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Electron Concentrations Calculated from the Lower Hybrid Resonance Noise Band Observed by Ogo 3

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A noise band at the lower hybrid resonance is often detected by the Stanford University–Stanford Research Institute VLF and ELF receivers on Ogo 3, using the electric antenna. In some cases the noise band is at the geometric mean gyrofrequency $(f_{He} f_{Hi})^{1/2}$ as measured by the Goddard Space Flight Center (GSFC) magnetometer, and local LHR in a dense $(f_{Pe} \gg f_{He})$ H$^+$ plasma is indicated. In other cases the noise band drops to lower frequencies, and a more dilute $(f_{Pe} \lesssim f_{He})$ plasma is indicated; in such cases, electron concentration can be calculated, if it is assumed that heavy ions are negligible. Observations at mid-latitudes and altitudes of a few earth radii show local concentrations as low as 1.4 el/cm^3. In one case the concentrations obtained from the LHR noise band agree with those measured simultaneously by the GSFC ion mass spectrometer within a factor of 2. In another case the concentration is observed to fall by a factor of 2 in 150 km and then to decrease roughly as R^{-4} in agreement with whistler measurements outside the plasmapause.

The difficulties in obtaining reliable measurements of electron concentrations in the outer magnetosphere by particle collection techniques are well known [*Parker and Whipple*, 1970; *Whipple*, 1972]. The low particle concentration and large Debye length make it difficult to distinguish the small desired particle flux from other currents caused by varying spacecraft potential, photoemission, and secondary emission. Hence measurements from ion mass spectrometers, Langmuir probes, and the like are open to large uncertainties in low-density regions of the magnetosphere. An alternative is to look for electromagnetic wave effects, such as resonances, produced by the particles to be measured.

The lower hybrid resonance (LHR) was first suggested to be the frequency of a noise band detected in the upper ionosphere by *Brice and Smith* [1964, 1965]. They noted that the Alouette hiss band often seen in the topside ionosphere had a sharp low-frequency cutoff, showed more frequent occurrence in the receiver fed from an electric antenna, and could be enhanced by whistlers at large wave normal angles. The latitudinal variations in the frequency of the hiss band under the LHR interpretation required variation of ion composition that agreed qualitatively with that found by other workers. Brice and Smith suggested that measurements of the LHR frequency and gyrofrequency at high altitudes would in principle yield the electron concentration. *Barrington et al.* [1965], using simultaneous VLF and topside sounder records from Alouette 1, found that the ion composition determined from the LHR noise band, together with the scale height obtained from the sounder, yielded ionospheric temperatures in agreement with those of other workers. *Laaspere and Taylor* [1970], using simultaneous Ogo 4 data in the topside ionosphere, showed that there was a clear correspondence between the LHR frequency calculated from ion mass spectrometer measurements and the frequency of the VLF noise band. However, they noted that agreement was not always precise and suggested that at times the frequency of maximum amplitude of the noise band may be more meaningful than the lower cutoff and that the noise might not always be generated in the immediate vicinity of the spacecraft. *Scarf et al.* [1972*a*, *b*] reported the LHR noise band at high altitudes on Ogo 5 and in one case used it to calculate positive ion concentrations in good agreement with those measured by the GSFC retarding potential analyzer.

The LHR measurements reported in this paper were made with the Stanford University–Stanford Research Institute Ogo 3 broad band

VLF (0.3–12.5 kHz) and ELF (15–300 Hz) receivers. The Ogo 3 antenna can be connected through a matching transformer either as an electric sensor or as a magnetic loop; otherwise, the VLF experiment package is similar to that flown on Ogo 1. A complete description of the instrumentation is given by *Ficklin et al.* [1967]. Ogo 3 maintained three-axis stabilization from launch until July 23, 1966, after which it was spin stabilized about the z axis with a period of ~100 sec.

