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Aloutte 1 and 2 Observations of Abrupt Changes in Whistler Rate and of VLF Noise Variations at the Plasmapause—A Satellite-Ground Study

D. L. CARPENTER AND F. WALTER[1]

Radioscience Laboratory, Stanford University
Stanford, California 94305

R. E. BARRINGTON AND D. J. MCEWEN

Radio Physics Laboratory
Defense Research Telecommunications Establishment
Ottawa, Ontario, Canada

Broadband VLF recordings on satellites Alouette 1 and 2 frequently reveal an abrupt spatial cutoff in whistlers propagating on magnetospheric paths from the conjugate hemisphere. In a typical case, the observed count of well-defined whistlers drops suddenly to zero within 10–100 km as the satellite moves poleward near invariant latitudes of about 60°. The whistler cutoff is frequently accompanied by a 'breakup' in the lower hybrid resonance (LHR) noise band, involving abrupt frequency and bandwidth changes as well as a transition from a smooth to an irregular appearance on frequency-time records. In each of 12 cases of simultaneous Alouette 1 observations and ground whistler data from Eights, Antarctica, on the 'knee' position, a close spatial relation was found between the whistler cutoff and the position of the plasmapause. In a typical Alouette-Eights comparison, the subsatellite point at the cutoff was less than 1000 km in a generally eastward direction from Eights. Events ranged from 52° to 66° invariant latitude and were observed in the interval 0100–1030 LT. A systematic small offset between the plasmapause position calculated from whistlers and the invariant latitude of the cutoff or noise breakup observed on Alouette may possibly be attributable to magnetospheric plasma current effects. Alouette 1 and 2 statistics from 27 occurrences of the cutoff reveal a variation of cutoff position with magnetic disturbance that is similar to the known behavior of the plasmapause, the cutoff being observed at lower invariant latitudes during periods of increased disturbance.

INTRODUCTION

According to ground-based whistler studies of the plasmapause, there is a relatively low probability of observing whistler components propagating on field-line paths through the tenuous region outside the plasmasphere [*Carpenter*, 1966]. A recent statistical study of the occurrence of whistlers as a function of observing station latitude and magnetic activity supports this conclusion [*Allcock*, 1966].

On a ground-station spectrogram, a plasmapause-controlled 'cutoff' in whistlers is manifested by the absence of detectable whistler components in a certain part of the frequency-time domain. For example, at Eights, Antarctica ($L \sim 4$), in the time range 0000–1600 LT, observed whistler components usually represent both the plasmasphere and also the portion of the tenuous region immediately outside the plasmasphere (i.e., the outer 'surface' of the plasmapause). Beyond this point there may be no apparent whistler activity, or, particularly on the dayside, there may be no activity in a region extending 1–2 R_E beyond the plasmapause. On a polar orbiting satellite, a spatial variation of this kind might be expected to appear as an abrupt change in the whistler occurrence rate as the satellite flies through the plasmapause. Such an effect has been found in the records of the Alouette 1 and 2 satellites.

Associated changes in VLF noise have also been found, one such effect being a sudden 'breakup' in the lower hybrid resonance (LHR) noise band (the LHR noise band is discussed by *Barrington et al.* [1963] and by *Brice and Smith*

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[1] On leave from Comissao Nacional de Atividades Espaciais (CNAE), Sao Paulo, Brazil.

[1965]). An initial study of the whistler cutoff and related VLF noise effects is reported in the present paper.

The basic approach in the research is to compare ground determinations of the magnetic shell of the plasmapause with the invariant latitudes of whistler cutoff and associated noise effects observed simultaneously on the satellite. Both a statistical and case-study approach are used, but particular emphasis is placed on the case studies.

DESCRIPTION OF THE EXPERIMENT

The study involved broadband VLF receptions on the satellites Alouette 1 and 2 and at the ground stations Eights ($L \sim 4$) and Byrd ($L \sim 7$) in the Antarctic (supplemented by receivers at Quebec City, Canada, in 1963 and Great Whale River, Canada, in 1963 and 1965). In the case studies, ground data in the local-time interval 0100–1030 were compared with simultaneous Alouette 1 passes for July–August 1963 (South Atlantic telemetry, 52°S, 60°W geographic) and July–September 1965 (Byrd telemetry). In a typical comparison, the subsatellite point at the cutoff was less than 1000 km in a generally eastward direction from Eights, the principal source of ground data. The local-time difference between the satellite position at the cutoff and the whistler paths detected in the ground study is estimated to be of the order of an hour. (The time difference is not known precisely, owing to lack of detailed information on the longitude distribution of the whistler paths.) Over the effective distance in space between the two experiments, the plasmapause radius near dawn is not expected to vary by more than 0.1–0.2 R_E [see *Carpenter*, 1966].

