NASA CR-132882

Final Report

for

Measurements of VLF Polarization and Wave Normal Direction on OGO-F

Contract No. NAS 5-9309

Prepared by

Principal Investigator: R. A. Helliwell
Research Physicist: R. L. Smith and J. J. Angerami

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for

Goddard Space Flight Center
Greenbelt, Maryland

RADIOSCIENCE LABORATORY

STANFORD ELECTRONICS LABORATORIES

STANFORD UNIVERSITY · STANFORD, CALIFORNIA

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I. INTRODUCTION

The Stanford University/Stanford Research Institute VLF experiment F-24 aboard the OGO-6 satellite has provided a number of important contributions toward understanding of VLF propagation in the earth's ionosphere and magnetosphere. The instrument was designed to provide a substantially greater amount of detailed information than had previously been available from satellite-borne VLF receivers. The fully operational lifetime of the instrument was relatively brief, but long enough to demonstrate the feasibility of advanced design concepts such as those involved in the broadband measurements of wave polarization.

The preparation of this report has been delayed and somewhat limited in terms of thoroughness by the return to Brazil of Jacyntho Angerami, who as a senior staff member at Stanford conducted much of the day-to-day operational work and data reduction activity during the lifetime of OGO 6. Angerami was responsible for much of the success of our OGO-6 program, an outstanding example being his recognition of the close relation between deep fading of narrowband upgoing VLF signals and irregular structure in the ionosphere detected by Hanson's OGO-6 instrument.

The next section presents a discussion of experimental objectives. This is followed by brief descriptions of the F-24 instrument and its operating history. There then follow a summary of experimental results and a series of spectrographic and chart records that illustrate in some detail various experimental findings. The block diagram of the instrument and the corresponding flow of signals are described in an appendix.

We are grateful to the many persons in the OGO program office whose

efforts underlie the fine technical and scientific achievements of the OGO satellites, and who have over the years given such strong support to individual experimenters. We wish to specifically thank James Meenan and his staff at the OGO Control Center for their invaluable assistance in the operation of experiment F-24 on OGO 6.

II. EXPERIMENTAL OBJECTIVES

A. GENERAL CONCEPTS

The purpose of the OGO-6 VLF experiment was to extend the work carried out on prior VLF experiments on other OGO satellites as well as the Alouette, ISIS, FR-1 and INJUN satellites. A number of new phenomena were discovered on the earlier satellites and these results led to the need for more extensive and sophisticated measurements. In the interpretation of many of the phenomena, the wave normal direction, wave polarization and wave impedance play important roles.

In view of the success of the FR-1 satellite in measurement of wave properties in a narrow bandwidth ($\sim$ 160 Hz) at one frequency, it appeared desirable to extend the concept of measurement of wave properties to cover a wider bandwidth. It was desired to examine the whole range of whistler-mode phenomena to verify theoretical predictions and assist in the interpretation of less well understood phenomena. The final configuration of experiment F-24 allowed simultaneous measurements of three magnetic field components and one electric field component. Although it is desirable to measure the other two components of the electric field, this is difficult to accomplish on a spacecraft other than one devoted to the purpose of measuring wave fields.

The experiment included on-board data pre-processing circuitry in order to simplify the analysis and to keep within the current requirements of recording equipment at the telemetry tracking stations. The problem is to be able to record a number of simultaneous wideband channels with matched phase coherence through all channels. By utilizing presumed properties of the waves and by a suitable choice of on-board pre-processing, the phase coherence requirement was circumvented.

B. SPECIFIC OBJECTIVES

The objectives of the experiment were:

1) Measure the polarization of whistlers. The theory of whistlers predicts that where ion effects can be neglected the magnetic field of a whistler wave is very nearly circularly polarized with a right handed sense with respect to the earth's magnetic field direction. The predicted behavior is somewhat more complicated below the proton gyrofrequency. Above a critical frequency called the "crossover" frequency but below the proton gyrofrequency, the existence of a left hand polarized wave is predicted in order to explain the "proton" whistler. Below the crossover but above the helium gyrofrequency, the polarization should again revert to the right hand polarized sense. One of the many possible modes of the experiment was designed to separate the two characteristic circular polarized modes and hence to verify the predicted polarizations. The polarization at the crossover is linear. By measuring the ratio of circular components as a function of frequency it was hoped to define the crossover to a higher degree of accuracy than had previously been possible. This is particularly important as a means of determining the fractional abundance of ions in the vicinity of the satellite with a method that eliminates the effects of local spacecraft contamination and the difficulties of conventional probe measurements.

2) Perform limited wave normal measurements. By examining the relative amplitudes of signals from three mutually orthogonal antennas one may determine a certain amount of information regarding the wave normal direction of incoming signals. There are several whistler phenomena in which wave normal direction plays an important role, such as the subprotonospheric whistler [Carpenter et al., 1964; Smith, 1964], the walking trace whistler

[Walter and Angerami, 1969] and the doppler shift effect on signals received from VLF transmitters [Walter and Angerami, 1969]. If the wave normal of a whistler coming down toward the ionosphere is nearly aligned with the earth's magnetic field, the whistler is probably ducted by field-aligned enhancements of ionization. If the wave normal is nearly vertical, the whistler may penetrate the ionosphere and be received on the ground. If the wave normal is nearly transverse to the magnetic field or nearly parallel to the ionospheric stratification, the wave is non-ducted and is likely to be absorbed or reflected in the lower ionosphere.

3) Investigate aspects of wave impedance. The wave impedance is the ratio of electric to magnetic fields. The magnetic fields are confined simply to the plane of the phase fronts of a wave, but the electric field may have a large component in the direction of the wave normal. One would like to know the wave impedance for examining phenomena possibly associated with resonances or electrostatic waves. Examples of interest are the lower hybrid resonance noise and auroral hiss. Wave impedance is particularly important for waves near a resonance or a resonance cone. Measurements of wave normal direction alone are somewhat limited when the wave is near a resonance cone, because a small error in wave normal will cause a very large change in the refractive index. A measurement of the wave impedance should indicate more accurately the refractive index involved.

If more than one wave is present in a given region there may be standing waves. Simultaneous measurements of electric and magnetic fields is required to determine whether energy is propagating up or down a magnetic field line. If all field components are measured, one may determine Poynting's vector. If measurements are made of an electric field normal to the static magnetic field and a wave magnetic field perpendicular to the static field and to the electric field, then the component of Poynting's vector along the static field may be determined. This may be useful in the study of whistler reflections, the subprotonospheric whistler, and various kinds of VLF emissions.

4) Obtain extended frequency coverage. Experience on the previous OGO satellites with a 12.5 kHz broadband channel and examination of the sweeping receivers going up to 100 kHz indicated the desirability of increasing the frequency range of the special purpose channel. On OGO 6 the broadband frequency coverage was extended to 30 kHz, so as to provide for example, more information on 'walking trace' whistlers and on triggered emissions from Omega and other VLF transmitters.

5) Measure the amplitude of VLF signals in a narrow band (100 Hz). The detailed variations of the amplitude and phase of fixed-frequency VLF signals have proven to be a powerful diagnostic tool for study of both geophysical and wave-propagation phenomena. On OGO 6 it was desired to extend this type of measurement, with emphasis upon detailed correlative experiments and the possibility of connecting the narrowband receivers to combinations of the four antennas.

6) Measure the ac impedance of the electric antenna. The purpose here was to extend our knowledge of the antenna impedance, with particular attention to obtaining models of the sheath impedance.

7) Correlation of the vlf experiment with particle experiments. The two major experiments with which it appeared most desirable to correlate are Hanson's experiment, in which fine scale electron density and temperature measurements are made, and Evans' experiment, in which spectra of auroral particles are measured. The correlation with Evans has not proven fruitful because of mutual interference problems and the lack of

the desired signals on the VLF channels, i.e., the so-called 'auroral saucers'. The reasons for the absence of saucers is not understood at this time. The interest in the correlation with Hanson's experiment follows from previous OGO experience. Very regular and deep fading of VLF signals from transmitters occurs on occasion. Upgoing signals at high latitudes also exhibit a dropout, reported by Heyborne et al [1969]. The signals are usually seen to recover at much higher latitudes, close to and above the auroral zone. The dropouts were observed to occur close to the position of the plasmapause, and were tentatively attributed to enhanced ionization in the D region. Recently Storey and Malingre [1972] have developed an explanation of the dropouts in terms of defocusing of upgoing rays by the ionospheric trough structures associated with the plasmapause.

III. DESCRIPTION OF EXPERIMENT F-24 ON OGO 6

OGO 6 was launched June 5, 1969 from the Western Test Range into an orbit with an inclination of 82^{o}, perigee of 408 km and apogee of 1091 km. The satellite is stabilized (see Figure 1) with the +Z-axis pointing down toward the center of the earth and the Y-axis such that the sun is in the Y-Z plane. The solar panels rotate around the X-axis to become normal to the sun line.

PCM digital data may be read out on the main commutator (MC) or the subcommutator (SC), or, on occasion, in an entirely different way on the so-called 'flexible format' (FF). Digital data may be either stored on the spacecraft tape recorder or telemetered directly in real time. There is also a special purpose (SP) channel for transmitting analog data over a 100 kHz bandwidth in real time. This band was shared among various experimenters on both a frequency and time sharing basis.

