A STUDY OF "SPREAD-F" IONOSPHERIC ECHOES AT NIGHT AT BRISBANE

I. RANGE SPREADING (EXPERIMENTAL)

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Summary

At frequencies well below the critical frequency, satellite echoes sometimes accompany the night-time F_2 echo, sometimes clearly separated, sometimes overlapping. In an investigation of these range multiplets, in addition to routine $P'f$ sounding records, continuous virtual range measurements at fixed frequency (at stations of various separations), and measurements of mean intensities, phase-path changes, and directions of arrival, have been carried out.

From a study of the results, certain simple relationships emerge, as first approximations, between the various quantities measured, namely: virtual ranges (group paths), phase-path change, zenith angle, azimuth, intensity, and the time. A parameter, having the dimensions of velocity, appearing in these relationships, has values of which 80 per cent. lie in the range 240 ± 140 km/hr, with directions of which 80 per cent. lie in the range $290 \pm 60°$. The mean duration of a satellite is 50 min. Satellites occur more frequently in winter than in summer and show a somewhat complex diurnal variation, which is described in detail, and which tends to recur from year to year. It is associated with the general night-time changes in equivalent height of the layer. Strongly reflecting E_s shows an inverse diurnal variation. No correlation with geomagnetic disturbance indices could be found.

I. Introduction

No one who examines regularly the night-time records of a swept-frequency ($P'f$) ionospheric sounding equipment operating at medium latitudes can fail to remark the diffuse character frequently exhibited by the F reflections at night. Although in routine reports from Brisbane (lat. 27° 30′ S., long. 153° 00′ E., geomag. lat. 35° 06′ S.) such occurrences are simply noted as "spread or diffuse echo", the phenomenon assumes, in fact, a wide variety of forms. Thus there may be only a broadening of the echo traces, of roughly the same extent, at all frequencies, giving a broad band on the record (narrowing as it sweeps upwards), as in Plate 1, Figure 1. On the other hand, the broadening may occur chiefly near the penetration frequency axis where the traces sweep upwards, as in Plate 1, Figure 2. The two effects can be present together and both can attain considerable magnitude, as in Plate 1, Figure 3, so that on the one hand, much of the range of virtual heights between the F and $2F$ traces is

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filled in with reflections, and on the other hand, a range of frequency of several megacycles per second is covered by the broadened upward sweep.

As reported by Gipps, Gipps, and Venton (1948), the broad horizontal band at lower frequencies is sometimes replaced by two or more distinct traces running parallel to each other, with constant separation in group path over most of the frequency band, as shown in Plate 2, Figure 1.* These traces usually, but not always, give the same penetration frequencies. Plate 2, Figure 3, shows a case in which the trace of greater group path gives higher penetration frequencies. In such cases the penetration frequencies usually change little, if at all, between successive $P'f$ records (taken at 10-min intervals).

Again, the horizontally broadened trace near the penetration frequency may be replaced by a few distinct upward-sweeping traces, as illustrated in Plate 2, Figure 2. Detailed examination excludes the possibility that any of these are due to the so-called Z reflection.

It is believed, in the light of all the available evidence, that the broadening of the traces in the $P'f$ records at frequencies well below the critical frequency is due to the presence of a large number of individual traces, which are not resolved.

It is convenient to refer to such occurrences as " multiplets ". The occurrence of multiple traces, with different group paths, at low frequencies will be termed a " range multiplet " (cf. Plate 1, Fig. 1) ; where the distinction lies chiefly in the penetration frequencies it will be termed a " penetration frequency multiplet " (cf. Plate 1, Fig. 2). The latter will be the subject of another paper from this laboratory.

The term " equivalent range " (R') rather than " equivalent height " is used for the semi-group path, because, as will be shown later, there is evidence that the echoes of range greater than the minimum are due to non-vertical reflection. When there is only one echo of increased range, or when only one such echo is clearly separated from its neighbours, the phenomenon will be described as a " range doublet " (cf. Plate 2, Fig. 1).

As pointed out by Gipps, Gipps, and Venton (1948), the separations in range of the components of a range doublet usually show a progressive change from frame to frame of the swept-frequency records (taken at 10-min intervals). Since the separations are independent of frequency, complicated changes can be followed much more readily by continuously recording echoes from a transmitter of suitably chosen fixed frequency. Such records form the main study of this paper. With a fixed frequency it is also practicable to carry out a number of ancillary measurements on the returning signals, as discussed below.

While this work was in progress, a paper by Uyeda and Ogata (1954) appeared which reports similar results.

Discussion of the physical significance of the observations is given in the second paper of this series.

* $P'f$ records of rather similar appearance to this may be produced by double-hop reflection, first from the F region, then from the E ; it is assumed that these are excluded.

II. Fixed-frequency Equipment

(a) *Virtual Range; Fixed-gain Records*

Three complete ionospheric sounders, operating mostly on 2·28 Mc/s were used, located, for the most part, at Brisbane, Buderim (95 km north of Brisbane), and Toowoomba (95 km west of Brisbane).

The transmitter power was 500 W, pulse duration 60 μsec, 50 pulses/sec. The receiver bandwidth was such that received pulses were resolved, in favourable cases, if their group paths differed by more than 25 km. The transmitter and receiver both used half-wave dipole aerials 50 ft above ground. The gain of the receiver was adjusted so that echoes down to 60 dB weaker than the strongest ionospheric echoes were clearly recorded.

Output pulses from the receiver were applied to a 6 in. cathode-ray tube in such a way as to black out (or, in some cases, brighten) the fluorescent spot. The tube was supplied with a linear time-base, the speed and time of starting of which were adjusted according to the particular group of echoes to be recorded. To improve resolution in the records two or more tubes were sometimes used, with different (expanded) portions of the time-base displayed on each. " Range marks ", generated by a stable oscillator, were applied to the tube for short periods at regular intervals. (Continuous application might have resulted in obscuration of some echo traces.) These brief applications of range marks also served as time marks. Small neon glow tubes, mounted alongside the cathode-ray tube and operated by a clockwork-driven contactor, provided a code for distinguishing the hours. Photographic records were made on 35-mm film using a camera with $f/4 \cdot 5$ aperture, with a film speed of 5 in/hr.

Simultaneous observations using all three stations have been made on more than 100 nights; and on many more nights using only one or two of the stations. A few observations were also made at Goondiwindi (about 300 km south-west of Brisbane). The transmitters were coded for identification.

Records were also made at Brisbane of echoes originating from the Buderim and Toowoomba transmitters. These will be referred to as *TR'* records, to distinguish them from those for which transmitter and receiver occupy the same site, which will be designated *TR*. Phase jitter (usually around ±50 μsec) led to a spurious broadening of the traces received; nevertheless, the records contain useful information. An example of a *TR* record is given in Plate 3, Figure 1, and of a *TR'* record in Plate 3, Figure 2.

(b) *Virtual Range; Swept-gain Records*

Records have been made at Brisbane using a receiver in which the gain was controlled by a motorized potential divider rotating once in 2 min. The gain of the receiver fell in steps of 2 dB, then rose suddenly, by 80 dB, to maximum gain. At minimum gain no echoes are recorded. The swept-gain records thus consist of regularly broken traces, the length of each segment being a measure of the relative intensity (in dB) of the particular echo (cf. Plate 3,

Fig. 3). Rapid fading tends to be averaged out, but slow fading can affect the measurements unless an a erage is taken over several segments.

Swept-gain records tend to show improved resolution, for, when the receiver gain reaches a value such that a particular echo only just records, only the peak of the echo shows. Thus towards the ends of the segments in the swept-gain records the traces narrow; this often permits the separation of closely spaced traces which, in the fixed-gain record, show as a single broad trace. Falconer (personal communication, 1955) has found that, even when separation is not possible in individual segments, an averaging process over several segments can reveal the major components of the broadened trace.

(c) "*Phase-path*" *Records*

Equipments for measuring changes in the phase path traversed by ionospheric echoes have been described by Findlay (1951) and Jones (1953). The equipment used in Brisbane was a simplification of that of Jones, and required only small modifications of the standard receiver-display combination. An external oscillator, tuned to a frequency about 40 kc/s above the intermediate frequency of the receiver, was switched on once each cycle by a rectangular voltage pulse, starting simultaneously with the modulator pulse for the transmitter. The initial phase of the oscillations was fixed by the injection into the oscillator circuit of an intermediate-frequency pulse derived, in the receiver, from the "ground" pulse of the nearby transmitter. A suitable fraction of the oscillator output was mixed in a non-linear circuit with the full intermediate-frequency output of the receiver, and the 40 kc/s component of the mixture was filtered out and rectified. This video output was fed to a display system similar to that described in Section II (*a*). A film speed of 15 in/hr was found necessary to record accurately the rapid phase-path changes which sometimes occurred. Plate 4 shows portion of a typical record.

(*d*) *Direction-of-arrival Records*

Special equipment has been installed at Brisbane for the determination of the direction of arrival (azimuth and altitude) of ionospheric echoes at 2·28 Mc/s. This is described elsewhere (Thomas and McNicol 1955). Automatic records provide simultaneous information concerning a whole group of echoes. The method fails in the case of echoes which overlap each other, as in a multiplet of small range separation.

III. Experimental Results

(*a*) *Satellites and their General Characteristics*

The frequency of 2·28 Mc/s is convenient for the investigation of range multiplets, since the *o*- and *x*-rays are rarely separated at this frequency. Range multiplets show on the *R′t* records as a multiplicity of traces, as exemplified in Figure 1, and Plate 3. It is convenient to distinguish the lowest trace, which is usually continuous over long periods (sometimes all night) from the upper traces, which show continuity for shorter periods, sometimes only a few minutes (cf. Fig. 1). The former is therefore termed the "main trace" and the latter are termed "satellites".

