Active Very Low Frequency Experiments on the Magnetosphere from Siple Station, Antarctica

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Active very low frequency experiments on the magnetosphere from Siple Station, Antarctica

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[Plates 1 and 2]

V.l.f. coherent waves transmitted from Siple Station, Antarctica, provide a novel means for the study and control of the magnetosphere and ionosphere. Through cyclotron resonance the waves exchange energy with radiation belt electrons, causing wave growth (*ca.* 10^3 in power), wave–wave interaction and modification of the distribution of electrons. The measured growth rates give information on the flux of energetic electrons along the path of propagation. Precipitation induced by v.l.f. waves from lightning, ground transmitters and power grids, alters the ionosphere, affecting propagation (e.l.f., v.l.f., l.f., h.f.) and providing a controlled forcing function for the study of ionospheric processes. The active experiments are supported by the $L = 4$ network of whistler stations in the Antarctic; they provide data on the distribution and movement of the magnetospheric plasma. Both the active and the passive v.l.f. experiments will contribute important data to the I.M.S. (International Magnetospheric Survey) and to the associated space experiments of the I.S.E.E. (International Sun–Earth Explorers) and E.E. (Electrodynamic Explorer) programmes.

Introduction

The purpose of this paper is to describe briefly the programme of active v.l.f. (3–30 kHz) experiments on the magnetosphere from Siple Station, Antarctica. Under investigation are new wave–particle interaction phenomena that are fundamental to an understanding of space plasmas. Included are wave growth, wave–wave interactions and wave-induced precipitation that are stimulated by v.l.f. signals from a ground transmitter. Possible applications of these experiments include measurements of the flux of radiation belt electrons, control of the ionosphere, control of the radiation belts and new methods of v.l.f. and u.l.f. communication.

Why have v.l.f. experiments in the magnetosphere attracted so much interest? The reasons stem from two remarkable properties of electromagnetic waves whose frequencies lie below the electron plasma and gyrofrequencies (generally called whistler-mode waves). First, their velocity is usually small, depending on the wave frequency and on the parameters of the medium. Second, the anisotropy of the medium tends to cause the wave energy to follow the direction of the Earth's field.

These properties make whistler-mode waves useful as detectors of the concentration of the thermal electrons in the magnetosphere. Field-aligned irregularities, or ducts, of ionization extending between the hemispheres further increase their value by trapping some of the wave energy. Trapping keeps the wave normal aligned on the average with the Earth's field. The trapped, or ducted, waves are more readily transmitted out of the magnetosphere, through the ionosphere so that they can be observed on the ground. The observed travel time versus frequency gives the path latitude and the equatorial electron density. Application of this technique led to the discovery of the plasmapause and to the first measurements of plasma convection within the magnetosphere.

Because of their low velocities and their field-aligned ray paths these waves interact strongly with charged particles trapped in the Earth's field. Both cyclotron and Cerenkov resonance play important rôles. In cyclotron, or transverse resonance, the charged particle rotates around the Earth's field in phase with the circularly-polarized wave fields. In longitudinal resonance the charged particle travels along the Earth's field at the same speed as the wave.

Such resonances can occur over a wide range of particle energies, down to less than 1 keV, giving whistler-mode waves access to an immense reservoir of kinetic energy in the trapped particle population. Wave–particle interaction produces two main effects. First, it can amplify injected coherent signals often more than 30 dB (10^3 in power). The amplified signals then trigger emissions that interact with other v.l.f. waves arising from lightning, power lines and v.l.f. transmitters. Second, the amplified waves and their associated emissions cause pitch-angle scattering that enhances particle precipitation. The leverage exercised by the input wave in this two-stage process can be enormous. It is estimated that the wave-induced precipitation flux may easily exceed the injected wave flux by a factor of one million. The waves in effect act like a valve in controlling the release of the trapped radiation. The precipitation flux in turn generates X-rays, light and enhanced ionization in the E region of the ionosphere. The latter causes pronounced changes in sub-ionosphere v.l.f. propagation. It has been suggested that if the precipitation flux were suitably modulated, u.l.f. waves might be generated by the horizontal a.c. currents resulting from the associated modulation of the E-region conductivity.

The elements of the experiment are sketched in figure 1. A ground transmitter at point T radiates v.l.f. waves into the Earth–ionosphere waveguide. A fraction of the radiated energy crosses the lower boundary of the highly refracting ionosphere and propagates slowly through the magnetosphere where it can be observed by satellites. Scattered throughout the magnetosphere are field-aligned irregularities, or ducts, of electron density that trap some of the v.l.f. energy. The waves then follow a particular field line, such as that shown in the sketch, like light in an optical fibre. Because the wave normal of a ducted wave is kept approximately aligned with the duct axis, the wave can reach the lower edge of the ionosphere. There it is partially reflected back into the magnetosphere and partially transmitted into the Earth-ionosphere waveguide. Within the waveguide the transmitted wave travels at the speed of light and can be detected by any receiver that is not too far from the exit point. Within the magnetosphere, some of the reflected energy is trapped by the same duct and by different ducts, repeating the same process in the opposite hemisphere. Non-ducted waves usually do not cross the lower boundary of the ionosphere, but follow complex multi-hop paths that depend on the distribution of refractive index.

Whistler-mode waves interact with particles throughout the magnetosphere except possibly at low altitudes near the equator. Activity is especially high near the plasmapause. This is a field-aligned irregular surface whose L-value (equatorial height in units of earth radius from earth centre) varies with longitude. It separates an inner region (the plasmasphere) of relatively dense thermal plasma from an outer low density or trough region. The plasmapause position varies from $L = 2.5$ during large substorm events to $L = 6$ or so during extended quiet periods. Much of the time it is near $L = 4$.

In the next sections of this report we discuss briefly the history of active experiments, the plan of the Siple Station experiments, the new results on wave growth and wave–wave interaction and plans for future experiments.

BACKGROUND

The idea for an active v.l.f. whistler-mode experiment arose, first from the chance observation in New Zealand, in the year 1959, of weak artificially-stimulated emissions (a.s.es) from a U.S. Navy v.l.f. station (NPG, located in the state of Washington) on 18.6 kHz. Further observations of stronger a.s.es were made off the Antarctic Peninsula on the Eltanin, by using signals on 14.7 kHz from station NAA, located in the state of Maine, not far from the Eltanin's conjugate point. Most curious was the fact that the Morse dashes (150 ms) produced strong emissions but the dots (50 ms) produced virtually none (Helliwell 1965).

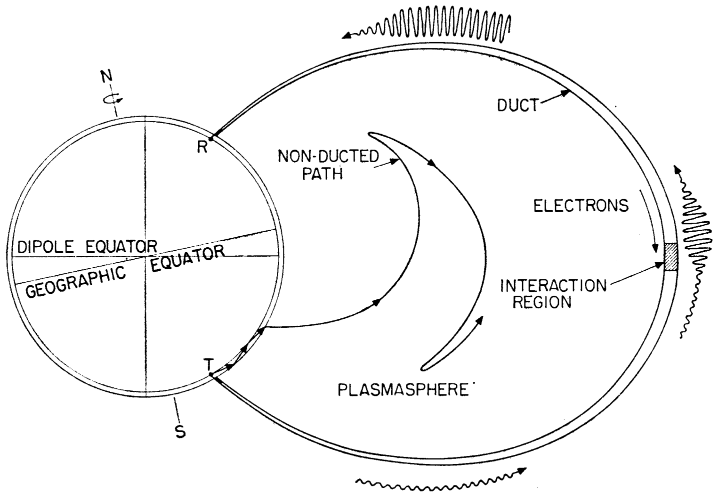


FIGURE 1. Sketch showing ducted and non-ducted whistler-mode paths in the magnetosphere. Three 0.5 s long ducted wave trains are shown before, during and after amplification on the equator. A group velocity of $c/20$ is assumed. Electrons precipitated by the ducted waves are absorbed in the shaded regions at the ends of the duct.