Experiment F-24 consists of several VLF receivers covering the range of frequencies 20 Hz to 30 kHz and fed by three orthogonal loops and one unbalanced electric dipole, as shown schematically in Figure 1. The loops, identified as B_X, B_Y and B_Z are located at the end of a 20-foot boom in the +Y direction. The loops are normal to the spacecraft axes X, Y and Z (vertical). Isolation between the loops and the boom permits the measurement of the electric field E in the Y (horizontal) direction. Each loop has an area of 1 m^2. The electric and magnetic preamplifiers are such that an electromagnetic wave propagating along Z in free space would yield the same amplitudes in E and B_X.

The dynamic spectra from two broadband receivers (20 Hz-30 kHz) can be simultaneously telemetered to ground in real time (special purpose channel); these receivers can be fed by any combination of signals from the electric or magnetic antenna preamplifiers. These broadband receivers incorporate a log compressor followed by a clipper producing an instantaneous AGC which suppresses weak signals in the presence of much stronger ones. The broadband VLF receivers flown on OGO's 1, 3, 2 and 4 (Experiments A-17, B-17, C-02 and D-02) had a similar characteristic, but the range of frequencies was less (0.3-12.5 kHz).

The magnetic field polarizations of waves in any 2.5-kHz band between 20 Hz and 30 kHz are obtainable by transmitting the multiple use band (MUB) in the special purpose channel. The MUB contains: the spectra in four 2.5-kHz-wide bands (each consisting of an appropriate sum of broadband signals whose relative phases may be changed on command by multiples of 90 degrees), four voltage-controlled-oscillators (VCO's) yielding the corresponding amplitudes in those bands, and two VCO's yielding the amplitudes in the two broadband (20 Hz-30 kHz) receivers.

Two independent narrowband (100 Hz) receivers may be tuned to any multiple of 0.1 kHz between 0 and 30 kHz, or may be commanded to sweep any 2.5-kHz band in that range. The phase and amplitude of each narrowband receiver are sampled once per main commutator frame (PCM data). A signal generated by each receiver at its center frequency can be inserted at the antenna on command, thus enabling the measurement of antenna impedance.

The antennas can also be biased on command, either with a bias voltage of +5 to -10 volts, or by a potential sweeping between these limits with a commandable period.

The appendix contains a block diagram of the F-24 experiment, with information on signal flow and descriptive details on functions of various elements of the system.

There are a very large number of possible states in which experiment F-24 could be configured. In general only a few changes in configuration could be made in a given day because of other demands on the Control Center. After a given configuration was agreed upon by the experimenters, a list of so-called matrix commands was generated using the signal flow diagram and a table of matrix command codes. The matrix command codes were then translated into a set of spacecraft commands. The command sequence was given to the OGO Control Center to be placed on temporary or permanent command tapes or as a manual sequence to be followed. The commands were transmitted to the satellite and verified. The sequence of commands sent is available as a Command History Report. The status of the experiment is also available (generally after the fact) from two status words on the subcommutator.

IV. OPERATING HISTORY OF EXPERIMENT F-24

The F-24 antenna was deployed on July 25, 1969 and between July 25 and August 22, 1969 the experiment was operated in a wide variety of configurations, including use of the multiple use band (MUB) for measurement of polarization, simultaneous comparisons of spectra of electric and magnetic fields in the 20 Hz to 30 kHz band, and comparison of simultaneous spectra of horizontal and vertical magnetic fields in this same frequency range.

On August 22, 1969 a malfunction developed in the command logic, precluding further connection of the magnetic loops. Determination of the nature of the failure required a number of months, after which the experiment was configured so as to present the 20 Hz to 30 kHz broadband spectrum obtained in the electric field channel on 2 out of 6 days of spacecraft operation. The operation subsequent to August 22, 1969 has provided valuable data, although the reduced sensitivity of the electric field channel as compared to magnetic field measurements of certain phenomena has discouraged taking a survey-type approach to the data. On the other hand, the information acquired prior to August 22, 1969 has been extremely helpful in investigating the specific objectives of the experiment.

A significant fraction of the available special-purpose data obtained prior to August 22, 1969 has been analyzed using the rayspan spectrum analyzer, which produces a continuous 35mm film record of frequency vs. time. This type of record forms the basis for a number of the figures shown in the accompanying data catalog. A limited amount of the PCM data on charts has been investigated, with special attention to comparisons with experiment F-03 of W. B. Hanson.

Additional difficulties in 1970 further complicated the analysis, including the failure of a tape recorder on August 10 and another failure in August that involved the loss of the 2461 Hz reference and of all PCM data. In spite of these difficulties, acquisition of the upper band of the F-24 special purpose data continued through the latter part of 1970 and into early 1971. This was particularly fortunate, since on January 2, 1971, OGO 6 passed over the northern hemisphere conjugate of Siple, Antarctica ($L \sim 4$) during a crucial experiment involving x-ray observations on balloons and recordings of VLF whistlers and emissions. Information on this experiment is presented below.

V. SUMMARY OF EXPERIMENTAL RESULTS

A. POLARIZATION AND WAVE NORMAL MEASUREMENTS OF WHISTLERS

A major achievement of the F-24 experiment on OGO 6 was a verification of the theory of the polarization of proton whistlers. The signal processing involved the multiple use band (MUB) in a way that is briefly outlined in an appendix of this report and described in detail in an article by Smith [1970]. It was shown for the first time that the polarization of whistlers could be successfully measured in space on a broadband basis. As predicted, the electron whistler was found to be right-hand polarized and the proton whistler left-hand polarized. The transition from right to left-hand polarization was found to occur very rapidly. Thus it appears that the experimental technique may allow great accuracy in the measurement of the cross-over frequency, a frequency that provides information on the ionic composition of the ionosphere.

Limitations on the amount of data obtained prior to the command logic failure precluded extensive study of wave normals. However, a number of cases were found that served to refine and extend our knowledge. In one case it was found that wave normals of several upgoing whistlers were near the vertical, but that other whistlers recorded within the same minute had wave normals sufficiently off the vertical to put a fairly strong signal into the B_Z channel. This is consistent with the recent work of James [1972] who studied in detail the wave normal information from the FR-1 satellite, which was restricted to a narrow band of frequencies near 16 kHz.

B. ASPECTS OF WAVE IMPEDANCE

This area has been particularly fruitful, although again dependent upon a rather limited period of spacecraft operation. New details were found on the ratio of electric to magnetic field strength in auroral hiss, with some indication that near its low frequency border the impulsive auroral hiss has a stronger and more well defined cutoff in the E channel. This observation suggests that the cutoff is caused by reflection at the lower hybrid resonance, as suggested by Thorne and Kennel [1967] and Mosier and Gurnett [1969].

Walking trace whistlers [Walter, 1969; Walter and Angerami, 1969] have been observed up to 29 kHz on OGO 6. The whistlers exhibited higher intensity at the high frequencies in the electric channel, thus confirming the proximity of the wave normal to the transverse resonance condition believed to exist for this mode of propagation. Other studies provided additional confirmation of the properties of LHR whistlers, showing pronounced noise effects near the LHR frequency in the E channel while none was observed in the B_X channel. Results of this general kind, but in a frequency band below $\sim$ 10 kHz, have been reported by Laaspere and Taylor [1970] and Gurnett et al., [1969].

C. EXTENDED FREQUENCY COVERAGE

Because of the coverage to 30 kHz, it was possible to extend measurements of a number of phenomena previously observed only to about 12 kHz. A number of results of this kind are presented in the catalog of illustrations. The observations have included discrete VLF emissions near 30 kHz and fixed frequency VLF transmissions above 12 kHz, some of which exhibited characteristics of the 'walking trace' mode of propagation. This mode is believed to be responsible for certain complex artificially stimulated emissions observed and reported earlier from the OGO-4 satellite [Walter and Angerami, 1969]. The OGO-6 data extended the observation of 'short striations' [Paymar, 1972] on whistler spectra to at least 30 kHz. These striations appear to be related to the fading of upgoing VLF signals, and in themselves are believed to indicate the presence of irregular structure in the ionosphere.

D. RESULTS ON VLF FADING VERSUS ELECTRON DENSITY IRREGULARITY

Valuable new results were obtained on the fading of VLF transmitter signals, a phenomenon known since OGO 1 [Heyborne, 1966]. This fading has only recently been tentatively explained as the result of interference between two wave fronts propagating in different directions. Support of this interpretation was provided by OGO 6 through simultaneous observations of the fading signals by the horizontal and vertical loops, showing the maxima and minima in the two channels to be out of phase. Further insight into this phenomenon was obtained by simultaneous observations of fading by the VLF experiment and ionospheric density irregularities reported from Hanson's experiment F-03. Deep fading near the plasmapause is being considered as the result of a direct signal to the satellite being combined with a signal reflected from irregularities. The two signals are thought to be approximately equal in amplitude, and give rise to a standing wave or fading pattern.

Jacyntho Angerami, research physicist in our group, was active in the study of the fading effects on VLF signals. Angerami left our laboratory to return to Brazil at the end of 1971, and partly because of a change in research activity, has not yet been able to complete the study of the correlated electron-density irregularity and fading effects. He does hope to complete this work, and we expect to use the knowledge gained thus far as a basis for further work at Stanford.

We are conducting an active and fruitful program of analysis of VLF data from OGO's 1 through 4, and consider that the OGO-6 experiment, with its particular insights into the VLF propagation details, is helping to provide a much improved theoretical basis for this continuing work.