RESULTS

A typical LHR noise band as detected with the Ogo 3 electric antenna is illustrated in Figure 1. The spectrograms in this and later figures were made with the Rayspan spectrum analyzer; the ordinate is frequency in kilohertz, the abscissa is time, and the darkness is related nonlinearly to amplitude. The upper panel in Figure 1 shows a band of noise increasing in frequency from slightly over 1 to 4 kHz over a 27-min period as the satellite moves in from about $L = 4$ to $L = 2$ in the morning sector (the orbits for this and later examples are shown in Figure 2). Background intensity variations are due to telemetry fading at the satellite spin period (~100 sec); horizontal interference lines occur at the inverter frequencies (400 and 2461 Hz and harmonics). Near the beginning of this example the noise is quasi-continuous and appears strongest near the well-defined lower cutoff of the band. Later, the noise becomes intermittent and in fact occurs only following whistlers. The lower panel is an 8-sec segment of the same record, greatly expanded to illustrate a whistler triggering the noise. Again, the lower-cutoff frequency is quite distinct and most of the time is the strongest frequency in the band. The double trace indicates that the whistler itself is nonducted and was magnetospherically reflected near the satellite location [*Smith and Angerami*, 1968].

With the electric antenna the LHR noise band is detected on a portion of 68% of Ogo 3 passes. With the magnetic antenna it is detected on only 7% of the passes and appears only following whistlers. Figure 3 shows additional examples observed with the electric antenna (orbits B, C, and D in Figure 2). The top (B) and middle (C) panels are from inbound passes in the afternoon sector and display a smoothly varying quasi-continuous band of noise. The bottom (D) panel from an outbound pass in

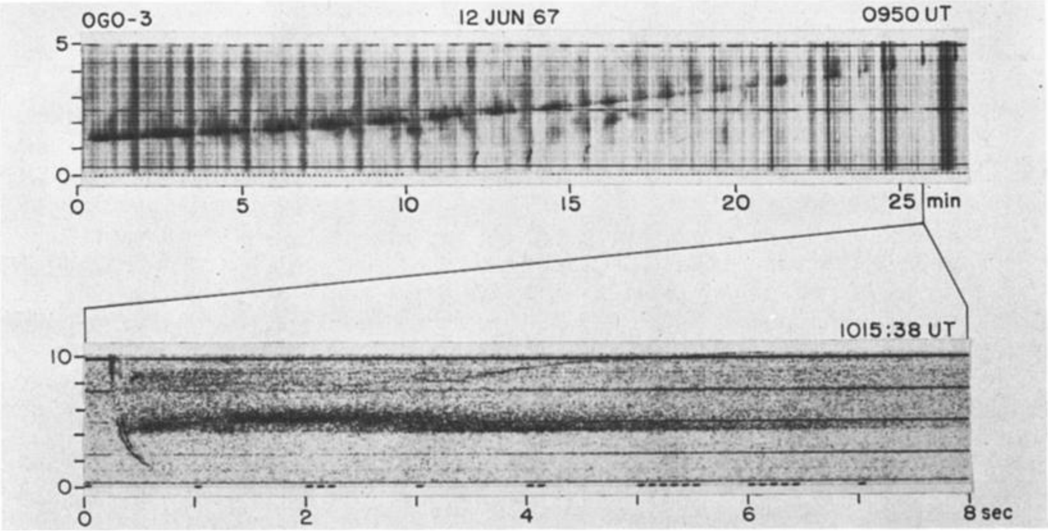

Fig. 1. Rayspan spectrograms (frequency in kilohertz versus time) showing an example of the LHR noise band detected by the electric antenna. Ogo 3 is inbound from $L = 3.9$–2.3, dipole latitude ≅ 30°S, LT ≅ 0400–0800, and $Kp = 1$. Background intensity variations occur at satellite spin period (~100 sec), and inverter lines at 0.4 and 2.461 kHz. Lower panel, time expanded and frequency compressed, shows triggering of LHR noise by magnetospherically reflected whistler.

local morning shows complex structure in the LHR band due to interactions with discrete emissions and perhaps to electron concentration variations. The *Kp* indexes for the top, middle, and bottom panels are 1−, 2+, and 4, respectively. At the end of the bottom example (L = 9.0, dipole latitude = 47°) the LHR frequency of 250 Hz is below any previously reported. With the use of the method outlined below this frequency indicates a local concentration of ~1.4 el/cm^3. This is within the range of values measured by *Chappell et al.* [1971] at L = 9 with an ion mass spectrometer, although their measurements were generally at lower latitudes.