The range separation between satellite and main trace usually increases or decreases considerably, and systematically, during the lifetime of the satellite; a range doublet or multiplet is therefore classified as divergent, convergent, parallel, or mixed, according to the behaviour of the satellites constituting it. When the successive points of junction between satellites and main trace are

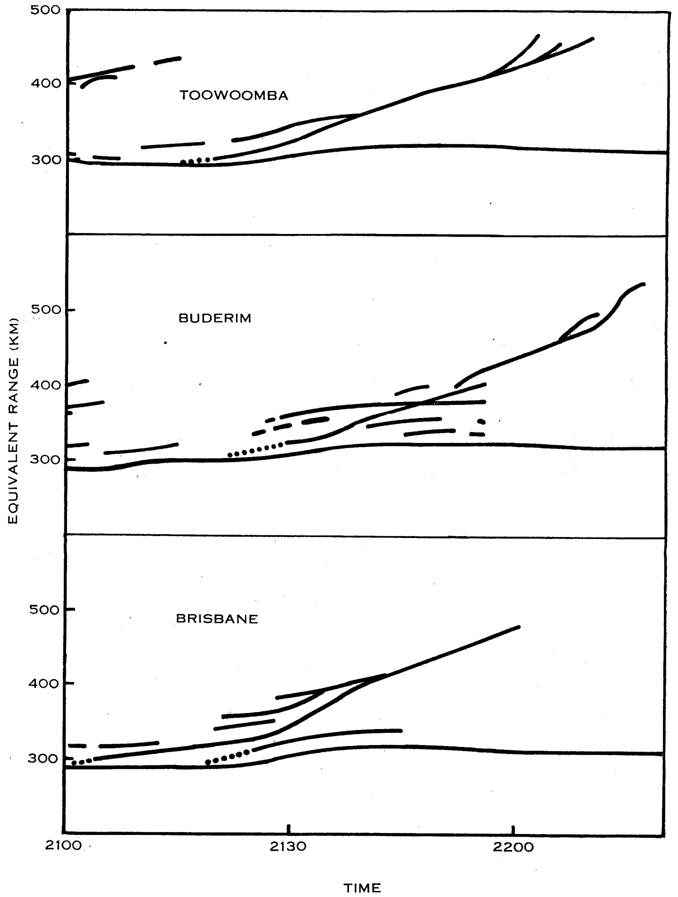


Fig. 1.—Divergent range multiplet recorded simultaneously at three separated stations. Portion of *R't* records for Toowoomba, Buderim, and Brisbane, July 22, 1950, replotted from readings. Some of the traces on the original records were broader than is shown and closely adjacent traces cannot be resolved from each other; the dotted portions are thus conjectural.

spaced at intervals less than about 2 min, the satellites are regarded as belonging to one and the same multiplet; this criterion is, of course, quite arbitrary. An example of a convergent range doublet is given in Figure 2 and of a mixed range multiplet in Plate 3. The relative frequencies of occurrence of parallel, convergent, divergent, and mixed range doublets are roughly in the ratio of 1 : 8 : 20 : 6.

It has been found that satellite traces usually, but not always, show a slight upward curvature. They often satisfy approximately the semi-empirical hyperbolic relationship

$$\sqrt{(R'^2-h'^2)}=k(t-t_0),$$

where h' represents the *lowest* range observed during the lifetime of the satellite,* and k and t_0 are constants (k may be negative). As an example, Figure 3 shows a plot of $x(=\sqrt{(R'^2-h'^2)})$ versus t in a favourable case. The slope $\mathrm{d}x/\mathrm{d}t$ $(=k)$, which has the dimensions of speed, has been determined† from a large number of satellites and the distribution of speeds is shown in Figure 4. The mean

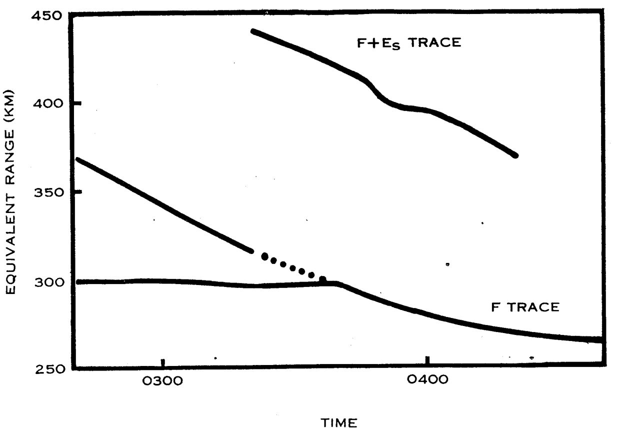


Fig. 2.—Convergent range doublet. $R't$ record for Brisbane, May 26, 1952. Replotted from readings. The original traces are considerably broader than the diagram would indicate and the final junction of the satellite is thus obscured ; a possible extrapolation is indicated by the dotted line. Note the parallelism between the $(F+E_s)$ trace (reflection first from F, then ground, then E_s) and the satellite.

value is 63 m/sec (230 km/hr). In Figure 5 the results for convergent and divergent satellites are shown separately. In view of the small number of cases, it is questionable whether the difference in distribution is significant.

Some satellite traces (in ordinary fixed-frequency records) show wide gaps and some resume, after a gap, with a trace corresponding to a slightly different value of t_0. These complications introduce a measure of arbitrariness into the interpretation of the records.

It is clearly of some interest to know whether the changes in R' arise from change in actual distance of the reflecting point, or from group-retardation effects. The horizontality of the swept-frequency traces at low frequencies makes the latter hypothesis improbable, but the point was more definitely checked by

* In reading h' it is assumed that a given trace retains its identity through any intersection or junction as long as there is no discontinuity in its slope. Thus the " lowest " range of a satellite will usually be read off a portion of the trace produced beyond the intersection with the main trace.

† The authors are indebted to Mr. D. Lamb for analysing these records.

comparing changes in phase path with the simultaneous changes in group path. Figure 6 shows the results of such a comparison. Except when special conditions operated, as discussed below, discrepancies between group and phase path changes exceeding 10 per cent. were never clearly demonstrated. It should be pointed out, however, that the fringes in phase-path records were

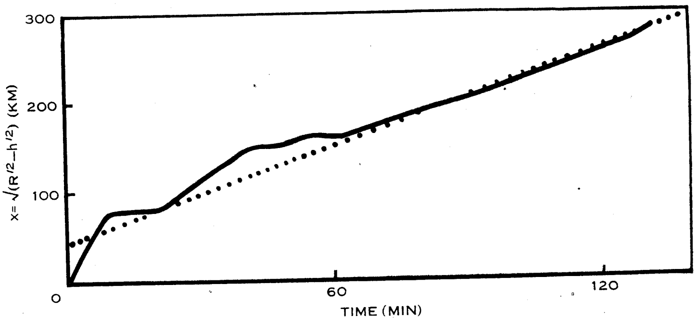


Fig. 3.—Plot of $x(=\sqrt{(R'^2-h'^2)})$ versus t. (Brisbane, October 16, 1954.) The full curve joins the points plotted, the broken curve is the best-fitting straight line. Note that since dx/dR' becomes infinite as x approaches zero, the lower part of the curve is subject to great error.

sometimes confused. In certain of these confused cases there was evidence of overlapping and intersecting satellites. (Nevertheless, complicated records could sometimes be disentangled more readily from the phase-path than from the ordinary records.)

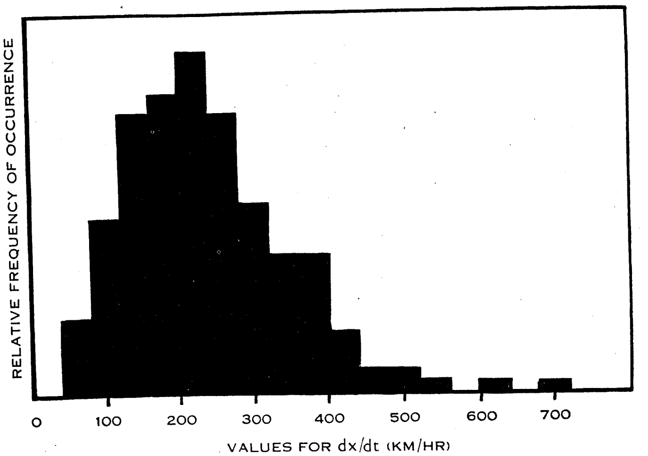


Fig. 4.—Distribution of values of dx/dt for all satellites in 1952.

An important characteristic of the majority of range multiplets is the close equality between the penetration frequencies (as indicated by the upward sweep of the curves on swept-frequency records) of satellites and main trace. A difference between satellite and main trace critical frequencies was detected on less than 10 per cent. of occasions. In such cases, the satellite critical frequency can be either lower or higher than that of the main trace; the former condition seems rather more prevalent, but this impression may arise because it is experimentally easier to detect. Sometimes the frequency difference gradually

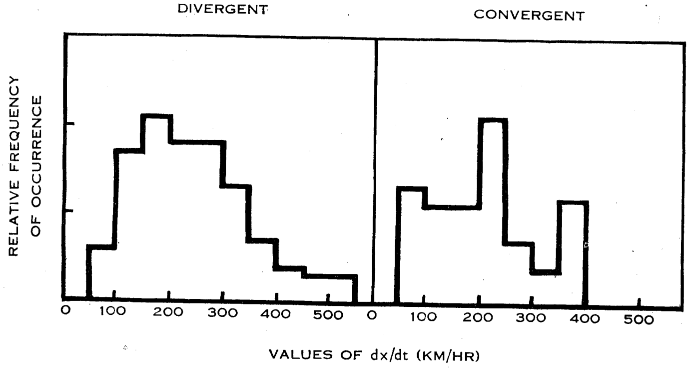


Fig. 5.—Distributions of values of dx/dt for 110 divergent and 79 convergent satellites separately.

disappears during the currency of the satellite. Plate 2, Figure 3, indicates one of the rare cases when the satellite has the higher critical frequency; it may be significant that the corresponding 2·28 Mc/s $R't$ trace has an unusual speckled appearance.

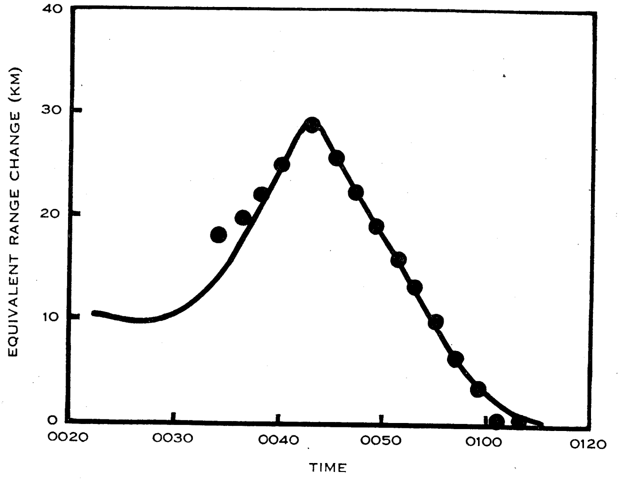


Fig. 6.—Comparison of group-path and phase-path changes. Changes of group path (full line) and phase path (dots) for lowest ("main") trace of a mixed range multiplet (June 23, 1955, at 0040 hr). The two plots have been adjusted to coincide at the peak.

