PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Alteration of the Ionosphere by Man-Made Waves

J. A. Fejer

Phil. Trans. R. Soc. Lond. A 1975 **280**, 151-165
doi: 10.1098/rsta.1975.0098

Phil. Trans. R. Soc. Lond. A. **280**, 151–165 (1975) [151]
Printed in Great Britain

Alteration of the ionosphere by man-made waves

By J. A. Fejer
Department of Applied Physics and Information Science, University of California, San Diego, La Jolla, California 92037

[Plates 7–10]

In recent years powerful radio wave transmissions beamed at the ionosphere at frequencies somewhat below the penetration frequency of the F2 layer produced the following, mostly unexpected, spectacular effects.

(*a*) Artificial spread F seen on ionograms and implying the presence of large scale field-alined irregularities in the ionospheric plasma density.

(*b*) Very strong additional absorption of probing waves reflected by the F2 layer.

(*c*) Field-alined 'on frequency' scattering of u.h.f. waves.

(*d*) Scattering of u.h.f. waves by Langmuir waves which are believed to be parametrically excited.

(*e*) The 630 nm airglow is artificially enhanced by a modifying wave of ordinary polarization but it is reduced in intensity by a modifying wave of extraordinary polarization.

(*f*) The shape of the F2 layer is modified.

The results of the observations are described and their tentative interpretation in terms of different parametric instabilities is outlined.

1. Introduction

High power ionospherically reflected h.f. transmissions having incident power densities of a few tens of $\mu W/m^2$ in the F region and about 5–10 times higher power densities in the E region have been used since 1970, at first with the intention of merely modifying the electron densities and temperatures of the ionosphere. The present discussion will be almost entirely restricted to experiments in which the wave was reflected in the F2 region and to modification phenomena in the F2 region. A much greater variety of physical phenomena was observed than anticipated. Many plasma instabilities of great interest to plasma physicists who are trying to demonstrate the feasibility of controlled thermonuclear fusion, appear to have been excited in the ionosphere. The following manifestations of these instabilities have been observed: (*a*) artificially created spread F, (*b*) artificially strongly enhanced radio wave absorption, (*c*) the creation of field alined density irregularities which scatter (this phenomenon is sometimes called field alined scatter or f.a.s.) an incident h.f., v.h.f. or u.h.f. wave with virtually no frequency change and make certain types of scatter communication circuits possible, (*d*) scattering processes in which the frequency of the scattered wave differs from the frequency of the incident wave by roughly the frequency of the high power h.f. transmissions, and finally (*e*) artificially strongly enhanced airglow on 630 nm; some enhancement on 557.7 nm is also observed.

No attempt will be made here to present a complete account of either the observations or of the theoretical developments in this still very active field. An attempt will be made instead to first outline the essential physical phenomena which must occur according to theory in the ionosphere in the presence of a strong radio wave. The main results of observations will then be described, commenting in each case on the physical processes of which each particular type of observation is thought to be a manifestation. Such an account is certainly not historical; most of the observations were not predicted theoretically and were not even understood theoretically for a long time after the observations. There was a strong interplay between observation and theory. Much of the theory was inspired by the observations and at least some of the observations were inspired by theory.

Since this presentation is therefore essentially non-historical, the history of the observations is briefly outlined here. The first 'heating' experiments were performed at Boulder, Colorado by W. F. Utlaut and his colleagues in 1970, following some preliminary theoretical work predicting the modification of ionospheric electron temperatures and densities and of the 630 nm airglow (Utlaut 1970, and companion papers). In addition to the observation of some of the predicted and some unpredicted airglow phenomena, the most striking (and unexpected) first result was the observation of strong artificial spread F. This latter result inspired a large number of scatter experiments at h.f., v.h.f. and u.h.f. by Fialer, Minkoff and their colleagues, starting in late 1970, using the Boulder transmissions. Moreover, plasma physicists, particularly F. W. Perkins, suggested on theoretical grounds that scatter might occur not only near the u.h.f. frequency of the incident wave, but also at a frequency shifted up or down from the u.h.f. frequency very nearly by the frequency of the h.f. 'heating transmitter'. This prediction was soon verified experimentally by H. C. Carlson and W. F. Gordon at Arecibo in 1971 by placing at the focus of their big reflector, serving their u.h.f. radar, a source of h.f. power which was capable of producing only slightly lower h.f. power densities incident on the F region over Arecibo than those produced over Boulder. Backscattered waves shifted up and down from the u.h.f. frequency by about the h.f. frequency were immediately observed. The waves were much stronger than those due to scattering by plasma waves excited by photoelectrons. The spectrum of the scattered waves was complex and prompted a great deal of work in theoretical plasma physics in 1971–2. More recently some theoretical understanding of the phenomena of artificial spread F, of field alined scatter and of airglow enhancement has also been obtained.

The purpose of the above brief historical account is to illustrate how a great deal of team work involving a group of experimenters and theoreticians frequently meeting and talking to each other has led to the present understanding of the very great variety of phenomena produced by high power ionospherically reflected h.f. transmissions. It should be emphasized that it is hoped that the history is not at its end. Much more experimental and theoretical work is needed before a full understanding of all the phenomena is achieved.

2. Decay instabilities

The most important mechanism that occurs in the presence of an intense high frequency electromagnetic wave (which we shall call a pump wave) in the ionosphere is the transfer of energy to another high frequency (electromagnetic or electrostatic) wave of nearly the same frequency and a low frequency (usually ion acoustic) wave. This mechanism becomes possible as a result of two effects.

The first is the existence of a nonlinear force acting on an electron which oscillates simultaneously in the fields of two high frequency waves (Bovt & Karvie 1957). In the absence of an external magnetic field this force $\boldsymbol{F}$, often called the pondermotive force, is given by

$$\boldsymbol{F} = (-e^2/2m\,\omega^2)\,\nabla\langle E^2\rangle,$$

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

where e is the charge, m is the mass of an electron, ω is the angular frequency and $\langle E^2 \rangle$ is the average over an oscillation period of the square of the electric field. The gradients in $\langle E^2 \rangle$ are those that characterize the interference field of the two high frequency waves.

Such a force is wave-like with a relatively low frequency $\omega_1 - \omega_2$ and wavevector $\mathbf{k}_1 - \mathbf{k}_2$ where $\omega_1, \mathbf{k}_1$ and $\omega_2, \mathbf{k}_2$ are the frequencies and wavevectors of the two high frequency waves. The force gives rise to a wave-like perturbation in plasma density characterized by $\omega_1 - \omega_2$, $\mathbf{k}_1 - \mathbf{k}_2$ whose magnitude is proportional to the product $E_1 E_2$. The density perturbation is larger if $\omega_1 - \omega_2$, $\mathbf{k}_1 - \mathbf{k}_2$ approximately satisfy the low frequency dispersion relation.

In the discussion of the second effect it will be helpful to imagine that the second of the two high frequency waves is much weaker than the first one and thus the density perturbations at the beat frequency are weak ones. It is well known that such weak density perturbations characterized by $\omega_1 - \omega_2$, $\mathbf{k}_1 - \mathbf{k}_2$ can scatter the strong wave at $\omega_1, \mathbf{k}_1$ to give rise to a weak wave at $\omega_1 - (\omega_1 - \omega_2) = \omega_2$ and $\mathbf{k}_1 - (\mathbf{k}_1 - \mathbf{k}_2) = \mathbf{k}_2$ whose amplitude is proportional to the product of amplitude of the low frequency wave which was seen to be proportional to $E_1 E_2$ and to the amplitude E_1, i.e. it may be written as $CE_1{}^2E_2$, where C is a constant of proportionality. If E_1 is large enough then $CE_1{}^2E_2$ could, in fact, be equal to E_2, i.e. the weak high frequency wave E_2 and the weak low frequency beat wave could be self-consistent in the presence of the strong high frequency wave (we ignored phase relations which must also be fulfilled for self-consistency). If E_1 is still greater than this threshold value, the second high frequency wave and the wave at the low beat frequency will grow simultaneously to large amplitudes out of the noise. In this case we have a so-called parametric instability (DuBois & Goldman 1965). The new wave E_2, can eventually grow to large enough amplitudes to itself decay into a third wave E_3 and another low frequency wave characterized by $\omega_2 - \omega_3$, $\mathbf{k}_2 - \mathbf{k}_3$ and so on until a so-called saturation spectrum is established by such a cascading decay process. When these calculations are actually carried out then it is seen that $\omega_1 > \omega_2 > \omega_3$. In terms of quanti the quantum of energy $h\nu_1$ decays into quanti with energies $h\nu_2$ and $h|\nu_1 - \nu_2|$ where conservation of energy demands that $h\nu_1 = h\nu_2 + h|\nu_1 - \nu_2|$ which is only possible if $\nu_1 > \nu_2$.

It was mentioned that the growing new high frequency wave could be electrostatic or electromagnetic. The Earth's magnetic field causes double refraction and both these processes are only possible if the pump wave has ordinary polarization. If the pump wave has extraordinary polarization then there are no electrostatic modes into which it can decay. Crudely speaking the reason is that electrostatic waves of interest propagate at frequencies somewhat but not very much higher than the plasma frequency, but the extraordinary wave is reflected at a height where its frequency is still very much higher than the local plasma frequency (whereas the ordinary wave is reflected where its frequency is equal to the local plasma frequency).

The important physical processes are thus: (*a*) a decay into other electromagnetic and electrostatic high frequency waves and corresponding low frequency waves in the case of the ordinary pump wave, and (*b*) a decay into other electromagnetic high frequency waves and corresponding low frequency waves in the case of a wave of extraordinary polarization.

It should be stressed that these instabilities occur only when the electric field of the pump wave exceeds a critical level. In the present experiment this occurs only when the pump wave is reflected in the ionosphere and therefore greatly enhanced electric fields exist near the height of reflexion.