Further interest in an active v.l.f. experiment was generated by the observation on 2 January 1971 of wave-induced precipitation (Rosenberg, Helliwell & Katsufrakis 1971). A balloon-borne X-ray detector, launched to 30 km altitude from Siple Station showed enhanced count rates of > 30 keV X-rays very close to the time a strong burst of v.l.f. noise was received on the ground. The noise bursts were triggered by whistlers excited by Northern Hemisphere lightning. Analysis showed that the X-rays were produced by > 30 keV electrons scattered backward near the equatorial plane by the noise bursts (see figure 1). Some of these electrons were then scattered in the ionosphere back to the Southern Hemisphere ionosphere where they created the observed bremsstrahlung X-rays.

Other evidence of wave-induced precipitation has been found quite unexpectedly in v.l.f. data from Eights Station, Antarctica, recorded in 1963 (Helliwell, Katsufrakis & Trimpi 1973). During certain periods the field intensity of NSS (Annapolis, Maryland) on 22.3 kHz as recorded at Eights Station suddenly increased 6 dB each time a typical strong mid-latitude whistler was received at Eights. The received NSS signal returned to its previous value in about

30 s. This association has been ascribed to an enhancement of ionization in the night-time E and D regions by >30 keV electrons that were scattered by the whistler on an L shell of 2.5.

These three experiments – emission (a.s.e.) triggering, emission-induced bremsstrahlung X-rays, and whistler-induced v.l.f. perturbations – suggest that a controlled experiment might provide new insights on wave–particle interactions. It appears in addition that an entirely new class of controlled experiments on the upper atmosphere might grow out of such experiments.

Much theoretical work has been done on wave–particle interactions in the magnetosphere. However, with one exception none of the phenomena to be described in this paper was predicted *a priori*. Pitch angle scattering by whistler-mode waves was predicted by a cyclotron resonance theory based on a broadband spectrum of waves (Kennel & Petschek 1966). It has been successful, at least in part, in explaining the formation of the electron slot between $L = 2$ and $L = 3$ (Lyons, Thorne & Kennel 1972). However, this broadband theory cannot account for the self-generation of coherent waves, for which a new theory is needed.

Several theories have been advanced to explain a.s.es (Helliwell 1967, 1970; Nunn 1974; Helliwell & Crystal 1973). They are all based on cyclotron resonance, for which the resonant whistler-mode wave frequency is given by

$$f = f_H - v_{\parallel}/\lambda, \tag{1}$$

where f_H is the electron gyrofrequency $(eB_0/2\,m)$, $v_{\parallel}$, the parallel velocity of resonant electron and λ, the wavelength. To explain the observed, narrowband, self-generated, variable frequency emissions a 'second order' resonance condition was postulated in which the change of frequency with time is given by (Helliwell 1967)

$$\frac{\mathrm{d}f}{\mathrm{d}t} \simeq ks, \tag{2}$$

where s is the distance from the geomagnetic equator in the downstream direction, and k, a constant, depending on the wave frequency and the plasma model used.

According to (2), natural rising tones would be generated on the downstream side of the equator (receiver side of figure 1) and falling tones on the upstream side. Some data supporting this prediction have been obtained from high-altitude satellite observations of chorus (Burtis & Helliwell 1976). Because of the mathematical difficulty of this problem, the computer has been used to simulate the interaction of representative test particles with a narrowband wave (Helliwell & Crystal 1973; Nunn 1974). Although computer simulation appears promising it cannot substitute for *in situ* measurements of the spatial distribution of wave fields and the associated perturbations of the resonant trapped particles. The latter require a satellite, preferably one whose orbit is closely aligned with the duct.

Experiment plan

The requirements for a controlled v.l.f. wave injection experiment are: (1) a radiated power $\simeq 1$ kW, (2) proximity to the plasmapause (near $L = 4$), (3) an accessible conjugate point, and (4) year-round operation. At these unusually long wavelengths (order of 100 km) requirement (1) dictates either that the antenna structure must be relatively efficient or that the transmitter power must be very large. Two types of antenna structure are suitable – a vertical wire supported by a balloon or helicopter or a horizontal dipole over low-loss ground. Requirement (4) eliminates the first of these as a practical alternative, leaving only the horizontal dipole. (Balloon-supported vertical antennas have been successfully employed in short duration experiments (McPherson *et al.* 1974).) To keep the transmitter power within reasonable bounds (< 100 kW) the horizontal dipole must be erected over low-loss ground, such as a thick ice sheet.

The base of the Antarctic Peninsula is probably the only place on the Earth's surface that simultaneously satisfies all four requirements. In addition it possesses other favourable characteristics, including, for example, many lightning sources in the conjugate region, a low local noise level (due to absence of local thunderstorms), a high density of ducts and high natural emission activity. Accordingly this region was selected for the construction of Siple Station. A 21.4 km long dipole antenna was erected 6 m above the ice surface to reduce induction losses in the ice. Efficiencies of about 4% at 10 kHz are achieved (Raghuram, Smith & Bell 1974) Every 2 years or so the antenna is raised, simply by extending the support towers, to keep induction losses down.

The transmitter and several passive experiments are housed under a steel arch 66 m long and 6 m high. Operation and maintenance of the transmitter and all passive experiments is carried out by two graduate engineers. The conjugate point to Siple is close to Roberval, Quebec, and is easily reached on a year-round basis. Balloons are launched at both Siple and Roberval for study of wave-induced precipitation. It is planned to extend the particle studies by launching rockets from Siple.

The best wave growth and emission effects are observed during a period of quieting after a magnetic storm (Carpenter & Miller 1976). Such emission activity has also been found to maximize when the transmitter frequency lies between 0.3 and 0.5 of the minimum gyrofrequency on the magnetospheric path. However, the path latitudes of good duct activity vary significantly with time. Thus it is advantageous for the transmitter operator to select frequencies and times of operation based on his concurrent observations of the natural background v.l.f. activity. This is done with the aid of a real time spectrum analyser at Siple Station. Results for 1974 show that of 2500 h of transmitter operation there were 500 h in which detectable magnetospheric signals were observed at Roberval. Many observations were scheduled independently of the known conditions in order to support other experiments (e.g. satellite passes, barium releases, routine monitoring).

Experimental results

The first transmitter experiment was aimed to understanding the dot-dash anomaly mentioned earlier. A series of 5 pulses at each of several pulse lengths was transmitted alternately on two frequencies, as shown in figure 2. Each sequence starts with 50 ms pulses and ends with 400 ms pulses. Within each sequence the pulse length increases by 50 ms at the end of each group of 5 pulses, as shown by the format at the bottom of figure 2. The shorter pulses are weak and trigger only falling tones, while the longer pulses are strong and trigger only rising tones. As the pulse length increases, the peak intensity increases from roughly the background noise level to well above the noise level. When the general level of activity increases, the transition from falling to rising tones occurs at shorter pulse lengths, as shown by figure 2, plate 1.

Intensity measurements of individual pulses show an exponential increase in the intensity with time, as shown in figure 3. Growth rates have been found to range from a minimum of 25 dB/s up to a maximum of 250 dB/s (Stiles & Helliwell 1976). (By contrast, the so-called 'spontaneous' emissions, observed in satellites outside the plasmapause, show growth rates from

200 to 2000 dB/s (Burtis & Helliwell 1975).) The total temporal growth is often as much as 30 dB and sometimes as high as 35 dB. The triggered emissions generally have the same amplitude (within a few decibels) as the final amplitude of the triggering pulse. Thus the difference between triggering by dots and dashes is simply explained by the fact that the short pulses do not have time to grow strong enough to trigger a detectable emission.

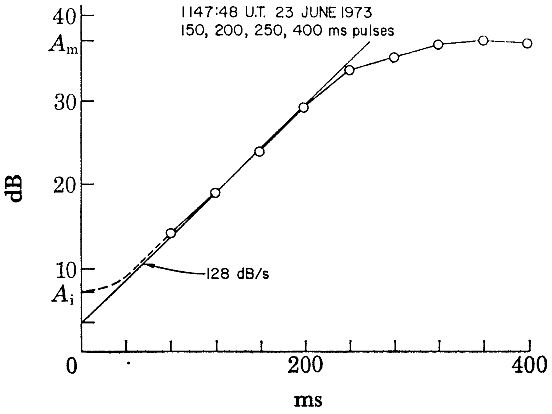


Figure 3. Average amplitudes of output pulses as a function of time after the start of the received pulse. Straight line fit gives exponential growth rate of 128 dB/s. Total growth is $A_m - A_i = 30$ dB. (From Helliwell & Katsufrakis (1974).)

