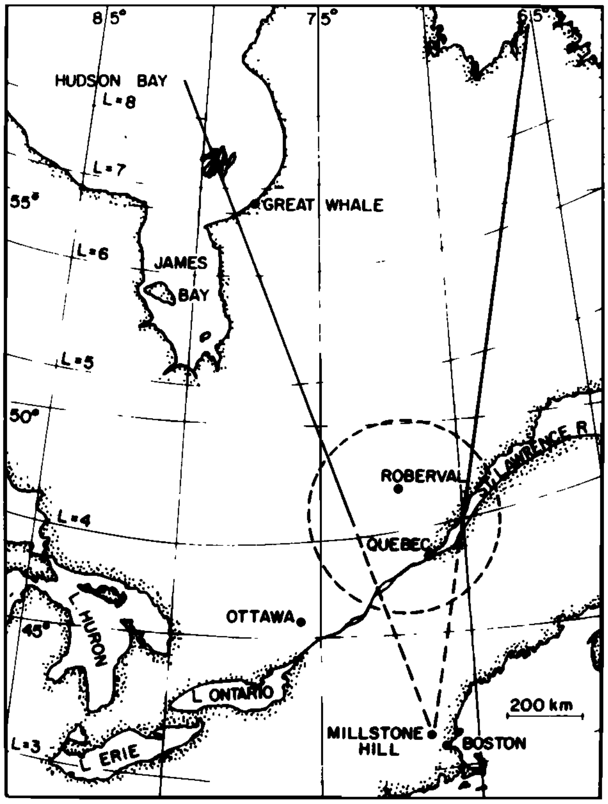

Fig. 1. Radar measurements at Millstone Hill (solid lines) and the estimated whistler viewing area (dashed circle).

to a decreased accuracy at higher L. However the larger fields at those latitudes partly compensate for the lesser accuracy. The second assumption introduces little error at any L value when low elevation angles are used at Millstone (Evans et al., 1979). A more detailed discussion is given by Gonzales (1979). The radar beam positions were selected such that the statistical error in the westward drift (magnetic northward E field) is about twice the error in the northward drift (magnetic eastward E field). A typical error bar for the northward drift is 10 m/sec or .5 mV/m (Evans et al., 1979). The analysis of the Millstone Hill radar data presented here (Gonzales, 1979) differs from that discussed by Evans et al. (1980), which was aimed at extracting the local-time dependent pattern of convection electric fields and was not suitable for study of universal time changes such as substorm events. The pulse length was such that the data points correspond to a resolution of about 1° in magnetic latitude.

The whistler data were obtained at Siple, Antarctica by the techniques described by Carpenter et al. (1972). A dashed curve in Figure 1 shows an estimated ionospheric projection of the field line region within which whistler paths were tracked. This projection is centered just south of the Siple conjugate station, Roberval, and midway between the two radar beam positions.

In Figure 2, we present measurements of the zonal component of the electric field obtained on July 10, 1978 by the radar and whistler techniques. The meridional component as measured by Millstone Hill is also included. The whistler recordings were made for 1 min every 5 min; the path data were processed so as to reveal variations with period 20 min or longer. From 3 to 5 whistler paths were typically tracked simultaneously. Duration of tracking on individual paths varied from 30 min to 5-1/2 hours, a typical value being 2 hours. Until 0830 UT the paths were widely distributed over the L range 3.5-4.7; after 0830 UT they were concentrated near L of four. No significant variations in the trends of the whistler data were noted as a function of L. The data shown in Figure 2 were therefore averaged over L. Values determined from the individual paths typically fell within ± .05 mV/m of the value plotted.

The radar data correspond to L = 4.4 and represents time averages over about 20 min. The difference in the E_E scales is a factor of 10, which corresponds closely to $L^{3/2}$ for the region of compared measurements. In spite of the various types of spatial and temporal averaging involved, the two independent measurements of the zonal electric field agree well both in general features and in many details.