E. OTHER STUDIES

OGO 6 passed over the conjugate to Siple, Antarctica ($L \sim 4$) on January 2, 1971 at a time when a unique correlation was found at Siple between bursts of $E > 30$ keV x-rays and bursts of VLF emissions observed on the ground [Rosenberg et al., 1971]. It was determined, partly from intercomparison of broadband information from OGO 6 and ground records from the conjugate pair, Roberval, Canada and Siple, that atmospheric whistlers entering the magnetosphere in the northern hemisphere were responsible for triggering the process by which the particles were dumped into the southern hemisphere, thus producing the x-rays. The OGO-6 data also confirmed the presence of the plasmapause near $L = 4$. This information was important in the description by Rosenberg et al. [1971] of the magnetospheric plasma-density environment in which the remarkable wave-particle interactions took place.

APPENDIX. BLOCK DIAGRAM OF THE EXPERIMENT

A block diagram of experiment F-24 is shown in Figure 2. This diagram shows the possible signal paths through the experiment. A similar diagram has been used for working purposes for specifying control commands and to keep a record of the precise configuration at a given time. The signal flow is as follows:

The signals from the three LOOP ANTENNAS (X, Y,and Z) and the unbalanced ELECTRIC ANTENNA (E) feed the corresponding PREAMPLIFIERS. Each PREAMPLIFIER covers the frequency range 20 Hz to 32 kHz.

The outputs of the PREAMPLIFIERS are connected via MATRIX SWITCH #1 to the LOW PASS AMPLIFIERS. As indicated by the symbolic switch arrangement, each LOW PASS UNIT is connected to exactly one PREAMPLIFIER, but any PREAMPLIFIER may feed none, one, two, three, or four of the LOW PASS UNITS.

Each of the LOW PASS UNITS (A, B, C, and D) has a frequency response of 0 to 32 kHz. The output of each unit is connected directly to the corresponding 'PHASE SHIFT AND FREQUENCY SELECTION' UNIT as well as to MATRIX SWITCH #2.

MATRIX SWITCH #2 allows the outputs from the LOW PASS UNITS to enter the BROADBAND units. The switching arrangement is different from that of MATRIX SWITCH #1. From none to all four of the LOW PASS UNITS can be connected to either or both BROADBAND UNIT in any combination. Any of the eight switches not connected to a LOW PASS UNIT is grounded.

The inputs to each BROADBAND UNIT are summed. The amplitude of the summed inputs is detected to feed a VOLTAGE CONTROLLED OSCILLATOR (VCO). The base frequency of the VCO is 19 kHz for unit 1 and 25 kHz for unit 2. The VCO outputs are sent to the SPECIAL PURPOSE CONTROL UNIT. The summed inputs to each BROADBAND UNIT are amplified and clipped, and then sent to the SPECIAL PURPOSE CONTROL UNIT.

The PHASE SHIFT AND FREQUENCY SELECTION UNITS are filters with a band pass of 2.46 kHz centered at 64.000 kHz (the 26th harmonic of the reference frequency 2.4615 kHz). Each unit may be tuned by local oscillators (at $64.000 + n \times 2.461$ kHz) to an effective center frequency of $n \times 2.461$ kHz where $n = 0$ to 13. The phase shift of each filter may be set to 0°, 90°, 180°, or 270° by appropriate commands. All bands include a notch at the center frequency to remove harmonics of 2.461 kHz. The lowest level ($n = 0$) covers the range -1.23 kHz to 1.23 kHz, so that a folding of the spectrum is present.

The OSCILLATOR GATE is in essence a double pole switch. When the switch is closed, the local oscillators of the FREQUENCY SELECTION UNITS C and D drive the mixers of units B and A, respectively, as well as their own. This is done to reduce phase jitter problems.

The outputs of the PHASE SHIFT AND FREQUENCY SELECTION UNITS are connected to the various BROAD IF units through MATRIX SWITCH #3. Each of the 16 switches of the MATRIX SWITCH may be open or closed.

The inputs to each BROAD IF UNIT are summed. The summed signals are then translated in frequency to the respective bands indicated. BROAD IF E is translated to cover 0-2.461 kHz, etc. All signal processing to this point is linear (no compression or clipping for signals within the dynamic range of the receiver). The amplitude of each of the signals in bands E through H is represented by deviation of VCO's with base frequencies from 11 to 14 kHz, respectively. The output of each channel is then clipped and band limited. The four spectral outputs covering 0 to 9.84 kHz and the 6 VCO's are summed to form the so-called MULTI-USE-BAND (MUB), which may be placed on the SPECIAL PURPOSE CHANNEL.

An unclipped and untranslated output from the BROAD IF UNITS is connected to the NARROW BAND (100 Hz) PHASE RECEIVERS through MATRIX SWITCH #4. Each PHASE RECEIVER is connected to only one of the BROAD IF UNITS.

Each PHASE RECEIVER may be tuned to any multiple of 100 Hz inside and near the BROAD IF bands. There are 32 steps covering 3.2 kHz. The frequency may be stepped automatically by using a sweeping mode. By tuning the FREQUENCY SELECT and the PHASE RECEIVER, any 100 Hz band from 0 to 32 kHz may be chosen. Each PHASE RECEIVER is tuned independently. The phase and amplitude of the outputs of the PHASE RECEIVERS are converted to digital data by the spacecraft analog to digital converter, and placed on the MAIN COMMUTATOR (MC) at locations 69, 70, 101 and 102, as indicated. (A flexible format mode was available, but not used).

The ZERO CROSSING COUNTER is used to measure the mean frequency or frequency of the predominant signal in the BROAD IF unit E. The output is available at MC 81.

The THRESHOLD DETECTORS indicate the variability of the signal in BROAD IF's G and H, and are therefore suitable to count impulsive phenomena (whistlers, impulsive noise, etc.) above a given level. The counts are telemetered in bits 1-5 and 6-9 of MC 17, as indicated.

The CALIBRATOR enables calibrating signals generated in the spacecraft at the frequencies to which the PHASE RECEIVERS are tuned to be injected in the PREAMPS. Either of two levels of calibration can be chosen.

A BIAS can be applied to the electric antenna, either fixed or sweeping. The antenna voltage and current are read out in MC71 and MC 103, respectively.

The SPECIAL PURPOSE CONTROL UNIT allows the outputs of BROADBAND UNITS 1 and 2, their sum and difference, and the MULTI-USE-BAND (MUB) to be placed on the SPECIAL PURPOSE CHANNEL in a variety of formats. For the use of this experiment, the SPECIAL PURPOSE CHANNEL can be considered to have a lower band, from 300 Hz to 32 kHz, and an upper band from 70 to 100 kHz. The outputs of the BROADBAND UNITS are clipped prior to summing or differencing. The purpose of this configuration is to perform a broadband correlation between magnetic and electric fields to determine the direction of propagation of waves.

PUBLICATIONS ACKNOWLEDGING NAS 5-9309

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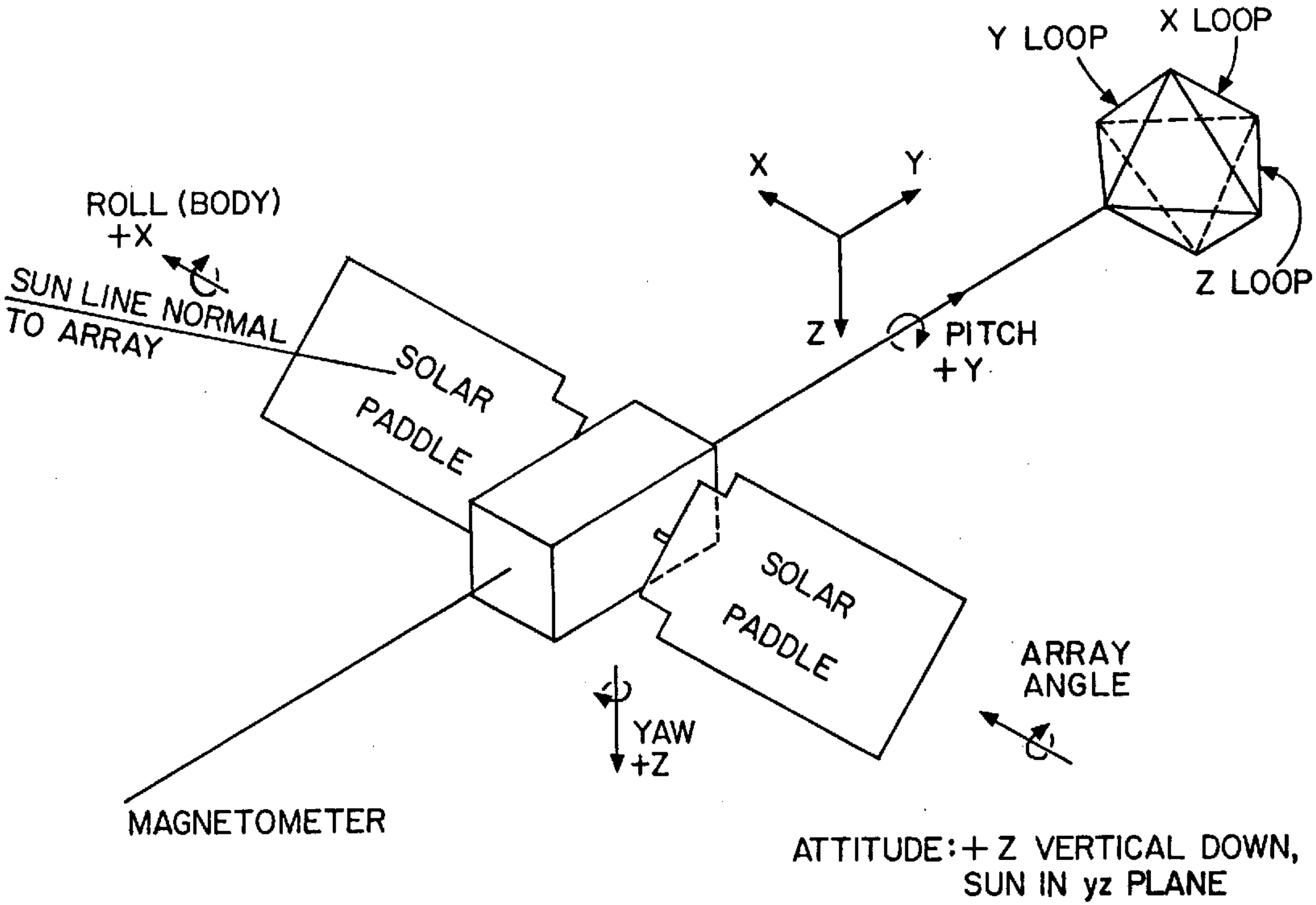