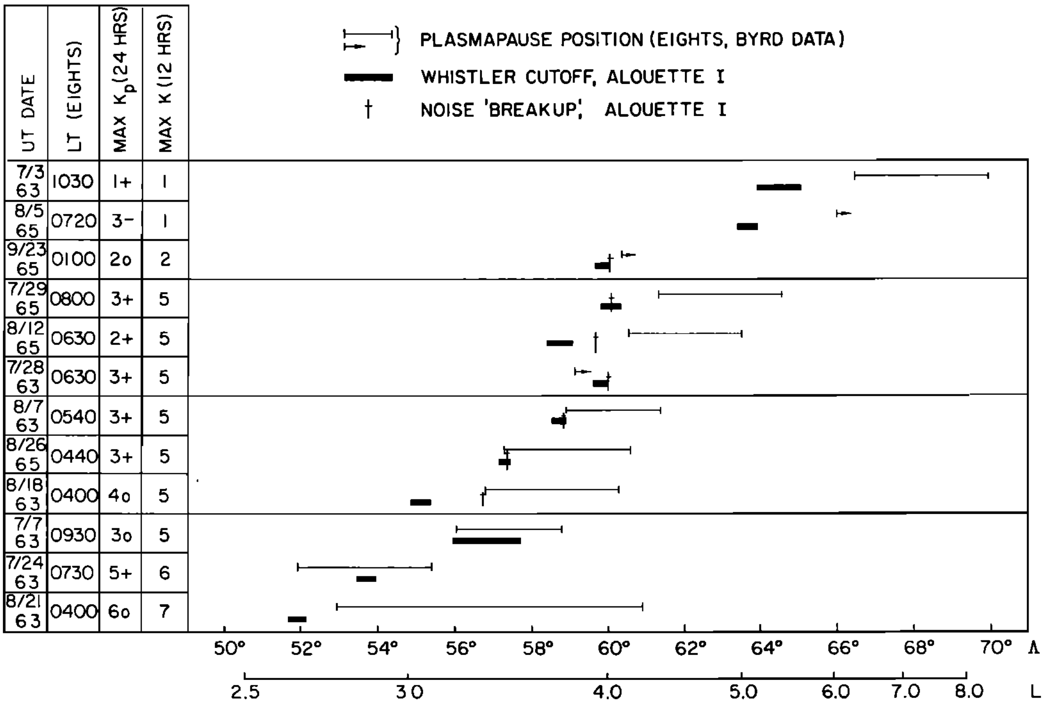
To obtain statistics on the cutoff, a survey was made of 1963 and 1964 Alouette 1 records for both northern and southern hemispheres. Alouette 2 records for mid-1966 were also included in the survey.

THE WHISTLER CUTOFF PHENOMENON

Figures 1 and 2 (see Plates 4 and 5, pages 2935 and 2936) show examples of cutoffs at three invariant latitudes, 54°, 57°, and 65°. Figure 1, showing a cutoff at ~54°, represents a southern hemisphere Alouette 1 pass at about 1240 UT (~0740 LT at Eights) on July 24, 1963, several days after the beginning of a protracted weak magnetic storm. Before the event there was nightly substorm activity, and the Kp index rose to 5+ early on July 24. The upper two panels show, respectively, a measure of whistler occurrence and the frequency-time spectrum (0–12.5 kHz) versus time and invariant latitude as the satellite moves poleward. The ordinate for whistler occurrence represents the fractional number of ~0.1-sec intervals occupied by visually detectable whistlers in successive ~10-sec periods. In this case, a value of 0.5 corresponds to a whistler count of roughly 20 independent events per minute. (The count was estimated using overlay techniques and source impulse identification methods. Only the more intense whistlers are evident on the spectrum in the second panel of Figure 1, owing to the compression of the time scale.) The activity is at first relatively steady, then begins decreasing at $\Lambda \sim 53°$, and drops to zero at $\Lambda = 54°$. As a later section will show (see Figure 3), there is a close relationship between this latitude and the latitude of the plasmapause calculated from simultaneous ground data.

The third and fourth panels in Figure 1 provide, respectively, an expanded view of the Alouette spectrum in the vicinity of the cutoff and the ground activity at Eights coincident with the expanded Alouette spectrum. Several of the Alouette whistlers occur at about the time of a ground whistler and exhibit features similar to those of the ground event. No obvious change appears on the ground record when whistler activity on the Alouette panel ceases.

Examples of the whistler cutoff at two higher invariant latitudes $\Lambda \sim 57°$ and $\Lambda \sim 65°$ are shown in Figure 2 (top and bottom, respectively). The pass of August 26, 1965 (Figure 2, top) occurred during a prolonged period of moderate magnetic agitation ($Kp = 2$–4). Before 0941 : 48, the whistlers are complex, well-defined, and relatively free from VLF noise except near the strong band at ~8.5 kHz. This type of whistler then disappears abruptly and is followed by several extremely faint events with traces at best only partially defined. Further whistler activity begins against a noisy background at ~0942 : 23 and involves bursts with diffuse trailing edges and a lower cutoff near 2 kHz. It is believed that this effect is produced by the 'knee' trace, the whistler component propagating in the tenuous region along or near the outer surface of the



UT DATE	LT (EIGHTS)	MAX K_p (24 HRS)	MAX K (12 HRS)
7/3 63	1030	1+	1
8/5 65	0720	3-	1
9/23 65	0100	2o	2
7/29 65	0800	3+	5
8/12 65	0630	2+	5
7/28 63	0630	3+	5
8/7 63	0540	3+	5
8/26 65	0440	3+	5
8/18 63	0400	4o	5
7/7 63	0930	3o	5
7/24 63	0730	5+	6
8/21 63	0400	6o	7

Fig. 3. Summary of case studies in which the whistler cutoff on Alouette 1 is compared with simultaneous ground measurements of the plasmapause position. The *K* values in the fourth column at the left are for Byrd Station. The systematic difference between the Alouette data and the ground measurements is discussed in the text.

plasmapause. When such events are observed, the term 'cutoff' signifies not a disappearance of whistlers but rather a drastic change in properties such as dispersion, intensity, degree of definition, and association with VLF noise.

The records of Figure 2 (bottom) illustrate a cutoff observed under very quiet magnetic conditions ($Kp = 0$–1). There is no abrupt change, as in the lower-latitude cases, but rather a transition, beginning at $\Lambda \sim 64°$, from multicomponent whistlers with nose frequencies as low as 2 kHz to faint, poorly defined events that are evidenced by a slight enhancement of the LHR noise band. The occurrence rate appears to reach zero at $\Lambda \sim 65°$.

Whistler components with nose frequencies near 2 kHz represent propagation from the conjugate hemisphere at $L \sim 5.5$. Such nose frequencies are observed on Alouette 1 only during magnetically quiet periods, a fact consistent with ground data showing that, except during very quiet conditions, the plasmapause is typically at $L < 5$ near dawn [*Carpenter,* 1967].

