NOTES ON BROADBAND WHISTLER MEASUREMENTS OF ELECTRIC FIELDS AND ASSOCIATED PHENOMENA

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(These notes briefly summarize certain recent work based on broadband VLF recordings in the Antarctic. They call attention to problem areas in which international spaced-station work may be of particular value in the future. Only limited bibliographic information is presented.)

1. Some Examples of Recent Work

The whistler experiment from which cross-L velocities of whistler ducts are inferred is shown schematically in Fig. 1. The dashed curve shows the estimated size of the viewing area of Eights or nearby Siple, Antarctica (Siple is at 76°S, 84°W, $L\sim4$). The viewing area is a statistical concept based in part on the distribution in L space of whistlers at Eights and in part on intercomparisons of data from Byrd, Antarctica and Eights (spaced about 1 hour apart in magnetic local

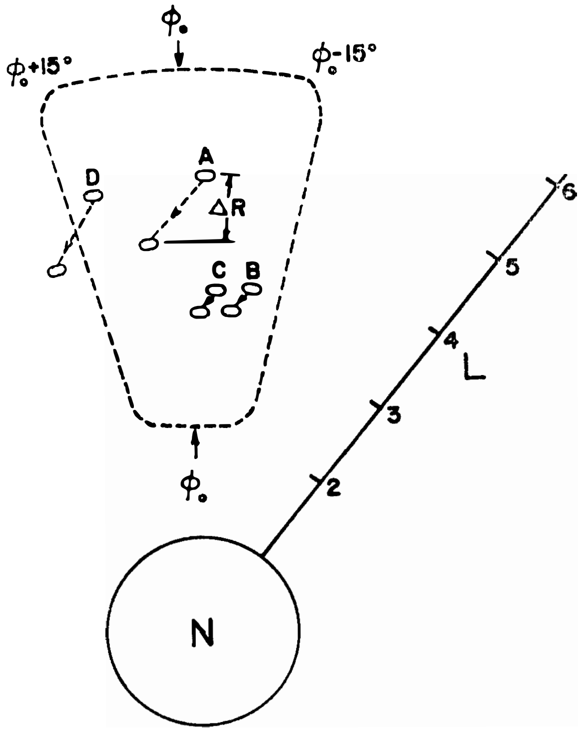

Fig. 1. Diagram of the whistler method of tracking the cross-L motions of whistler ducts. The dashed curve outlines the approximate equatorial region that a ground station at longitude φ_0 and $L\sim4$ is capable of observing, given the presence of suitable lightning source activity in the conjugate region. The equatorial positions of four representative whistler ducts are labeled A, B, C and D. In general the ducts are in motion with respect to the viewing area. The radial component of this motion may be relatively accurately determined by present techniques (from CARPENTER *et al., 1972).*

time). During a given drift event, ducts may be distributed over a relatively large portion of the viewing area. Hence there are possibilities for determining the extent of drift activity in L space and in longitude and for investigating the spatial coherence of the activity.

The whistler nose frequency is sensitive to the effects of fluctuating magnetospheric currents, and thus may be used to infer certain properties of the total, potential plus induced, magnetospheric electric field. In contrast, ionospheric observations by radar, balloon, barium cloud, etc. are relatively insensitive to the effects of high altitude fluctuating currents, and thus are limited in their capacity to determine electric fields at great heights (BLOCK and CARPENTER, 1974).

As part of efforts to measure drift effects on many paths simultaneously, a detailed study was made of exceptionally well-defined multi-component whistlers recorded on July 15, 1965 at Eights, Antarctica (CARPENTER *et al.*, 1972). Figure 2 shows a plot vs. time of τ_n^{-1}, the reciprocal of travel time at the whistler nose. Each sequence of dots represents a particular trace, and interruptions or terminations in the dots indicate times beyond which the continuity of the trace could no longer be determined. The paths for which data are shown range from $L=3.7$ to