FIGURE 1. Diagram of the OGO-6 spacecraft and the orientation of the three orthogonal loops and unbalanced electric antenna for experiment F-24.

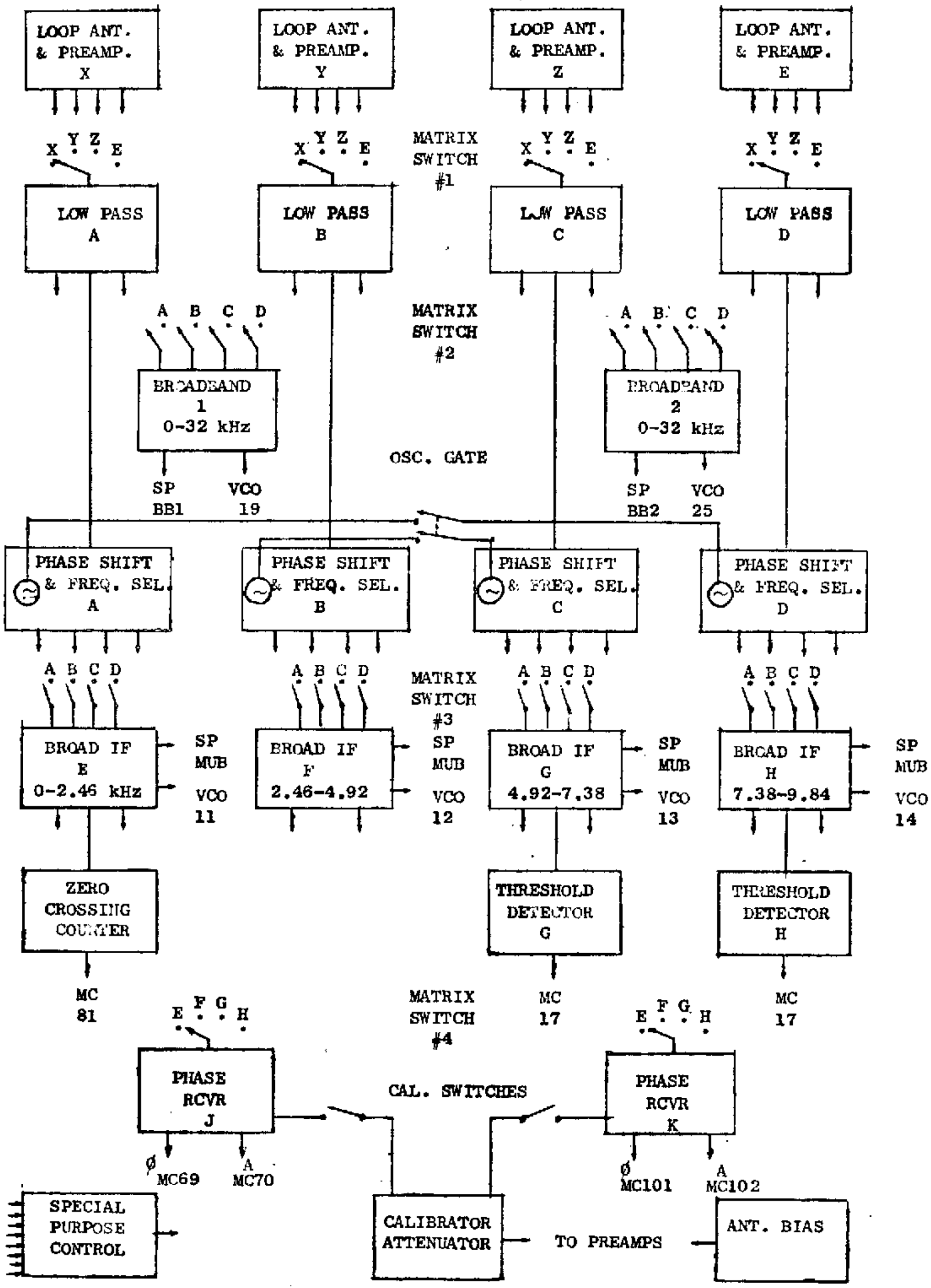

FIGURE 2. Block diagram of vlf experiment F-24 on OGO 6, showing possible signal paths.

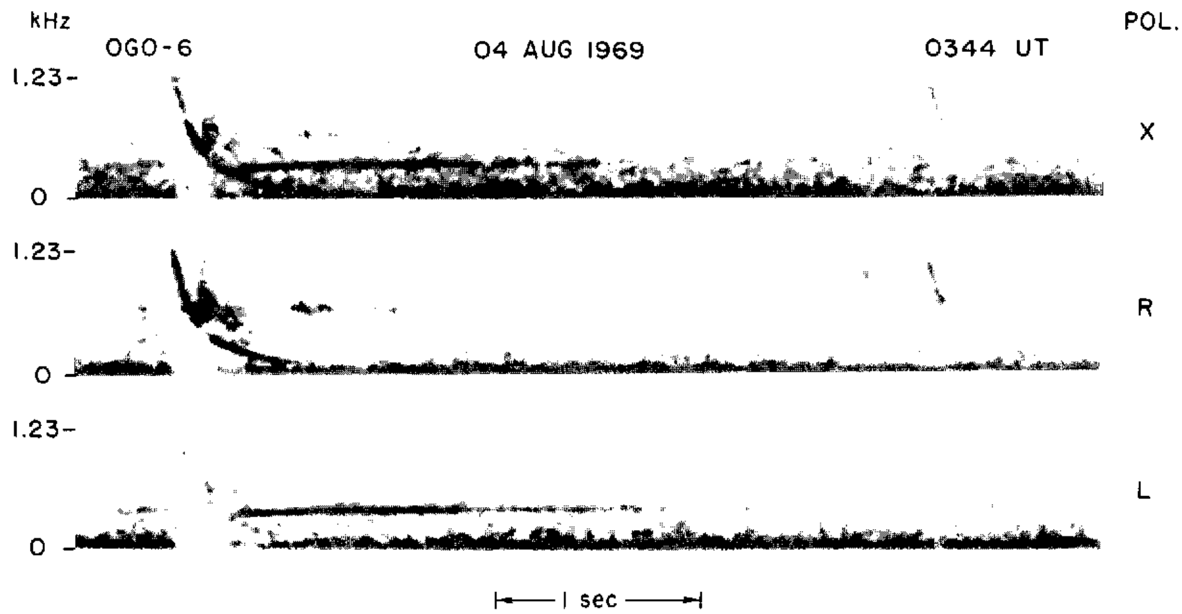

FIGURE 3. FREQUENCY-TIME SPECTRA ILLUSTRATING OGO-6 MEASUREMENTS OF THE POLARIZATION PROPERTIES OF A WHISTLER. The top panel shows the linearly polarized component, the middle panel the right circularly polarized component, and the bottom panel the left circularly polarized component. The bottom panel shows the characteristic features of the proton whistler, with its asymptotic frequency-time behavior above the crossover frequency at which it joins the electron whistler. Details of the method of data processing aboard OGO 6 have been described by Smith [1970].