Before turning to the results of observations, one more physical process should be pointed out. It was mentioned that in the presence of two high frequency waves a so-called ponderomotive force acts on an electron. If the beat wave has a very low frequency and long wavelength, then collisional dissipation in the interference field of the two high frequency waves gives rise to pressure gradients caused by gradients of electron temperature at the beat frequency $\omega_1 - \omega_2$ and wavevector $\boldsymbol{k}_1 - \boldsymbol{k}_2$. The force acting on an electron due to these pressure gradients exceeds the ponderomotive force when the wavelength $2\pi|\boldsymbol{k}_1 - \boldsymbol{k}_2|^{-1}$ is longer than the electron mean free path. Physically this domination of the 'thermal' over the ponderomotive force is due to the ineffectiveness of heat conduction caused by the long wavelength $2\pi|\boldsymbol{k}_1 - \boldsymbol{k}_2|^{-1}$. In the presence of the Earth's magnetic field heat conduction across the field lines is in any case poor and therefore the force due to differential heating by collisional dissipation predominates over the ponderomotive force if the wavelength measured along a field line $2\pi|(\boldsymbol{k}_1 - \boldsymbol{k}_2)_\parallel|^{-1}$ is much longer than electron mean free path. This means that parametric instabilities in which the low frequency wavevector is perpendicular to the magnetic field are strongly favoured and hence field alined very low frequency irregularities are favoured.

3. Artificial spread F, wide band attenuation and Z echoes

The transition from sharp echoes to diffuse spread echoes begins to appear on the ionogram records within seconds after turning on the pump transmitter (Utlaut & Violette 1974) as illustrated by figure 1, plate 7. The spread echoes persist 10–20 min after a prolonged heating period. It is believed (Perkins & Valeo 1974; Cragin & Fejer 1974) that spread F is at least partly caused by a decay process into an electromagnetic mode and a low frequency mode of a special type in which both the pump wave and the excited high frequency wave are standing waves and the low frequency wave has in fact zero frequency. Field alined irregularities with wavelengths greater than about 100 m across the field can be produced according to theory in this manner. This instability is sometimes called a focusing instability. Spread F is produced by using a pump of either magnetoionic polarization.

Spread F irregularities have also been studied in some beautiful observations using satellite transmissions from 1 to 400 MHz by Bowhill (1974) who verified the field alined nature of the irregularities and who found that the most prominent field alined structures have perpendicular wavelengths of 100–500 m with some wider structure also present, thus confirming the predictions of theory. The persistence of spread F may be understood when it is realized that the irregularities have in a sense been produced by different collisional heating of different field lines and that heat conduction across the field lines is very ineffective in removing the temperature differences.

Wide band attentuation is illustrated by figure 2, plate 8, where the spread ordinary echo trace only extends up to the pump frequency but not beyond, while the pump transmitter using ordinary polarization is on. When the transmitter is switched off, the ordinary trace extends to higher frequencies within seconds. This effect is not seen or at least is not seen nearly as definitely when the pump transmitter has extraordinary polarization. Clearly some of the spread F irregularities scatter the incident wave into other waves which are not seen on the ionogram. In the case of the ordinary mode we have seen that decay into both unstable electromagnetic and unstable electrostatic high frequency modes and their associated low frequency modes is possible. It was at first thought that the low frequency modes associated with electrostatic high frequency modes may scatter the incident wave into Langmuir waves but the time constant for that mechanism is much shorter than the observed ones. According to Allen, Meltz, Rao & Thome (1974) the scattering by the low frequency modes associated with electromagnetic high

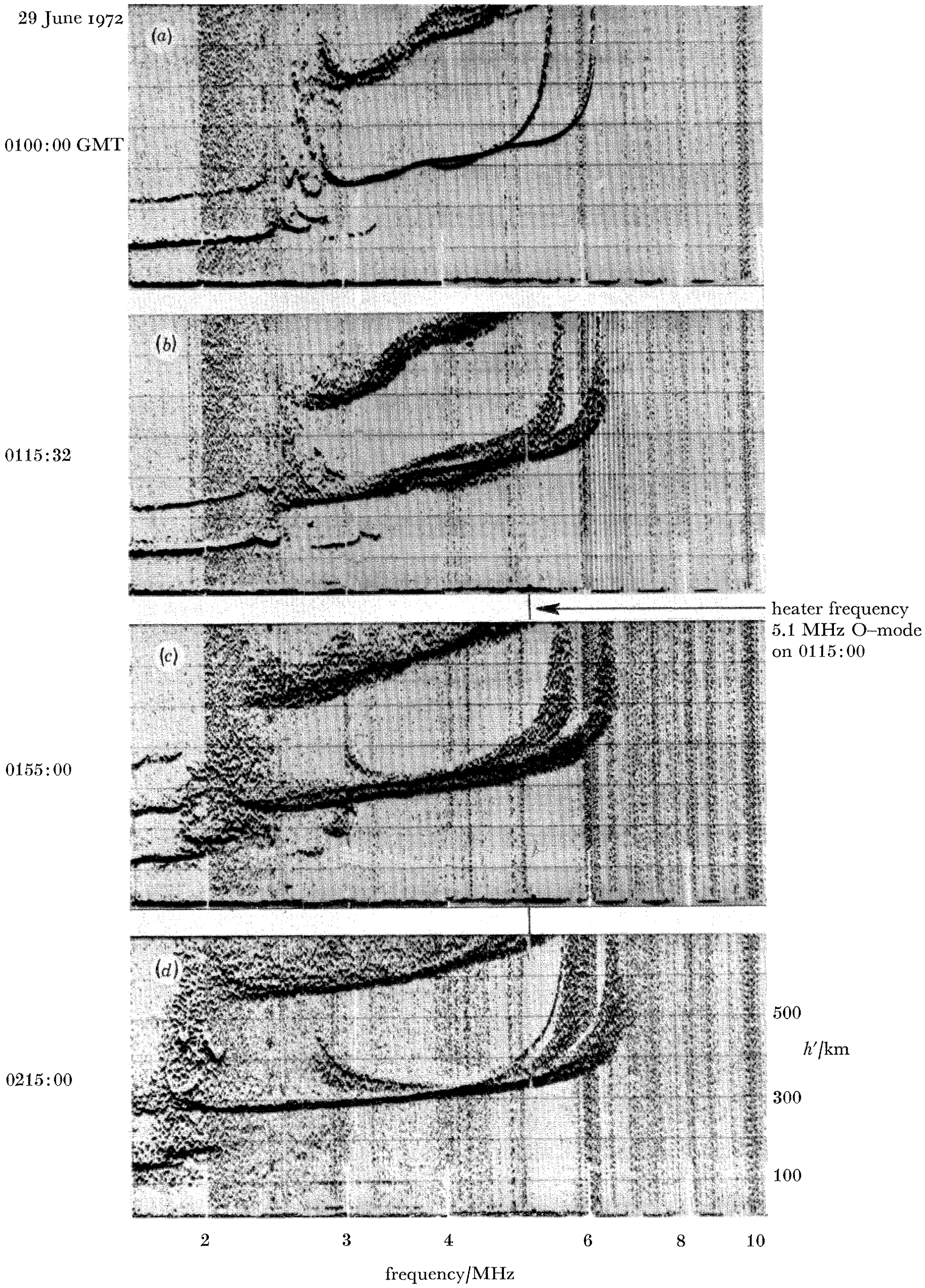


FIGURE 1. Ionograms showing (the distance travelled by light during) the bounce time of an echo as a function of the (swept) ionosonde frequency. Note the spread nature of the echo, and the presence of additional (so-called 1F2 and on the bottom ionogram Z) traces after the heating transmitter has been switched on. (From Utlaut & Violette 1974.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

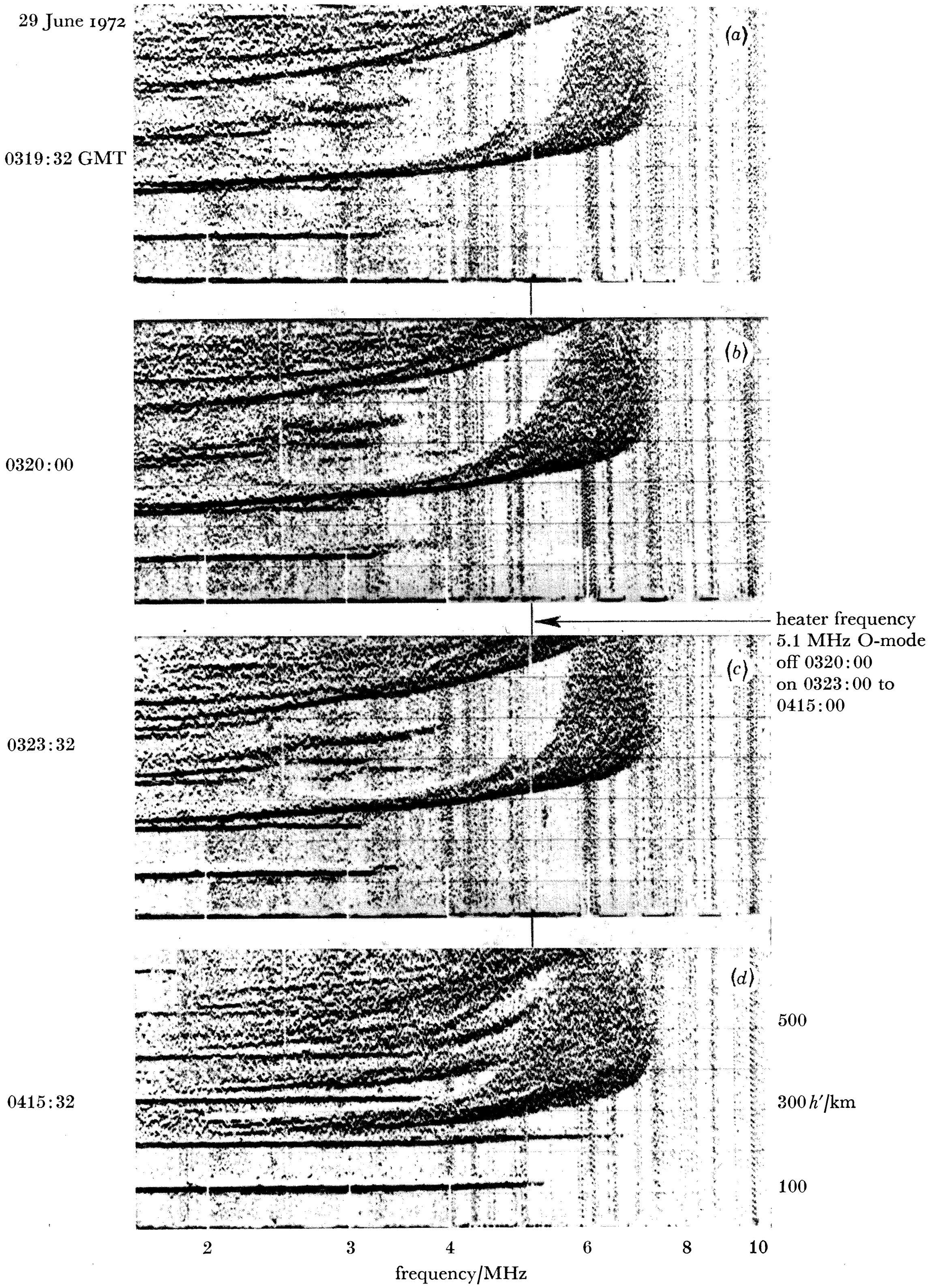


FIGURE 2. Ionograms illustrating 'wide band attenuation'. The spread ordinary echo trace does not extend above the heater frequency when the heating transmitter is on. (From Utlaut & Violette 1974.)