VLF Noise Effects at the Plasmapause

Dramatic changes in VLF noise phenomena are often associated with the whistler cutoff. Several striking effects involve noises not detected on the ground, one of these being the lower hybrid resonance (LHR) noise band. Figures 1 and 2 show some representative examples of the behavior of VLF noise near the whistler cutoff. In the case of July 24, 1963, Figure 1, second and third panels, an LHR noise band with a lower frequency limit of about 8 kHz appears before 1245 and shows evidence of strong interaction with whistlers. Shortly after 1245, a second noise band, wider and less regular than the first, appears near the top of the record. Its limiting lower frequency decreases rapidly until the two bands appear to merge. Following the cutoff, the noise activity becomes irregular and relatively broad in bandwidth, with high intensities near a lower limiting frequency. Beginning at $\Lambda \sim 55°$, a diffuse noise structure appears to rise slowly in frequency

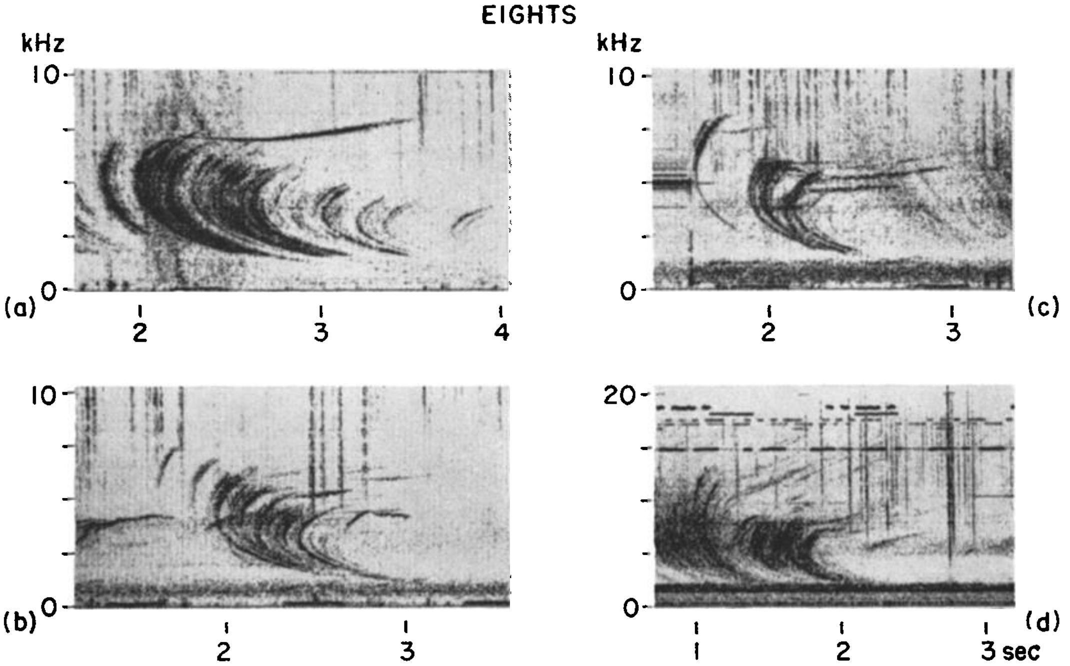
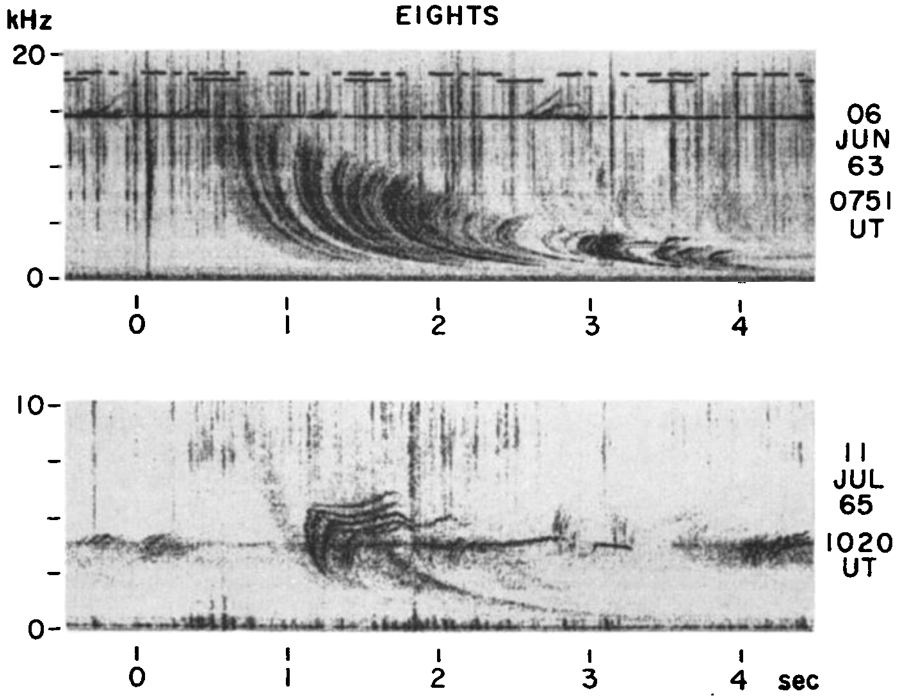


Fig. 1. *Carpenter.* Multicomponent whistlers illustrating the upper intensity cutoff. The spectra were recorded at Eights, Antarctica, during the synoptic intervals: June 6, 1963, 1450 UT (*a*); July 2, 1963, 1050 UT (*b*); July 2, 1963, 0950 UT (*c*); June 13, 1963, 1250 UT (*d*). The 5-kHz tone at the left in (*c*) is part of a system calibration. Case (*d*) is complicated by additional diffuse whistler activity in the background. Time is indicated in seconds from the causative atmospheric. Cases (*a*), (*b*), and (*c*) show the frequency band 0–10 kHz, case (*d*) shows 0–20 kHz.