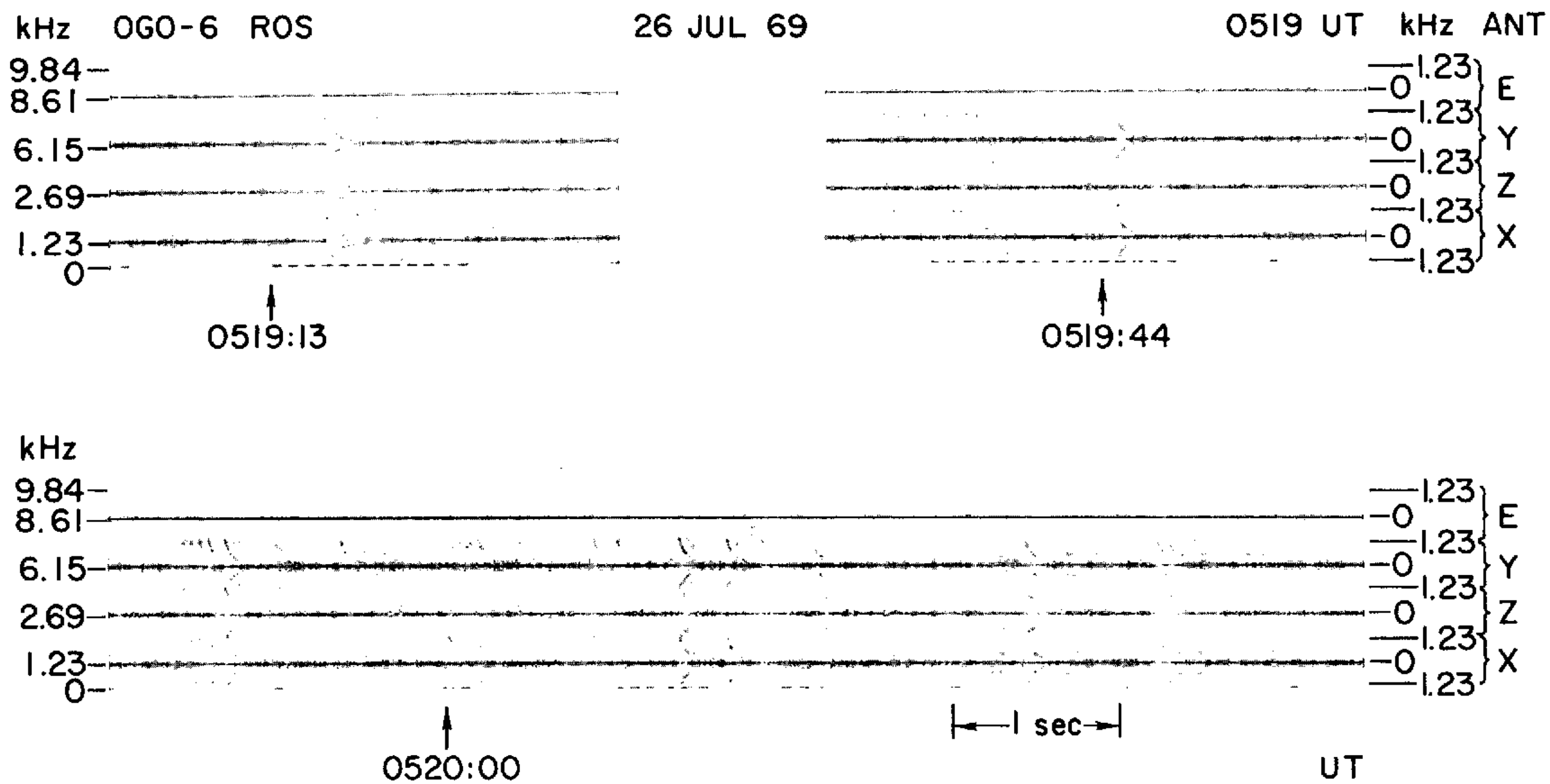

FIGURE 4. SIMULTANEOUS SPECTRA FROM THE THREE MAGNETIC ANTENNAS (X,Y,Z) THE ELECTRIC ANTENNA (E), SHOWING USE OF THE MULTIPLE USE BAND (MUB). The manner in which the spectral display is generated is discussed by Smith [1970] and is also discussed briefly in the appendix of this report. In the figure, both positive and negative frequencies are shown. The sensitivity of the electric antenna to whistlers is considerably less than that of the magnetic antennas. The whistler at 0519:13 shows roughly equal amplitudes in all three magnetic channels. The whistler at 0519:44 is much weaker in the Z magnetic channel, indicating a nearly vertical wave normal. Similar whistlers are seen in the time range 0519:58 to 0520:06.

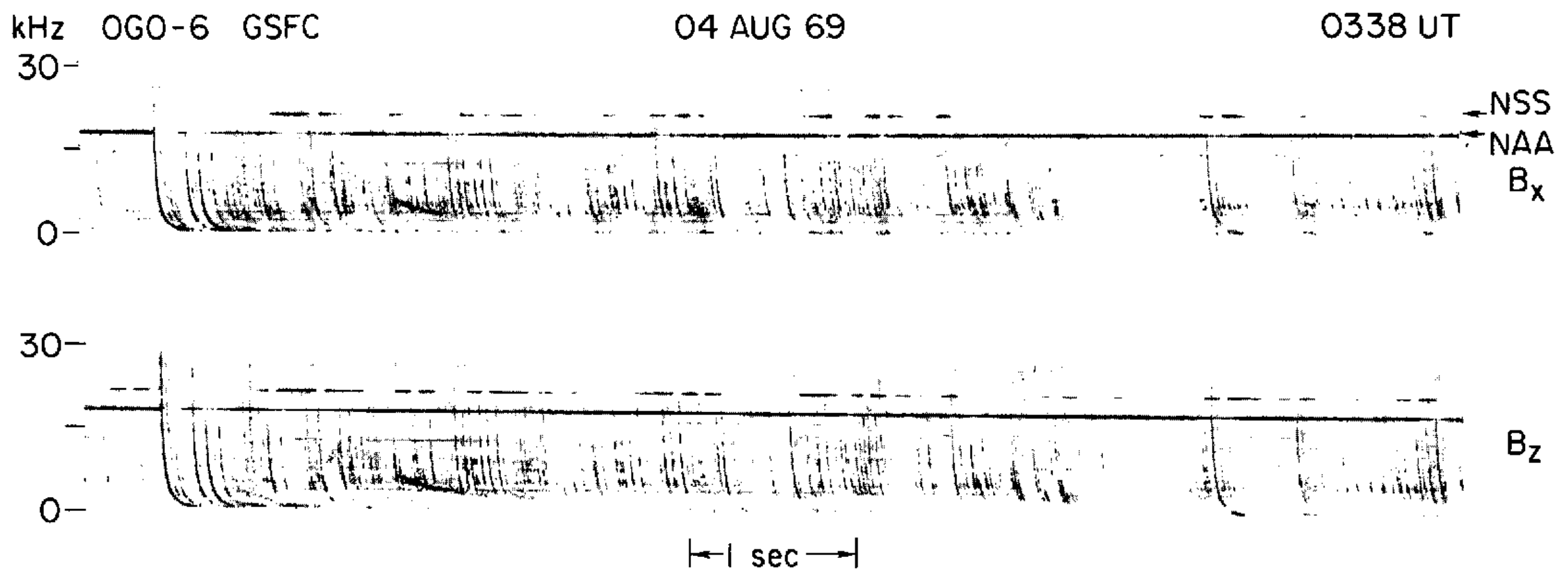

FIGURE 5. SIGNALS FROM A VLF TRANSMITTER OBSERVED ON A HORIZONTAL-AXIS LOOP (B_x) AND A VERTICAL AXIS LOOP (B_z). Note that the signals are sometimes stronger on one channel than in the other, possibly indicating standing-wave fading patterns.

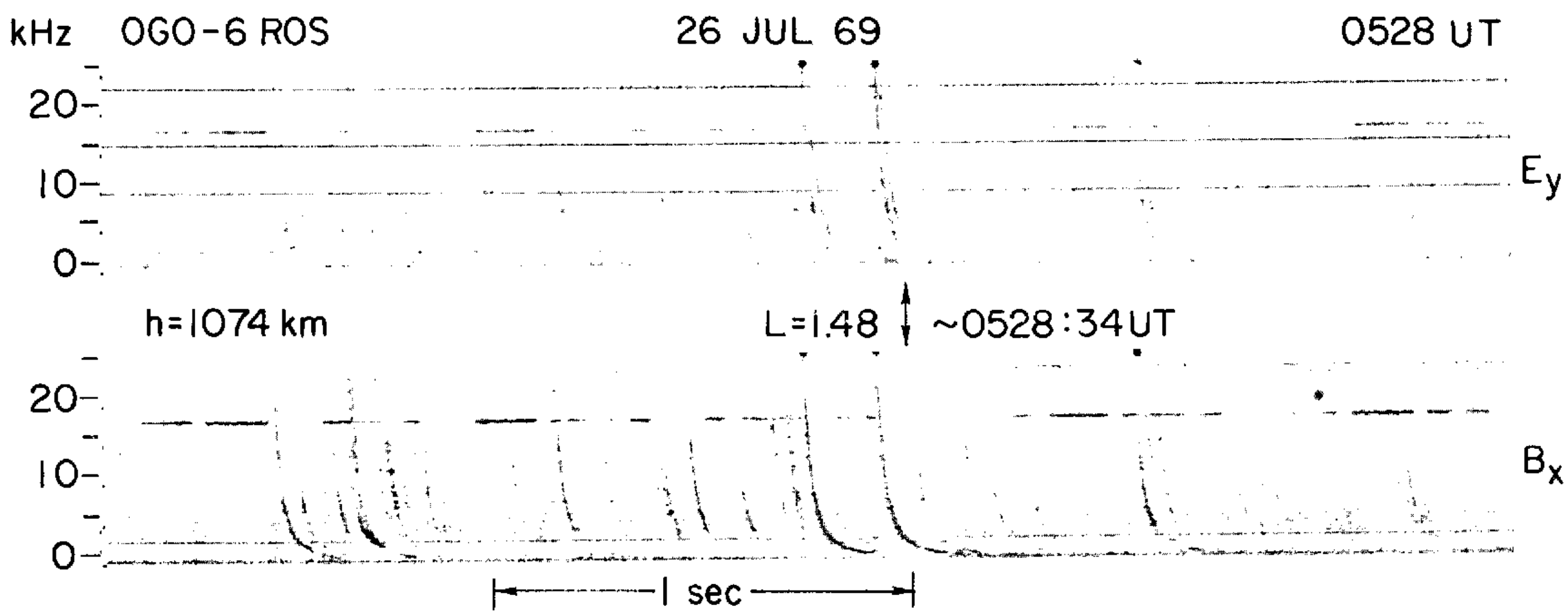

FIGURE 6. WHISTLERS OBSERVED SIMULTANEOUSLY ON THE ELECTRIC (E_y) AND MAGNETIC (B_y) ANTENNAS. The electric channel indicates less sensitivity to whistlers than the magnetic channel. The second harmonic of the whistlers in the electric spectra and the third harmonic in the magnetic spectra (see in particular the events marked with asterisks) are instrumental effects.