In the topside ionosphere the LHR frequency is strongly influenced by the positive ion composition. At higher altitudes, however, the heavy ions settle out and leave mostly hydrogen. If a cold collisionless two-component (e, H^+) plasma is assumed, the lower hybrid resonance frequency f_L is given by [*Stix*, 1962]

$$1/f_L^2 = 1/(f_{Hi}^2 + f_{Pi}^2) + 1/f_{He}f_{Hi}$$

where f_{He} and f_{Hi} are the electron and ion gyrofrequencies, and f_{Pi} is the ion plasma frequency. Figure 4 is a plot of LHR frequency as a function of electron concentration N. For high concentrations ($f_{Pe} \gg f_{He}$) the LHR frequency equals the geometric mean gyrofrequency $(f_{He}f_{Hi})^{1/2}$ and is independent of concentration. At lower densities ($f_{Pe} \leq f_{He}$) the LHR frequency is a sensitive function of electron concentration. At extremely low densities the LHR

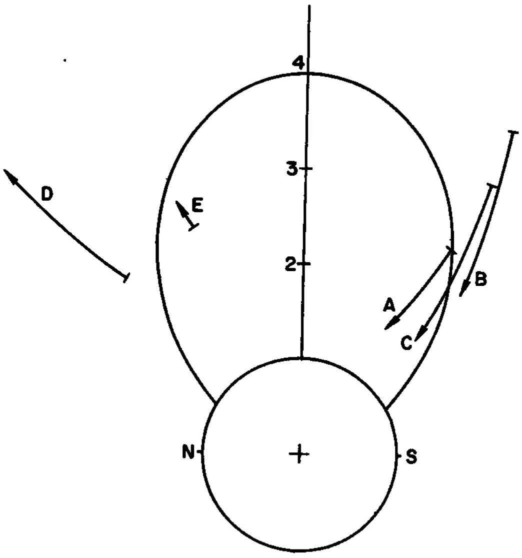

Fig. 2. Orbits of illustrated passes (altitude versus dipole latitude): A, June 12, 1967; B, December 8, 1966; C, December 6, 1966; D, October 6, 1966; and E, July 9, 1966. The dipole field line at L = 4 is shown for reference.

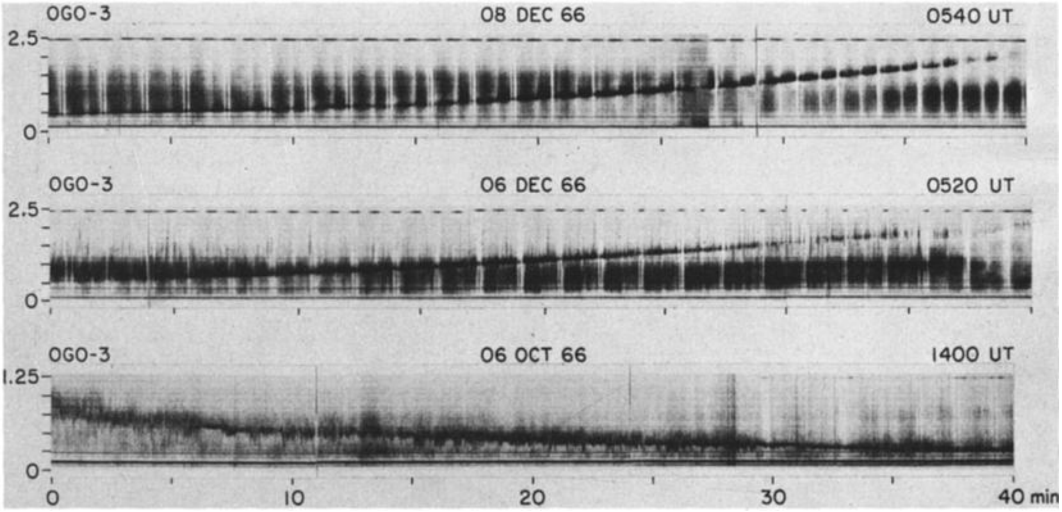

Fig. 3. Examples of the LHR noise band observed with the Ogo 3 electric antenna. Top panel: inbound, L = 5.5–4.3, dipole latitude ≅ 35°S, LT ≅ 1400–1600, and Kp = 1−. Middle panel: inbound, L = 4.9–3.8, dipole latitude ≅ 40°S, LT ≅ 1500–1700, and Kp = 2+. Bottom panel: outbound, L = 5.3–9.0, dipole latitude ≅45°N, LT ≅ 0930–1030, and Kp = 4.