In the course of these experiments it was soon discovered that the emissions triggered by Siple pulses were often cut off by other Siple pulses. In turn the triggered emissions were cut off or changed slope at the frequencies of certain of the power-line harmonics (Helliwell & Katsufrakis 1974). Several examples of emission cut-off can be found in figure 2. These results suggested, but did not prove, that radiation from the North American power grid was leaking into the magnetosphere.

Accordingly an experiment was performed, using available magnetic tape recordings from Siple and Roberval, to determine whether or not power line radiation (p.l.r.) could be observed at Siple (Helliwell Katsufrakis, Bell & Raghuram 1975). An example of the results is shown in figure 4, plate 1, in which magnetospheric lines of the same frequency appear simultaneously at both Siple and Roberval. These lines show intensity modulation which is 180° out of phase at the two ends of the path. The period of modulation equals the two-hop travel time of a strong whistler observed concurrently, thus confirming the magnetospheric origin of the lines.

A puzzling feature of the magnetospheric lines is their offset in frequency with respect to the Roberval local induction lines. This offset is usually positive and within 20 or 30 Hz. It appears to be related to the tendency for triggered emissions to lie above the frequency of a continuous triggering signal.

P.l.r. may play a significant rôle in controlling the precipitation of electrons from the radiation belts. As energetic electrons drift into the Canadian sector from the west, they resonate with the power-line components and are scattered in pitch angle. A substantial number may be precipitated before they reach the longitude of the South Atlantic anomaly.

Further confirmation of the presence of p.l.r. in the magnetosphere comes from maps of v.l.f. noise intensity obtained with the Ariel 3 and 4 satellites (Bullough, Tatnall & Denby 1976). Startling changes in 3.2 kHz noise intensity occur at the boundary separating North America

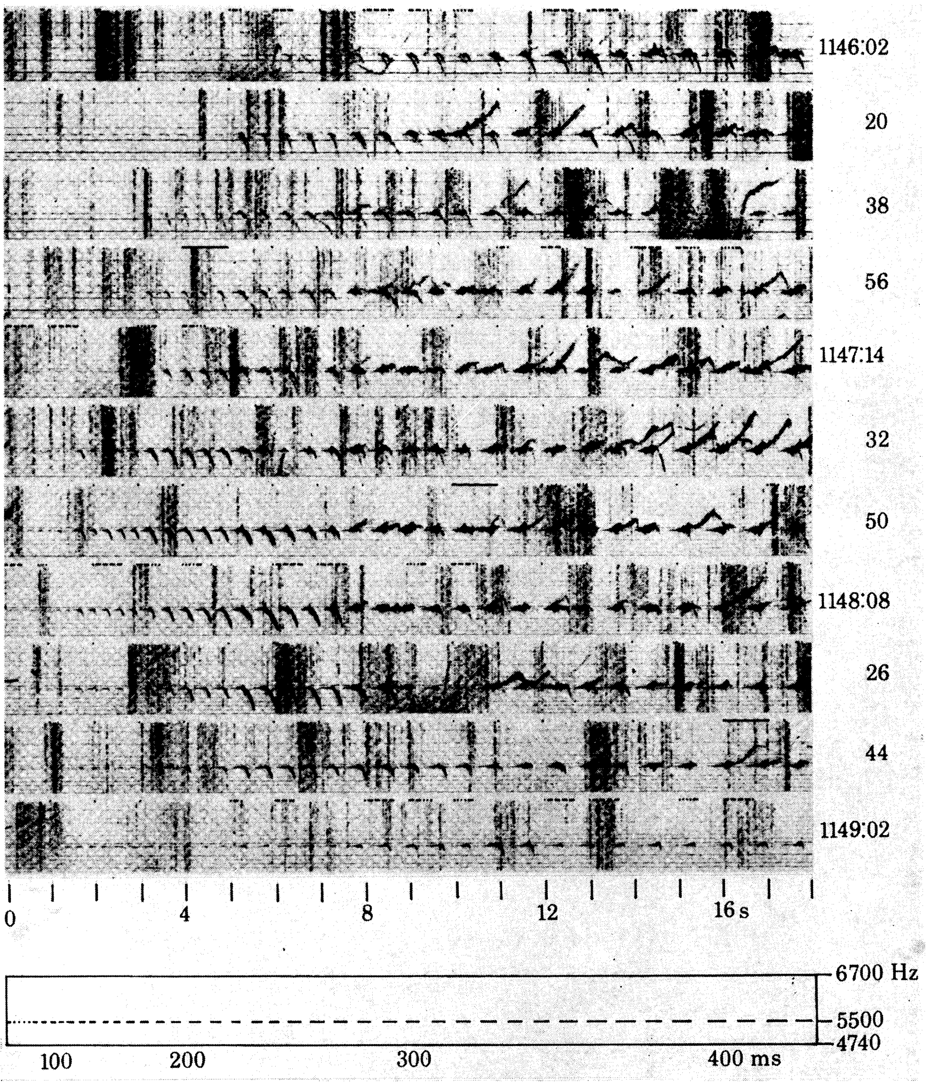


FIGURE 2. Compressed spectra from 23 June 1973, showing how the transition from fallers to risers moves to shorter pulse lengths as growth rates increase. (The 91st harmonic of the power system appears 40 Hz below the transmitter frequency.) (From Stiles & Helliwell (1976).)

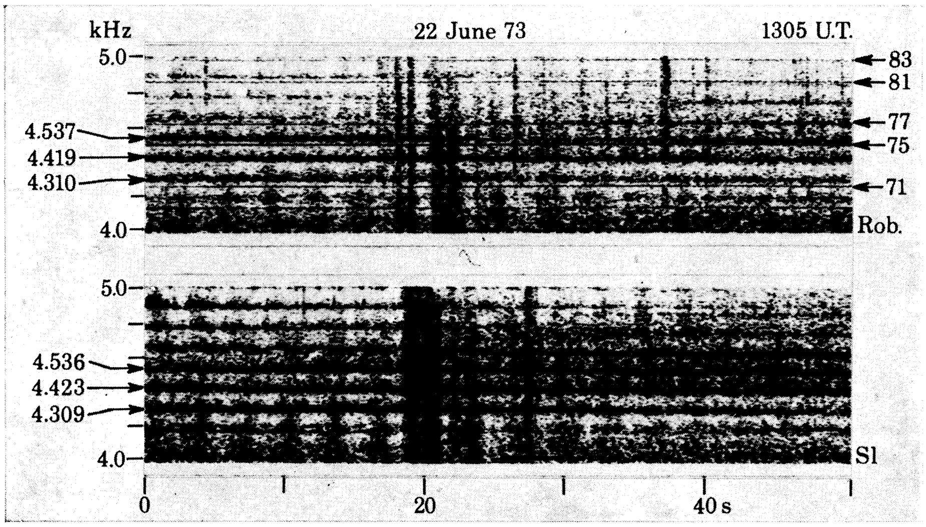
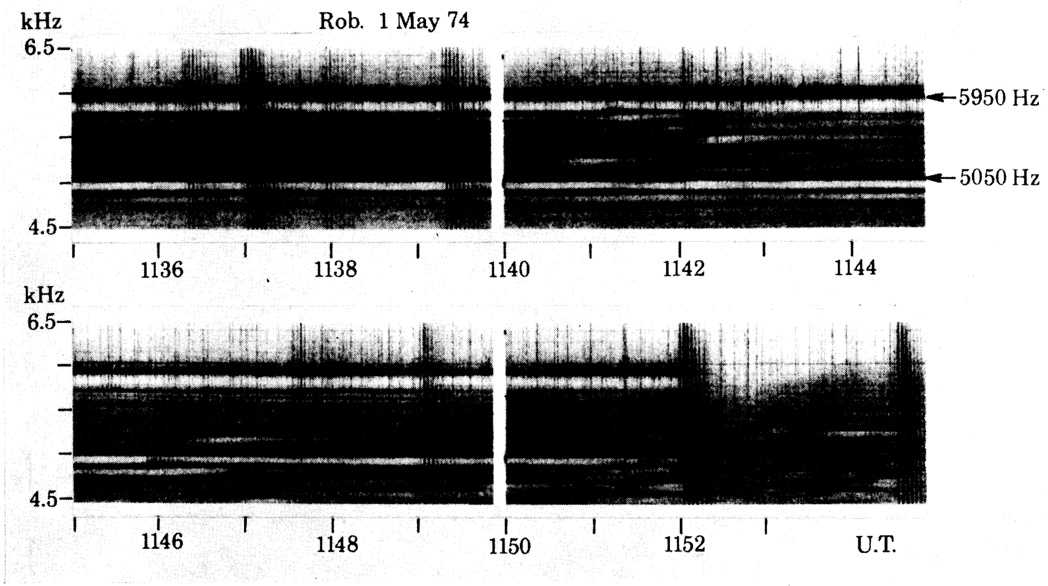
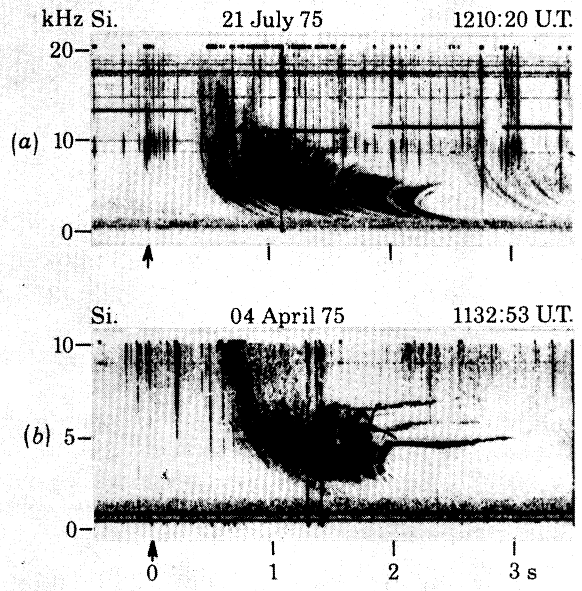