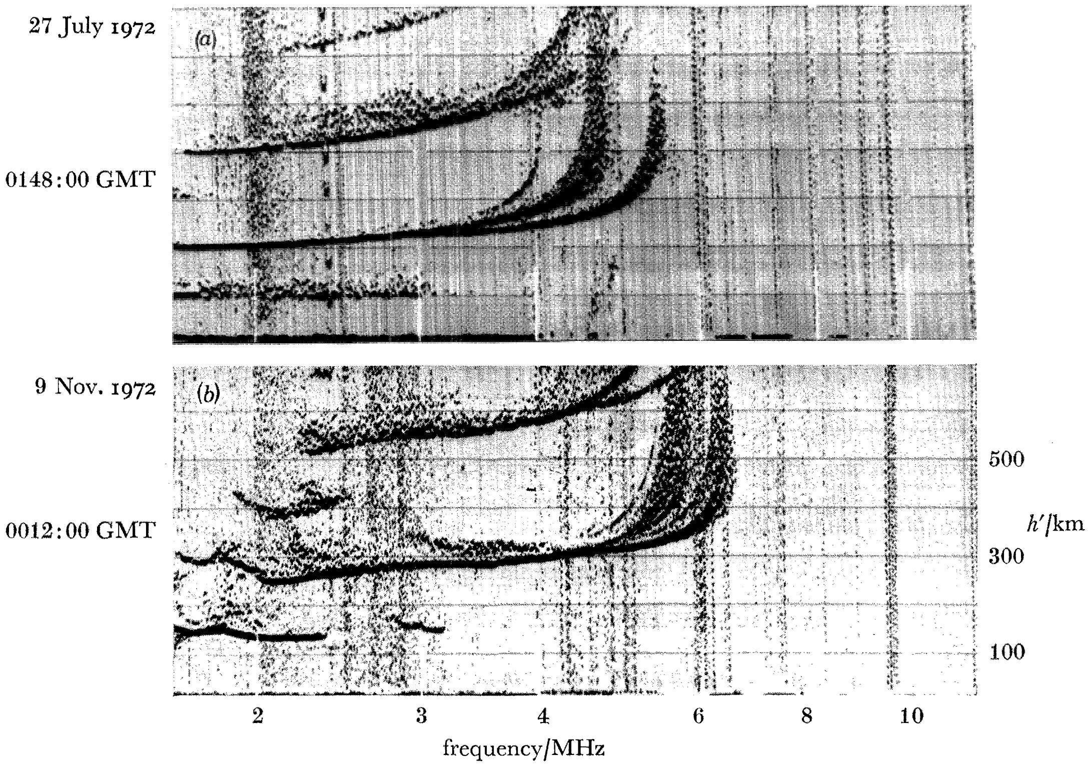


FIGURE 3. Ionograms illustrating weak so-called Z traces that do not show a spread and have a longer bounce time than the spread ordinary and extraordinary traces. (From Utlaut & Violette 1974.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

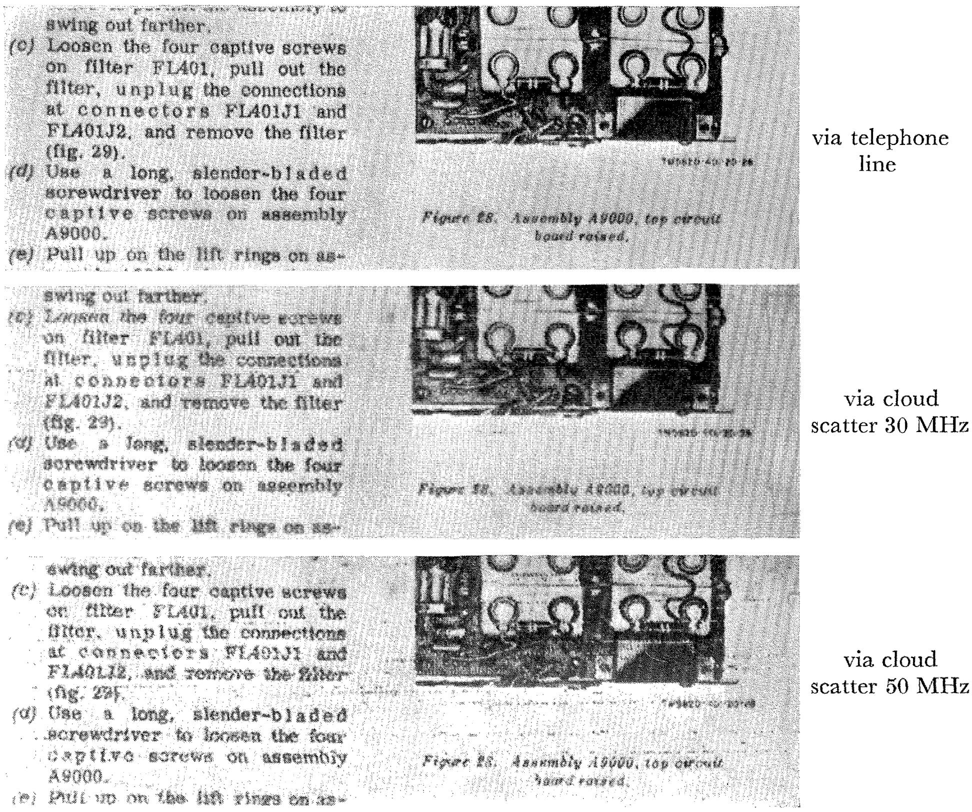


FIGURE 11. Facsimile transmitted via scatter by field alined irregularities produced artificially over Boulder. (From Barry 1974.)

frequency modes scatter the incident ordinary wave into ordinary waves going in a different direction. According to Allen *et al.* this mechanism is only effective if the incident wave has ordinary polarization. There is the further possibility of scattering into waves in the extraordinary mode (Z mode) which may never return to the ground. Wide band attentuation is not always observed (Utlaut & Violette 1974) and is not yet fully understood theoretically at present; the attenuation is almost certainly caused by scattering into other high frequency waves by some of the parametrically excited low frequency modes.

A third interesting effect seen on ionograms is the appearance of a Z trace, usually at night (Utlaut & Violette 1974; figure 3, plate 9), shows a typical ionogram where the Z trace is caused by heating; it is not spread and this is also typical of natural Z echoes. Such an echo must result from coupling from the ordinary into the Z mode on the way up and vice versa on the way down. Coupling is made possible by the density gradients due to parametrically excited low or zero frequency irregularities which also cause spread F; the effect has not yet been investigated theoretically.

Ionograms also show a modification of the ionospheric electron densities (Utlaut & Violette 1974). Incoherent scatter measurements show that the ionospheric electron temperatures are modified (Gordon & Carlson 1974). These large scale distortions of the F region by heating are discussed by Meltz, Holway & Tomlijanovich (1974).

4. Plasma line enhancement

We have seen that an electromagnetic wave of the ordinary magnetoionic mode can decay into a high frequency electrostatic wave or Langmuir wave and into an ion sound wave. Some of the electrostatic waves are excited by the pump in the F region above Arecibo at half the 430 MHz radar wavelength and these waves produce backscatter at frequencies which are shifted up and down by slightly less than the pump frequency. Figure 4 (Gordon & Carlson 1974) shows some Langmuir wave frequency spectra seen at Arecibo. The downward marked lines on the horizontal frequency axis represent 430 ± 8.195 MHz where 430 MHz is the u.h.f. radar frequency and 8.195 the h.f. pump frequency. The distance between the upward marked lines is 5 kHz. These effects are only seen when the 8.195 MHz transmitter has ordinary polarization.

Theories (Fejer & Kuo 1973*a*, *b*; Perkins, Oberman & Valeo 1974, and references therein) of the saturated decay instability show that the unstable waves produced have wavevectors forming angles less than about 20° with the geomagnetic field and the Arecibo radar detects wavevectors at 45°. According to theory the waves seen at Arecibo are due to scattering of the pump wave and of the unstable Langmuir waves by thermal ion acoustic waves into Langmuir waves propagating at an angle of 45°. A typical theoretically calculated spectrum is shown by figure 5. The corresponding spectrum at angles of 20° and less which shows the cascading processes discussed earlier is shown by figure 6 and has about 10^4–10^5 times as much total spectral power; the corresponding experimental spectra have not yet been obtained in spite of two attempts to obtain them.

There are manifestations of scattering with other frequency shifts near the gyrofrequency (Dias & Gordon 1973), but these are not discussed here. It should also be mentioned that backscattering by ion acoustic waves with small Doppler shifts of a few kilohertz has also been seen (Hagfors & Zamlutti 1973), but again much stronger effects should be seen when the radar beam is pointed in the direction along the geomagnetic field rather than at an angle of 45°.