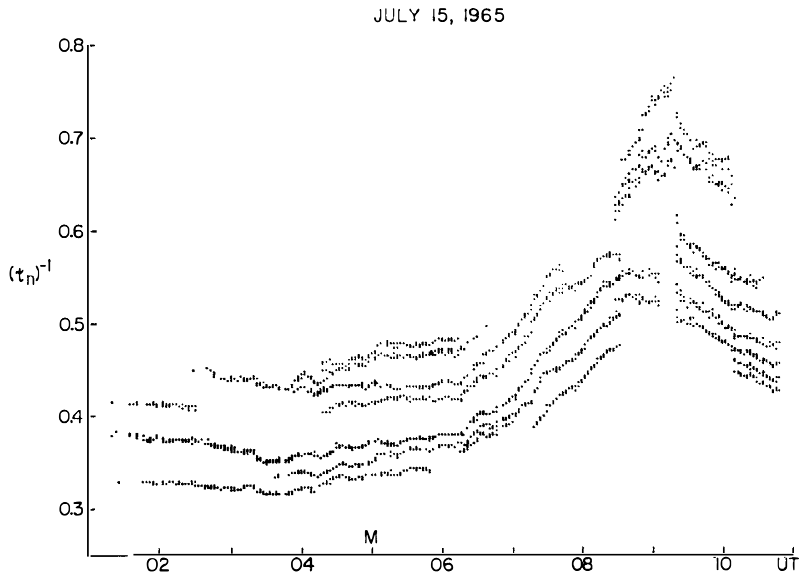

Fig. 2. Graph of the reciprocal of whistler travel time at the nose (τ_n^{-1}) vs. time, illustrating convection activity on several whistler paths over a 10-hour period on July 15, 1965 that included an isolated substorm. Local midnight at the observing whistler station (Eights, Antarctica) is indicated by M. The data gap near 0910 UT is due to a magnetic recording-tape change during a period of increased difficulty in determining continuity of whistler paths (from CARPENTER et al., 1972).

4.5, and at any one time there were typically five or six ducts being followed. The distinct upward trend after about 0630 UT is apparently a substorm effect. The upward trend in τ_n^{-1} indicates a drift of paths to lower L shells. (If f_n had been scaled and plotted, the result would be similar to the present plot of τ_n^{-1}, since τ_n^{-1} increases with increasing whistler nose frequency during a drift event.) Figure 2 is interpreted as showing relatively fixed path positions prior to about 0620 UT. Then, during the substorm, the paths drift rapidly inward, and later near 0900 UT begin a reversal in direction. There is close similarity among the various paths with regard to both the longer term and many of the short term variations.

The complex behavior near 0900 UT is of particular interest from the standpoint of future measurements at stations spaced in longitude, and in particular with regard to DF measurements. Near 0830 UT, several of the paths at lower values of τ_n^{-1} show a reversal in direction of drift, while paths at higher values of τ_n^{-1} continue to drift inward until about 0900 UT. This is inferred to be the result of fine structure in the convection fields that develops during the decay of