Fig. 5. *Carpenter.* Multicomponent whistlers illustrating the upper intensity cutoff. The upper record shows the effect over a wide range of paths (equatorial radii ~3–5.5 R_E) within the plasmasphere. The lower record illustrates triggering of noise tones at the cutoff frequency on several paths outside the plasmapause. In the upper record near 15 kHz are rising tones triggered by Morse-code dashes from NAA transmissions at 14.7 kHz [see *Helliwell et al.* 1964].

Fig. 7. *Carpenter.* Multicomponent whistlers showing evidence of wave growth near the upper intensity cutoff. In the upper panel, a whistler with third- and fifth-hop echoes coexists with a sequence of discrete periodic emissions. There are at least nine identifiable emission groups, each propagating on the echoing whistler path with a 2-hop travel time nearly identical to that of the whistler. In the lower panel, the whistler rate on one path is ≥ 10/sec, while on other paths it is less than 1/sec. Many weak events are detected only above the nose and near the cutoff frequency. Each separate event on the 'good' path appears to consist of two traces spaced by ~20 msec. Some of the finer horizontal structure on the records near 3.5 kHz is of instrumental origin.


EIGHTS
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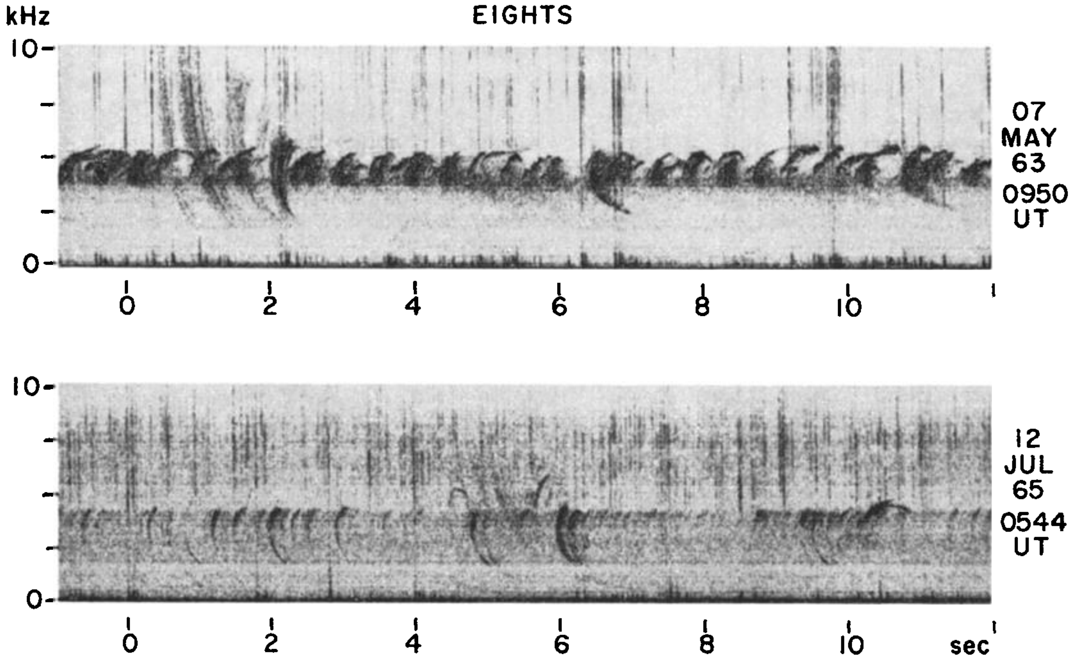
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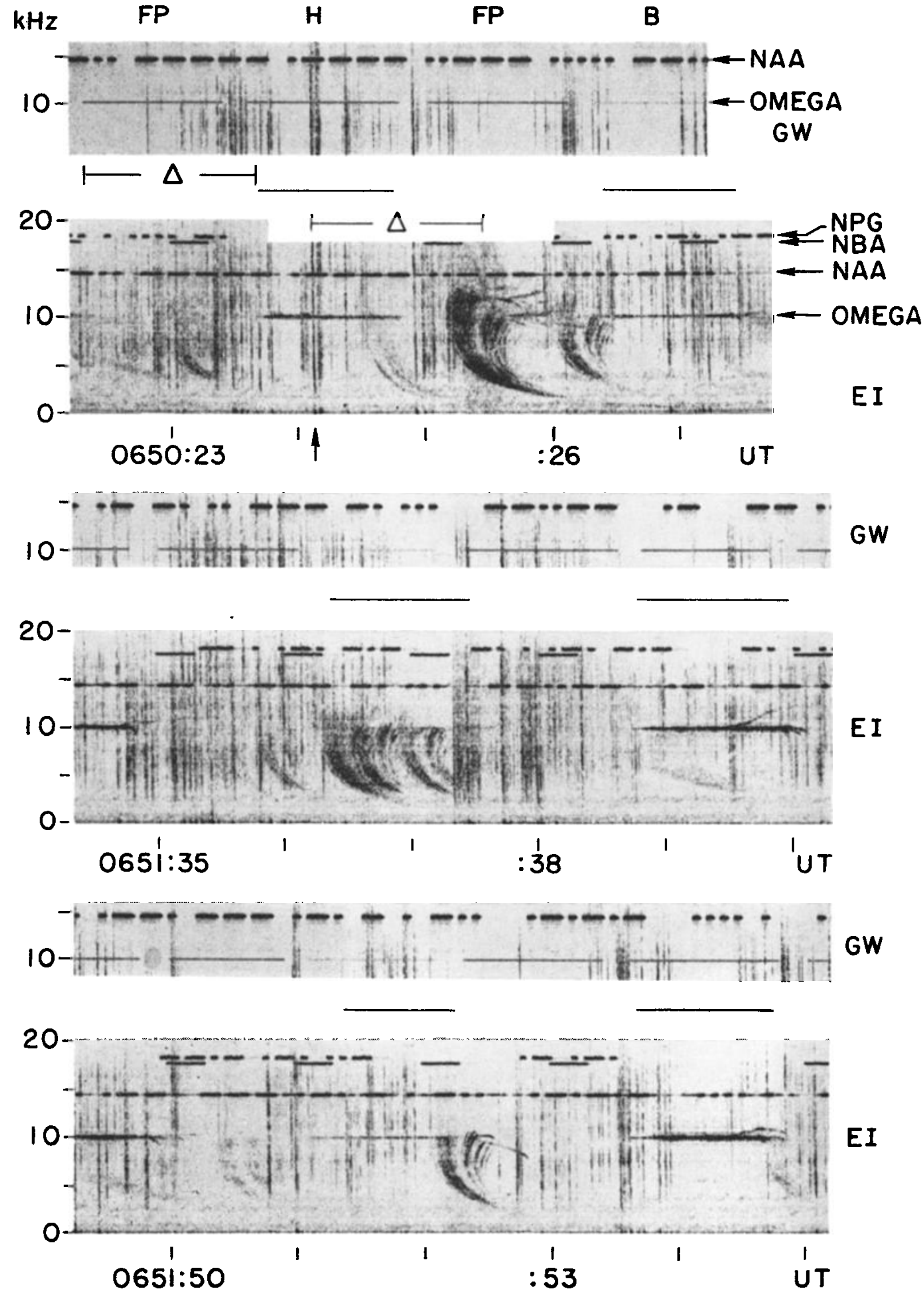