It is perhaps worthy of note that the peculiar satellite traces (characteristic of oblique-incidence propagation) reported by Meek (1952) and others in Arctic recordings are never observed in Brisbane.

Determinations of directions of arrival show that, for the main trace, the echoes nearly always arrive vertically (within limits of experimental error) while the satellite echoes arrive at an angle with the vertical. It is found that in nearly all cases, the zenithal angle θ satisfies approximately the relationship

$$\sec \theta = R'/h'.$$

Table 1 shows the results of a comparison of values of θ deduced from the expression and values determined directly. Departures are of the same order of magnitude as the estimated experimental errors.

TABLE 1

CALCULATED AND OBSERVED ZENITH ANGLES FOR PARTICULAR SATELLITES*

Time	Zenith Angle, θ	
	Calculated (deg)	Observed (deg)
2309	43	46
{2330	36	32
2351	41	44
0106	25	26
{2206	38	36
2236	24	20
2330	30	32
0000	52	54
{0151	16	15
0218	40	44
0203	38	37
0045	34	35
1957	27	27
0254	53	54
1930	24	28
2218	48	48
{2100	14	0
2245	40	53
2257	41·5	39
2303	43·5	42
2227	32	33
{2303	29	26
2315	31	22 ?
2321	34	34
2345	37	37
2351	40	40

* The authors are indebted to Mr. W. Woolcock for many of these values.

(*b*) *The Junction or Intersection of a Satellite with the Main Trace*

The general appearance of many mixed multiplets, especially those where there are only a small number of satellites, strongly suggests the crossing-over of two sets of traces, i.e. the lower set after intersection is continuous with the upper set before intersection and vice versa (cf. Plate 3). In such cases it is assumed that the roles of main trace and satellite are exchanged at the intersection. Measurements of the azimuths of arrival of the echo giving the lowest trace confirm this view. On several occasions it was possible to determine the azimuths; it was found that an abrupt 180° change occurred at the intersection. Furthermore, an $R't$ plot, using the lower trace on both sides of the intersection,

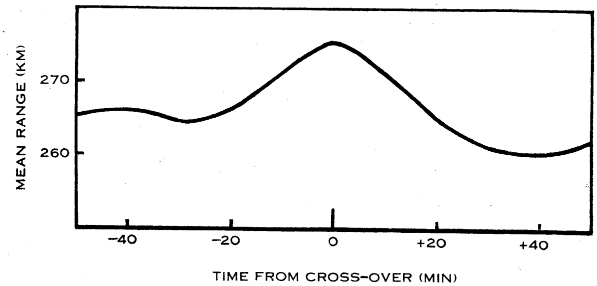


Fig. 7.—Average course of the lowest trace in the vicinity of the intersection of the traces in 54 mixed range multiplets.

shows a characteristic change of slope at that point. This is brought out in Figure 7, which is an average taken over a number of cases, setting the time zero at the point of intersection. It will be noted that the average range at intersection is 10 km higher than at some time previously and subsequently.

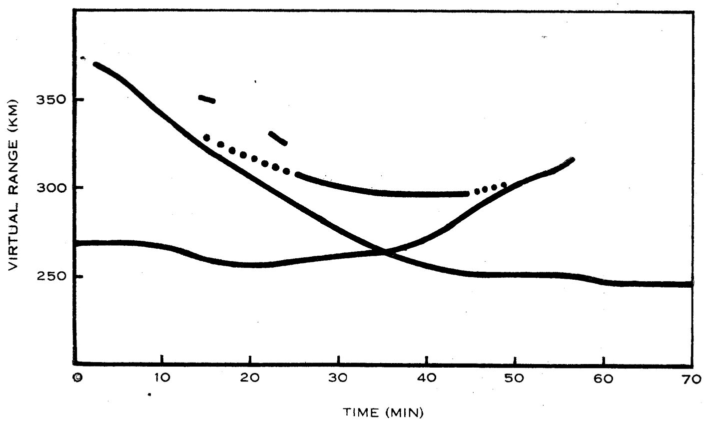


Fig. 8.—Mixed range multiplet showing traces of upper member $R't$ record for Brisbane, March 17, 1953, replotted from readings. The dotted portions are conjectural, since the lower trace was broader than the diagram suggests and these portions of the upper satellite, if present as indicated, would have been obscured.

A few range doublets of the mixed type show fragments of a third satellite forming a roughly parabolic curve connecting the ends of the other two satellites (cf. Fig. 8).

For the two major intersecting traces in a mixed range doublet, designated A and B, the value of $x_A - x_B$ is approximately constant. Values of this quantity for nine selected traces are plotted in Figure 9 against the corresponding values of dx/dt. There is no indication of any definite relationship between the two variables. The average value of $x_A - x_B$ for the cases plotted is about 280 km.

The durations (and intensities) of the satellites on the two sides of the intersection are often very different. We can therefore regard convergent and divergent range doublets as limiting cases of mixed doublets in which one

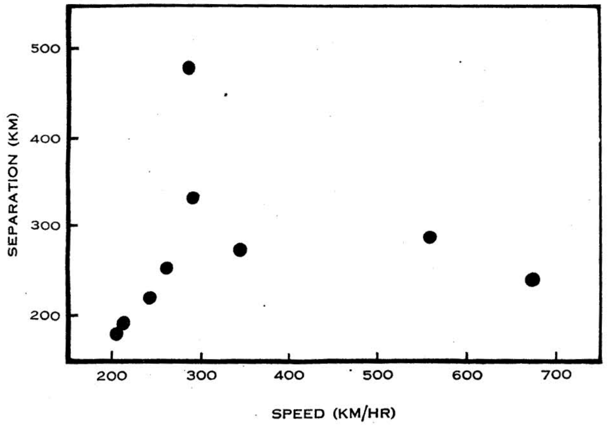


Fig. 9.—Plot of $(x_A - x_B)$ against dx/dt for mixed doublets.

satellite has completely disappeared. In support of this view it is noted that a satellite in a convergent or divergent doublet frequently (but not always) appears to be continuous with the main trace on the far side of the junction (cf. Fig. 2). Moreover, an $R't$ plot, again using the lower trace throughout, shows a change of slope at the (estimated) junction point in these cases also. Figure 10 illustrates the average behaviour for 20 convergent and 75 divergent doublets respectively.

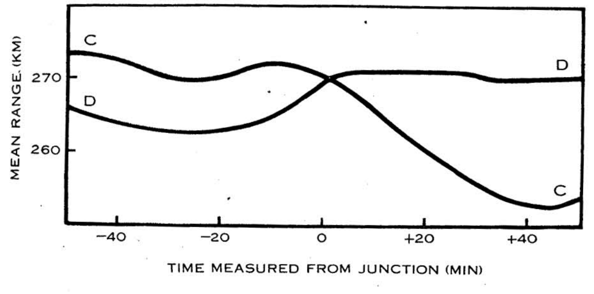


Fig. 10.—Average course of the lowest trace in the vicinity of the junction of the traces in 20 convergent doublets (curve C) and 75 divergent doublets (curve D).

While there are fairly wide differences between individual cases, the small increase in range of the main trace at the time of junction, for a divergent satellite, and small decrease for a convergent satellite is almost always noted.

Only a few satellites, and those mostly of short duration, fail to meet the main trace, if present, at some time during their existence. However, during periods when strongly reflecting E_s is present (indicated by multiple E_s reflections), so that all F echoes, on 2·28 Mc/s, are " blanketed " for long intervals, the record appears to consist only of satellite traces (cf. Fig. 11). Some satellites show a range decrease to a minimum, followed by an increase.

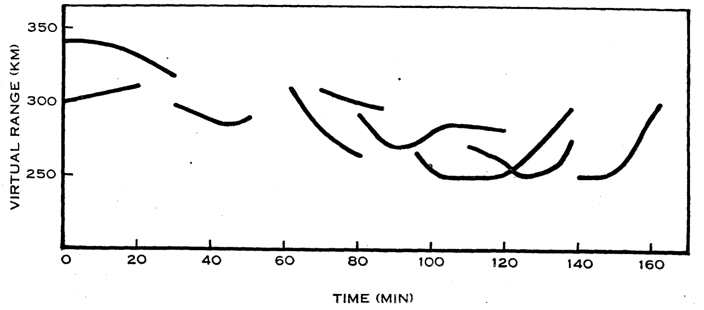


Fig 11.—Absence of continuous main F-region trace. Replot of portion of $R't$ record for Brisbane, Oct. 21–22, 1954. Strong E_s reflections were present but have not been plotted.

(c) R′t *Records when Magneto-ionic Splitting is Apparent*

On a few occasions, because a higher working frequency (5·8 Mc/s) was used, or because the critical frequency was abnormally low, or group-retardation effects present, records of multiplets were obtained in which o- and x-rays

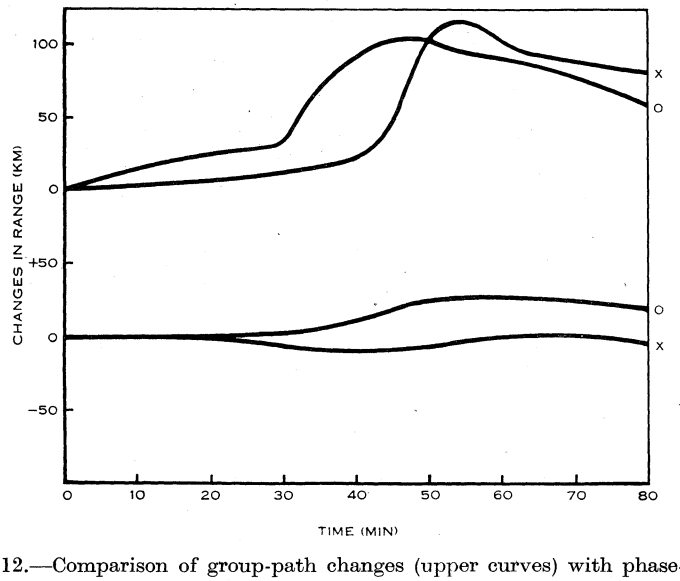


Fig. 12.—Comparison of group-path changes (upper curves) with phase-path changes (lower curves) during a rapid change involving separation of o- and x-rays, Mar. 5, 1955, starting at 0400 hr. Note that the phase path record for the x-ray was very weak and this curve is not wholly reliable.

produced clearly separated traces. (The possibility of mistaking a simple separation due to this cause for a range doublet was excluded by always checking against the swept-frequency records.) In many such cases, there was evidence of separation of o and x on the satellite, as well as on the main trace. As a general rule the satellite traces showed large gaps; correspondingly, it frequently happens that the satellite trace on swept-frequency records is incomplete, especially near the critical frequency.