FIGURE 4. Simultaneous spectra from the conjugate stations Siple and Roberval. The frequencies of prominent magnetospheric lines are given. The harmonic numbers of the induction lines seen at Roberval are given. Note the difference in bandwidth between magnetospheric and induction lines. Measurement uncertainty ± 5 Hz. (From Helliwell *et al.* (1975).)





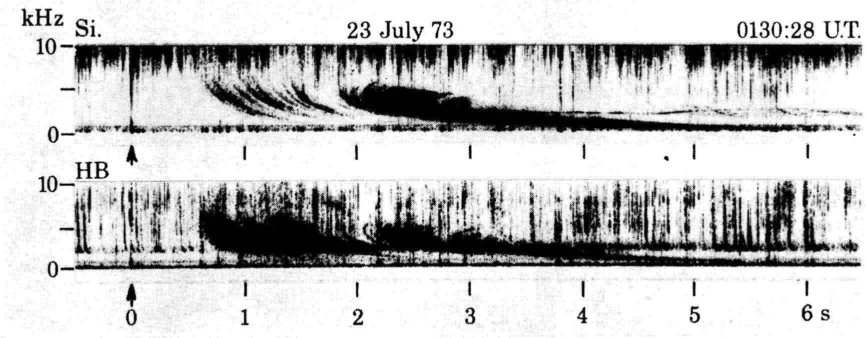


FIGURE 6. Roberval spectrograms illustrating 'quiet bands' immediately below the 5950 and 5050 Hz transmitter frequencies. The transmissions terminated at 1152 U.T. (lower right). (From Helliwell & Katsufrakis (1975).)

FIGURE 7. (*a*) Siple Station multi-path whistler. (*b*) Whistler stimulated emissions. Arrows designate source 'sferic.

FIGURE 9. Siple Station–Halley Bay simultaneous whistlers. Arrow designates source 'sferic.

from the Atlantic Ocean. The changes are attributed by the authors partly to p.l.r. and partly to whistlers originating in lightning activity over the North American continent.

A prominent feature of the controlled experiments is the phenomenon of entrainment. Free-running oscillations, triggered by whistlers or by the Siple pulses, are often entrained by externally-generated coherent waves, including p.l.r. (Helliwell & Katsufrakis 1974). Examples of cut-off, reversal and change in slope can be found in figure 2, especially at harmonics of the power system. Thus it appears that the plasmasphere is characterized by natural oscillations of changing frequency which are continually being entrained and released by weak coherent signals from ground sources (whistlers, v.l.f. transmitters and p.l.r.).

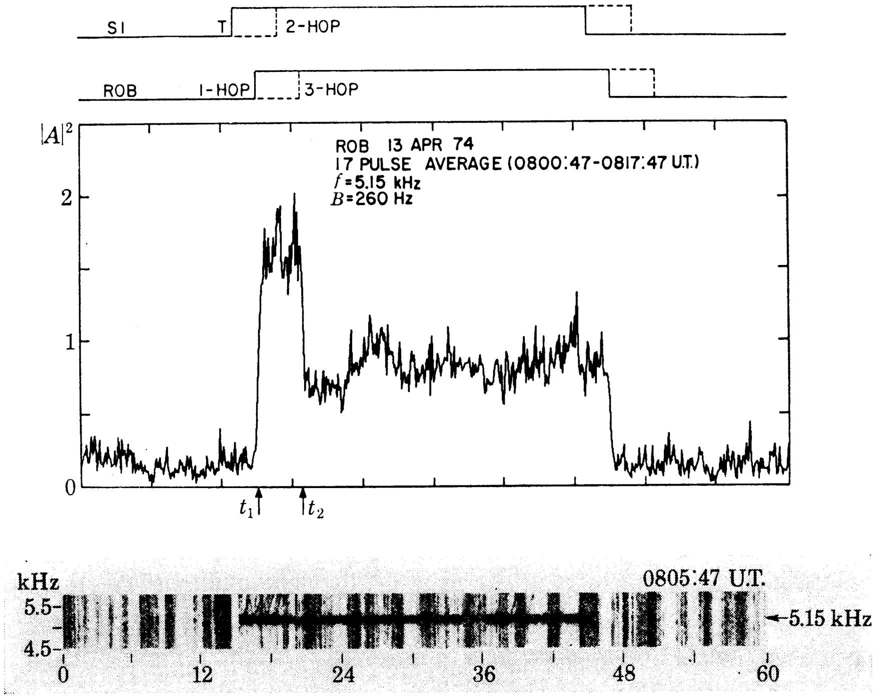


Figure 5. Variation in amplitude of 30 s pulses received at Roberval. The top panel shows the time sequence of the various hops. The middle panel shows the square of the amplitude as a function of time. The plot is a 17 pulse average. Echo-induced suppression is seen in the form of a reduction in amplitude 4.0 s from the start of the pulse. The bottom panel shows the frequency time spectrogram of a typical pulse from this time interval. Echo-induced suppression is again clearly seen. (t_1 is the time at which triggering of emissions begins. t_2 is the time of arrival of this event as it appears in the three-hop echo.) (From Raghuram (1976) to be submitted to the *J. geophys. Res.*)

In the course of the study of magnetospheric wave amplification it was found that when whistler-mode echoes were present, amplification was often reduced. An example is shown in figure 5. Four seconds after the start of the signal there is a sudden decrease in strength, by about 3 dB. Whistler analysis shows that this is the two-hop travel time over the path of the Siple pulse, indicating that the three-hop signal of the Siple pulse is superimposed on the one-hop signal, causing its growth to be reduced. A most remarkable aspect of growth suppression is the fact that the echo itself may be 30 dB below the signal being suppressed. (In figure 5, the echo cannot be identified directly because it is below the background noise.) Growth suppression by weak echoes confirms the important rôle played by p.l.r. which may itself be at the threshold level of detection.