Fig. 8. *Carpenter*. Simultaneous conjugate recordings at Great Whale (GW) and Eights (EI), May 9, 1963, illustrating triggering of magnetospheric noise by ~1-sec 10.2-kHz pulses from the low power (~100 watts) Omega transmitter at Forest Port, New York. See text for details.

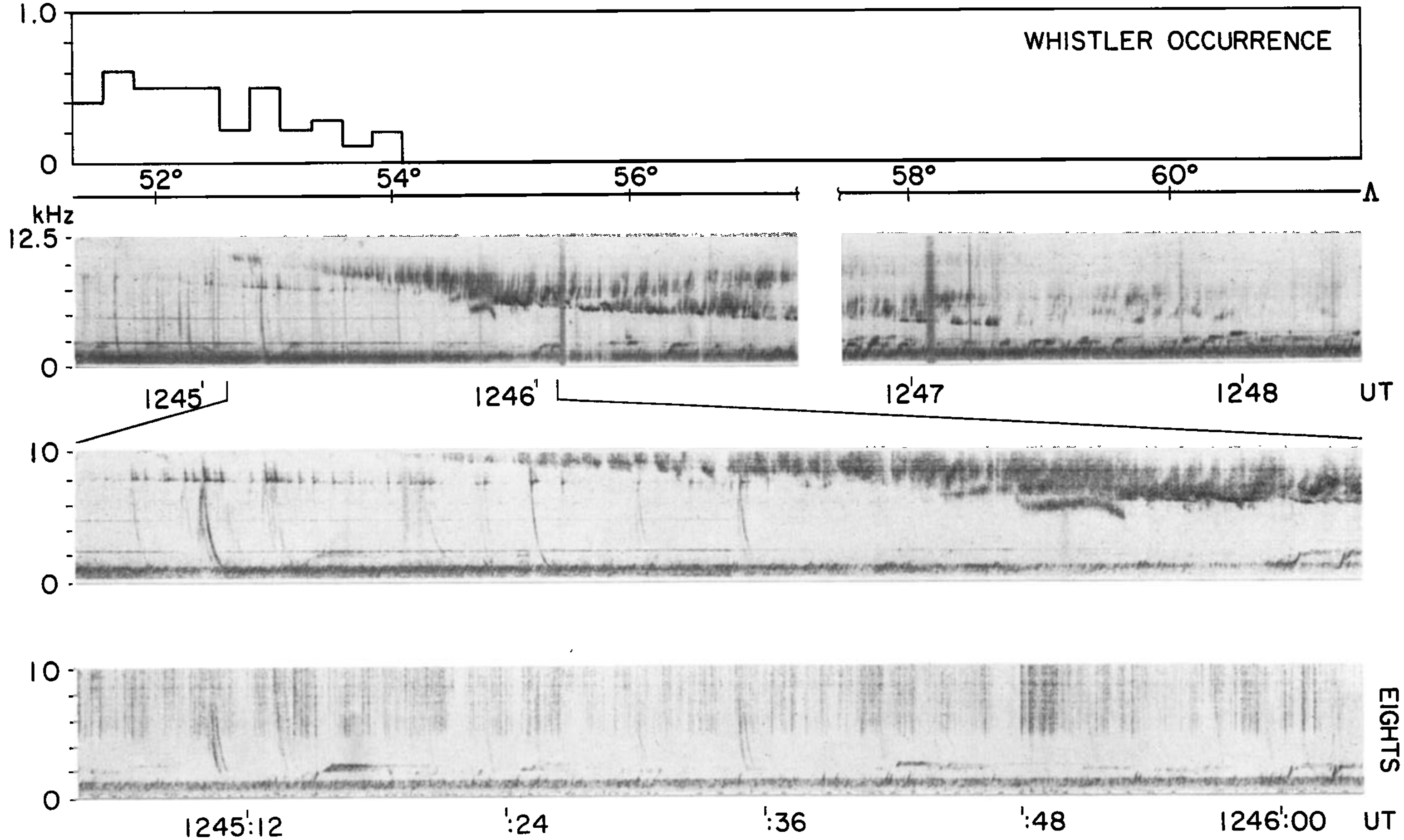

Fig. 1. *Carpenter et al.* Example of a whistler cutoff observed on Alouette 1 at $\Lambda \sim 54°$ ($L \sim 2.9$). Simultaneous ground whistler data indicated the plasmapause radius to be somewhere between ~2.7 and 3.1 R_E (in dipole coordinates). For further details, see text and Figure 3, case of July 24, 1963. There is a slight discrepancy, of instrumental origin, between the time scales of the lower two records.