Another phenomenon sometimes observed is a brief separation of *o*- and *x*-rays, accompanying a rapid increase in group path; this is termed a "lenticel" because of its appearance on the *R't* records. In such cases, the group path increases much more rapidly than the phase path (cf. Fig. 12). Rapid group-path rises, not accompanied by separation of *o*- and *x*-rays, show similar, but less marked, discrepancies.

Lenticels are frequently accompanied by satellites, branching off where the rapid group-path rise ceases. Upon an occasion when a satellite was present prior to the lenticel, it showed a similar rise in group path and evidence of separation of *o*- and *x*-rays.

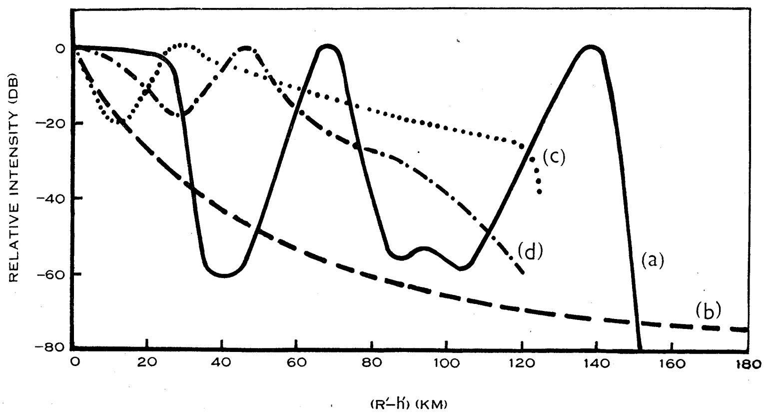


Fig. 13.—Changes of intensity (in dB) of satellite plotted against excess of range over minimum. Curve (*a*) represents a case of extreme fluctuation; curve (*b*) a case of unusually uniform change. Curves (*c*) and (*d*) represent more usual behaviour.

(*d*) *Intensities of Satellites*

When the separation of the satellite and main trace is barely sufficient to permit resolution, the intensities are usually equal, within a few decibels. As the satellite range increases, the echo intensity falls. Figure 13 shows the behaviour in some typical cases. The intensity changes are highly irregular, often showing successive maxima and minima, different by 40 dB or more. In Figure 14 intensity I (in dB) is plotted at intervals against range increment ($\Delta R'$) for a number of independent traces, taking the intensity (dB) and range increment zero at minimal range. (The sets of points have not been connected up.) The scatter diagram produced is crudely consistent with a linear relationship between I and $\Delta R'$, with a slope of $-0\cdot4$ dB/km. In spite of this general tendency to weaken with increasing range, some divergent satellites first appear at a range considerably above that of the main trace, and conversely some convergent satellites weaken markedly, or disappear, before they reach the main trace.

A cursory study was made of the relative intensities of satellites and the $(F+E_s)$ echo. Many multiplets, including the more complex ones, are unaccompanied by $(F+E_s)$. Where present, it is usually 15 dB or more weaker than the main F echo, and is weaker than the satellites lying between it and that echo.

(*e*) *Multiple-hop Satellites*

When a satellite appears on the one-hop F echo, in 20–30 per cent. of cases a satellite appears also on the two-hop, the separation between the respective satellites remaining constant throughout their duration. On a very few occasions, two $2F$ satellites have been observed, the second (weaker) satellite

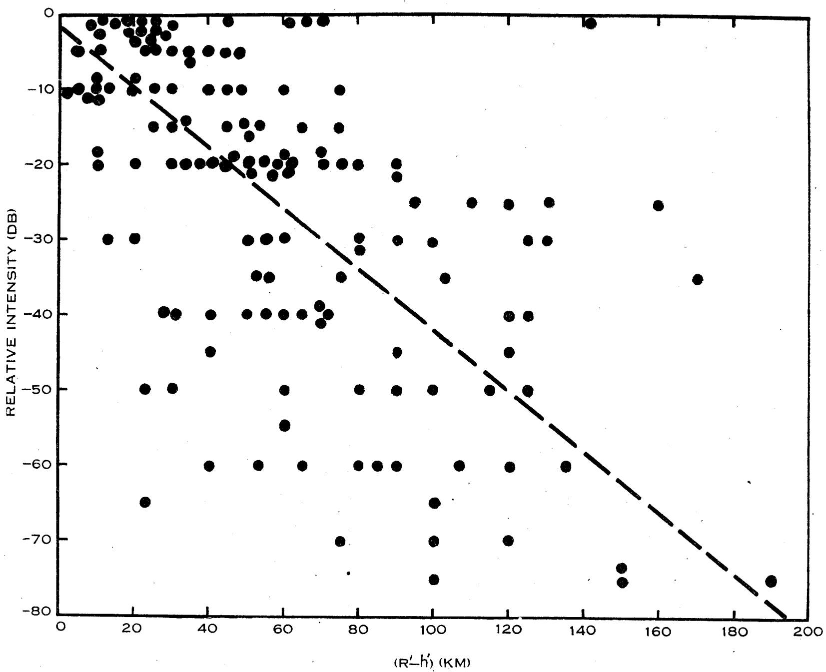


Fig. 14.—Relative intensity *v.* excess of range over minimum for satellites. Intensity taken as 0 dB at zero range excess. The broken line has a slope of $-0 \cdot 4$ dB/km.

having a separation from its main trace which is around two-thirds of the separation of the other satellite (cf. Fig. 15). The second satellite may start later than the first. Three-hop satellites are also of fairly frequent occurrence. On one occasion Baird (1954) recorded satellites on all echoes up to the five-hop, the separations decreasing progressively after the second.

(*f*) *Spatial Correlation of Satellites*

The $R't$ records at three stations 100 km apart are often closely similar (cf. Fig. 1). Not only does a multiplet at one station nearly always correspond to a multiplet at the others, but also 80–90 per cent. of individual satellites showing on one record (excluding those of less than 30 min duration) have counterparts on the other two. However, there are, at times, considerable differences in intensity, freedom from gaps, and duration of the individual satellites on the three records, especially when the multiplet contains many

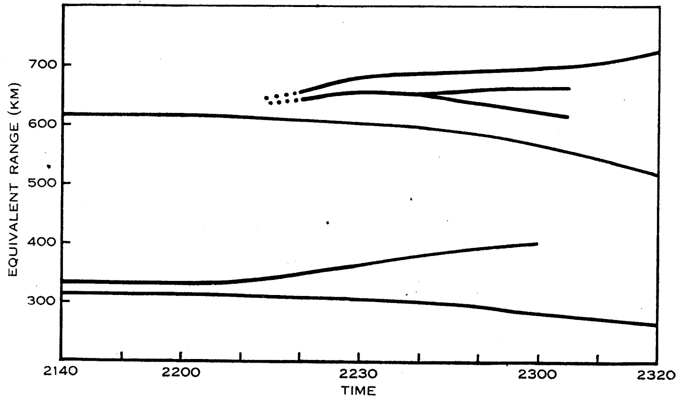


Fig. 15.—Re-plot of portion of $R't$ records of Brisbane, Oct. 27, 1952, 2·28 Mc/s showing two (at times three) satellites on the double-hop trace.

satellites. With stations located 300 km apart the correlation is noticeably lower, rather less than 30 per cent. of individual satellites showing definite correspondence.

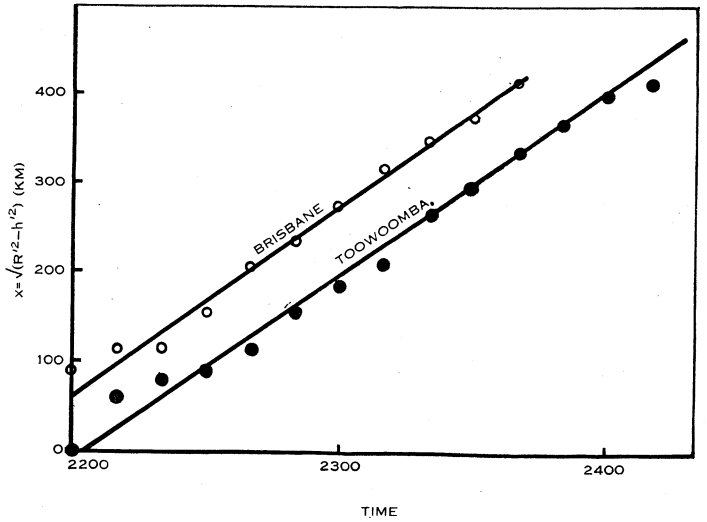


Fig. 16.—Plot of $x = \sqrt{(R'^2 - h'^2)}$ versus t for corresponding satellites, Brisbane and Toowoomba, Sept. 4, 1952, at 2200 hr.

The TR' records showed markedly fewer and shorter satellites than the TR records at either end (cf. Plate 3, Figs. 1 and 2). Strohfeldt, McNicol, and Gipps (1952), recording at Brisbane pulses on 5·8 Mc/s from Camden 760 km away, found very few satellites.

Where correlation was established, it was found that the traces were usually displaced in respect to time, i.e. different values of t_0 were found. Figure 16 illustrates a case where such a displacement occurs. Figure 17 illustrates a case in which, in addition, dx/dt shows systematic variations, these occurring at different times at the two stations.