Growth suppression by echoes can be understood qualitatively in terms of the resonance conditions of (1) and (2). First we must assume that the echo consists of a broadened spectrum of waves, as is usually observed. Broadening is the direct result of emission triggering on the upper side of the transmitted frequency (see figure 2). The echo is therefore no longer coherent. It is added to the direct input signal at its unamplified level and hence the two signals can be of comparable intensity at the input to the interaction region (even though the echo may not be detectable). The sum of the coherent direct signal and the incoherent echo is therefore significantly incoherent. According to (1) and (2) resonance occurs over a distance of several hundred wavelengths. Each electron must see an essentially monochromatic wave as it passes through the interaction region, or the phases of the radiation from the resonant electrons will not be organized effectively for coherent radiation. Calculations show that resonance is degraded significantly when the bandwidth of the wave is greater than $(\Delta t)^{-1}$, where Δt is the required time for an electron to pass through the interaction region. For a typical transit time of 30 ms, this bandwidth is accordingly about 30 Hz. The measured bandwidths of emissions plus signal usually exceed this value considerably, thus accounting qualitatively for suppression.

Another equally remarkable effect is the stimulation of a noise-free, or quiet band by the Siple pulses. An example is shown in figure 6, plate 2, in which pulses are transmitted alternately on frequencies of 5050 and 5950 Hz. These pulses are amplified in the magnetosphere. Just below each transmitter frequency is a band, about 200 Hz wide, in which the noise is suppressed (by about 6 dB). Elsewhere on the record the observed hiss-like background is whistler-mode noise from the magnetosphere. The quiet band requires 5–15 s to develop after the transmitter is turned on and several seconds to recover after the transmitter is turned off Similar quiet bands appear below some of the amplified p.l.r. lines as shown in figure 6.

Calculations based on the electron cyclotron resonance interaction of (1) indicate that the band can be accounted for by a reduction in the flux of energetic particles over a small range in $v_{\parallel}$. As the amplified Siple pulses leave the equator, they resonate with electrons which, in the absence of scattering, would resonate at the equator with lower frequency waves (because f_H is lower at equator). Some of these electrons are removed from the resonance band by scattering in the amplified wave train. Thus the hiss which is amplified by electrons in the resonance band sees fewer electrons and hence is not amplified as much. Quiet bands can provide new information about the interaction and might also be used in communication circuits for the purpose of reducing the background noise level.

Wave-induced precipitation can enhance the electron density over a localized area in the E region as mentioned earlier. A study has shown that u.l.f. (~ 1 Hz) waves could be excited by modulating the precipitation flux at the same frequency (Bell 1976). The changing flux changes the electron concentration that in turn changes the conductivity. This causes the horizontal current driven by the *in situ* electric field to be modulated, giving rise to a 1 Hz hydromagnetic wave that travels into the magnetosphere where it may be amplified on streams of protons through cyclotron resonance. Transmissions from Siple Station have provided some statistical data supporting this hypothesis (Fraser-Smith & Cole 1975).

Supporting experiments

To interpret the active experiments just described certain measurements on the magnetosphere and the ionosphere are required. In the magnetosphere we need to know the location and electron content of the propagation paths. In the ionosphere we want to know the perturbations caused by precipitating particles as well as the vertical and horizontal profiles of electron density.

The magnetospheric parameters can be found from whistlers recorded at nearby ground stations. An example of a multi-path whistler that can be used for this purpose is shown in figure 7*a*, plate 2. The frequency of minimum time delay of each parabola-shaped trace measures the latitude of the path and the travel time at that frequency is a measure of the equatorial electron density in the magnetosphere. From a set of such whistlers a model of the magnetospheric plasma can be constructed. Changes in path latitude give the north–south component of convection drift and hence define the east–west component of electric field. The same type of whistler often triggers a narrowband discrete emission at the whistler upper cut-off frequency, as shown in figure 7*b*. Thus the whistlers themselves contribute directly to the study of wave–particle interactions as well as measuring path parameters. In fact, whistlers and their associated emissions have been, so far, the main source of information on wave-induced precipitation effects.

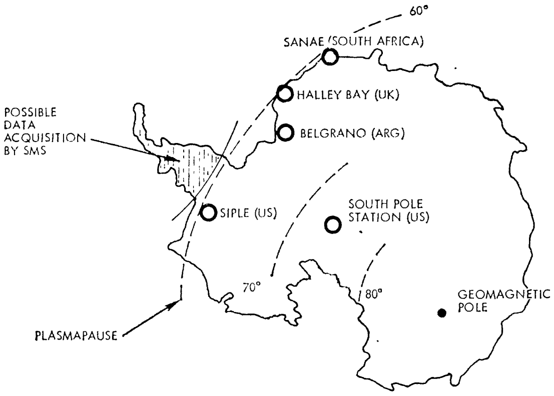


Figure 8. Map of Antarctic $L = 4$ stations (SMS, synchronous meteorological satellite). (From *International Magnetospheric Study, Detailed Plan for U.S. Ground-based Research Program*, National Academy of Sciences, Washington, D.C., 1974, p. 38.)

In order to study the distribution of the thermal plasma and its dynamic behaviour it is proposed to make measurements during the I.M.S. at several stations located along the $L = 4$ belt in Antarctica, as shown in figure 8. Measurements from Sanae, Halley Bay and Siple are among those that are expected to provide new information on the location of whistler paths and the distribution and movement of the plasma in the plasmasphere.

An especially challenging and exciting experiment is the attempt to locate the end points of whistler paths using direction finders. Currently only the latitude of the path can be measured with adequate accuracy. The longitude is crudely estimated to within ± 15° from the relative whistler amplitude. The east–west motion (gives north–south electric field) cannot be estimated accurately by this method. By measuring simultaneously the directions of arrival from spaced stations we can obtain the required information (Sagredo & Bullough 1972; Leavitt 1975).

The baseline for a pair of direction finders must be small enough that the rate of occurrence of simultaneous whistlers is reasonable. For example, Siple Station and Halley Bay are separated by 1500 km but they frequently see the same whistler components, as shown in figure 9, plate 2. Some of the traces are the same at these two stations and some are not. Differences in the sferics background are also apparent. In spite of these differences it should be possible to make simultaneous direction-of-arrival measurements on a number of discrete whistler components from Siple and Halley Bay. By locating the ducts on which wave–particle interactions are being measured it will be possible to determine the relevant particle parameters from simultaneous satellite data. This study and the active experiments constitute an important part of the I.M.S.-Antarctic programme on upper atmosphere physics.

Measurements of ionospheric parameters have two principal uses in the active v.l.f. experiment. Thus the electron density profile aids in finding the ray path, travel time, and attenuation of the magnetospheric signal from Siple. For electron density profile measurements in the ionosphere, ionosondes (both topside and bottomside) are especially useful. For attenuation measurements, both riometers and ionosondes can be used. The other use of ionospheric data is to define the ionospheric perturbations caused by wave-induced particle precipitation. The main effects are bremsstrahlung X-rays, light and enhanced ionization, the first and third of which have already been detected. Instruments that can be used include balloon-borne and satellite-borne X-ray detectors, photometers, t.v. cameras, riometers, magnetometers, magnetic pulsation detectors, and ionosondes. However, precipitation effects well above the lower boundary of the E layer (< 30 keV electrons) are difficult to measure by any ground-based method except the ionosonde. The desired information on the lower energy (< 30 keV) precipitation flux can best be obtained by rockets and satellites.

Most of the ideas described above are based on ground observations. There are few detailed measurements of *in situ* properties of the v.l.f. waves together with their associated particles. Thus it is necessary to make a coordinated experiment in which the waves and the particles responsible for their generation are measured simultaneously at several points along a particular field line. The proposed Electrodynamics Explorer satellite is designed to accomplish that objective. It will be possible, for example, to allow the satellite to drift along the field line (see figure 1) while test pulses are transmitted from Siple Station. Then the predicted spatial distribution of wave intensity and the associated particle perturbations can be measured. We expect to find, for example, where natural rising and falling tones are generated, thus testing the prediction of (2). The unperturbed electron distribution function will be measured so that calculations of growth rate based on available interaction models can be compared with measurements.

Future work

One of the goals of the Antarctic v.l.f. programme is to discover the nature of the plasmasphere in terms of both its static and dynamic characteristics. Another is to understand the processes whereby waves and energetic particles interaction to create more waves and to modify the ionosphere and the radiation belts. To reach these goals we shall need coordinated passive and active v.l.f. experiments together with a variety of supporting experiments, as noted.