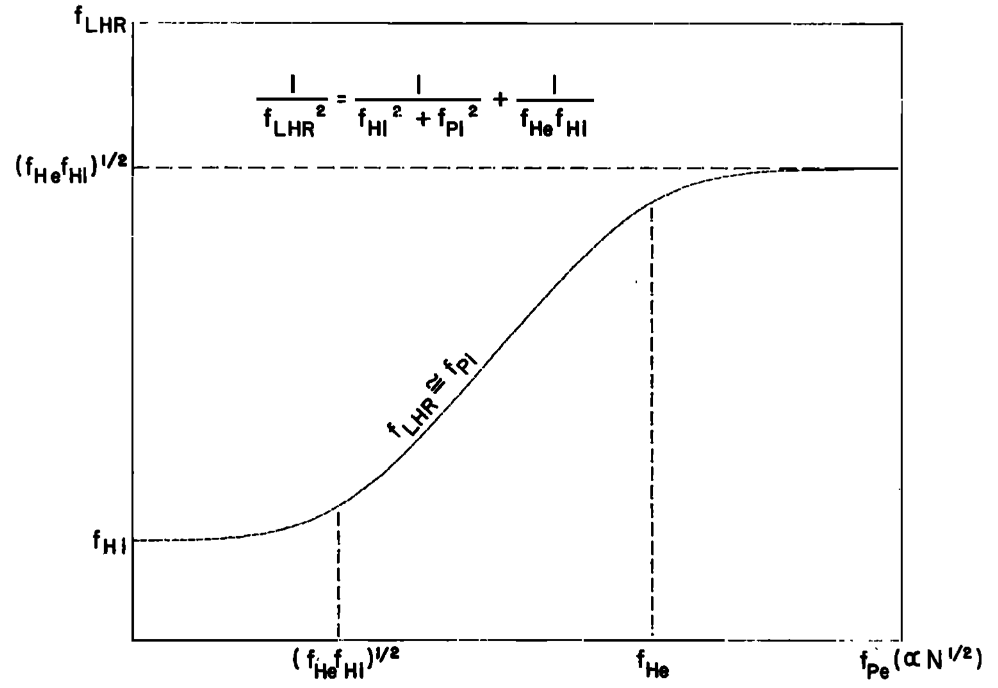

Fig. 4. LHR frequency plotted as a function of electron plasma frequency for a two-component plasma. Note that the LHR frequency is a sensitive function of electron concentration when $(f_{He}f_{Hi})^{1/2} \le f_{Pe} \le f_{He}$.

is again independent of concentration; this part of the curve has not been encountered in the Ogo 3 data. Thus the LHR method can in principle monitor a 43:1 range in plasma frequency (1840:1 range in electron concentration) for any given gyrofrequency. Small percentages of heavy ions do not markedly change the LHR frequency [*Brice and Smith*, 1965]. For example, a composition of 90% H^+ and 10% $He^+(O^+)$ has an LHR frequency only 4% (5%) below that for pure H^+.

On many passes the LHR noise band closely follows the geometric mean gyrofrequency over wide regions. Figure 5 illustrates data from an inbound pass near local noon. The broken curve is the measured value of the mean gyrofrequency provided by the on-board GSFC Rb vapor magnetometer; gaps occur during magnetometer calibration. The vertical lines indicate the frequency of the LHR noise band from the lower to the upper cutoff, as measured from broad band VLF data every 20 sec. In this high-density region well inside the plasmasphere the LHR noise band closely follows the mean gyrofrequency, and thus evidence that the satellite is detecting local LHR noise is provided.

Concurrent ion mass spectrometer data are available for comparison on the outbound Ogo 3 pass of July 9, 1966 (afternoon sector, orbit in Figure 2). The top panel of Figure 6 is a spectrogram showing the LHR noise band. At 1335 UT the noise band abruptly vanishes as the antenna is switched from electric to magnetic mode. The interference line at 0.8 kHz is a satellite inverter. In the middle panel the continuous curve shows the mean gyrofrequency as measured by the GSFC Rb vapor magnetometer. The vertical lines indicate the measured frequency of the LHR noise band from the lower cutoff to the upper cutoff. These measurements were more closely spaced (approximately every 2 sec) in the central region, where the noise band is well defined, than at either end. The LHR noise band is roughly 25% below the mean gyrofrequency; thus we are near the upper breakpoint in the curve of LHR frequency versus concentration. In the lower panel the vertical lines indicate the range of electron concentrations computed from the corresponding range of frequencies, i.e., from the lower to the upper cutoff of the LHR noise band. The uncertainty in the absolute concentration is least (~±40%) in the central region, where the LHR band is well defined and well below the mean gyrofrequency. (On other passes in which the LHR band is far below the mean gyrofrequency, uncertainties of ±20% can be obtained.) The circled points in the lower panel are the H^+ concentrations measured by the Ogo 3 ion mass spectrometer [*Taylor et al.*, 1970]. These values are believed to be accurate within a factor of 2 (H. A. Taylor, private communication, 1972). It is seen that both experiments show similar time variations in concentration and agree in absolute value to within the uncertainties of the measurements.