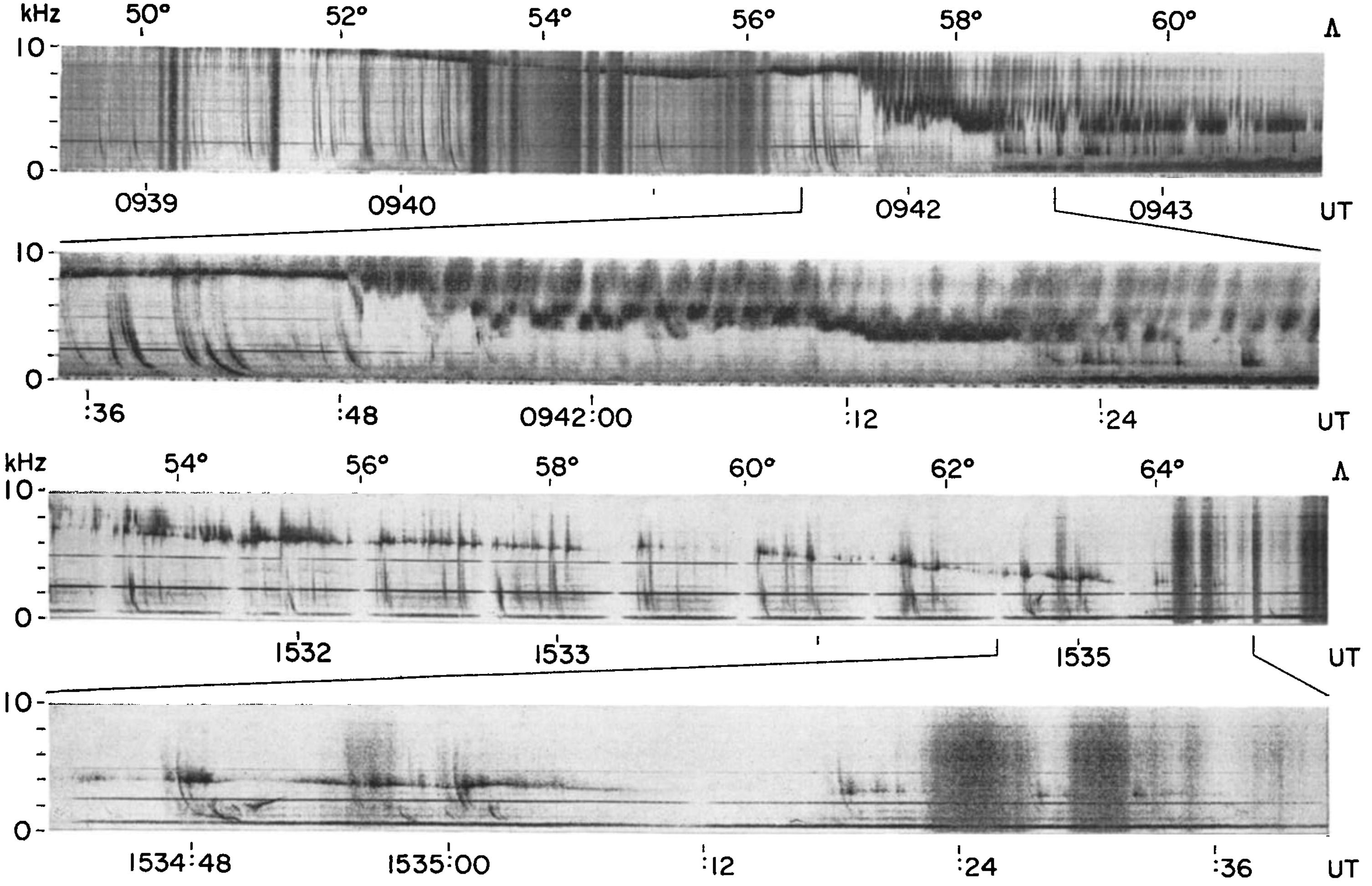

Fig. 2. *Carpenter et al. Top.* Example of a whistler cutoff at Λ ~ 57° ($L \sim 3.4$). Simultaneous ground whistler data indicated the plasmapause radius to lie somewhere between ~3.4 and 4.1 R_E (in dipole coordinates). For further details, see text and Figure 4, case of August 26, 1965. *Bottom.* Example of whistler 'cutoff' behavior near Λ = 65° ($L \sim 5.5$). Simultaneous ground whistler data indicated the plasmapause radius to lie somewhere between ~6 and 8 R_E (in dipole coordinates). For further details, see text and Figure 4, case of July 3, 1963.

with time. Another such effect begins at Λ ~ 58°.

In contrast to the activity just described, noise phenomena below ~3 kHz are observed by both satellite and ground receivers, and plasmapause effects, although apparent, are not dramatic. On both the satellite and ground records (third and fourth panels), two types of noise appear below 3 kHz, a succession of closely spaced rising 'chorus' tones (with a noisy background) in the range ~500–1200 Hz, and an occasional burst of noise that rises above the lower band and then tends to remain for several seconds at a level near 2500 Hz. A study of the records preceding those of Figure 1 showed that close agreement between ground and satellite on the form of discrete elements in the 500- to 1200-Hz band begins at 1243 : 30, two minutes (~6°) before the cutoff. The less frequent noises extending to 2500 Hz also begin to appear on Alouette records at this time, but they remain relatively faint until a few seconds after the cutoff and only then begin to show high intensity. This may be seen by comparing the two noises at the right of the third and fourth panels with the earlier noise at ~1245 : 15, which is strong only on the ground record. The propagation paths of the chorus are not well known, but it is believed that the bursts rising to ~2500 Hz may have propagated on paths several degrees in latitude beyond the plasmapause. As the satellite proceeded to the end of the pass at ~67°, these noises continued to be well defined.