The time period in which these data were obtained corresponded to one of moderate magnetic disturbance (see Figure 3) approximately 5 days after the maximum of a moderate magnetic storm (D_{st} was -100γ on July 5). The K_p index

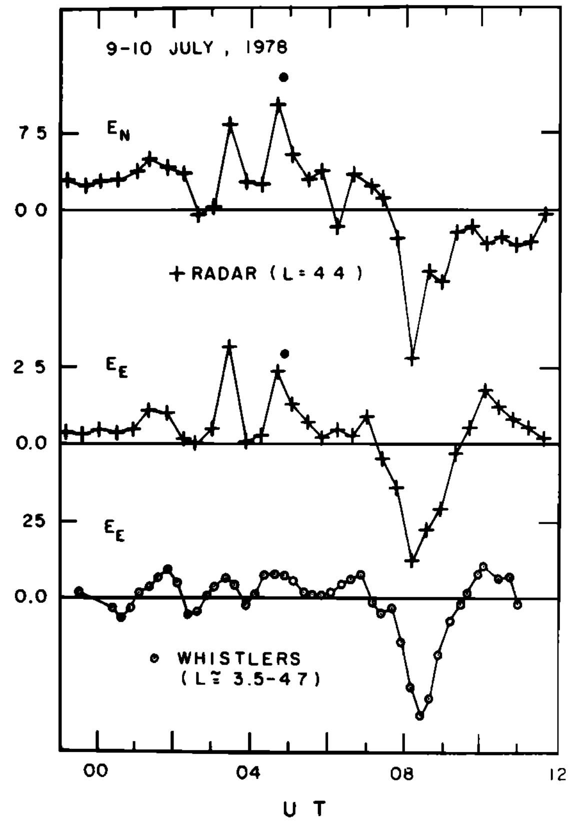

Fig. 2. Ionospheric electric field perpendicular to the local magnetic field: (a) Magnetic northward direction (E_N); (b) Magnetic eastward direction (E_E); (c) The plasmaspheric zonal electric field (whistlers). Note the different scales.

varied from 2 to 3^+ and D_{st} from −9 to −27 during the observing period. The largest perturbation occurred after 0800 UT when a substorm developed as shown in Figure 3. The westward electrojet appeared to peak at about 0830 UT (0330 LT) with a 500 gamma negative bay recorded at Great Whale, Canada, which is an auroral zone station located at approximately the same magnetic meridian as Millstone Hill. After 0700 UT, near the first indications of magnetic bay activity at Great Whale, both zonal electric field measurements turned westward, a result in good agreement with previous measurements during substorm activity (Carpenter et al., 1972; Carpenter and Akasofu, 1972; Gonzales et al., 1978). There is a difference of about 15 min in the westward peak of the two zonal electric field sets. This discrepancy falls within the limits on time resolution of the measurements, but may in part be a real effect which cannot be assessed at present. The wave forms of the zonal field data are remarkably similar to the magnetic disturbance observed at Great Whale. Simultaneously, the meridional component of the electric field turned southward during the substorm period.

During the period of observation, the field lines of the tracked whistlers were entirely within a moderately dense plasmasphere as determined from the whistlers themselves. For example, at 0830 UT, during one of the substorm events, the equatorial electron density at 4 R_e was found to be 220 cm^{-3} (with measurement error of a few per cent and theoretical uncertainty of ± 20%). The plasmapause position was not explicitly defined in the data; however, the outermost paths of observed propagation in the plasmasphere were near L = 5.2 at 0200 UT, near L = 4.8 at 0825 UT (during the substorm), and near L = 4.5 at 0900 UT. It is believed that the plasmapause was located near these limits; direct evidence for a plasmapause located at L = 4.8−5.0 was found at 1300 UT.