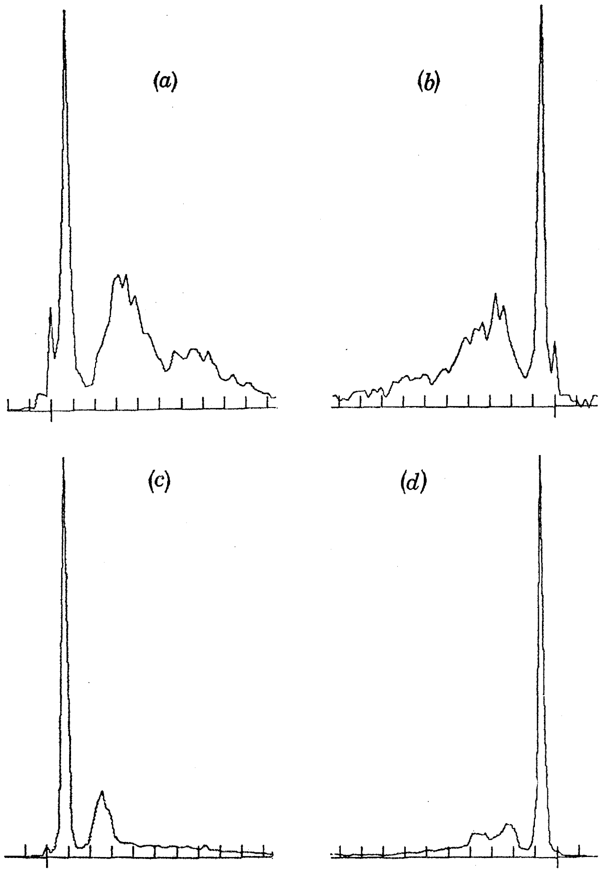


FIGURE 4. Langmuir wave (plasma line) spectra observed at Arecibo. The downward marked lines on the horizontal frequency axis represent 430 ± 8.195 MHz where the + sign applies to (*b*) and (*d*), the − sign to (*a*) and (*c*). The distance between the upward marked lines is 5 kHz. (From Gordon & Carlson 1974.)

5. Field alined scatter (f.a.s.) and plasma line scatter (p.l.s.)

Perhaps the greatest experimental effort has gone into the study of scatter paths for which the scattering wavevector $\boldsymbol{k}_s - \boldsymbol{k}_i$ ($\boldsymbol{k}_i$ and $\boldsymbol{k}_s$ are the wavevectors of the incident and scattered waves respectively) is perpendicular to the magnetic field for one of the field lines which passes through the F2 reflexion region illuminated by the h.f. transmitter, an area of about 100×100 km. The 'radar cross section' for this type of scattering can be extremely high, particularly at h.f. and v.h.f. as shown by figure 7 which summarizes the results of experiments. The scattering is only observed for ordinary polarization of the pump wave and is highly aspect sensitive; no upper limit on the length of the striations along the field line can be obtained due to insufficient angular resolution of the measurements but some of the striations are certainly longer than 200 m with the dimensions across the field lines of only a few metres. The observations are described in great detail by Fialer (1974) in the 10–200 MHz range on both backscatter and forward scatter paths, and by Minkoff, Kugelman & Weissman (1974) at the v.h.f. frequencies of 157.5 MHz and u.h.f. of 435 MHz, with radars of the White Sands Missile Range. The latter are particularly interesting because both returns near the original radar frequency (f.a.s.) and near frequencies up and down shifted by the pump frequency (p.l.s., plasma line scatter) were observed; only the former indicated field-alined structure. Both f.a.s. and p.l.s. signals were narrow band, of the order of 10 Hz wide.

Figure 8 shows that the locus of points of maximum scattering from the f.a.s. signals is the perpendicularity contour for the geometry of the scatter path, thus indicating field-alined structure, but that for the p.l.s. signals the locus is the region where the pump wave is reflected. Neither of these two scattered signals are fully understood theoretically. The f.a.s. signal has recently been tentatively explained by Perkins (1974) as being due to an instability in which the saturation spectrum of plasma waves acts as a pump and causes the growth of field-alined striations. In a sense this instability could also be called a focusing instability in which focusing of the waves of the parametric saturation spectrum occurs. Further theoretical work on this problem would be desirable.

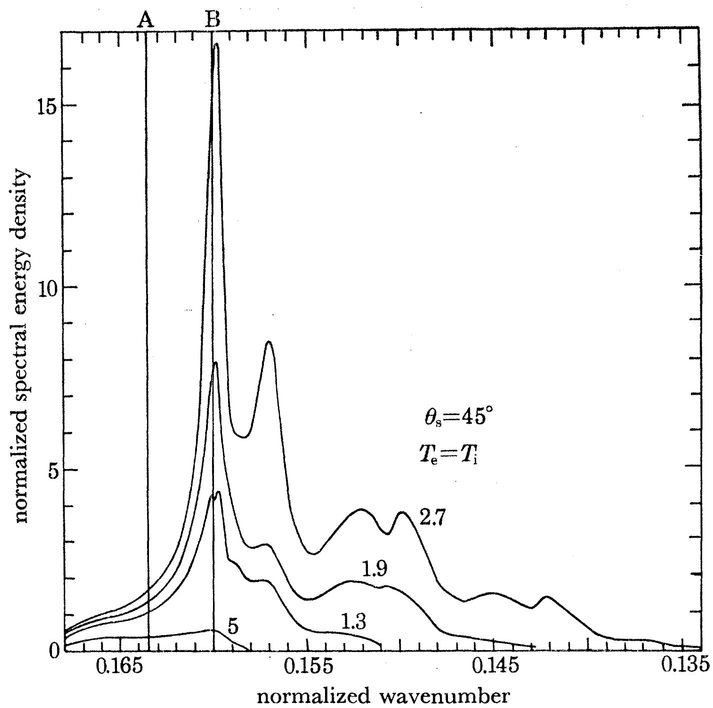


FIGURE 5. Computed theoretical plasma wave backscatter spectra for an angle of 45° between the radar beam and the geomagnetic field. The wavenumber of those Langmuir waves whose frequency is equal to the pump frequency is marked by A, the wavenumber of those Langmuir waves of slightly lower frequency which first become unstable at threshold, is marked by B. The labels of the curves indicate the ratio of the actual pump power to the threshold power. (From Fejer & Kuo 1973*b*.)

The mechanism leading to the p.l.s. signal is less well understood. The pump wave has a component perpendicular to the magnetic field and thus could be scattered by the intense f.a.s. irregularities into Langmuir waves with $\boldsymbol{k}$ vectors nearly perpendicular to the field; this would explain the narrow spectrum. The plasma waves can then propagate away and change their $\boldsymbol{k}$ vector and this could explain why the scatter is not exactly field alined. Thus the physical mechanism by which the p.l.s. signal is produced is similar to the one leading to the Arecibo plasma line signals except that the low frequency scatterers are not thermal ion-acoustic waves but the much more intense f.a.s. irregularities. It is interesting that the f.a.s. and p.l.s. signals are of comparable radar cross section at u.h.f. (435 MHz) but the f.a.s. signal is 25 dB stronger at v.h.f. (157.5 MHz). This would be explained by the much longer wavelength of the plasma waves of interest at v.h.f. and therefore the much narrower height range (closer to the reflexion height) in which they occur. In addition, the component of the pump electric field normal to the magnetic field is much weaker closer to the reflexion height for the ordinary wave.

It should be stressed that the observed p.l.s. radar cross section at u.h.f. is one or two orders of magnitude greater than the scattering cross section predicted theoretically for backscattering by parametrically excited electrostatic plasma waves propagating nearly along the magnetic field (Fejer & Kuo 1973*a*). The latter cross section is still another 4–5 orders of magnitude greater than the typical radar cross sections of the 'plasma line' signals observed at Arecibo. Indeed it seems that a considerably more 'sensitive' u.h.f. radar is needed to observe backscatter

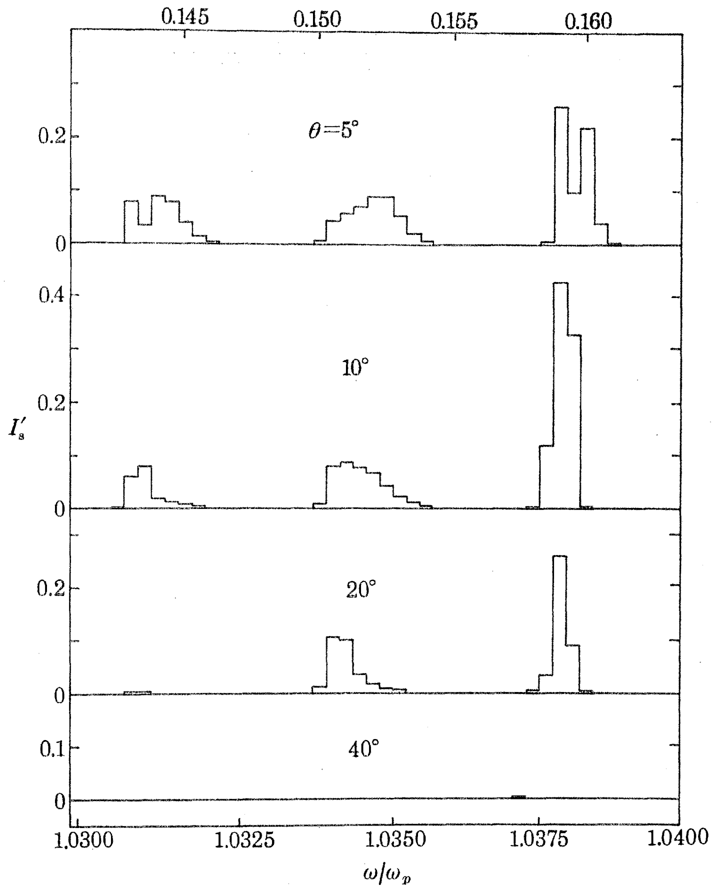


FIGURE 6. Theoretical angular and frequency (wavenumber) distribution of spectral power for parametrically excited Langmuir waves. The pump power is 2.7 times the threshold power. The quantity I_s' is the ratio of the energy density in each wavenumber range to the threshold energy density of the pump wave. It should be noted that the total electric energy density in the Langmuir waves is greater than the energy density of the pump wave and vastly greater than the energy density of the Langmuir waves propagating at large angles and shown in figure 5. (From Fejer & Kuo 1973*b*.)

from parametrically excited electrostatic plasma waves then the radars that are adequate to detect the p.l.s. signals; this probably explains the failures of two previous attempts to detect the parametrically excited electrostatic plasma waves propagating in directions nearly parallel to the Earth's magnetic field. Presumably the observers expected that scattering by these theoretically predicted electrostatic plasma waves should be at least as intense as the p.l.s. signals which were not theoretically understood at that time; in fact, they should be much weaker.