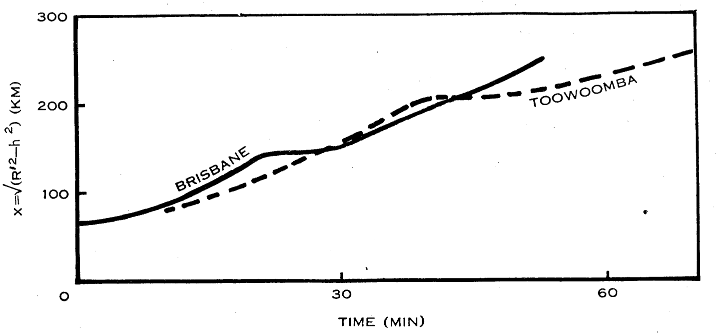


Fig. 17.—Plot of $x=\sqrt{(R'^2-h'^2)}$ versus t for corresponding satellites, Brisbane and Toowoomba, Aug. 21, 1952, at 2330 hr.

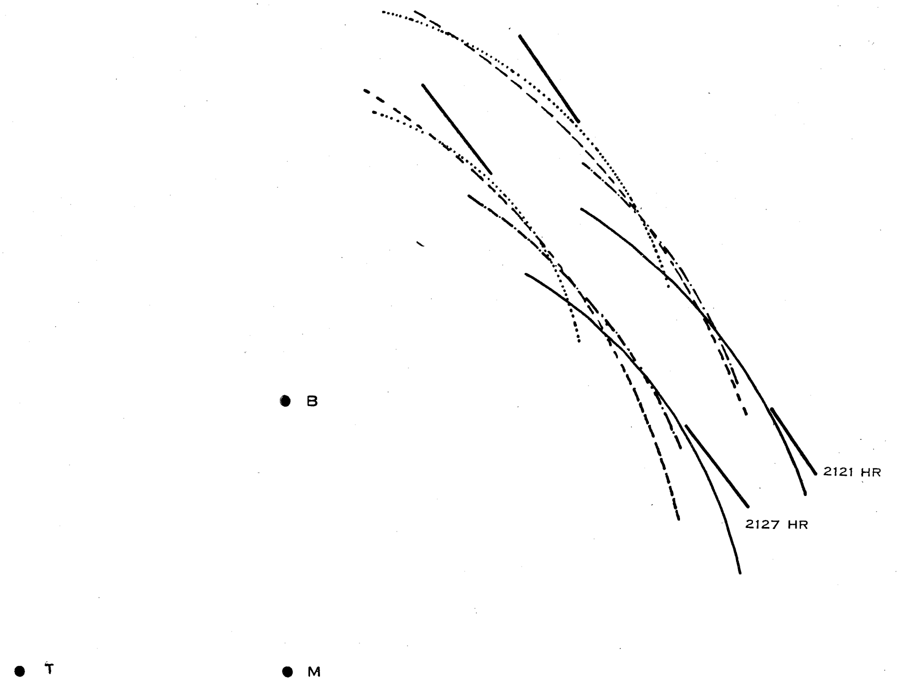


Fig. 18.—Plan of stations, with circles drawn to indicate simultaneous values of $x=\sqrt{(R'^2-h'^2)}$ for a satellite observed at three stations—Brisbane (M), Toowoomba (T), and Buderim (B), June 23, 1955. Full lines for Brisbane ; broken lines for Toowoomba ; dotted lines for Buderim. The " dot-dash " line is the ellipse deduced from TR' observations (2121 hr Buderim to Brisbane, 2127 hr Toowoomba to Brisbane). The straight lines indicate the common tangent in each case.

Where three records are available, it has been found that an important relationship exists between the values of x, namely, x_1, x_2, x_3, for the three stations at a given time t. This is most simply stated by reference to a diagram (cf. Fig. 18). If three points are marked in representing the plan positions of the three stations, and if circles are drawn round these points with radii corresponding to x_1, x_2, x_3, then the three circles have (fairly closely) a common tangent. There is rarely, if ever, any indication of a common intersection.

TABLE 2

CALCULATED AND OBSERVED AZIMUTHS FOR PARTICULAR SATELLITES

Time	Azimuth, φ	
	Calculated (deg)	Observed (deg)
2100	355	20
2227	0	327
⎧ 2303	325	302
⎪ 2315	329	320
⎨ 2321	307	290
⎪ 2345	355	339
⎩ 2351	355	341
⎧ 2342	313	307
⎩ 2351	312	314
2354	197	200
2221	224	227
⎧ 2315	307	311
⎩ 0000	302	299
⎧ 0154	326	328
⎩ 0218	324	326
2230	37	25
⎧ 0136	322	328
⎩ 0200	322	326
0206	325	321
1954	289	283
2218	303	315
2118	316	329

This result (and also the x,t relationship) was discovered while investigating the validity of one of the hypotheses discussed in Part II of this series.

It is furthermore found that the normal to the tangent corresponds roughly in direction to the azimuth of arrival φ as determined directly. Table 2 gives a few typical results. A rough determination of velocity would thus be possible from observations from a single station (if azimuthal determinations are included).

In the simplest cases the common tangent moves roughly parallel to itself as time proceeds (cf. Fig. 18). In many cases, however, the direction changes somewhat; this would be true, for example, if the results given in Figure 17 were plotted in the way illustrated in Figure 18. Table 3 shows a comparison of the rate of motion of the common tangent with the corresponding values of dx/dt, as measured at Brisbane.

In the case pictured in Figure 18, a second satellite, not plotted, was also present. This gave a tangent moving in a different direction. The simultaneous occurrence in this way of two independently moving tangents is fairly common.

TR' records were also available for the multiplet represented in Figure 18, and results calculated from them have been plotted in the form of ellipses on

TABLE 3

COMPARISON OF OBSERVED SPEEDS (AS DEDUCED FROM MOTION OF COMMON TANGENT) WITH VALUES OF dx/dt

Date and Time	Tangent Speed (m/sec)	dx/dt (m/sec)
15.vii.50 0130	90	78
22.vii.50 2130	107	103
23.vii.50 2300	48	51
23.viii.51 2000	48	56

the figure. The diagram shows that the common tangents to the circles are also tangential to the ellipses :

$$\sqrt{(x_1^2+h'^2)}+\sqrt{(x_2^2+h'^2)}=2R'.$$

It is thus possible to plot the tangent without complete data from the three stations, provided *TR'* data are available from the station for which the *TR* data are missing.

The speeds and directions of movement of the common tangent for the cases fully examined* are shown in Figure 19. The most noteworthy feature is the tendency for the directions to group around 300°, and for the speeds to lie in the range 150–350 km/hr.

(g) *Duration of Multiplets and of Individual Satellites*

It is often impossible, especially when the multiplicity persists all night, to assign a definite beginning or end to individual multiplets, as the multiplets overlap. Broadly speaking, however, a typical duration for a mixed multiplet would be 1–2 hr.

It is somewhat easier to assign a value to the duration of individual satellites, although here also there are uncertainties (of the order of 5 min), because of the nature of the records. A histogram showing durations of such satellites for a series of periods distributed over June–November 1952, is shown in Figure 20. Satellites with durations less than 10 min have been excluded, for these are often obscured by the broadening of the trace. For the satellites shown, the mean duration is about 52 min. Figure 14 would suggest that an increase of,

* The authors are indebted to Messrs. Lamb and Woolcock for most of this analysis.

say, 10 dB in the overall sensitivity of the system would increase the measured durations, a rough estimate making the increase 10 min. However, the intensity usually falls off much more rapidly than 0·4 dB/km during the last few minutes of the life of the satellite and thus the actual dependence of measured satellite duration on equipment sensitivity is probably not very great.

Corresponding satellite traces for different stations frequently show considerable differences in duration. Examination of a sample of 60 pairs of satellites which joined their respective main traces simultaneously (some junctions being

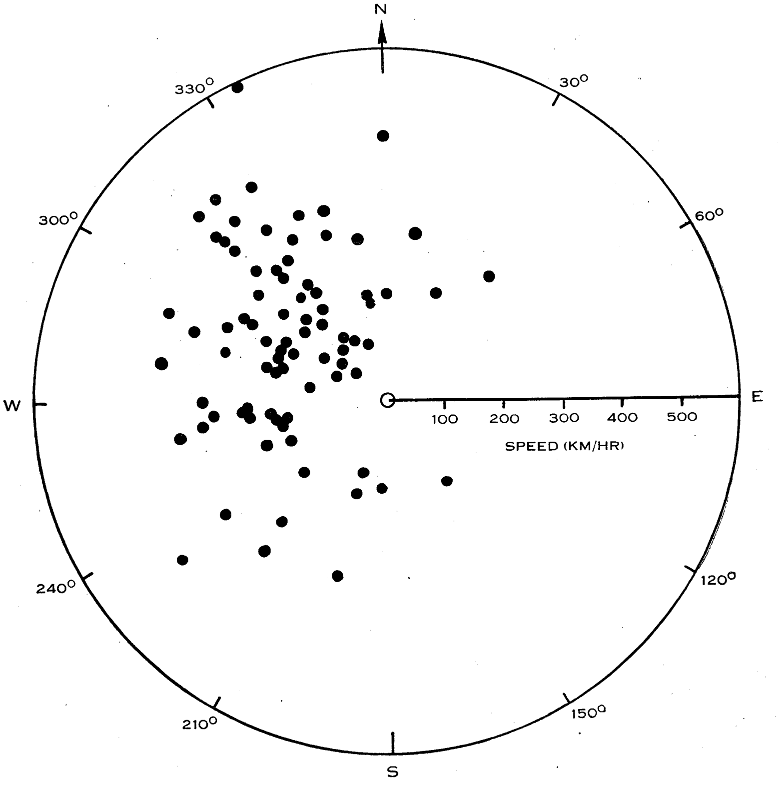


Fig. 19.—Polar plot indicating speed and directions of movement of the common tangent to the circles on the plan-position diagrams.

found by extrapolation) showed about two-thirds with time differences of 10 min or more in their commencements (if convergent) or conclsuions (if divergent). On the other hand, if pairs of convergent satellites starting simultaneously and pairs of divergent satellites finishing simultaneously were examined, differences of more than 10 min in the duration of the satellite were found in about one-half of the cases.