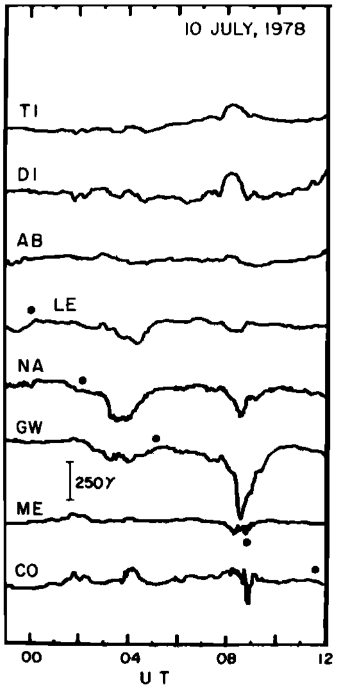

Fig. 3. The H component of the magnetic field variation observed around the global auroral zone. The magnetic midnight of the ground stations are separated by approximately 3 hours as indicated by the dots. The stations are: Tixie (TI), Dixon (DI), Abisko (AB), Leirvogur (LE), Narssarssuaq (NA), Meanook (ME), College (CO), and Great Whale (GW).

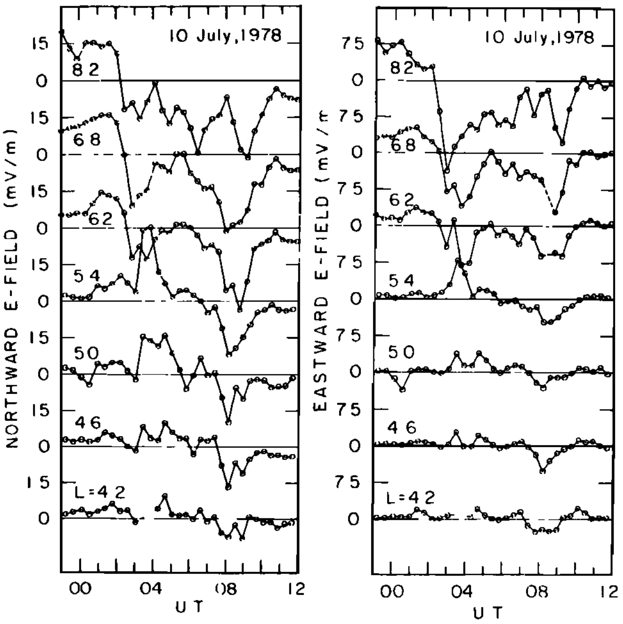

Fig. 4. Eastward and northward electric field components at various L values determined from the Millstone Hill radar.

Radar data from L = 4.2−8.2 are plotted in Figure 4. During the 0800 UT substorm event, the electric field patterns were roughly similar at all the observing latitudes, while during a substorm near 0400 UT there was a reversal in the sign of the field components between L = 5.4 and 6.2. The reversal occurred beyond the outer observed limits of plasmapause whistler propagation as noted above.

The drifts at $L \leq 5.4$ in the premidnight event were westward and poleward, in contrast to the eastward and equatorward motions observed near 03 MLT. The poleward component of motion prior to midnight is a regular feature of whistler observations near L = 4 (Park, 1978; Carpenter and Park, 1979).

Discussion and Conclusions

Under conditions of moderate disturbances, we have found good agreement between the data obtained by the whistler and the radar techniques, lending further support to the results obtained independently by these methods. The equatorial and ionospheric data differ by about a factor of 10, which corresponds to the mapping factor of $L^{3/2}$ (Mozer, 1970) that would be expected in a dipole field under conditions of equipotential field lines and with a direct calculation of the magnetic field line spreading using the IGRF 1975 model. The latter yields a mapping factor of 9.83. We conclude that the observed eastward component of electric field in the outer plasmasphere was consistent with a curl-free condition even when moderate substorm magnetic perturbations were present. This is consistent with the findings of Block and Carpenter (1974), who compared substorm whistler drift information with magnetometer data. On the basis of the 20 min averages, we conclude that our data is consistent with zero potential drop along the field lines in the outer plasmasphere near L = 4.4. This agrees with prolonged observation of ducted whistlers, whose propagation might have been interrupted if field-aligned potential drops and associated shears in transverse drift velocity had altered the guidance properties of the plasma ducts. Exceptions to the mapping ratio occurred near magnetic midnight where the zonally symmetric model cannot reflect the distortion of the magnetic field expected there. More simultaneous measurements are needed to determine whether the distortion is sufficient to explain the larger ratio of ionospheric to magnetospheric fields.