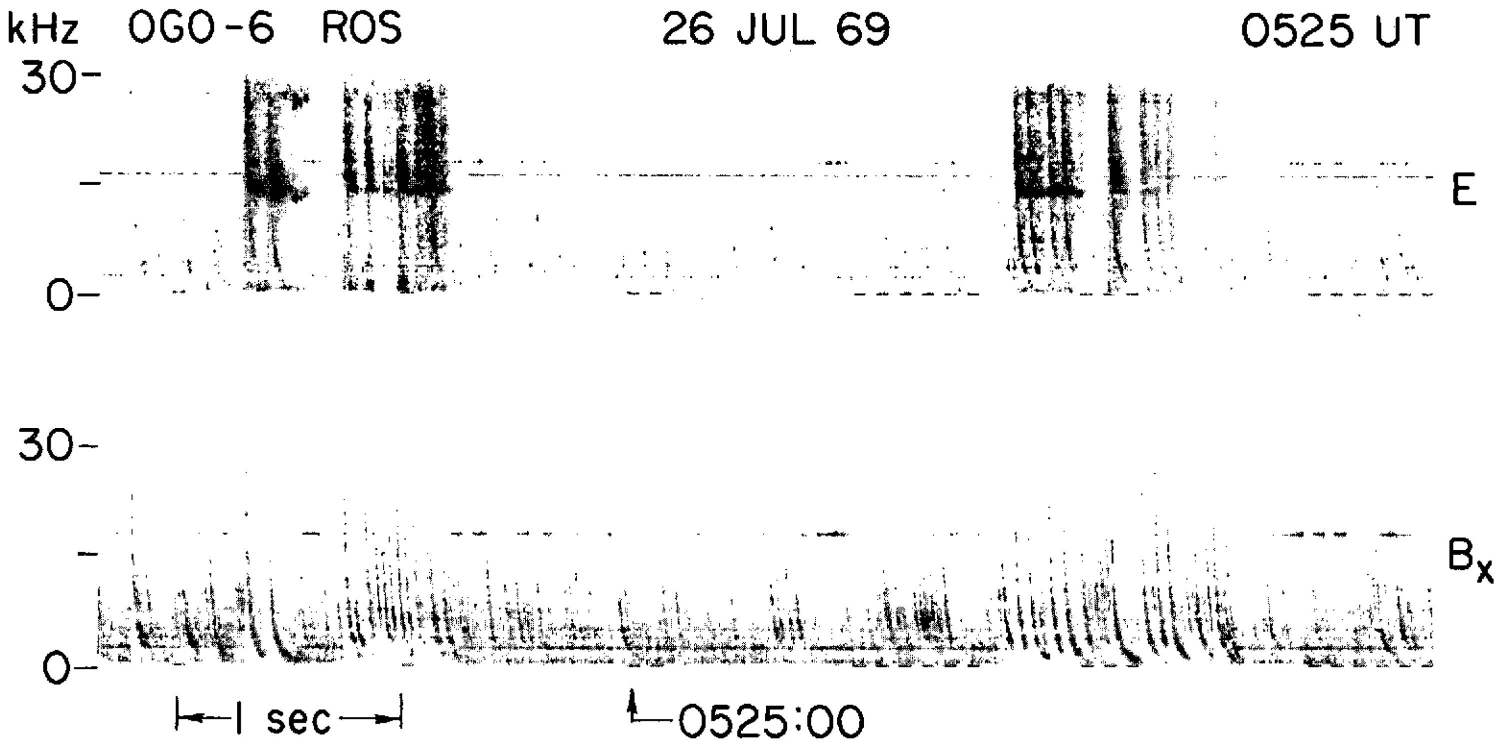

FIGURE 7. LOWER HYBRID RESONANCE (LHR) WHISTLERS OBSERVED SIMULTANEOUSLY ON THE ELECTRIC (E) AND MAGNETIC (B_X) ANTENNAS. The LHR noise is evident only in the electric channel. Some of the whistlers are cut off in the electric channel below the LHR frequency of about 14 kHz.

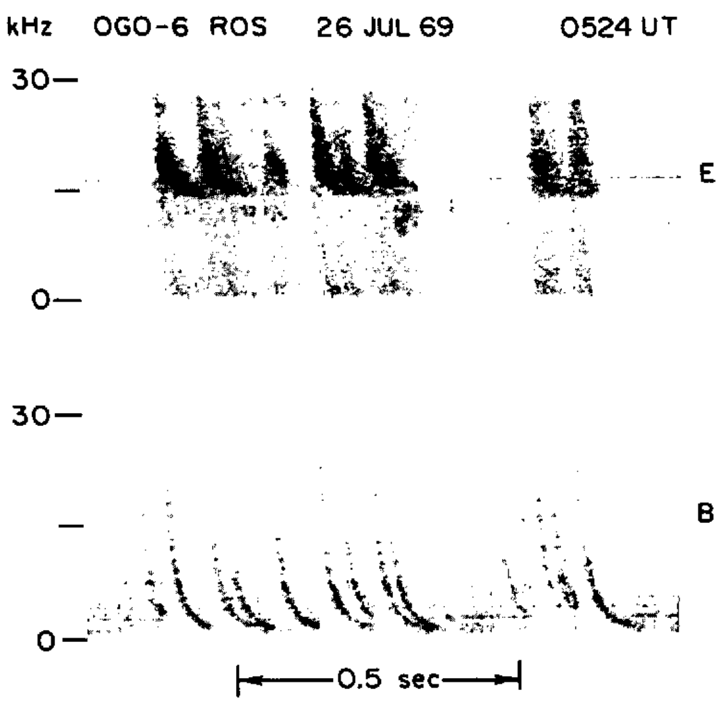

FIGURE 8. LHR WHISTLERS SHOWING A DISPERSION EFFECT. In the electric data, the low-frequency cutoff of the lower-hybrid resonance noise near 14 kHz seems to follow a dispersion law similar to that of the whistlers on the magnetic channel. This effect has been mentioned by Gurnett et al., [1969] and Laaspere and Taylor [1970] in connection with other electric measurements of whistlers.

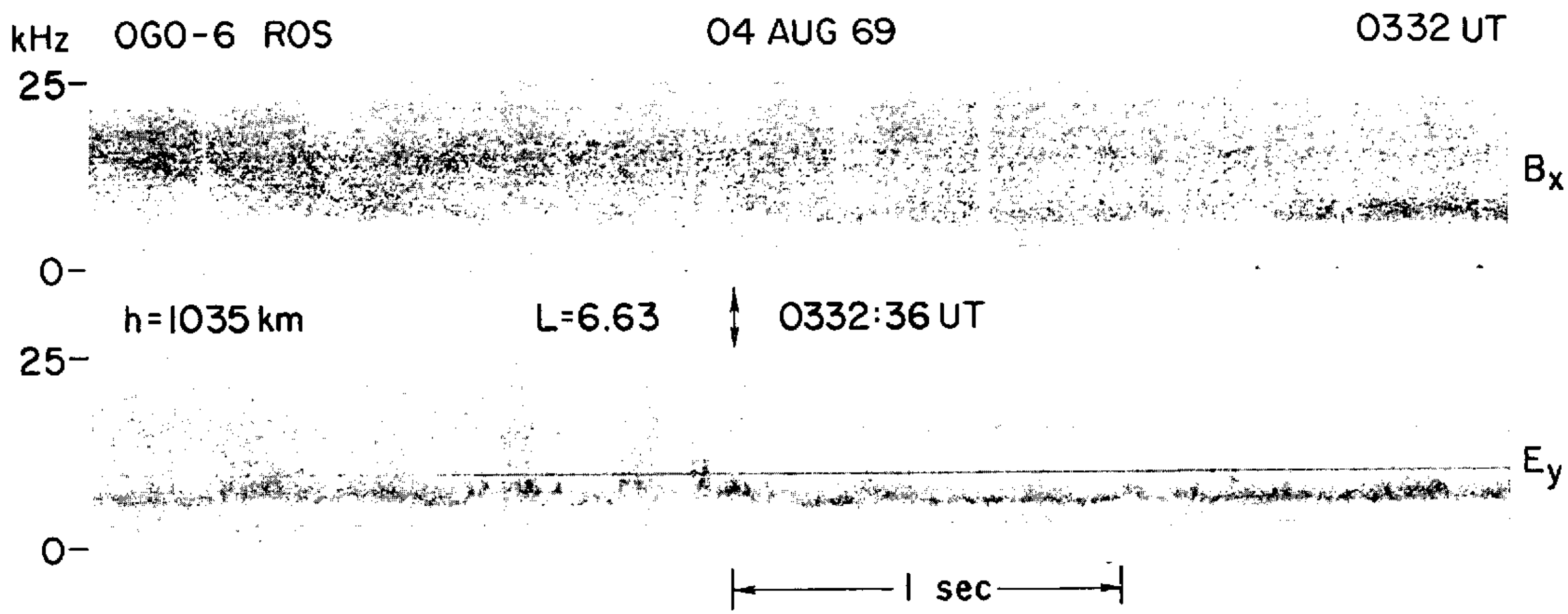

FIGURE 9. AURORAL HISS OBSERVED SIMULTANEOUSLY ON ELECTRIC AND MAGNETIC ANTENNAS. The hiss is stronger and has a more well defined lower cutoff in the electric channel.