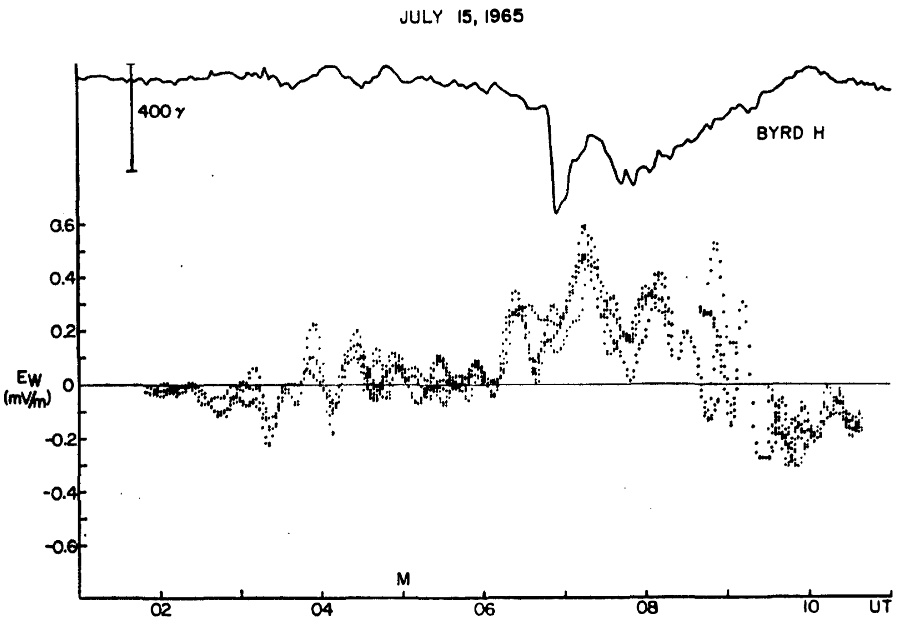

Fig. 3. Values of westward electric field E_w in the magnetosphere near $L=4$ on July 15, 1965, determined from the data of Fig. 2 through smoothing and differentiation. Data from all whistler paths are superposed. The Byrd, Antarctica, H component is shown as a crude indication of magnetic substorm activity near the meridian of the whistler E_w observations. Local midnight at the Eights, Antarctica, whistler station is indicated by M. (Byrd is about 1 hour behind Eights in magnetic local time.) (From CARPENTER et al., 1972).

the substorm. It may well be a longitude effect in which outward drifts develop in the eastward part of the station's viewing range while continued inward drift occurs for some time in that portion of the viewing range closer to midnight.

The electric fields deduced from the travel-time data of Fig. 2 are plotted in Fig. 3. At the top is an indication of a substorm as detected by the Byrd magnetometer. The similarity in behavior on the various paths over both longer and shorter periods is clearly evident, and the dissimilarity in behavior near 0900 UT is also clear. At one time it was believed that this event showed a rise in the westward electric field that preceded the substorm observed at Byrd. This indeed appears to be the case from the figure, but is not now considered to be evidence of a growth in the westward field prior to the expansion phase of a substorm (CARPENTER *et al.*, 1972). This point is discussed in connection with a later figure.

The reversal of the westward field to eastward in the aftermath of relatively isolated substorms has frequently been observed by the whistler method. In contrast, such effects have not been observed at slightly higher latitudes by the incoherent scatter method nor by the balloon technique. It seems possible that this effect is due to interaction between the moving ions and the neutral air, although an interpretative model of the effect has not yet been worked out. It would be desirable to search for evidence of such effects near $L=4$ under fairly quiet conditions. When the inner magnetosphere is perturbed by a relatively isolated but not exceptionally large substorm, it may be possible to combine whistler measurements with observations by incoherent scatter radar, interferometers, and other techniques of the overall behavior of the neutral air and associated ionospheric parameters.

One of the most important questions concerning magnetospheric electric fields concerns their development during substorms. In this connection there has been controversy over whether there is a 'growth-phase' or rising westward electric field near midnight prior to the expansion phase of a substorm. The controversy has not been entirely resolved, but within the plasmasphere there appears to be relatively strong evidence that the westward field does not rise to high substorm levels prior to the auroral expansion, but rather rises rapidly at the time of the expansion (CARPENTER and AKASOFU, 1972). This is illustrated in Fig. 4, which shows results from a particularly well defined whistler drift event observed at Eights, Antarctica. The figure includes all-sky camera records from Byrd, Antarctica, which is located at $L\sim7$ and within $\sim$one hour of Eights in magnetic local time. At the top of the record is a series of all-sky camera pictures showing auroral activation at approximately 0522 UT, when a Pi 2 micropulsation event was observed at Eights (second panel). This type of Pi 2 event is frequently observed at the time of the substorm expansion phase. The westward electric field inferred from Eights whistlers is shown on a slightly expanded time scale in the third panel. There is a rapid rise in the westward field at about 0522, very close to the time of the Pi 2 and auroral events. Below the westward field plot are tracings of the Fredericksburg magnetometer D and H component. The D component shows a particularly large westward deflection, which is frequently interpreted as a