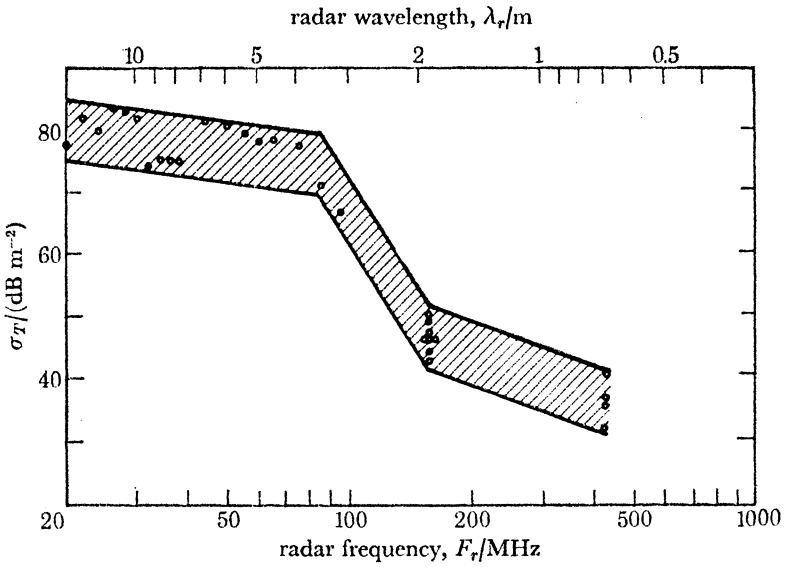


FIGURE 7. Measured radar cross section as a function of the radar frequency for field alined scatter (f.a.s.). (From P. B. Rao & G. D. Thome 1974 *Radio Sci.* 9, p. 987.)

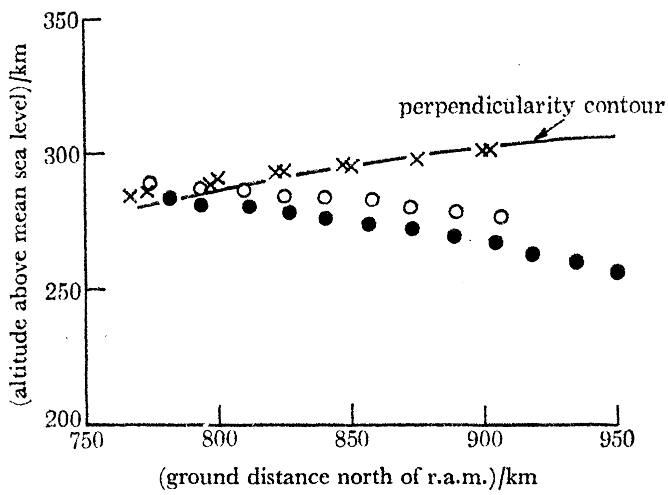


FIGURE 8. Location of scatterers for f.a.s. (centre line scatter) and p.l.s. (plasma line scatter) as determined by the r.a.m. radar looking from White Sands at the heated region above Boulder. (From Minkoff *et al.* 1974.) ●, Lower plasma line; ○, upper plasma line; ×, centre line (455 MHz).

It should be mentioned that it takes times of the order of a minute or more for the f.a.s. signals to reach their full strength but that after short interruptions of the transmissions the full strength is reached in about a second. It would seem that some of the large scale irregularities responsible for spread F which take longer times to develop, cause focusing and the production of 'hot spots', thereby greatly enhancing f.a.s. The irregularities responsible for the hot spots do not disappear during short interruptions of the signal.

An interesting effect associated with the f.a.s. signals is their behaviour when the pump frequency is slightly above the vertical penetration frequency of the F2 layer. Figure 9 shows the strength of the f.a.s. radar return as a function of range and azimuth angle (time); the hole in

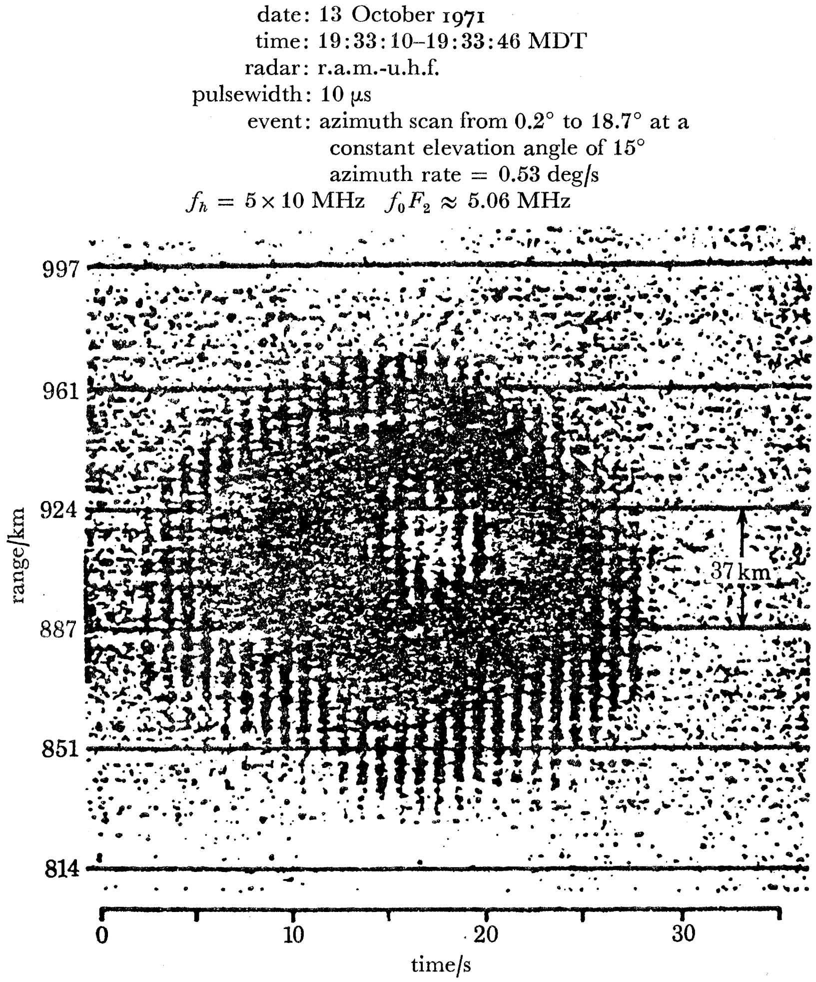


FIGURE 9. Strength of radar return as a function of range and azimuth angle for a constant elevation angle. (From Minkoff *et al.* 1974.)

the middle, i.e. the lack of f.a.s. there, is believed to be caused by the penetration of the pump wave at vertical incidence while it is still reflected at oblique incidence. The observed position of the 'hole' was almost exactly above the transmitter.

6. Communication circuits using field alined scatter

In view of the field alined nature of the scatter, an ionospheric scattering 'point' would cause transmissions from one point on the ground to be received along a curve which is the intersection of a scattering cone with the Earth's surface. In fact, we have a scattering area illuminated by the high power transmitter near Boulder and thus reception is possible over a relatively narrow curved strip. Two transmitting sites in Texas and two receiving sites in California were used as illustrated in figure 10 to test the use of field alined scatter for communication purposes (Barry 1974). Also shown by figure 10 are curves on the Earth from which a ray reaches the scattering area at a certain angle with respect to the magnetic field; this angle minus 90° is the one labelling the curves. For effective scattering the transmitter and the receiver should lie approximately on the same curve. By using 1 kW transmitted power and 19 dB antenna gain on both transmission and reception and conventional modulation techniques, single side band voice (3 kHz bandwidth) communication was perfectly intelligible. Successful teletype and facsimile transmission was also achieved. An example of transmitted facsimile is shown by figure 11, plate 10.

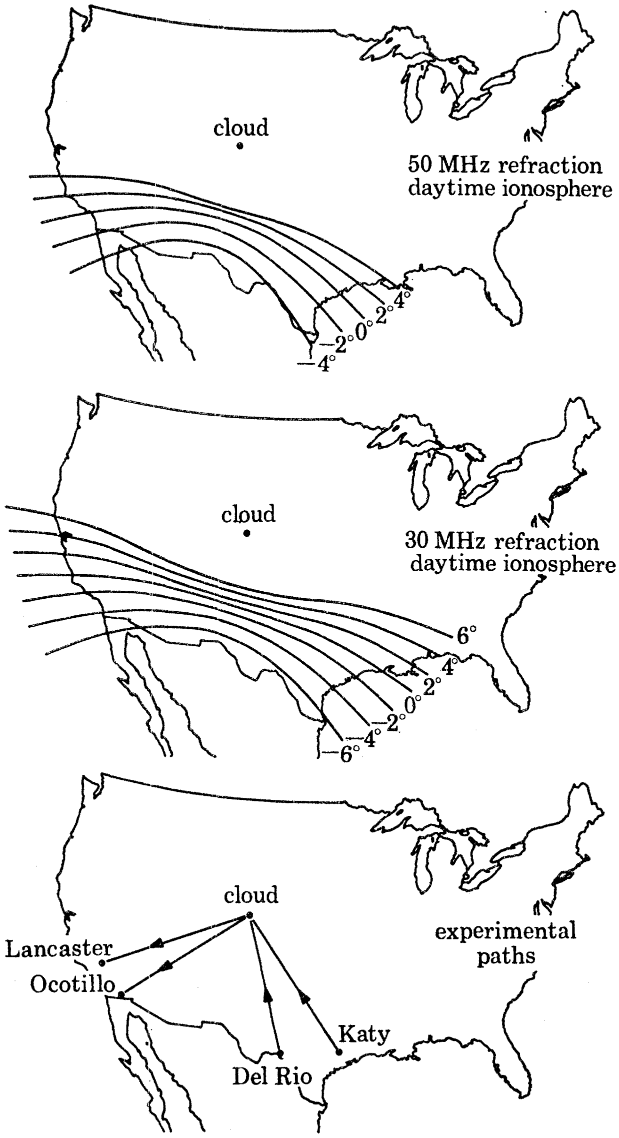


Figure 10. The transmitting and receiving sites for a communication link are shown by the bottom figure. The top two figures indicate curves on the earth from which a ray reaches the scattering region (cloud) at a certain angle with respect to the geomagnetic field. (From Barry 1974.)