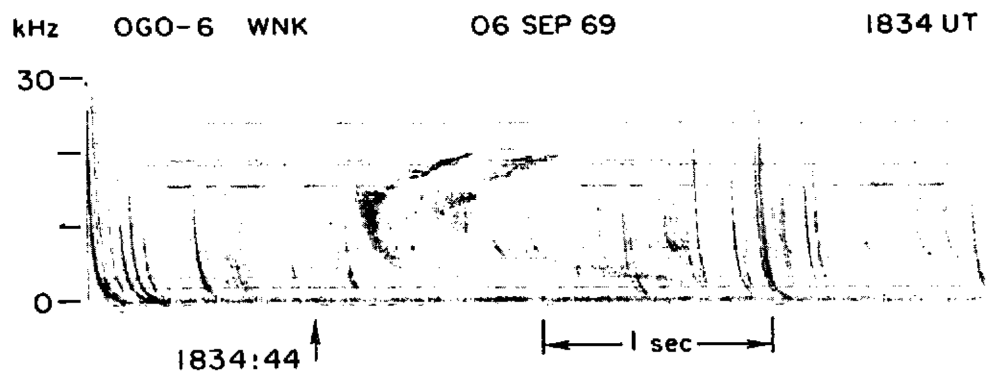

FIGURE 10. EXAMPLE OF A 'WALKING TRACE' (WT) WHISTLER. The upper frequencies exceed 21 kHz.

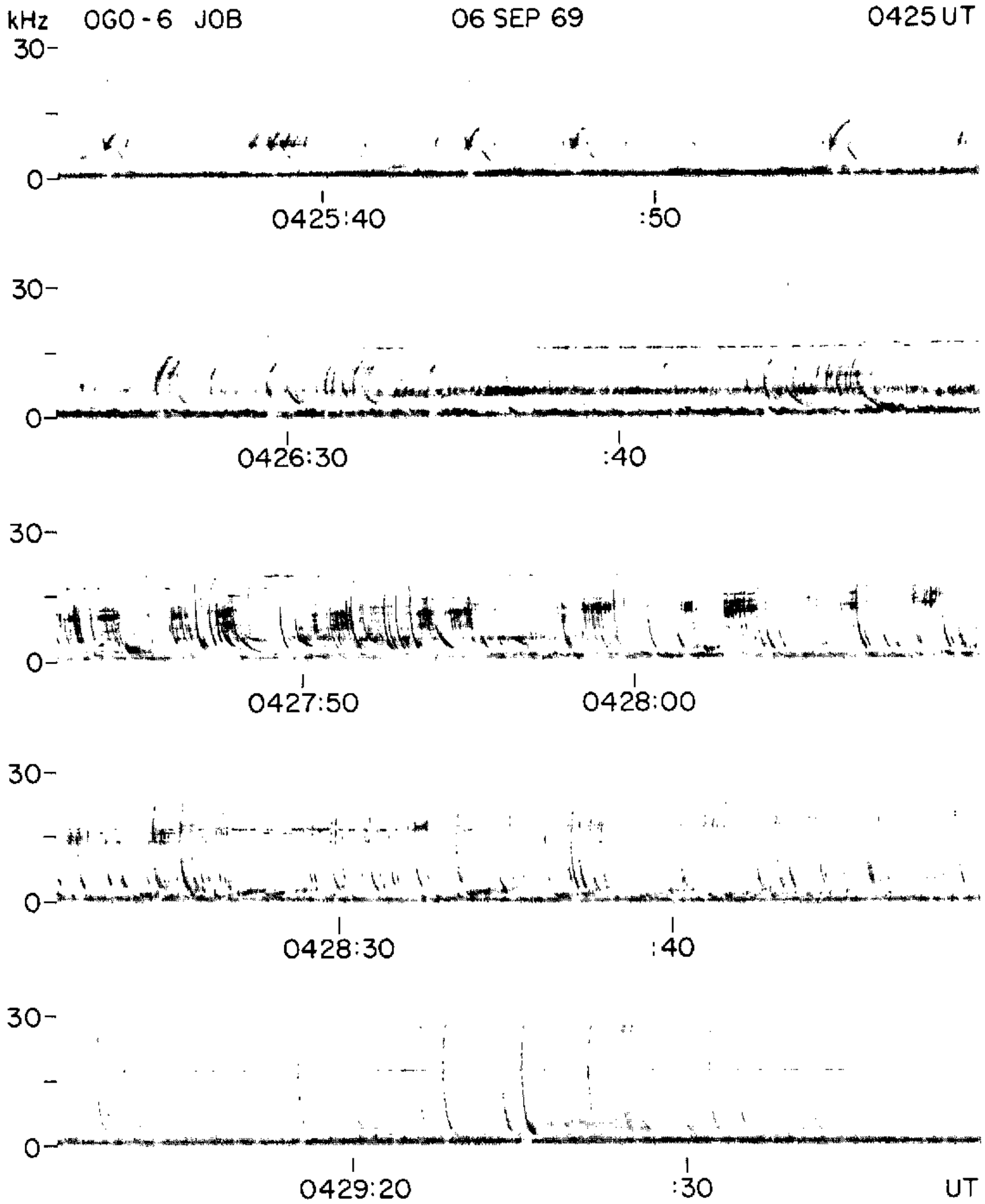

FIGURE 11. SEQUENCE OF 'WALKING TRACE' WHISTLERS. The intersection of the pro-longitudinal mode and the pro-resonance or walking-trace mode rises in frequency as the satellite progresses in time to lower latitudes. The geomagnetic latitude in this sequence runs from 45^{o}S to 31^{o}S. The effect is observed over a large frequency range and there are banding effects evident in the third and fourth panels. This presumably involves interference between the two mode types.

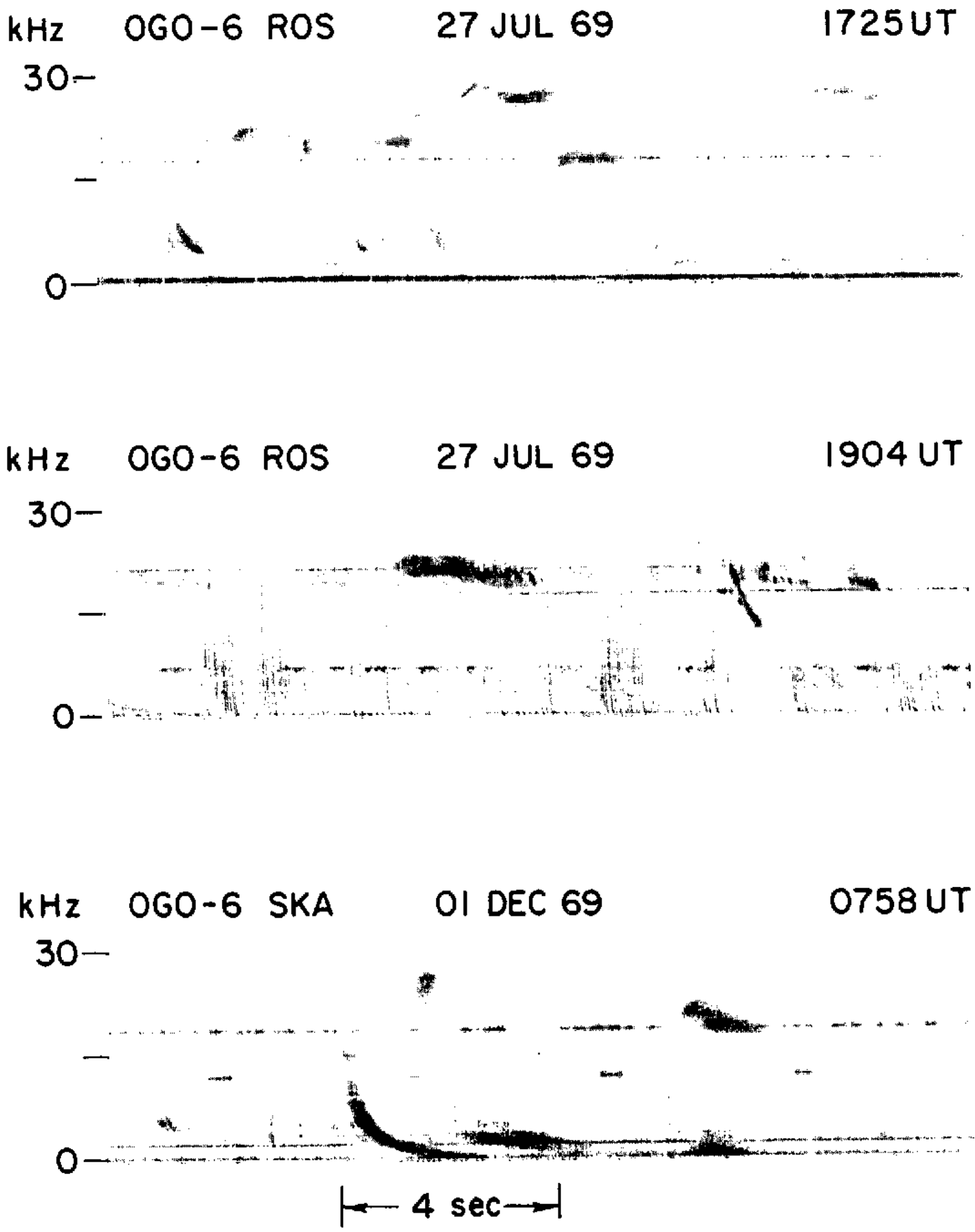

FIGURE 12. High frequency vlf emissions.