The example in Figure 7 exhibits a large density gradient, perhaps part of the plasmapause. Ogo 3 is outbound from $L = 2.9$ to 5.5 in the afternoon sector. The upper panel is a spectrogram showing the LHR noise band decreasing rapidly in frequency at first and then more gradually. Spin modulation of background intensity is apparent. The lower panel, expanded in time and frequency, shows details of the initial rapid decrease in LHR frequency. The striations at 26 and 35 sec are whistlers, whereas those at 43 and 47 sec seem to be discrete emissions. Figure 8 shows the calculated electron density profile. The lower-cutoff frequency of the LHR band was measured about every 2 sec and used to compute concentrations with the measured value of gyrofrequency. (Since the LHR band is far below the mean gyrofrequency, the diffuse hard to measure upper cutoff would give only slightly higher concentrations.) The initial rapid decrease in concentration seems likely to be the outer edge of the plasmapause. Independent location of the plasmapause from whistler or ion mass spectrometer data is not available, but the location at $L = 3.05$ seems reasonable for the strong magnetic activity (Kp reached 9 on the previous day). The electron concentration decreases by a factor of 2 in ~150 km, or $\Delta L = 0.05$. Outside the plasmapause the concentration falls approximately as R^{-4} while the satellite moves outward more or less perpendicular to magnetic field lines. The concentration decreases to less than 10 el/cm^3 at $L = 5.4$. Whistler measurements also commonly show an R^{-4} profile outside the plasmapause in the equatorial plane [*Angerami and Carpenter*, 1966]. This R^{-4} distribution across field lines may be due to the R^4 variation in magnetic flux tube incremental volume. The distribution along field lines, however, depends on the dynamic processes involved and may be quite different [*Banks et al.*, 1971]. Therefore no attempt is

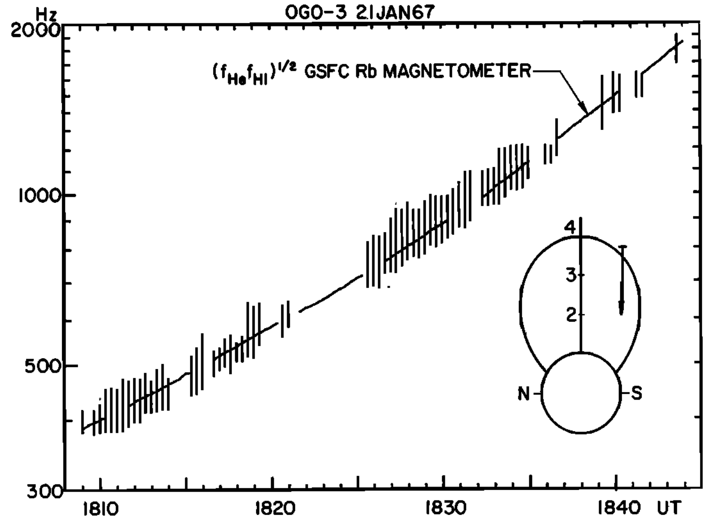

Fig. 5. In high-density regions the LHR noise band, whose bandwidth is shown by vertical line segments, closely follows the measured local mean gyrofrequency, shown by the broken curve. Ogo 3 is inbound, $L = 4.1$–2.9, LT ≅ 1200–1300, and $Kp = 1$.