It was also noted that, considering pairs where the junctions were displaced by at least 10 min, about one-third were simultaneous, within 5 min, at the end of maximum range, while about one-quarter gave equal range separations, within 10 km, at that end.

A plot of durations against speeds (determined by dx/dt) for satellites is shown in Figure 21. There is evidently a tendency for the duration to decrease

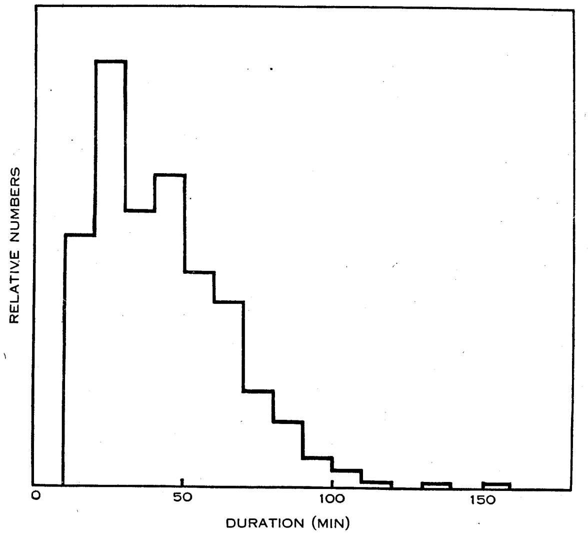


Fig. 20.—Histogram showing the distribution of durations for a large number of satellites in 1952.

as the speed increases. It has been found that, as a rough approximation, the satellite terminates when x reaches a critical value, independently of the speed.

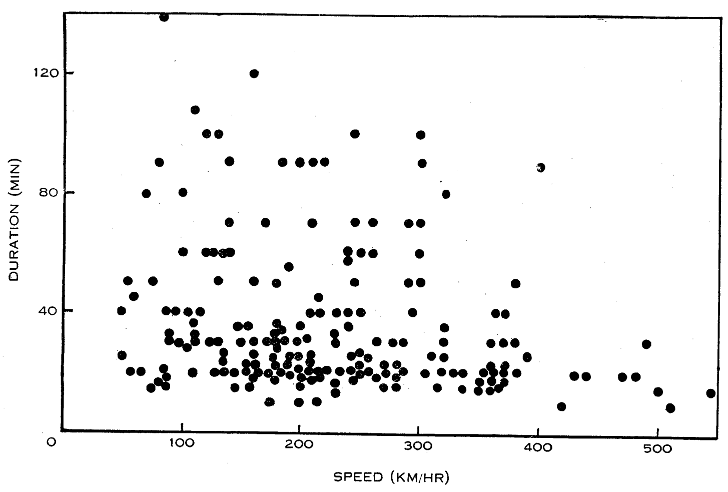


Fig. 21.—Plot of durations of individual satellites *v.* corresponding values of dx/dt.

(*h*) Seasonal *Distributions of Range Multiplets*

The total duration per night (1900–0500 hr) of some degree of range multiplet structure, as observed on the fixed frequency records, has been examined for five nights in each month for a year, 1952–53. The following figures were obtained :

June–August (inclusive)	7 hr,
December–February (inclusive)	4 hr,
Other months in the year	2 hr.

The general agreement with the published "spread-*F*" curves of Gipps, Gipps, and Venton (1948) suggests that the spreading or diffuseness index has the same seasonal distribution as range multiplicity.

The number of occurrences of well-separated range doublets in each month for the years 1952–53* is plotted in Figure 22. The seasonal variation is clearly not large.

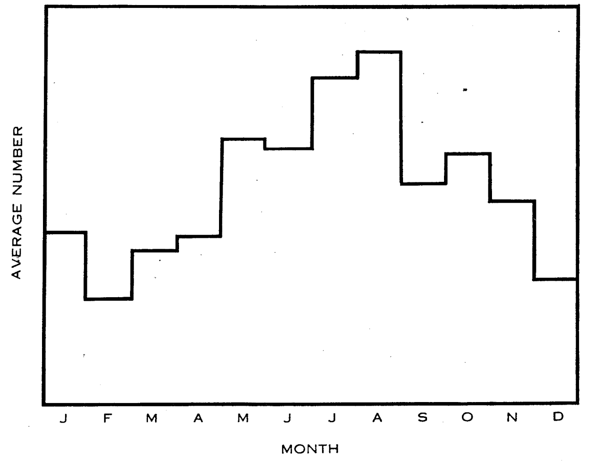


Fig. 22.—Seasonal distribution of occurrence of range doublets, 1952–53.

(*i*) *Diurnal Distributions of Range Doublets*

Since the number of range doublets in a single month is rather small, histograms have been constructed showing the total numbers of divergent, convergent, and mixed doublets, for each hourly period following actual ground sunset, during the six winter months, April–August (Fig. 23) and the six summer months, September–March (Fig. 24). Results for each year (1950–54 and 1952–53 respectively) are shown separately. The total numbers for the different years are not comparable, as for some years not all doublets were included, but only those of a more clear-cut character (usually greater duration).

The results suggest that, for winter months, the divergent doublets have a maximal probability of occurrence 2–3 hr after sunset, with a possible second maximum about 5 hr after sunset ; the convergent doublets have a maximum 3–4 hr after sunset, and the second (major) maximum an hour or two before sunrise ; and the mixed multiplets a single maximum around midnight. In

* The authors are indebted to Mr. D. Lamb for the 1952 analysis.

summer, for which season information is available for only two years, for both divergent and convergent doublets the first maximum occurs at much the same

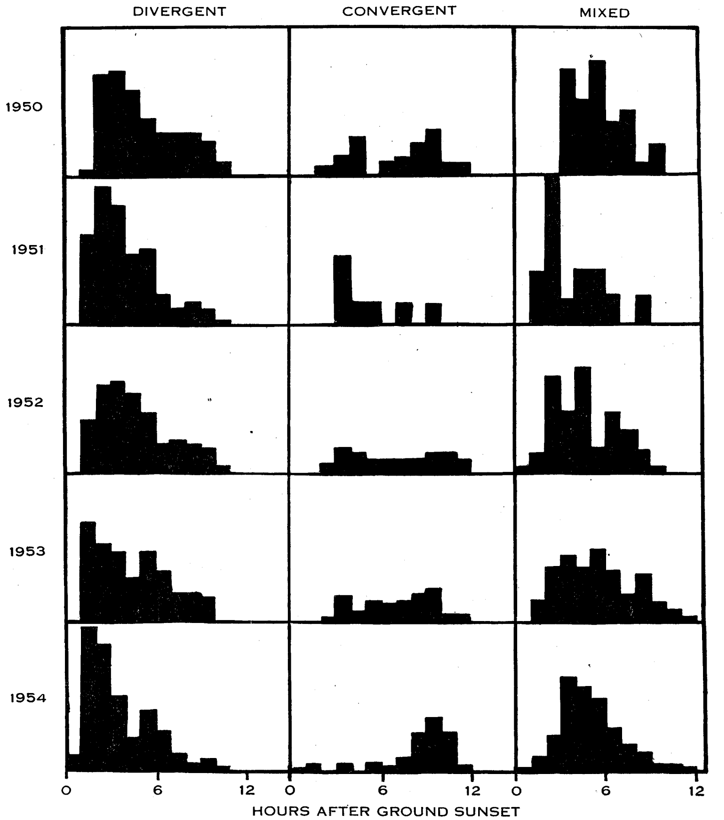


Fig. 23.—Diurnal distribution of range doublets, winter, 1950–54.

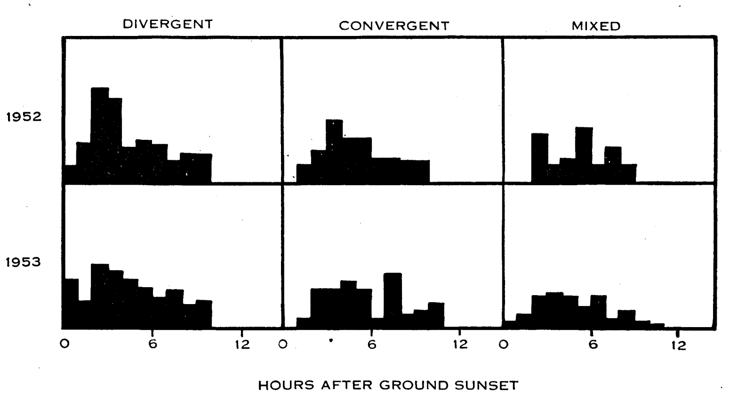


Fig. 24.—Diurnal distribution of range doublets, summer, 1952–53.

time as in winter, but the existence of a second maximum is doubtful. Data on mixed doublets in summer are insufficient to be significant.

(j) Relationship of Satellites to Other F-*region Behaviour*

The average equivalent height of the *F* region at Brisbane (as determined from the swept-frequency records) has been plotted in Figure 25 against hours after sunset. The averages were taken over six-month periods, for summer 1952–53 and winter 1953. On the curves are also marked the hours at which convergent and divergent satellites were most prevalent. It will be seen that divergent satellites occur most frequently on the rising portions of the curves, and convergent on the falling.

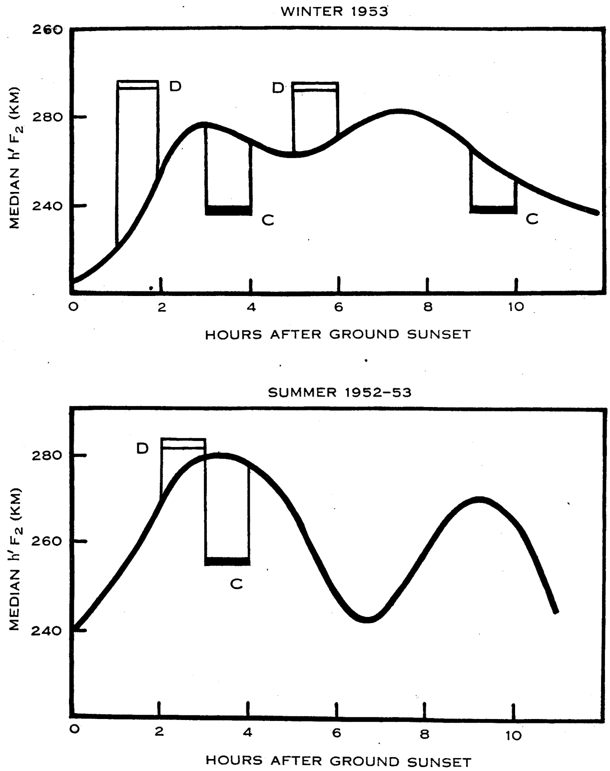


Fig. 25.—Diurnal variation of $h'F$ at Brisbane. Upper curve winter, 1953; lower curve, summer, 1952–53. Symbols attached indicate the positions of maximum frequency of occurrence of range doublets, open rectangles indicating divergent and filled-in rectangles convergent doublets.