7. Airglow

A modification of the natural 630 nm airglow (which occurs in the course of the recombination process) emitted by oxygen atoms in the O(^{1}D) state was predicted by Biondi, Sipler & Hake (1970) before the observations. The predictions which only took an increase in electron temperature caused by heating into account and assumed a Maxwellian velocity distribution, were

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

confirmed by observations (Biondi *et al.* 1970) in which extraordinary polarization of the 'heating' transmitter was used. The predicted effect was a slight temporary decrease in airglow for a few minutes after switching on the heating transmitter; a similar increase follows switching off. The results of one of the observations are shown by figure 12.

When ordinary polarization of the heating transmitter is used, the observed effects are shown by figure 13 during a particular night. Enhancements of the 630 nm airglow by 20–30 Rayleigh

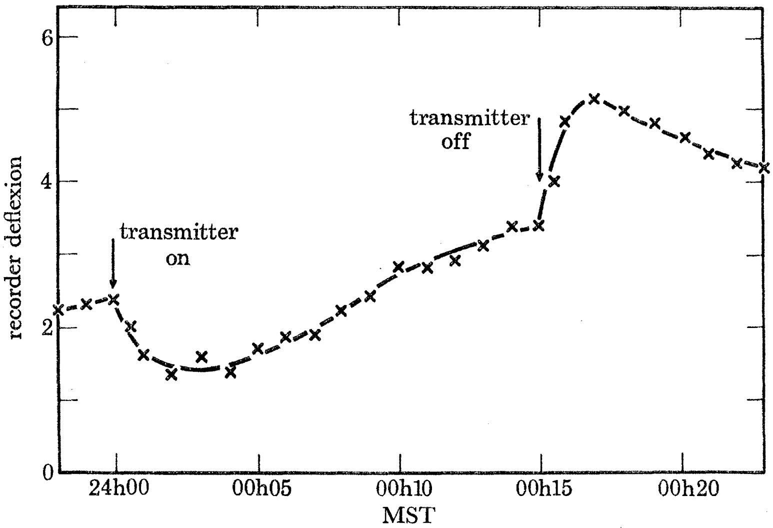


FIGURE 12. Changes in the 630 nm airglow produced by heating transmissions in the extraordinary mode. Courtesy of Haslett & Megill 1974.

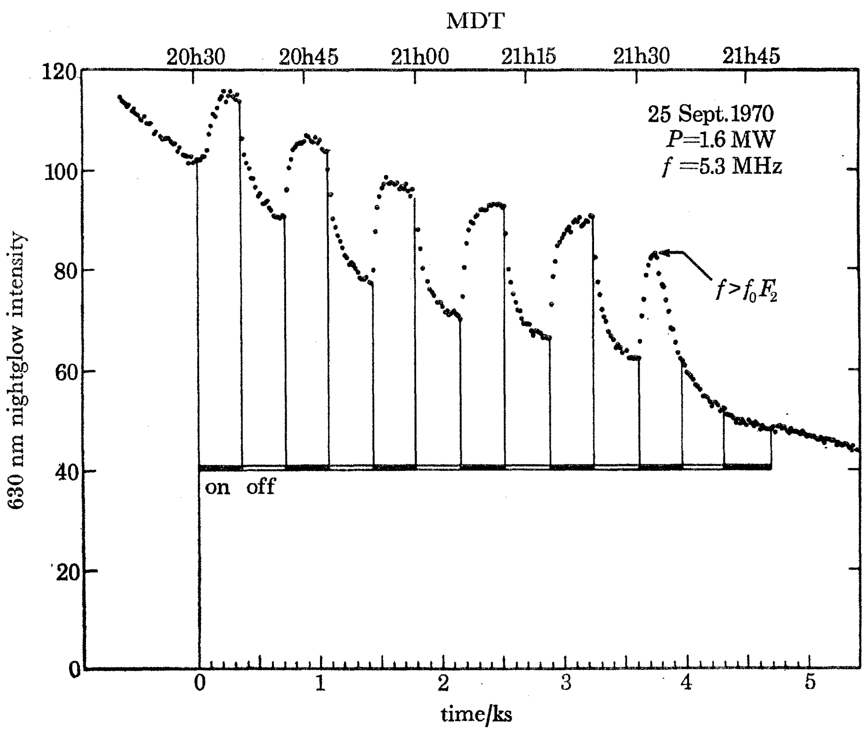


FIGURE 13. Changes in the 630 nm airglow produced by heating transmission in the ordinary mode. (From Sipler & Biondi, *J. geophys. Res.* **77**, 6202.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

are observed during the periods of h.f. transmission and such enhancements must be due to collisional excitation of the O(^{1}D) state by electrons having energies greater than 2 eV. A comparison of the airglow enhancements on 630 nm and 557.7 nm shows that the electrons do not have Maxwellian distribution and that somehow energetic electrons are produced by the parametrically excited plasma waves. Fejer & Graham (1974) showed by some crude calculations that electrons from the tail of the Maxwell distribution encountering the parametrically excited electrostatic plasma waves, whose phase velocity is slightly greater than the velocity of the tail electrons, can easily be accelerated to energies in excess of 2 eV. A single encounter is sufficient for this purpose. The mechanism is simply the failure of the electron to climb the potential barrier of the electrostatic wave and the consequent reversal in sign of the relative velocity of the electron with respect to the wave. The simple mechanism appears to adequately account for the observations.

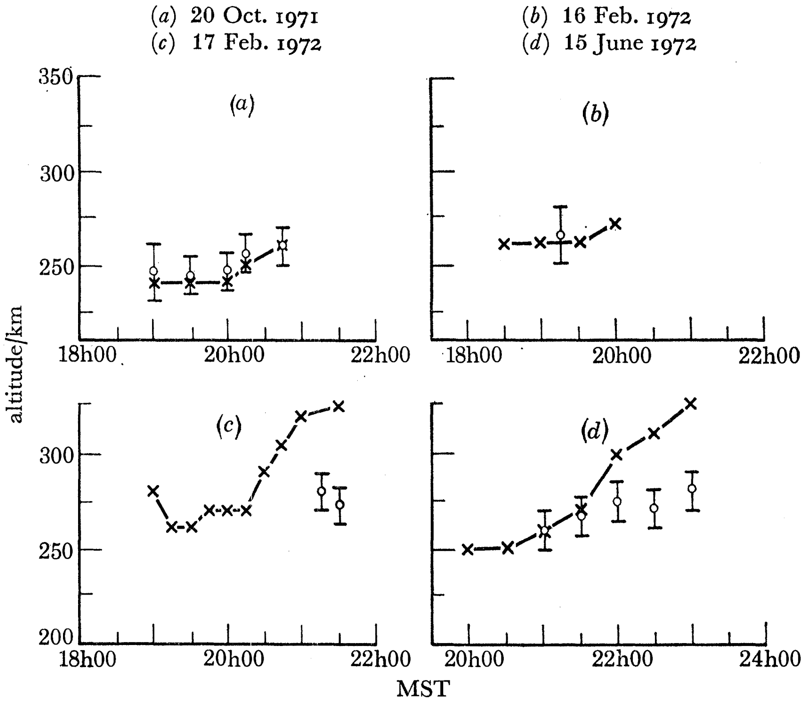


FIGURE 14. Altitude of reflexion (×) and altitude of the airglow ($\mathrm{\bar{\underset{\circ}{\dot{}}}}$) during different nights over Boulder, Colorado. (From Haslett & Megill 1974.)

Triangulation measurements show that the 650 nm airglow is always produced at a height of about 270 km, independently of the height of reflexion of the pump wave which may be considerably greater as shown by figure 14. The energetic electrons are believed to be produced in an interaction region slightly below the reflexion height of the pump wave. The airglow may be produced considerably below that height in the region where there are enough oxygen atoms to which the electrons can give up their energy as shown by figure 15. Haslett & Megill (1974) estimate that typically about 1 % of the incident radio wave power is converted into energetic electrons. The mechanism of Fejer & Graham has no difficulty to explain this conversion. Acceleration caused by diffusion in the fields of the Langmuir waves responsible for p.l.s. scatter could provide an alternate (but less likely) mechanism.

On one occasion airglow enhancement by 260 Rayleigh was observed; the enhancement was therefore much greater than the natural airglow itself. On this occasion the frequency of the transmitter was approximately twice the gyrofrequency at the interaction height. It could well be that the acceleration on this occasion was due to so-called Bernstein modes which propagate nearly perpendicularly to the magnetic field. No precise theoretical explanation exists at present.

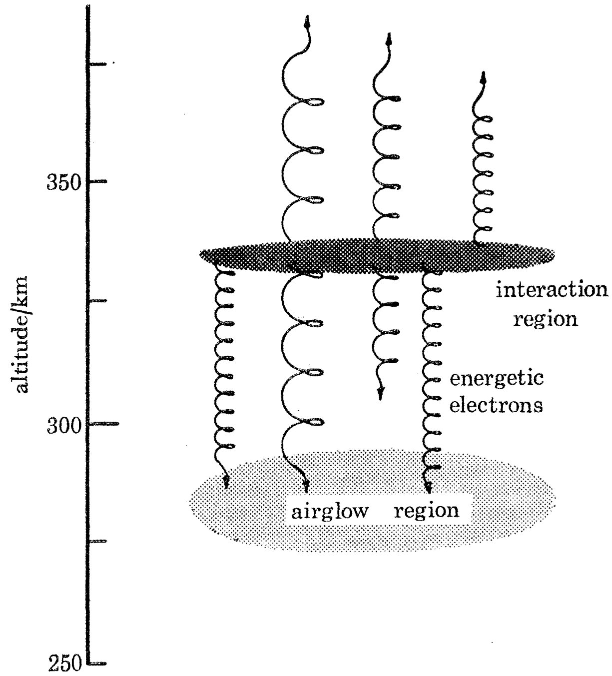


FIGURE 15. Illustration of energetic electron production in the interaction region which is several kilometres thick (and is just below the reflexion height). The accelerated electrons usually produce airglow at somewhat lower heights. (From Haslett & Megill 1974.)

8. CONCLUSIONS

The present very brief review should indicate the large variety of observed phenomena during high power ionospherically reflected HF transmissions. Many of these phenomena are still poorly understood in spite of the considerable theoretical advances that have been made. In addition, not all the predictions of the theory have been experimentally verified. There is thus need for more theoretical and observational work in order to gain a better understanding of the fascinating subject of ionospheric modification by high power radio wave transmissions.