The data obtained during a substorm event centered at 0830 UT confirm previously published results from whistler observations (Carpenter et al., 1972) at similar L values. One important addition to these results is a meridional component of the electric field measured at Millstone Hill. Taken together, these data indicate an enhanced flow inward and towards dawn in the equatorial plane during the substorm. Following the substorm there was a period of reversal from inward to outward flow as the fields turned eastward. This behavior is frequently observed in the outer plasmasphere following temporily isolated substorms (Carpenter et al., 1972; Carpenter and Seely, 1976).

As noted above, the middle magnetospheric fields do not just follow the pattern at high latitudes. The meridional component turned sharply southward just after 0200 UT at high L values and remained that way throughout the data interval. At lower L values the meridional component remained poleward until the sharp decrease in the auroral zone magnetic field occurred at substorm onset. A similar pattern held for the zonal component. This suggests that the middle magnetospheric effects associated with the postmidnight substorm were closely related to the reconfiguration of magnetospheric current systems. Such a relation was also inferred from whistler, magnetic and auroral data by Carpenter and Akasofu (1972).

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References

Block, L.P., and D.L. Carpenter, Derivation of magnetospheric electric fields from whistler data in a dynamic geomagnetic field, J. Geophys. Res., 79, 2783, 1974.

Carpenter, D.L. and S.I. Akasofu, Two substorm studies of relations between westward electric fields in the outer plasmasphere, auroral activity, and geomagnetic perturbations, J. Geophys. Res., 77, 6854, 1972.

Carpenter, D.L. and N.T. Seely, Cross L plasma drifts in the outer plasmasphere: Quiet time patterns and some substorm effects, J. Geophys. Res., 81, 2728, 1977.

Carpenter, D.L., K. Stone, J.C. Siren and T.L. Crystal, Magnetospheric electric fields deduced from drifting whistler paths, J. Geophys. Res., 77, 2819, 1972.

Carpenter, D.L., C.G. Park, and T.R. Miller, A model of substorm electric fields in the plasmapause based on whistler data, J. Geophys. Res., 84, 6559, 1979.

Evans, M.V., J.M. Holt and R.H. Wand, Millstone Hill incoherent scatter observations of auroral convection over 60 << 75, 1. Measurement techniques in print, J. Geophys. Res., 1979.

Farley, D.T., Methods of Experimental Physics, Vol. 9B, Chpt. 14, ed. by H. Griem and H. Lovberg, Academic Press, 1971.

Gonzales, C.A., M.C. Kelley, L.A. Carpenter, and R.H. Holzworth, Evidence for a magnetospheric effect on midlatitude electric fields, J. Geophys. Res., 83, 4397, 1978.

Gonzales, C.A., Electric fields in the low latitude ionosphere and their relationship to magnetospheric and interplanetary phenomena, Ph.D. Thesis, Cornell University, 1979.

Kelley, M.C. and F.S. Mozer, Simultaneous measurement of the horizontal components of the Earth's electric field in the atmosphere and in the ionosphere, J. Geophys. Res., 3275, 1975.

Mozer, F.S., Electric field mapping from the ionosphere to the equatorial plane, Planet. Space Sci., 18, 259, 1970.

Mozer, F.S., R. Serlin, D.L. Carpenter and J. Siren, Simultaneous electric field measurements near L = 4 from conjugate balloons and whistlers, J. Geophys. Res., 79, 3215, 1974.

Park, C.G., Whistler observations of substorm electric fields in the nightside plasmasphere, J. Geophys. Res., 83, 5773, 1978.

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