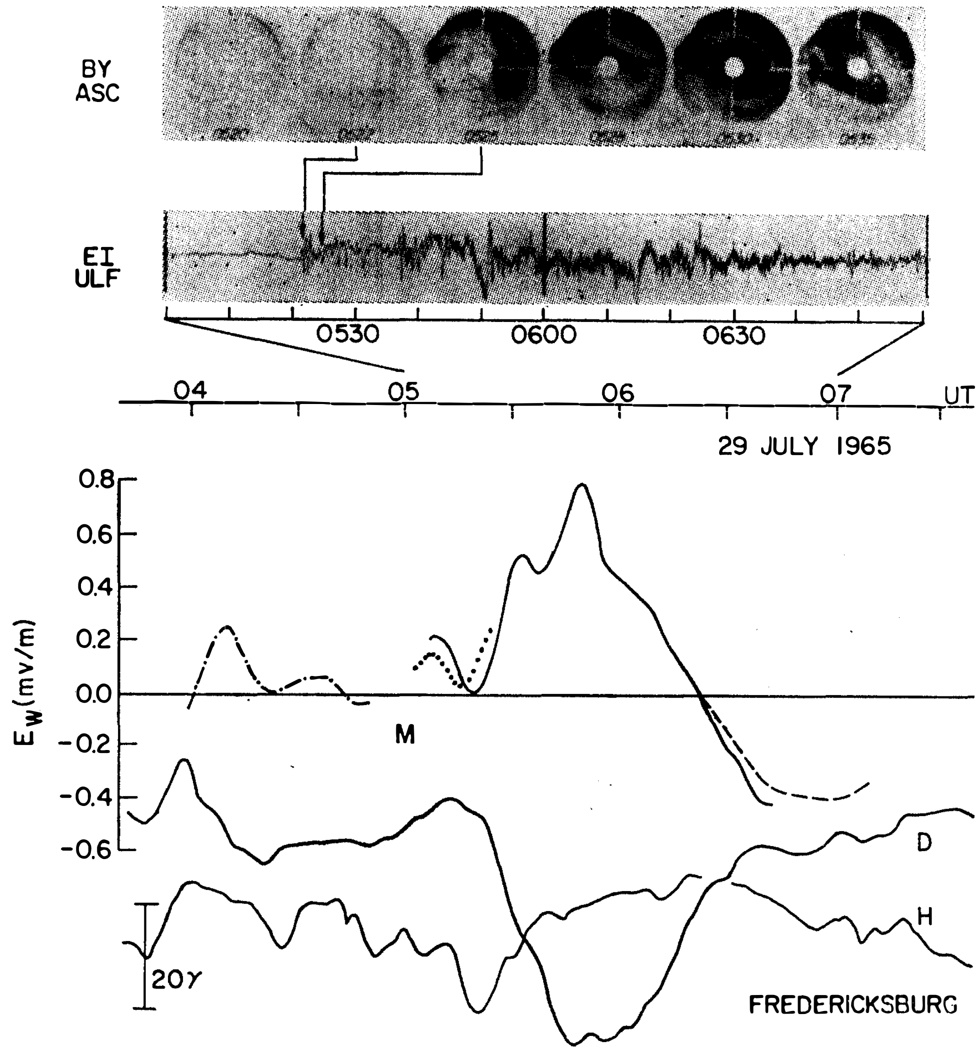

Fig. 4. A substorm event showing the near simultaneity of an auroral expansion, a Pi 2 micropulsation event, a rapid increase in westward electric field in the outer plasmasphere, and a westward turning of the magnetic D component at a midlatitude observatory (from CARPENTER *and* AKASOFU, *1972).*

measure of field-aligned current activity rather than an indication of overhead current. This interpretation is reinforced by the fact that when the electric field swings eastward at about 0630 UT, there is no corresponding reversal in the *D* component.

The subject of whistler ducts has as yet received little detailed attention. As increasing emphasis is placed upon direction finding and for example, upon identifying the magnetospheric regions in which certain wave-particle interactions are taking place, more attention will certainly be given to ducts and the ducting process. Figure 5 shows an example of the apparent "erosion" or "disappearance" of whistler ducts observed from Eights Station during a substorm. Evidence of