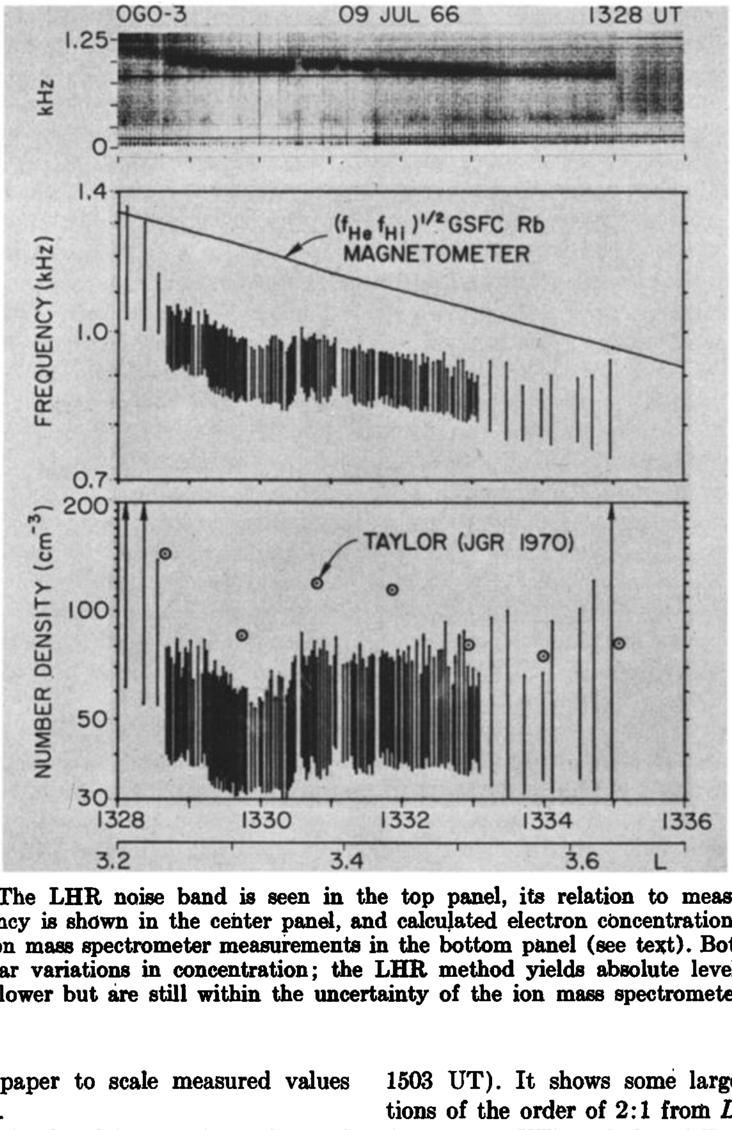

Fig. 6. The LHR noise band is seen in the top panel, its relation to measured mean gyrofrequency is shown in the center panel, and calculated electron concentrations are compared to ion mass spectrometer measurements in the bottom panel (see text). Both methods show similar variations in concentration; the LHR method yields absolute levels that are somewhat lower but are still within the uncertainty of the ion mass spectrometer measurements.

made in this paper to scale measured values to the equator.

The LHR noise band is sometimes detected at quite high dipole latitudes, perhaps in the cusp region. In Figure 9 Ogo 3 is outbound from (dipole) $L = 4.6$ to 17 at dipole latitudes from 49° to 63° during local morning. Magnetic conditions are quiet, Kp being equal to 1−; for the previous 24 hours Kp remained below 2+, although 48 hours earlier it had reached 7−. Again the electron concentration profile was computed by using the measured gyrofrequency and the lower cutoff of the LHR noise band. The concentration decreases fairly smoothly and very steeply ($\sim R^{-14}$) through the low (6400–8500 km) altitude trough region (1456–1503 UT). It shows some large-scale fluctuations of the order of 2:1 from $L = 8.0$ to 10.5 (1504–1511 UT) and then falls slowly ($\sim R^{-3}$) but somewhat erratically from 10,500- to 19,500-km altitude (1511–1534 UT). The concentration decreases to ~2.3 el/cm^3 before jumping up about 30% at 1529 UT.