It was found that selecting months over a period of 10 years when the 6-hr component of *F* height variation was prominent, the two maxima of frequency of occurrence of doublets of the two types showed out much more clearly.

The total electron constant of the *F* semi-layer has been determined* using the Kelso (1951) method for 10-min intervals during 12 range doublets, using the main swept-frequency trace. The changes were found to be small

* The authors are indebted to Mr. J. R. Hanscomb for carrying out this analysis.

and not related in any systematic way to the behaviour of the doublet. Some investigations have also been made, with negative results, of possible correlations with changes of semi-thickness and of critical frequency.

(*k*) *Relationship between* F *Satellites and* E_S *Phenomena*

The equipments used provide data concerning the E_s layer similar to that provided for F. The fact that the seasonal variation of occurrence of F range multiplets is not dissimilar to the seasonal variation of occurrence of E_{sc} (McNicol and Gipps 1951) suggests that their diurnal variations might also be similar. No such correlation was found. However, if the diurnal variation of occurrence of three-hop E_s is compared with that of multiplets, some measure of inverse correlation is obtained. This is most clearly brought out by using the E_s results

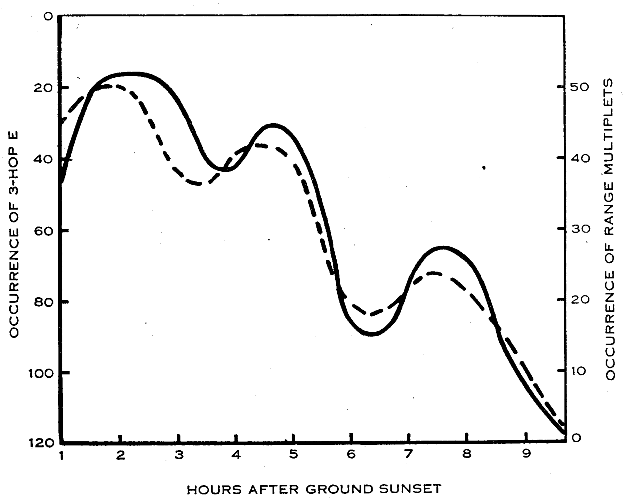
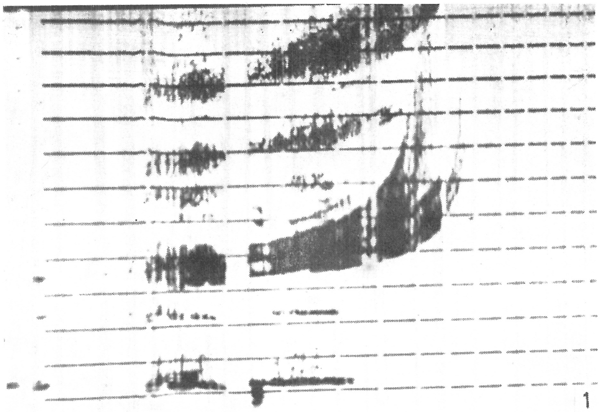


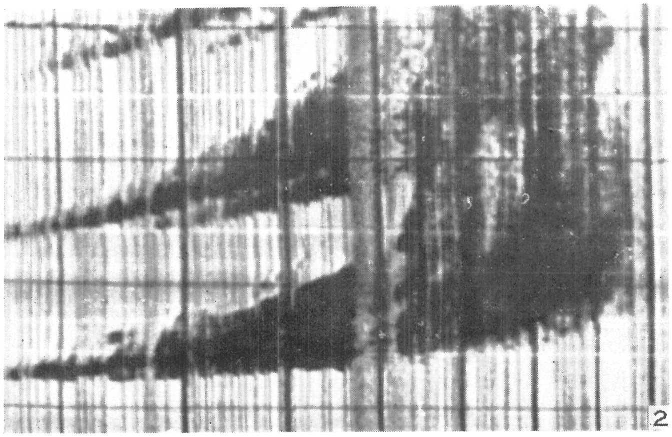
Fig. 26.—Inverse correlation between occurrence of range multiplets and $3E_s$ reflections. Diurnal variation of occurrence of three-hop E_s determined by number of 6-min periods for which it was present (full curve, plotted downwards). The broken curve gives frequency of occurrence of range multiplets (plotted upwards).

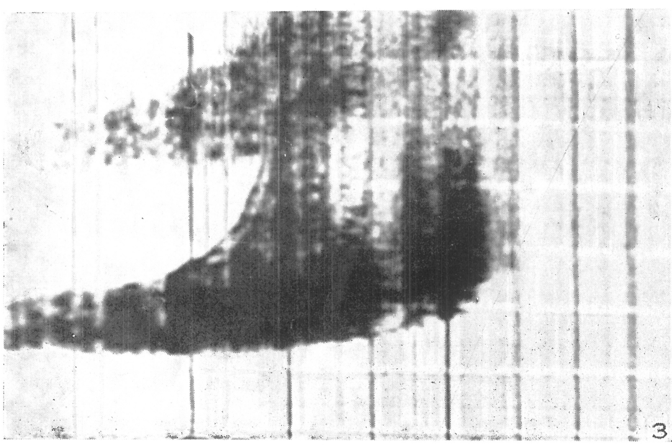
for July–August 1953, and the multiplet results for the same months (cf. Fig. 26). The results have been plotted as smooth curves, derived from the histograms by a " running means " method.

Echoes from the E_s region sometimes vary in range at an appreciable rate; the traces usually show upwards curvature. If such curved E_s traces occur at a time when E_s traces of constant range are also present, the appearance of the E_s portion of the record is similar to that of the F region when it shows satellites. However, many isolated curved E_s traces also occur (cf. Plate 5, Fig. 1). In a few cases there is excellent simultaneity between F satellites and E_s curved traces, as in Plate 5, Figure 2, but the overall correlation, over a period of several months, of two years, was found to be less than 20 per cent. In fact, although some E_s was present during 65 per cent. of F satellites in 1952 (Lamb 1954),

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. I







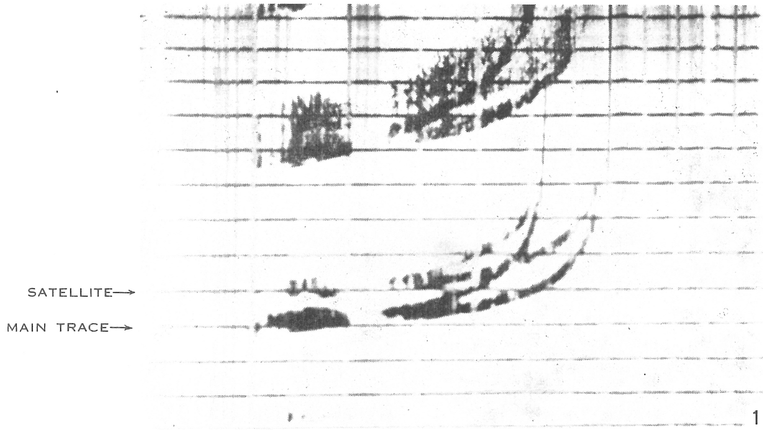
Examples of "spread-F" on $P'f$ records

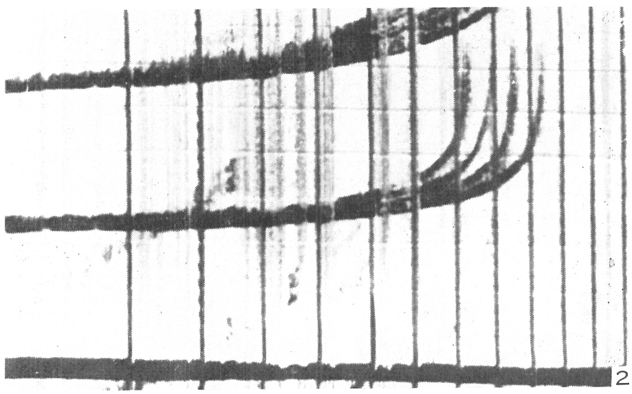
Fig. 1.—Broadened F echo; similar broadening at all frequencies. May 15, 1952, at 0215 hr.

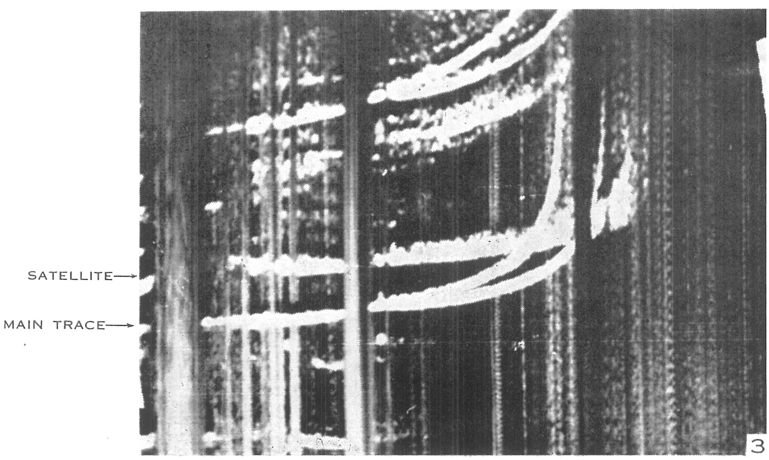
Fig. 2.—F echo broadened near critical frequencies. June 13, 1946, at 1840 hr.

Fig. 3.—Extreme cases of spread-F (echo broadened in both range and penetration frequency). June 1, 1946, at 2200 hr.