There are many possible future applications of active experiments. Thus the ground-based active experiment on wave growth and a.s.es should be able to give data on the flux of energetic particles in the magnetosphere, thus reducing the need for monitoring satellites. Another application is the use of v.l.f. wave injection to modify the magnetosphere and the ionosphere. The ability to control the precipitation of particles into the Earth's atmosphere will be of tremendous value in further studies of our atmospheric environment. Although the ground-based v.l.f. transmitter is very effective for this purpose, an even broader range of the parameters can be investigated by placing a v.l.f. transmitter in a satellite (e.g. the Shuttle). Finally, these experiments will provide data needed to assess the feasibility of magnetospheric communication paths at v.l.f. and u.l.f. Thus there are many exciting opportunities for advancing our knowledge of the upper atmosphere using controlled v.l.f. wave injection.

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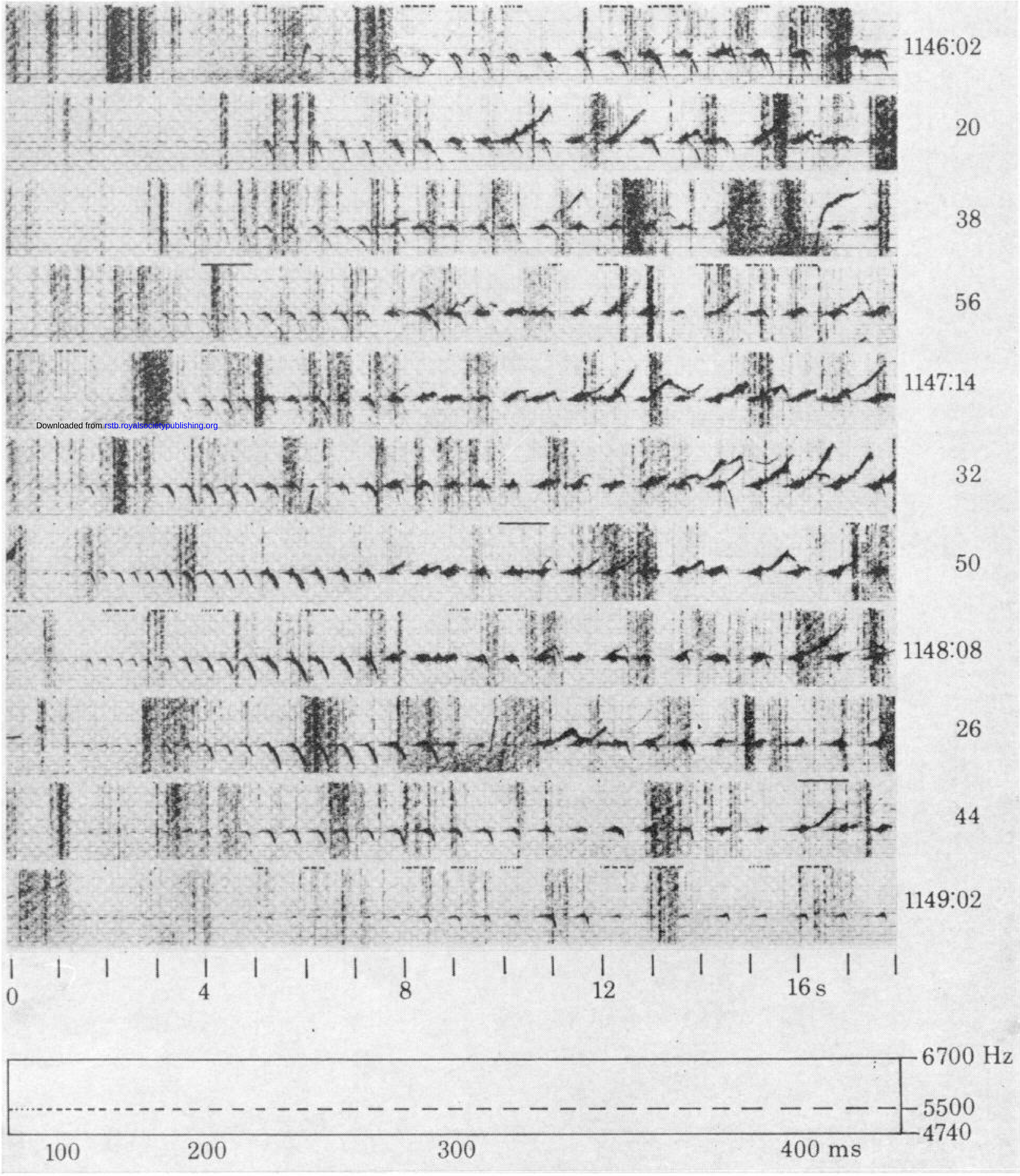
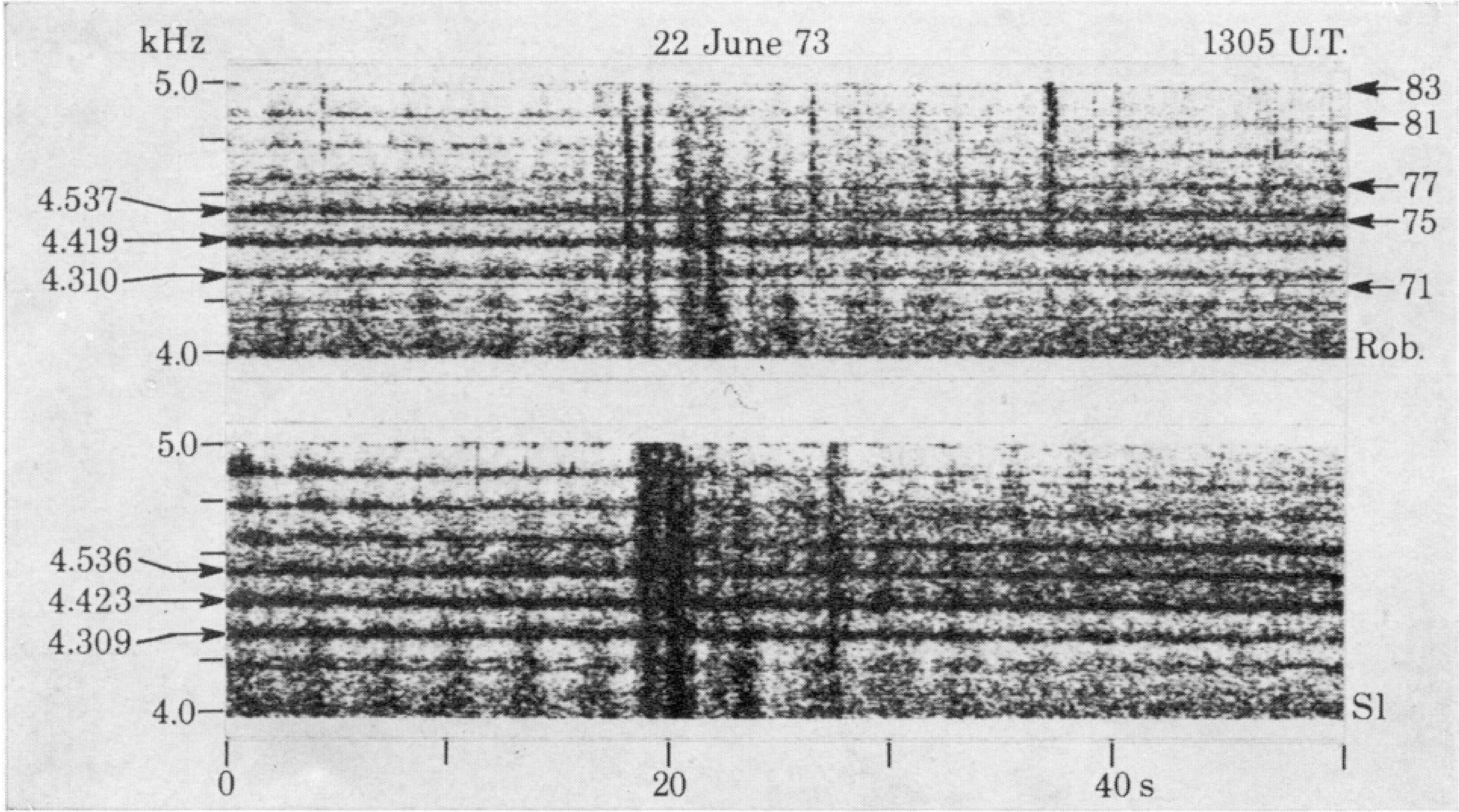
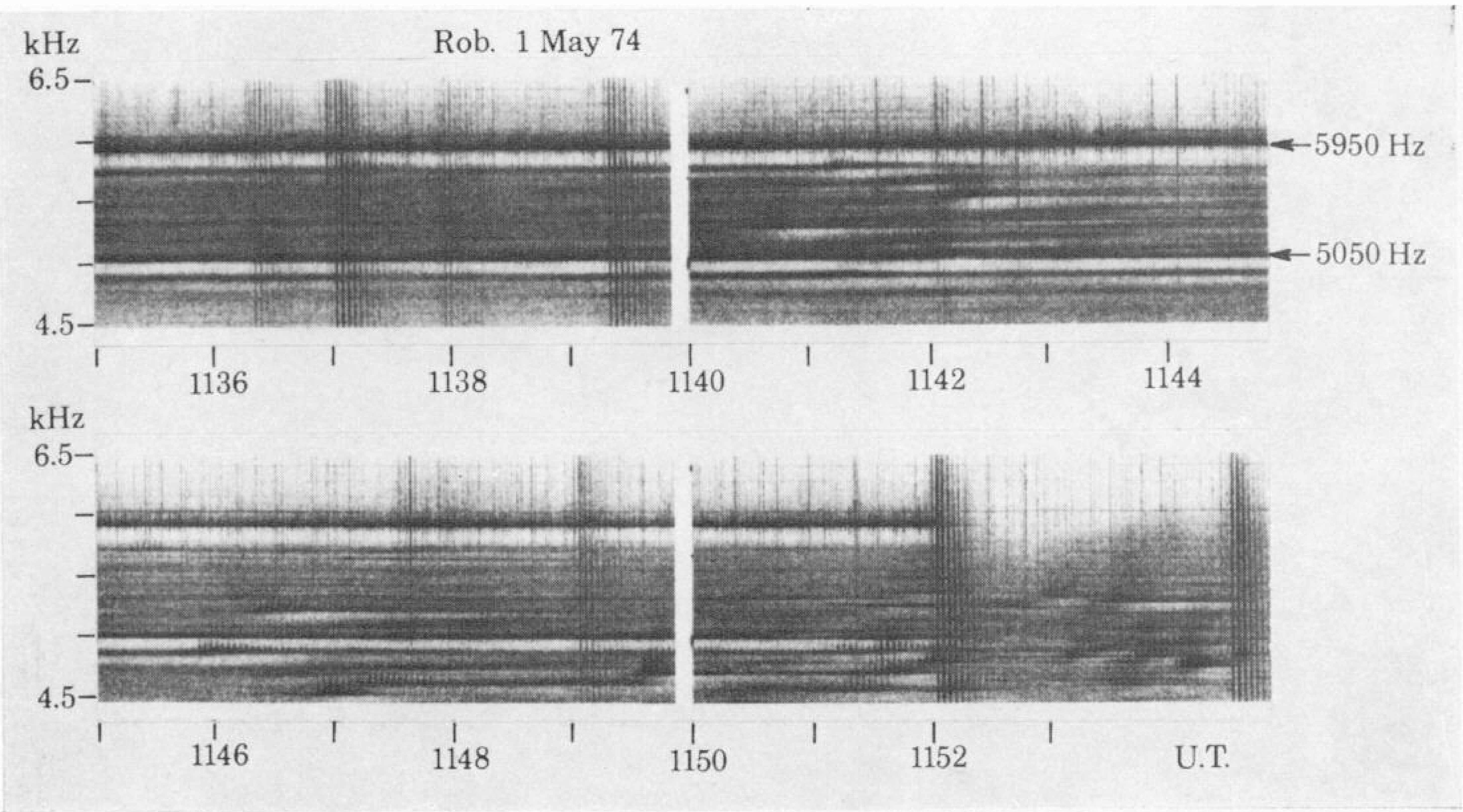
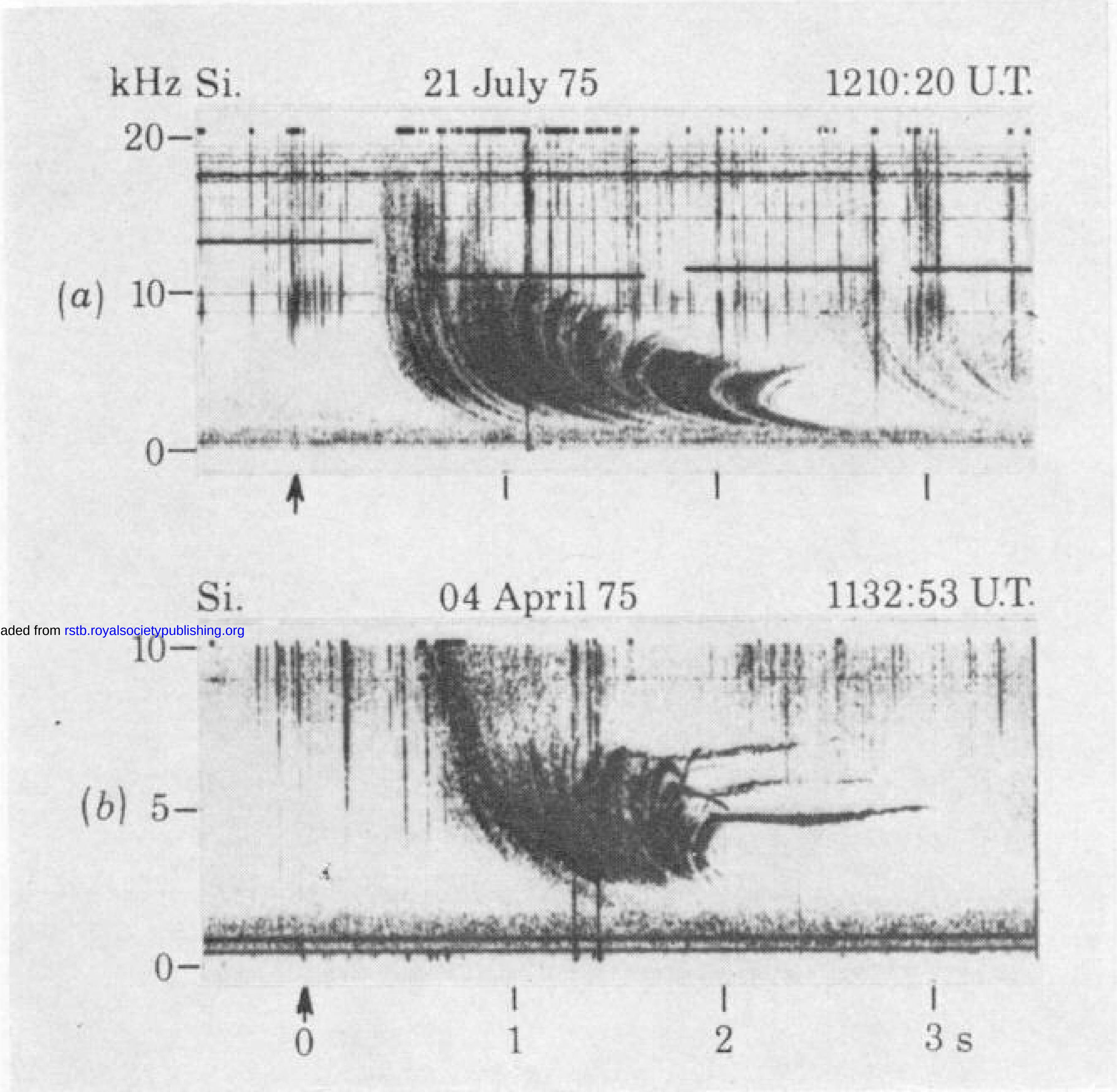


FIGURE 2. Compressed spectra from 23 June 1973, showing how the transition from fallers to risers moves to shorter pulse lengths as growth rates increase. (The 91st harmonic of the power system appears 40 Hz below the transmitter frequency.) (From Stiles & Helliwell (1976).)



IGURE 4. Simultaneous spectra from the conjugate stations Siple and Roberval. The frequencies of prominent magnetospheric lines are given. The harmonic numbers of the induction lines seen at Roberval are given. Note the difference in bandwidth between magnetospheric and induction lines. Measurement uncertainty ± 5 Hz. (From Helliwell *et al.* (1975).)