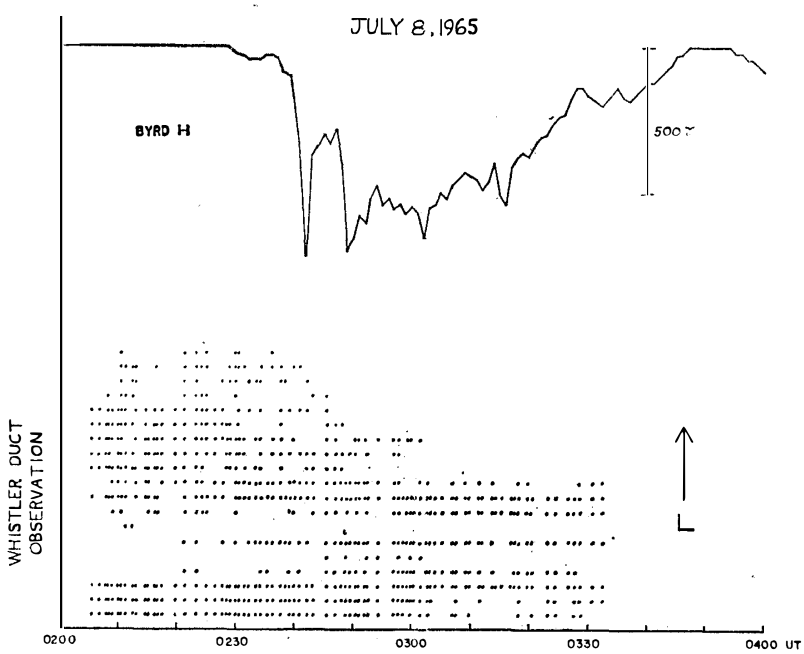

Fig. 5. Example of the apparent 'erosion' of whistler ducts observed from Eights Station during a substorm. Above is a transcription of the Byrd, Antarctica magnetic H component. Dots show the presence of individual whistler traces observed at Eights, Antarctica. The L coordinate is not shown explicitly, but L increases upward.

the substorm is shown at the top of the record by a transcription of the Byrd H magnetometer trace. The dots at the bottom of the record show as a function of time the occurrence of whistler components at various L values. The L coordinates are not shown explicitly, but L increases upward. The record shows that during the course of the substorm the outermost paths (they were near $L\sim5.5$) progressively disappeared from the view of the observing station. Some paths were observed throughout and following the substorm event. No substantial cross-L motions of ducts were detected during the substorm. The cessation of propagation may have been due to a process that inhibited ducted propagation progressively inward, or alternatively may have been caused by a convection event in which the outermost ducts were rapidly carried in azimuth (westward) out of view of the ground station.

2. Comments on Future Studies

A number of points can be made with regard to future cooperative studies using broadband VLF:

1. There is a need for worldwide comparisons of convection activity and

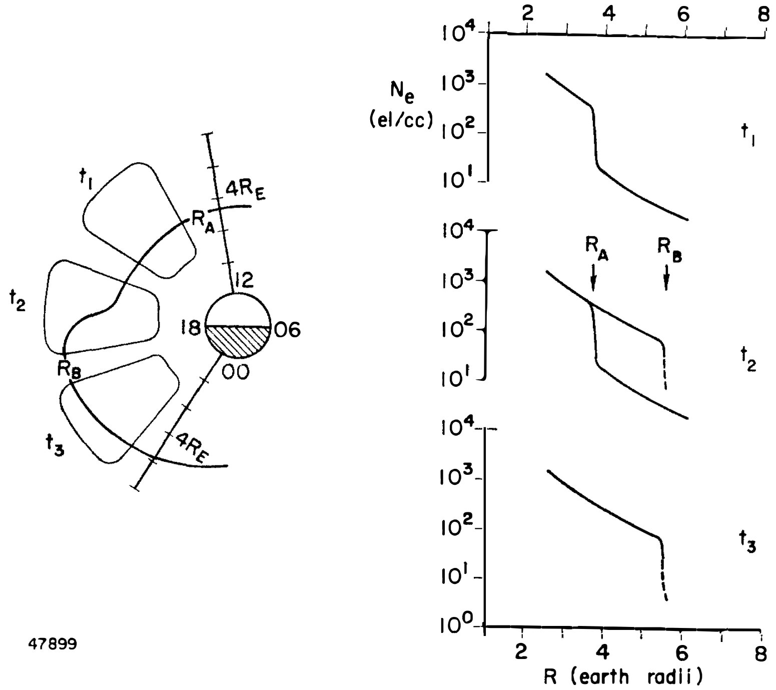

Fig. 6. Diagram of the method by which the viewing area of a single station is used to detect the presence of the dusk-side bulge in the plasmasphere. The equatorial viewing area of the ground station is shown at three successive times, t_1, t_2 and t_3. The corresponding equatorial profiles deduced from the data (without considering longitudinal spread of the paths) are shown at the right (from Carpenter, *1970).*

plasmapause morphology of the type recently reported by Corcuff *et al.* (1972). This calls for station separation near $L=4$ of order 100°.