A dramatic type of plasmapause-associated VLF effect is the noise 'breakup' shown in Figure 2 (top). This is a common feature of the plasmapause crossing when the boundary is in the vicinity of $L = 4$. Before the crossing, an LHR noise band is well-defined, with an intense lower frequency border. Within less than a second (<7 km) the smooth band disappears, and an irregular pattern of noise begins. The activity is characterized by intense blob-like bursts that are trailed by diffuse, rising noises. The center frequency of the bursts decreases irregularly with increasing latitude. Details of a possible relationship between whistlers and the bursts are not yet known, nor is there a clear relationship between the frequency of the bursts and the LHR frequency. Following 0942 : 23, the LHR at the satellite is probably associated with the lower cutoff of the whistlers at ~2 kHz (see earlier remarks).

The noise breakup is not always as abrupt as the one shown in Figure 2 (top) but it usually occurs within a matter of seconds, or less than ~20 km.

The records in Figure 2 (bottom) illustrate conditions of low magnetic activity and show an LHR noise band that does not break up but instead disappears near the plasmapause position. As the whistler cutoff is approached, the noise becomes somewhat irregular and decreases more rapidly in center frequency.

Results of the Case Studies

For the period July–August 1963 and July–September 1965, twelve cases were found in which there was a southern-hemisphere Alouette 1 pass coincident with ground observations, indicating the plasmapause or knee position. The results are summarized in Figure 3, which includes information on the date, approximate local time at Eights, and two indices of magnetic activity, maximum K at Byrd in the preceding 12 hours and maximum Kp in the preceding 24 hours. Horizontal flags or limiting arrows indicate the plasmapause position as determined from Eights and Byrd ground data (the method of measurement is described by *Carpenter* [1966]). A solid bar represents the whistler cutoff or, more precisely, the estimated zone within which the rate of well-defined whistlers observed on Alouette 1 reached a negligibly low value. Crosses mark the observation of an LHR noise breakup. The 12 cases illustrated were first ordered according to maximum K at Byrd and then, within the large $K = 5$ group, according to the latitude of the plasmapause as determined by the ground data. The local-time range at Eights is 0100–1030 (local time at Eights is 5 hours behind UT; at Byrd, ~6 hours).

Some remarks are needed on the quantities measured in the experiment. The ground data on the plasmapause position provide information on the range of minimum (approximately equatorial) gyrofrequencies between which the plasmapause lies. Dipole coordinates are then used to relate this range of equatorial gyrofrequencies to magnetic shells and their associated invariant latitudes. In the case of Alouette, spatial coordinates at the whistler cutoff are determined, and the invariant latitude is then found either from information on the L value or from an integration along the field line through the position of the satellite. The integration uses the Jensen and Cain field [*Jensen and Cain,* 1962] to obtain the geocentric distance to the point of minimum gyrofrequency, and invariant latitude is then determined from this geocentric distance. There are obvious uncertainties in these methods, but they do not appear great enough to obscure the basic results. Note that most of the measurements were made under conditions of only moderate magnetic disturbance.

The graph of Figure 3 indicates a close spatial relationship between the whistler cutoff, as observed on Alouette, and the plasmapause position. The agreement persists over a wide range of variation in magnetic activity, and a corresponding invariant latitude range of 52°–66°. The expected strong negative correlation of latitude with K or Kp is evident.

In most cases the cutoff occurs within less than 2° equatorward of the calculated plasmapause latitude. When observed, the LHR breakup tends to agree more closely with the plasmapause position than does the whistler cutoff. Of some 39 cases involving an LHR breakup, 23 showed the cutoff and breakup at the same position, i.e., within a range of $<\sim 0.2°$, four showed the breakup equatorward of the cutoff and twelve showed it on the poleward side, but usually within less than 2° of the last well-defined whistler. It appears that the LHR breakup, when observable, is the more precise indication of the plasmapause position, since the LHR noise is essentially a local phenomenon, whereas the whistlers observed are dependent upon many complex propagation factors along a path from a distant source.

The tendency for the whistler cutoff and LHR noise to occur slightly equatorward of the calculated plasmapause position is not understood. The fact that the disagreement is nearly always in the same direction suggests that uncertainties in the knowledge of the earth's magnetic field may be involved. In recent reports *Mead and Cahill* [1966] and *Heppner et al.* [1967] suggest that the earth's field is regularly dilated by currents in the magnetospheric plasma. Were such a model of the field used in calculating the position of the plasmapause, the flags in Figure 3 would tend to be displaced toward lower latitudes.

RESULTS OF A STATISTICAL STUDY

To augment the case studies, statistics on the location of the whistler cutoff and LHR breakup were obtained from 1963 and 1964 Alouette 1 data and from mid-1966 data from Alouette 2. The number of available passes was limited by the need for a sufficiently high whistler rate to allow determination of a cutoff. In Figure 4, the Alouette data (filled symbols) are compared with statistics on the position of the plasmapause near dawn for the period June–August 1963 and for meridians near those of most of the Alouette passes [from *Carpenter,* 1967]. The 27 Alouette data points represent the local time period 0400–1000. Squares indicate northern hemisphere passes read out at Ottawa and Resolute, and circles indicate southern hemisphere data obtained at South Atlantic and Byrd. The agreement is quite good, although there are relatively few Alouette data points on the right side of the distribution. This may be due to a number of factors, including (1) the tendency for whistler-calculated invariant latitudes to be slightly larger than those of the cutoff (Figure 3), and (2) the fact that the plasmapause data for the right side of the distribution and for $<4\ R_E$ typically represent the first day or two of weak magnetic storms [*Carpenter,* 1967]. Relatively few of the Alouette cases happened to coincide with such periods.