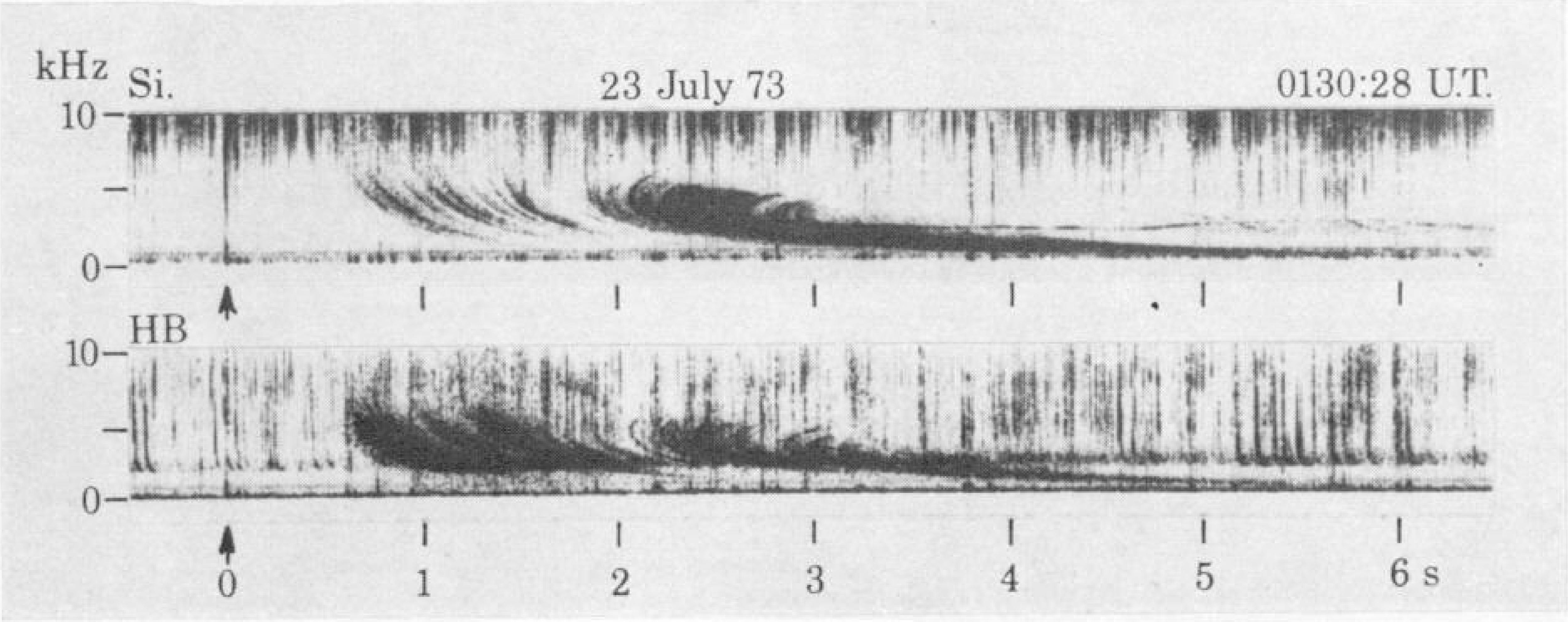


FIGURE 6. Roberval spectrograms illustrating 'quiet bands' immediately below the 5950 and 5050 Hz transmitter frequencies. The transmissions terminated at 1152 U.T. (lower right). (From Helliwell & Katsufrakis (1975).)

FIGURE 7. (*a*) Siple Station multi-path whistler. (*b*) Whistler stimulated emissions. Arrows designate source 'sferic.

FIGURE 9. Siple Station–Halley Bay simultaneous whistlers. Arrow designates source 'sferic.

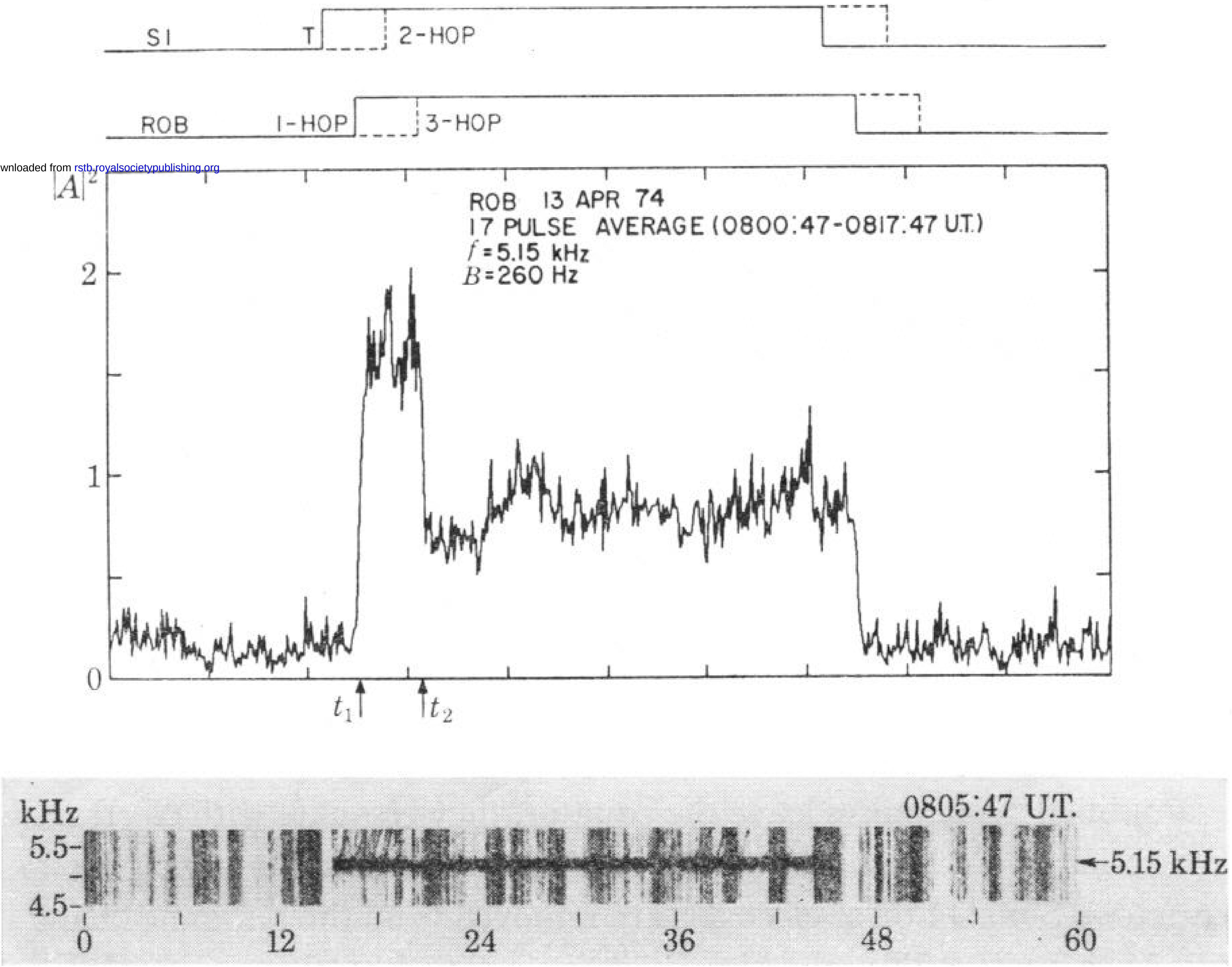


FIGURE 5. Variation in amplitude of 30 s pulses received at Roberval. The top panel shows the time sequence of the various hops. The middle panel shows the square of the amplitude as a function of time. The plot is a 17 pulse average. Echo-induced suppression is seen in the form of a reduction in amplitude 4.0 s from the start of the pulse. The bottom panel shows the frequency time spectrogram of a typical pulse from this time interval. Echo-induced suppression is again clearly seen. (t_1 is the time at which triggering of emissions begins. t_2 is the time of arrival of this event as it appears in the three-hop echo.) (From Raghuram (1976) to be submitted to the *J. geophys. Res.*)