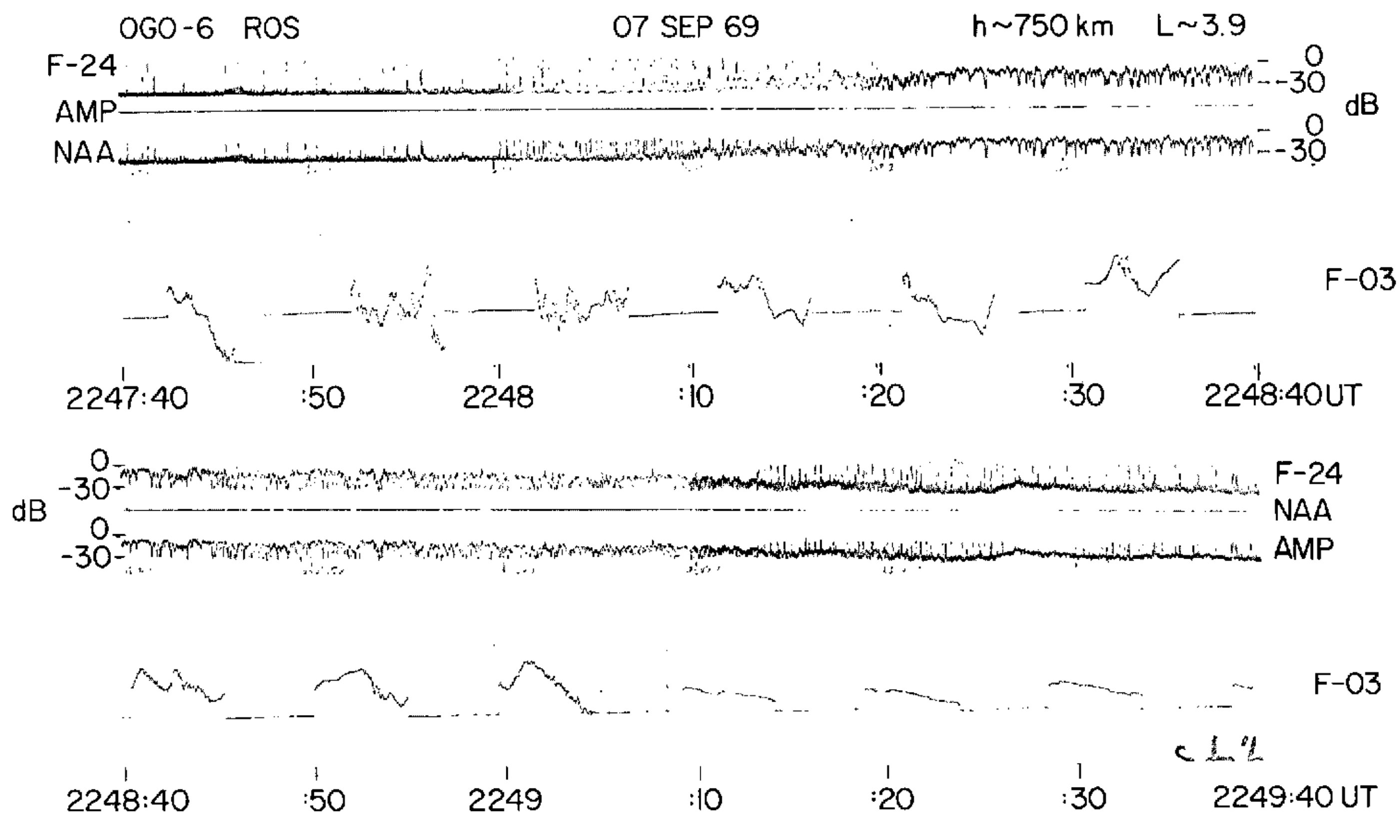

FIGURE 13. SIMULTANEOUS OGO-6 OBSERVATIONS OF SMALL ELECTRON DENSITY IRREGULARITIES BY HANSON'S EXPERIMENT F-03 AND OF FADING OF THE NAA TRANSMITTER SIGNAL BY THE F-24 VLF EXPERIMENT. The smooth portions of the F-03 data (second and fourth panels) correspond to the low-sensitivity mode of the instrument. In the intervening portions, full-scale variations of 6% in ion density are represented. The F-24 records show redundant information on the amplitude of NAA signals on a 0 to -30 db scale. Along the top panel the amplitude of NAA builds up at about 2248:10 when irregular structure is already being observed by F-03. Deep fading of the high amplitude VLF signals is then observed until the amplitude of the signals decreases substantially about 2249:10, at which time the amount of irregularity activity observed by F-03 drops abruptly. See Figure 28 for additional details of this data.

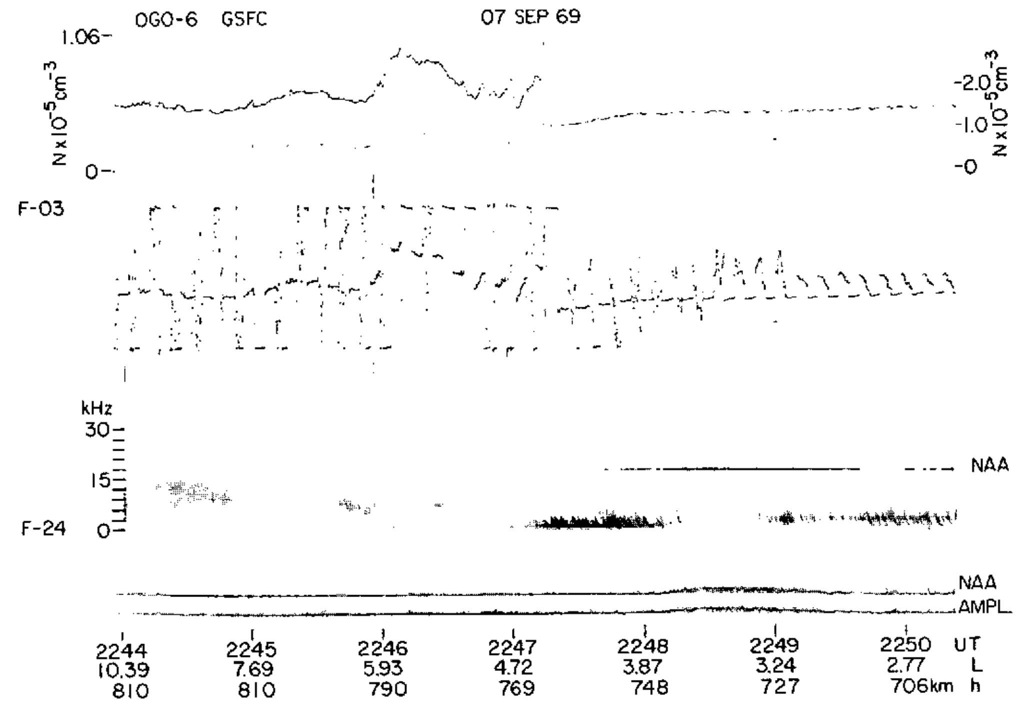

FIGURE 14. A REVISED AND EXTENDED PRESENTATION OF THE RESULTS FROM FIGURE 27, COMPARING RESULTS FROM HANSON'S ION DETECTOR ON OGO 6 WITH THE VLF F-24 EXPERIMENT ON OGO 6. The top panel shows the data from the low sensitivity mode of the ion instrument giving at the left a density scale for the upper curve and at the right a scale for the lower curve. The plasmapause is indicated by a jump in density shortly after 2247 UT. The second panel is a repetition of the high sensitivity mode of the F-03 experiment. At the left, prior to the plasmapause crossing, variations greater than the full scale of 6% are present. The third panel shows the broadband 0-30 kHz VLF from the F-24 experiment. Auroral hiss is present until about 2246:30 and there is also an apparent peak in intensity of the fixed-frequency 22.3 kHz NSS signal in the region outside the plasmapause. At the plasmapause, near 2247 UT, there is a relatively sudden beginning of whistlers propagating from the conjugate hemisphere and the amplitude of the NAA signal begins to increase. The bottom panel shows the NAA amplitude scale, repeated from Figure 27. The complex relationships between irregular structure and the reception of upgoing signals from VLF transmitters is under continuing investigation.