Discussion

The LHR noise band seems to provide a relatively precise measurement of local electron concentrations in low-density regions of the magnetosphere. The observations that the measured LHR frequency is often equal to the measured mean gyrofrequency over wide regions suggest that the receiver is detecting local

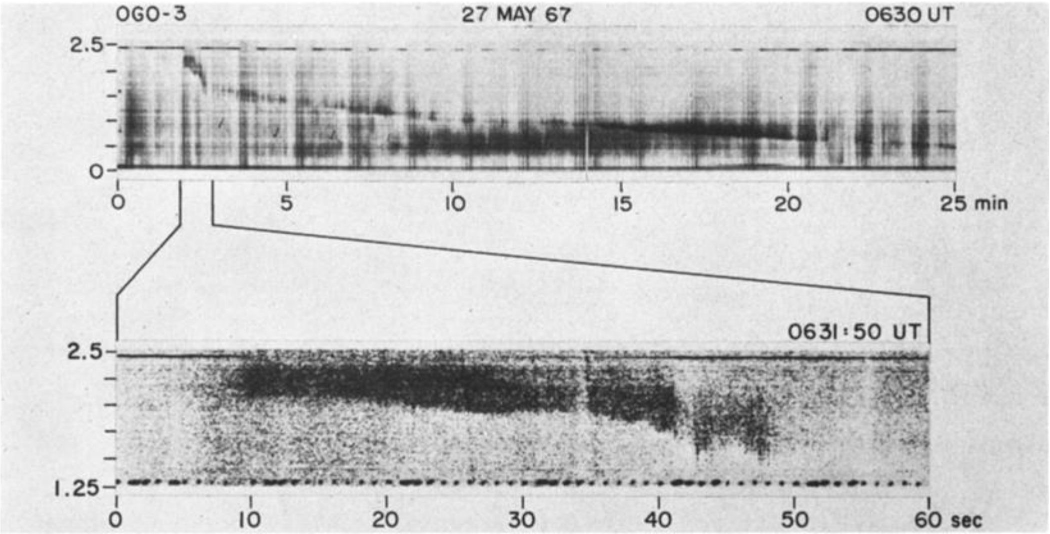

Fig. 7. Example of the LHR noise band showing rapidly decreasing frequency, indicating a large density gradient perhaps at the plasmapause. The orbit and the calculated density profile are shown in Figure 8.

LHR noise. Furthermore, the absence on all passes of spin periodic frequency modulation, which might be produced from satellite wake or bow compression effects, provides evidence that the receiver is measuring the ambient electron concentration.

The question of whether the maximum amplitude or the low-frequency cutoff relates better to the local LHR frequency is difficult to resolve with the broad band data, which have been subjected to logarithmic amplitude compression and clipping. The fact that the

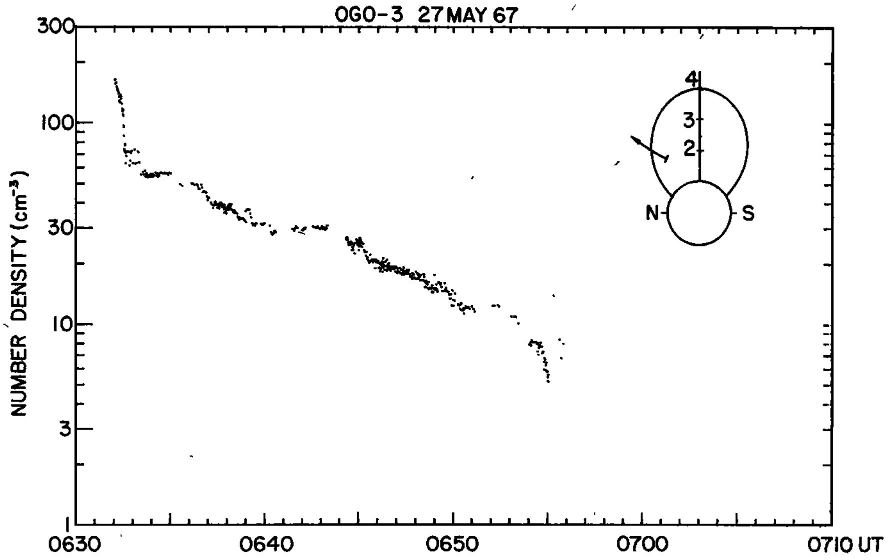

Fig. 8. Density profile calculated from the measured gyrofrequency and the lower-cutoff frequency of the LHR noise band illustrated in Figure 7. Ogo 3 is outbound, $L = 2.9\text{–}5.5$, dipole latitude ≅ 40°N, LT ≅ 1600–1800, and $Kp = 3+$. The initial rapid decrease in concentration occurs at $L \cong 3.05$; Kp was as high as 9 during the previous 24 hours.