This research was supported by National Aeronautics and Space Administration Grant NGR-05-009-076 and the National Science Foundation Grant GA-30628. The author is indebted to numerous experimenters and theoreticians for very useful conversations and for permission to use their figures.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

References (Fejer)

Allen, E. M., Meltz, G., Rao, P. B. & Thome, G. D. 1974 Angular distribution of scattering associated with artificial spread-F and wideband attenuation. URSI Annual Meeting, 14–17 October 1974 at Boulder, Colorado.

Barry, G. H. 1974 HF-VHF communications experiment using man-made field-aligned ionospheric scatterers, *Radio Sci.* **9**, 1025–1032.

Biondi, A. A., Sipler, D. P. & Hake, R. D., Jr 1970 Optical (6300) detection of radio frequency heating of electrons in the F region. *J. geophys. Res.* **75**, 6421–6424.

Bovt, H. & Karvie, R. 1957 Charged particles in a non-uniform radio frequency field. *Nature, Lond.* **180**, 1187.

Bowhill, S. A. 1974 Satellite transmission studies of spread-F produced by artificial heating of the ionosphere. *Radio Sci.* **9**, 975–986.

Cragin, Bruce L. & Fejer, J. A. 1974 Generation of large-scale field-aligned irregularities in ionospheric modification experiments. *Radio Sci.* **9**, 1071–1075.

Dias, L. A. & Gordon, W. E. 1973 The observation of electron cyclotron lines enhanced by HF radio waves. *J. geophys. Res.* **78**, 1730–1732.

DuBois, D. F. & Goldman, M. V. 1965 Radiation-induced instability of electron plasma oscillations. *Phys. Rev. Lett.* **14**, 544–546.

Fejer, J. A. & Kuo, Y.-Y. 1973*a* Structure in the non-linear saturation spectrum of parametric instabilities. *Phys. Fluids* **16**, 1490–1496.

Fejer, J. A. & Kuo, Y.-Y. 1973*b* The saturation spectrum of parametric instabilities. *Proc. AGARD Conference on non-linear effects in electromagnetic wave propagation*, Edinburgh, Scotland, 12–15 November 1973, pp. 11–1/11–8.

Fejer, J. A. & Graham, K. N. 1974 Electron acceleration by parametrically excited Langmuir waves. *Radio Sci.* **9**, 1081–1084.

Fialer, P. A. 1974 Field-aligned scattering from a heated region of the ionosphere—Observations at HF and VHF. *Radio Sci.* **9**, 923–940.

Gordon, W. E. & Carlson, H. C., Jr 1974 Arecibo heating experiments. *Radio Sci.* **9**, 1041–1047.

Hagfors, T. & Zamlutti, C. 1973 Observations of enhanced ion line frequency spectrum during Arecibo ionospheric modification experiment, *Proc. AGARD Conference on non-linear effects in electromagnetic wave propagation*, Edinburgh, Scotland, 12–15 November 1973, pp. 5–1/5–12.

Haslett, J. C. & Megill, L. R. 1974 A model of the enhanced airglow excited by RF radiation. *Radio Sci.* **9**, 1005–1019.

Meltz, G., Holway, L. H., Jr & Tomljanovich, N. M. 1974 Ionospheric heating by powerful radio waves. *Radio Sci.* **9**, 1049–1063.

Minkoff, J., Kugelman, P. & Weissman, I. 1974 Radio frequency scattering from a heated ionospheric volume, 1, VHF/UHF field-aligned and plasma-line backscatter measurements. *Radio Sci.* **9**, 941–955.

Perkins, Francis W. 1974 A theoretical model for short-scale field-aligned plasma density striations. *Radio Sci.* **9**, 1065–1070.

Perkins, F. W. & Valeo, E. J. 1974 Thermal self-focusing of electromagnetic waves in plasmas. *Phys. Rev. Lett.* **32**, 1234–1237.

Perkins, F. W., Oberman, C. & Valeo, E. J. 1974 Parametric instabilities and ionospheric modification. *J. geophys. Res.* **79**, 1478–1496.

Utlaut, W. F. 1970 Radio-wave modification of the ionosphere. *J. geophys. Res.* **75**, 6402–6405.

Utlaut, W. F. & Violette, E. J. 1974 A summary of vertical incidence radio observations of ionospheric modification. *Radio Sci.* **9**, 895–903.

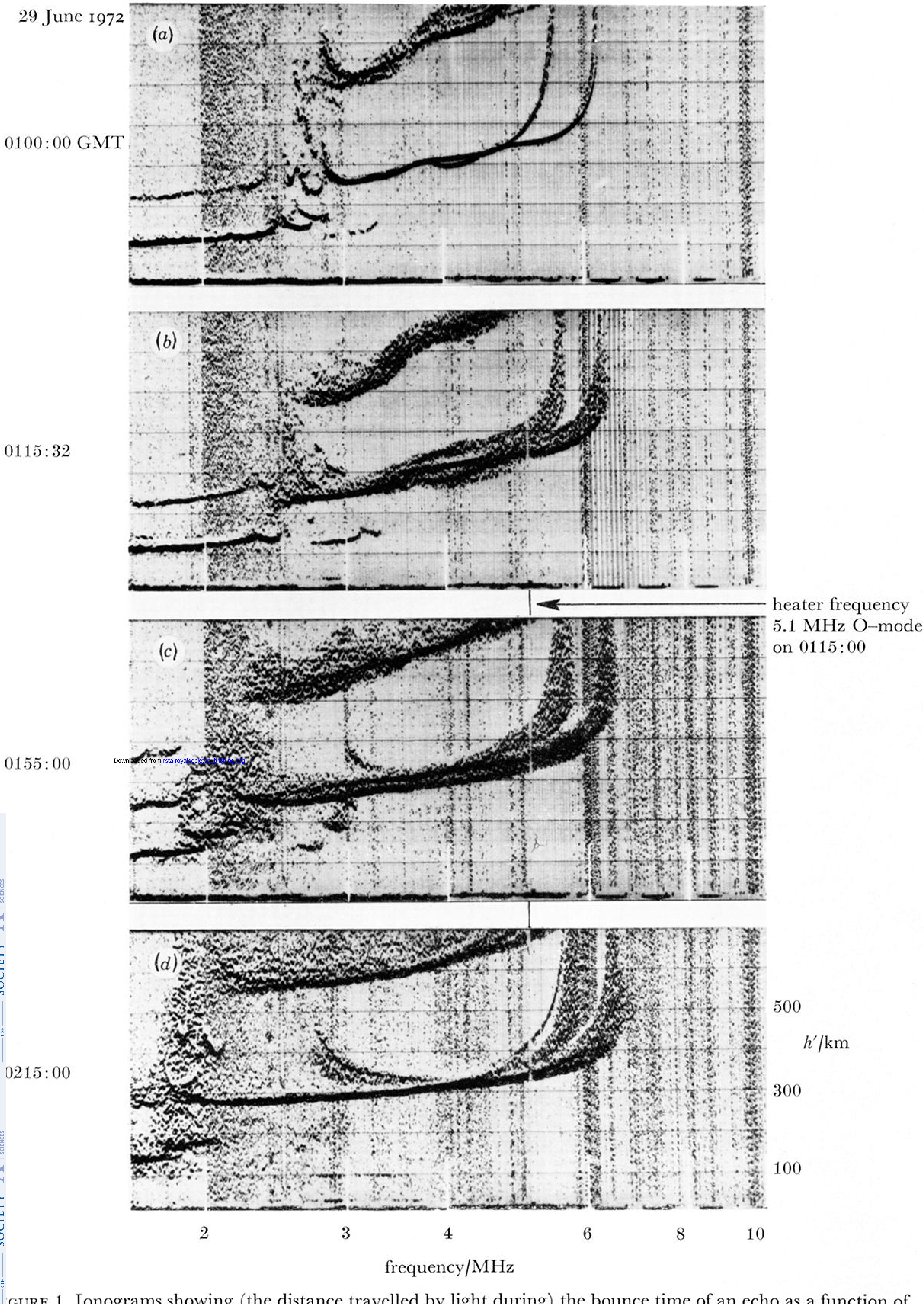
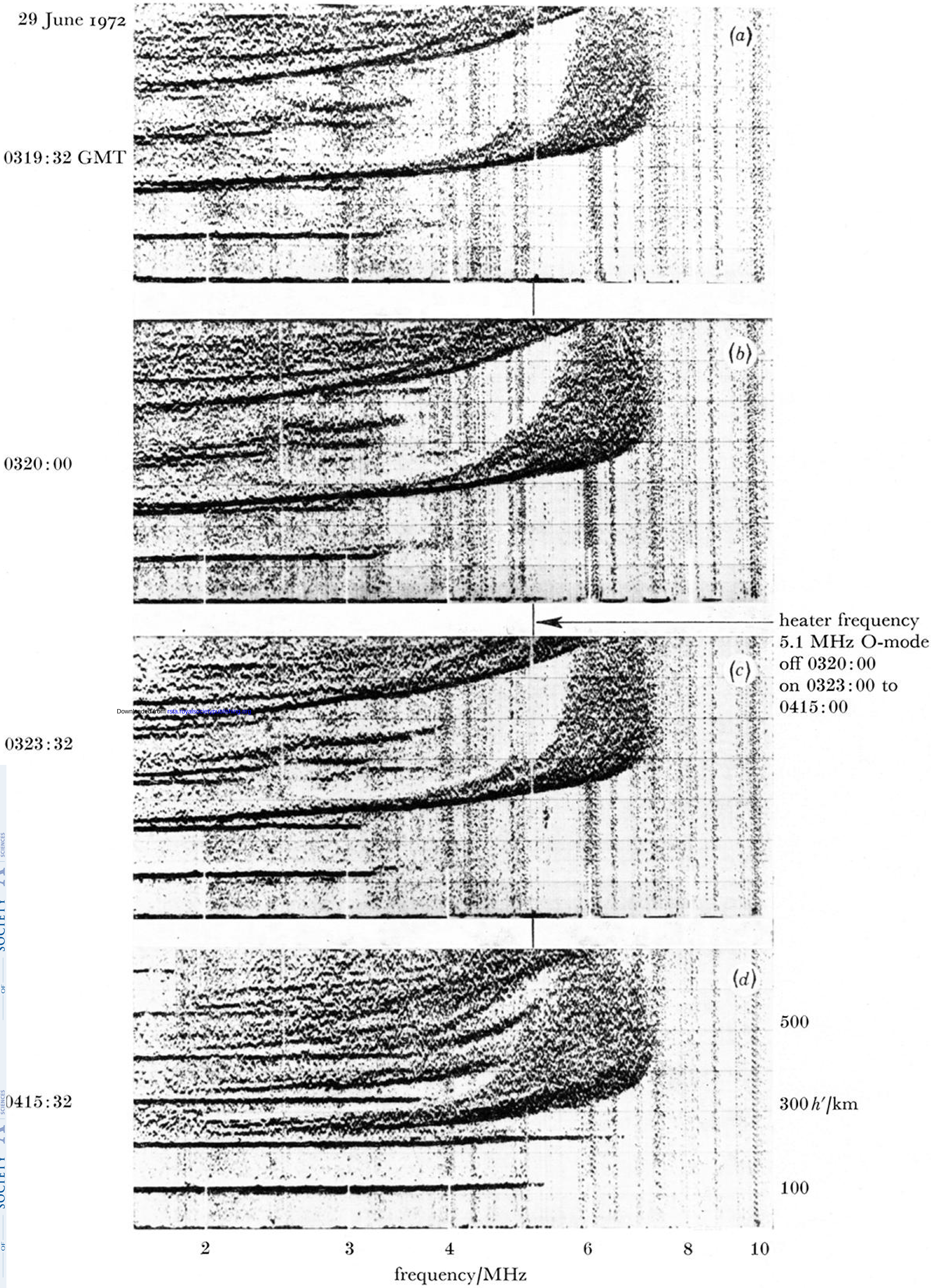
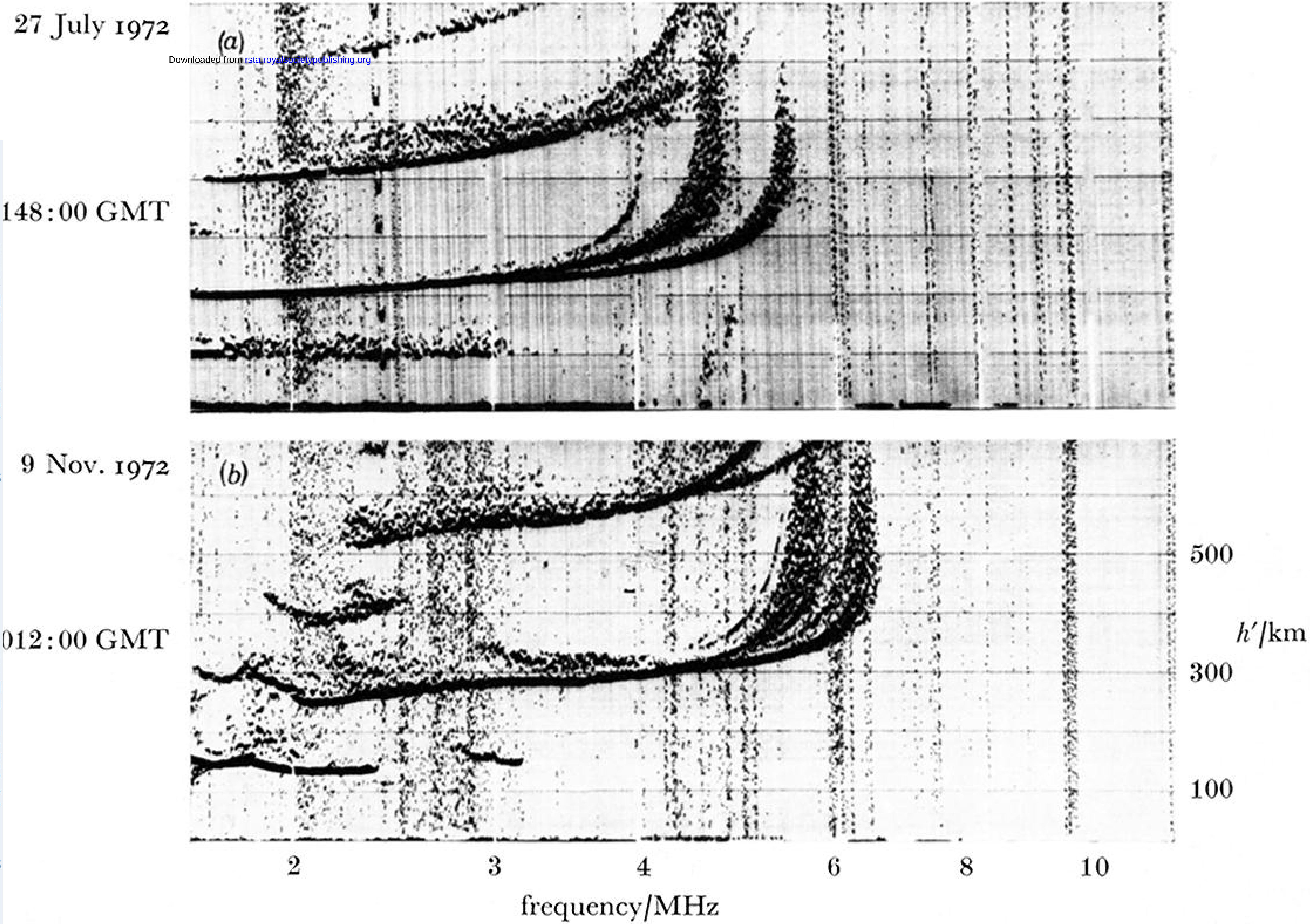