2. There is a need for coordinated studies at longitudinal separations of order 20–30°. These should focus upon certain important matters of detail such as the existence and topology of the evening bulge in the plasmasphere, the drift of whistler ducts in longitude between the viewing areas of longitudinally spaced stations, and the development of direction finding techniques from pairs of stations. The diagram in Fig. 6 shows how the viewing area of a single ground station has in the past been used to detect the presence of the duskside bulge in the plasmasphere. The position of the viewing area at successive times t_1, t_2 and t_3 is shown (this is a 'northern' hemisphere view). Much more detailed information could be obtained if two or three stations spaced in longitude could successively sweep underneath the bulge structure, examining its morphology and perhaps identifying temporal changes in bulge position of the kind that have previously been inferred from whistler studies. The existence of outlying or detached regions of dense plasma in the late afternoon sector has been described in remarkable detail through data from the light ion mass spectrometer on OGO 5 (Chappell *et al.*, 1971).

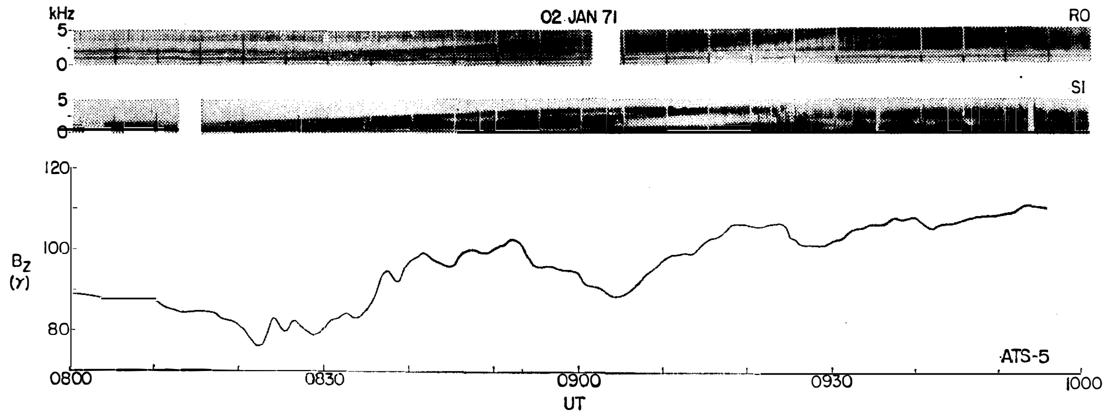

Fig. 7. Illustration of certain changes in center frequency of VLF noise during a substorm. The VLF records above, 0 to 5 kHz versus time, show data from the Roberval (RO)-Siple (SI) conjugate pair (L~4). The lower panel shows the magnetic Bz component from the ATS-5 GSFC magnetometer.

Evidence of such effects is believed to be present in the whistler data from a single station. Data from stations spaced 20–30° in longitude should provide a basis for identifying and investigating such structures. Here again direction-finding should be attempted.

3. There is a need for both closely spaced and widely spaced longitudinal studies of the occurrence of propagation beyond the plasmapause. Relatively little is known of the conditions under which ducted or partially ducted propagation occurs in this large outer region.

4. During certain types of magnetospheric events such as substorms, the center frequency of VLF noise observed at ground stations may change steadily in a way that may be interpretable in terms of convection in the magnetosphere (see, in this connection, VERSHININ, 1970). Figure 7 shows (above) VLF noise (0–5 kHz) versus time observed at Siple and Roberval during the 2 January 1971 X-ray-VLF correlation event (ROSENBERG *et al.*, 1971). A substorm expansion phase begins near 0820 UT. This is evidenced (below) by recovery of the B_z component of the earth's field as detected on ATS-5. During the period of rising center frequency of the noise at the conjugate stations, a cross-L inward drift of the plasma in the outer plasmasphere was detected from Siple whistlers. More work is needed to establish relations between the drifting whistler paths and the motion of regions of VLF noise generation. Spaced stations at separations of 20–30° in longitude would be helpful in this work. Direction finding would again be an important technique.

Acknowledgements

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