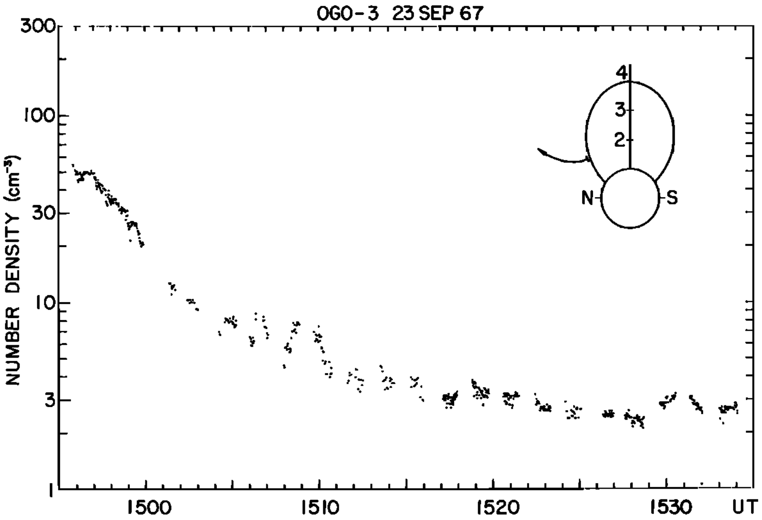

Fig. 9. The electron concentration profile calculated from an LHR noise band observed at very high dipole latitudes. The data gaps are due to VLF receiver saturation during part of the spin period; otherwise, there is no apparent spin modulation of the LHR noise band. Ogo 3 is outbound, $L \cong 4.6$–17, dipole latitude $\cong$ 49°–63°N, LT $\cong$ 0700–1100, and $Kp = 1-$.

center, rather than the lower edge, of the LHR band follows the mean gyrofrequency in Figure 5 may be due to a small heavy ion component or to a concentration dilution approaching the upper breakpoint of the curve in Figure 4. Either of these conditions would have the effect of slightly depressing the LHR with respect to the mean gyrofrequency. Although it is of considerable physical interest, the lack of resolution of this question does not seriously impair LHR electron density measurements. Since the LHR noise band typically has a bandwidth of ±10% of the center frequency, it can yield densities with an uncertainty of ±20%. This uncertainty is less than that for most particle collection techniques. For example, *Brinton et al.* [1968] compared five independent low-latitude measurements of average charged particle concentration at an altitude of 1 R_E and found that average concentrations varied between 2 and 4 × 10^3 particles/cm^3. Admittedly, some of this variation may be due to seasonal or geomagnetic differences. But at greater altitudes and lower concentrations the uncertainties are undoubtedly higher [*Whipple,* 1972]. On the other hand, whistler techniques allow measurements of equatorial concentration with errors as small as 10% [*Park,* 1972]. However, whistlers are relatively less common outside the plasmasphere [*Carpenter,* 1968] and, when they are present, do not provide the continuous profile obtainable from the LHR noise band.

The electron concentration profiles in the trough region outside the plasmasphere, shown in Figure 8 and the first part of Figure 9, are of interest in their effect on the propagation of whistler mode waves. For example, VLF chorus has been interpreted as largely following nonducted propagation paths in the outer magnetosphere [*Burtis and Helliwell,* 1969]. The observation of the steep concentration gradient at the start of Figure 8 indicates that the LHR method can resolve spatial changes in concentration over distances of the order of 100 km. On the other hand, some of the scatter in the data points later in this profile is due to difficulties in precisely measuring the lower cutoff of the LHR noise band. Yet the slow undulations in the profile and some of the better-defined rapid variations of the order of 10% are believed to be real. The effects of these nonuniform gradients on the propagation of chorus are being investigated and will be reported in a later paper.

The physical processes involved in the generation of the LHR noise band are not clearly understood. Empirically, the band is most often seen when there is other VLF activity in the same frequency range, although this is not always the case. The band appears to be largely electrostatic except immediately after triggering by whistlers. In a warm plasma the resonance at large wave normal angles normally associated with the slow electromagnetic (whistler mode) wave is taken over by the ion plasma wave [*Allis et al.*, 1963]. This wave may perhaps be excited by the motion of the spacecraft through the plasma or by mode coupling with whistler mode waves. There exists a real need for a deeper theoretical study of the ubiquitous and useful LHR noise band.

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