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. I







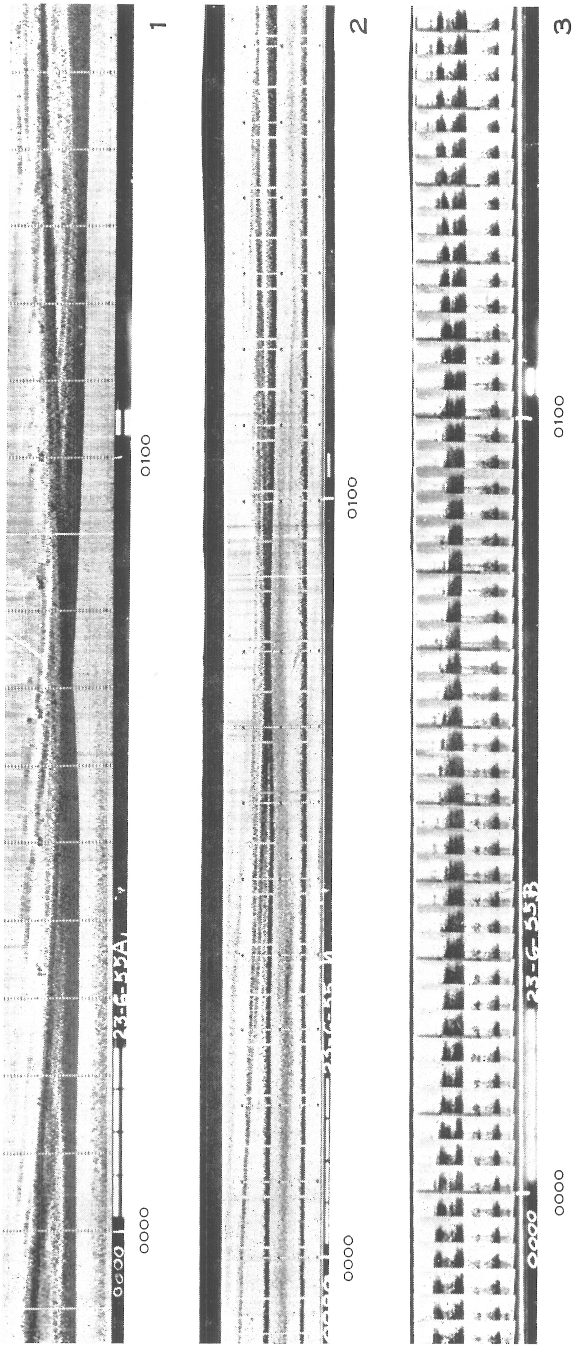
Examples of "doublets" on *P′f* records

Fig. 1.—Range doublet, both components having same critical frequency. October 11, 1952, at 0150 hr.

Fig. 2.—Range doublet, upper trace giving higher critical frequency. February 3, 1955, at 0210 hr.

Fig. 3.—Penetration-frequency doublet. December 17, 1955, at 2130 hr.

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. I



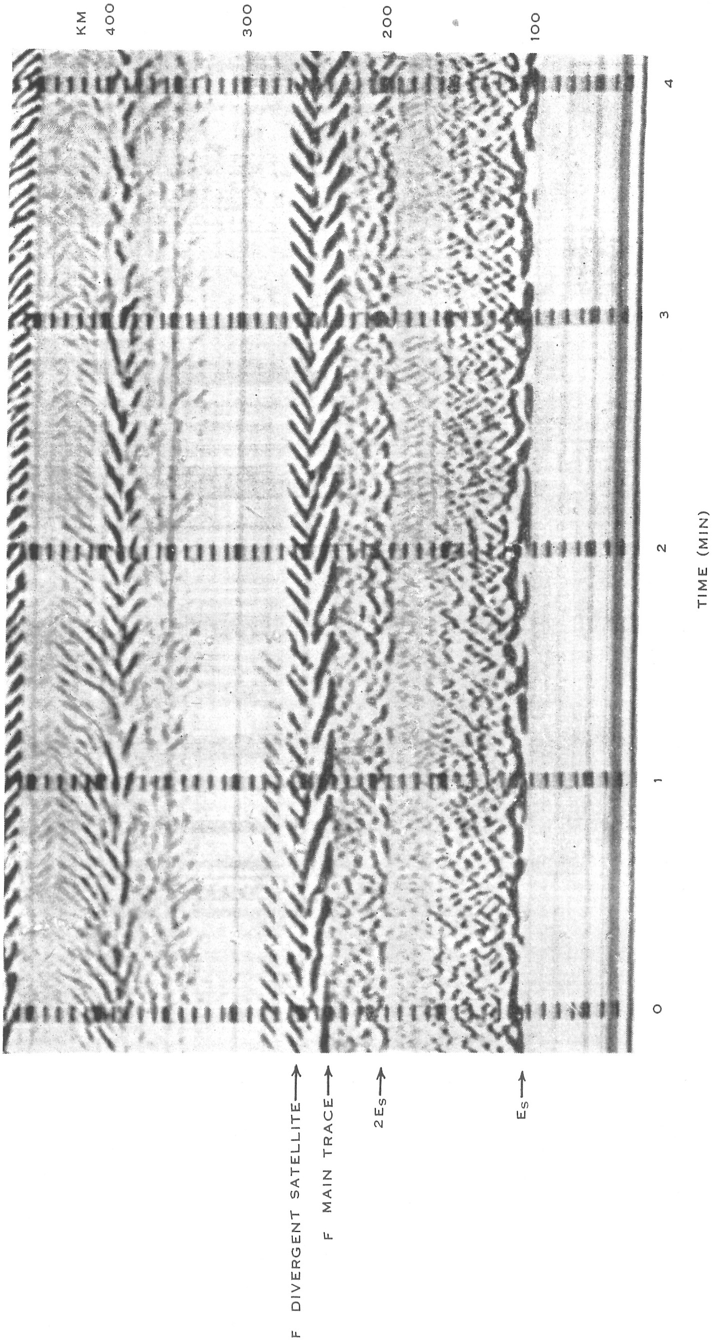
Mixed range multiplet (June 23, 1955)

Fig. 1.—Record made at normal incidence at Brisbane, fixed gain.

Fig. 2.—Record made with pulses transmitted from Toowoomba, received at Brisbane, fixed gain.

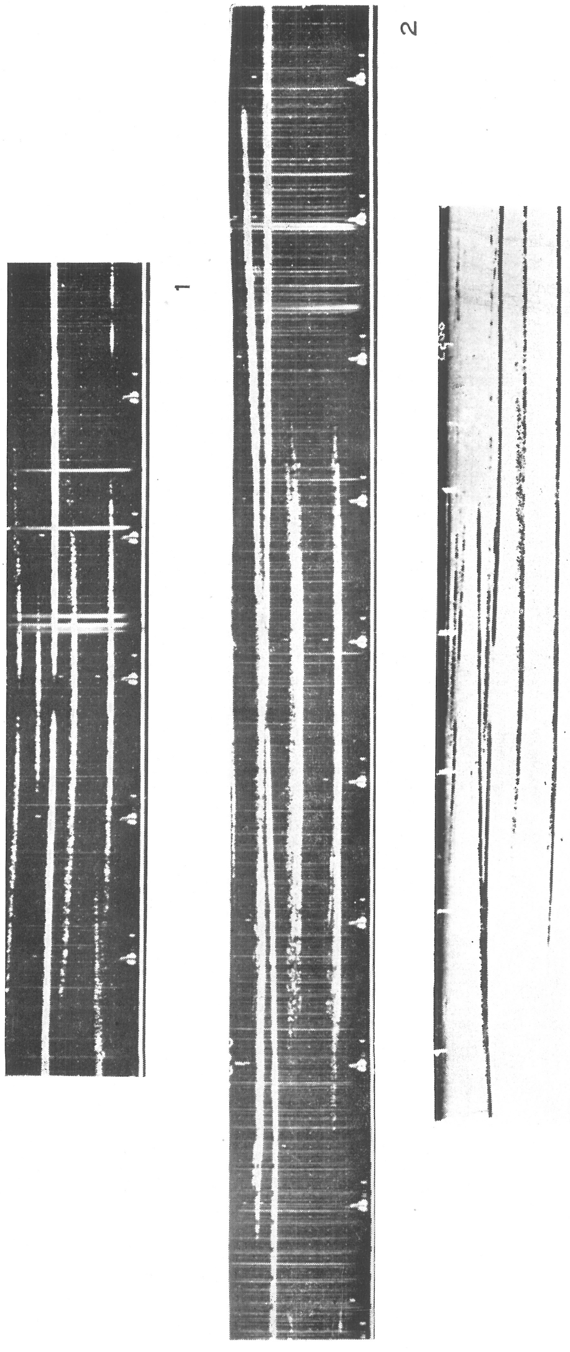
Fig. 3.—Record made at normal incidence at Brisbane with swept-gain receiver.

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. I



Portion of phase-path record, showing behaviour of main *F* trace and satellite during divergent range doublet. June 20, 1955, at 1900 hr. (The short lines sloping upwards to the right, which compose the satellite trace, indicate that the phase path is increasing; short lines sloping downwards to the right, which compose the main trace, indicate that the phase path of this trace is decreasing.)

SPREAD-F IONOSPHERIC ECHOES AT NIGHT AT BRISBANE. I



1 2 3

Relations between *F* satellites and E_s phenomena

Fig. 1.—Strongly reflecting curved E_s traces, no *F* satellites. March 15, 1952, at 0100 hr.

Fig. 2.—Good simultaneity between curved E_s traces and *F* satellites. March 13, 1952, at 0230 hr.

Fig. 3.—E_s region blankets main *F* region trace, but not *F* satellite. April 2, 1952, at 2130 hr.

this is close to the ordinary probability of occurrence of E_s echoes on 2·28 Mc/s at night at Brisbane (Thomas, personal communication 1955).

On some occasions E_s region blankets the main F trace (2·28 Mc/s) but not the satellite (cf. Plate 5, Fig. 3), and vice versa.

(*l*) *Relationship to Geomagnetic Behaviour*

An investigation* of the relationship between occurrence of Brisbane range doublets and magnetic disturbance indices for Toolangi (lat. 37° 32′ S., long. 145° 28′ E.) led to negative results, in agreement with the findings of Uyeda and Ogata (1954).

IV. Acknowledgments

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* The authors are indebted to Mr. W. M. Coleman for carrying out this analysis.