Conjugate observations of the plasmapause were made on the Alouette 1 pass of August 10, 1964, at ~1000 UT, with both crossings at $L \sim 4.5$. Many pole-to-pole recordings are available, but few provide unambiguous cutoff determinations in both hemispheres. For the interpretation of such cases, the satellite must encounter relatively high rates of either one-hop or two-hop (reflected) propagation in both conjugate regions. The fulfillment of this condition is limited by the seasonal variation in local thunderstorm activity and by the reduced occurrence of detectable two-hop as compared with one-hop propagation.

DISCUSSION

It is not yet clear whether the whistler cutoff effects may be attributed primarily to iono-

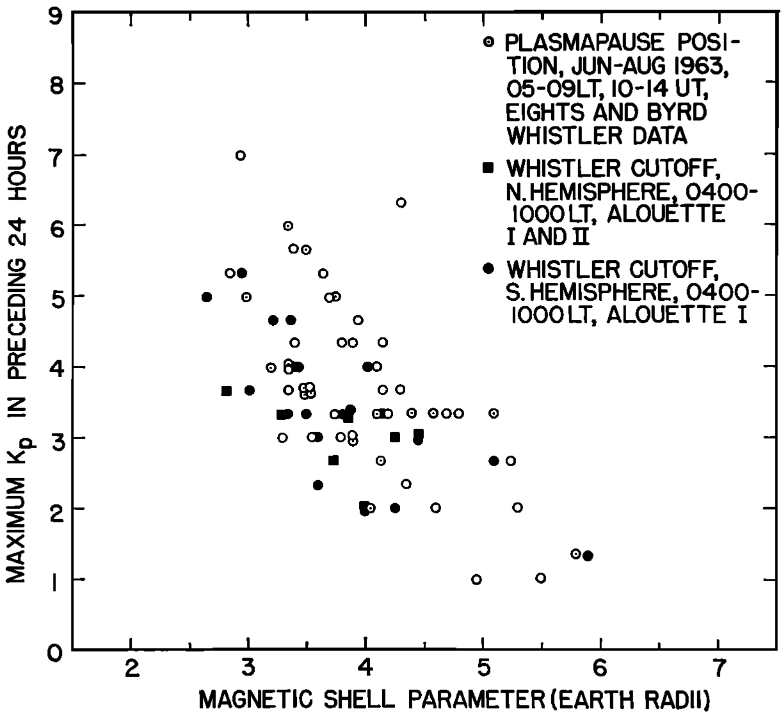

Fig. 4. A comparison of ground measurements of the plasmapause position with Alouette data on the whistler cutoff, both plotted in coordinates of maximum *Kp* in the preceding 24 hours versus a magnetic shell parameter. In the case of the whistler measurements, the parameter is approximate geocentric equatorial crossing in earth radii, whereas for the Alouette data it is *L* value calculated for 1000 km in the *Jensen and Cain* [1962] field.

spheric effects or to propagation conditions along the magnetospheric portion of the path.

Heyborne [1966] made a satellite study of the field strength of fixed-frequency signals from VLF transmitters. Digital data from the polar-orbiting satellite OGO 2 showed that as the satellite moved poleward near $L \sim 4$, there occurred field-strength decreases of about 25 db in less than 5° in daytime (1600 LT) and about 20 db in less than 10° at night (0400 LT). Heyborne considered it likely that increased absorption in the lower ionosphere accounted for the effect.

The argument for an ionospheric cause of the cutoff is weakened by evidence on some satellite records of continued upward propagation of short fractional hop (0_+) whistlers at latitudes poleward of a cutoff of whistlers reflected from (or originating in) the conjugate hemisphere. This effect is not easily interpreted, since a well-defined cutoff of one-hop whistlers and a high level of local 0_+ whistler activity are not commonly observed simultaneously. More study of this effect is required, including measurement of plasmapause-associated changes in the intensity of short path whistlers.

It may be noticed in the Alouette records of Figures 1 and 2 (top) that the interfering converter frequency lines disappear at about the whistler cutoff. In view of this, it might be suggested that the cutoff is primarily an AGC effect, in which intense noise effects cause the receiver to discriminate against whistlers. A check of the AGC information in several Alouette 2 cases showed no significant gain change at the time of the whistler cutoff. Furthermore, there are many Alouette 1 passes on which a well-defined cutoff is observed and on which the converter lines are not noticeably affected. There may indeed be an AGC effect in some cases, but it seems clear that the cutoff phenomenon is not an AGC effect.

CONCLUDING REMARKS

A combination of satellite and ground VLF data for the period 0100–1030 LT shows that whistler propagation to the conjugate hemisphere tends to be interrupted at latitudes above the plasmapause. Associated with this cutoff are drastic changes in VLF noise observed by the Alouette 1 satellite, in particular, a breakup in the LHR noise band. A well-defined breakup is most commonly observed during periods of moderate magnetic agitation and occurs within a time of the order of a second, or a distance of the order of 10 km. Just poleward of the plasmapause, a succession of rising noise forms is frequently observed, and further whistler activity appears to be confined to the whistler component propagating along the outer surface of the plasmapause. A systematic small offset between the plasmapause position calculated from whistlers and the invariant latitude of the cutoff or noise breakup observed on Alouette may possibly be attributable to magnetospheric plasma current effects. Such effects, if included in the whistler calculations, would tend to reduce the disagreement.

The abruptness of the whistler cutoff and noise effects in comparison with the range of uncertainty in estimating the plasmapause position from ground records encourages continued use of polar-orbiting satellites for studying the behavior of the plasmapause. On such satellites, detailed measurements of plasmapause-associated variations in ion composition, electron concentration, and other parameters may require instruments with km-scale resolution.

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