FIGURE 1. Ionograms showing (the distance travelled by light during) the bounce time of an echo as a function of the (swept) ionosonde frequency. Note the spread nature of the echo, and the presence of additional (so-called 1F2 and on the bottom ionogram Z) traces after the heating transmitter has been switched on. (From Utlaut & Violette 1974.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



IGURE 2. Ionograms illustrating 'wide band attenuation'. The spread ordinary echo trace does not extend above the heater frequency when the heating transmitter is on. (From Utlaut & Violette 1974.)



IGURE 3. Ionograms illustrating weak so-called Z traces that do not show a spread and have a longer bounce time than the spread ordinary and extraordinary traces. (From Utlaut & Violette 1974.)

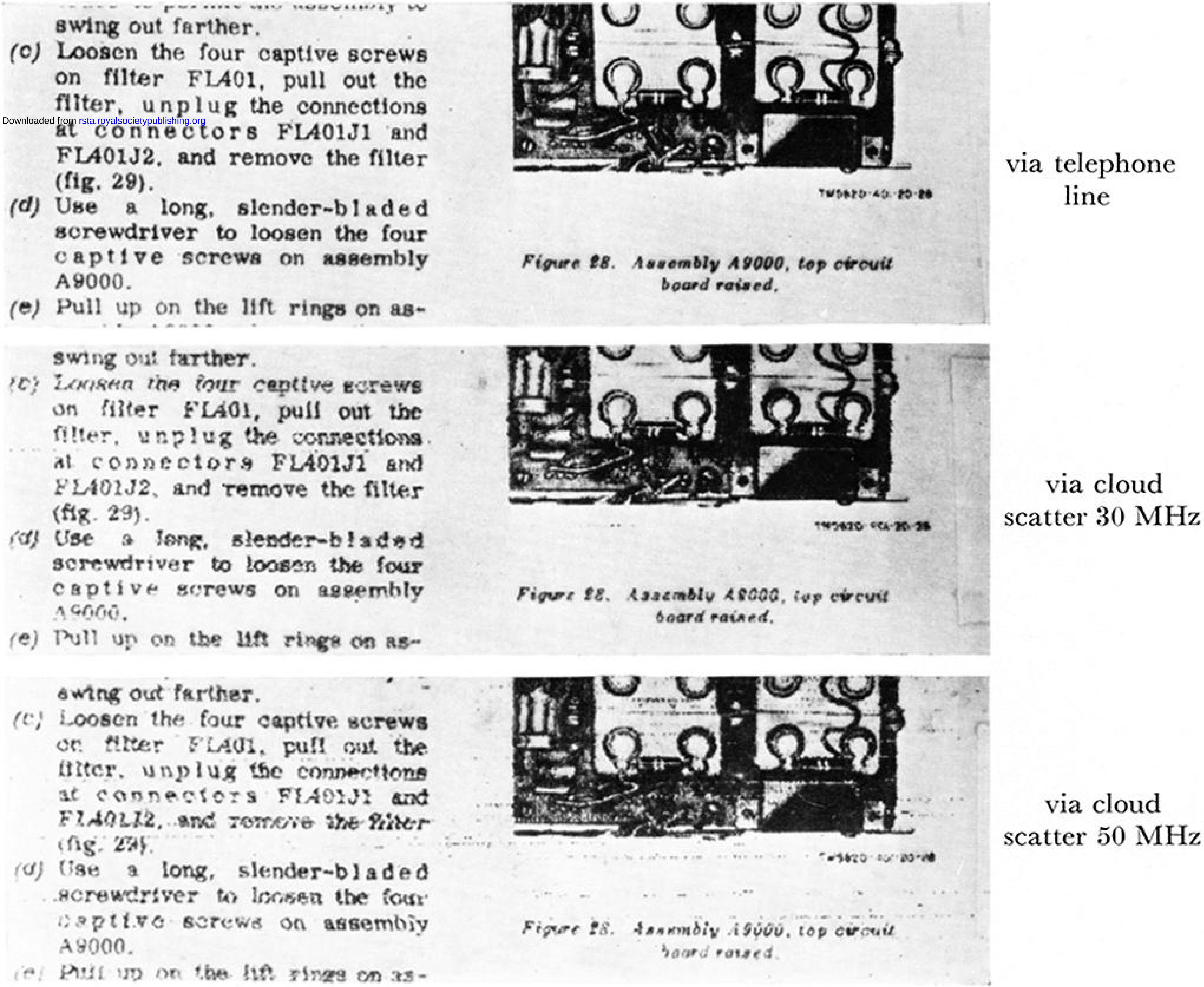


FIGURE 11. Facsimile transmitted via scatter by field alined irregularities produced artificially over Boulder. (From Barry 1974.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES