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RADIO ECHO OBSERVATIONS OF METEORS

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Summary

(1) Apparatus is described with which echoes due to meteors have been observed by radio technique during 1946 June–August.

(2) Simultaneous visual and radio echo observations were made during the 1946 Perseid epoch. Good correlation with meteors was obtained for echoes lasting more than 0·5 sec. The correlation with echoes of shorter duration was very poor.

(3) The ranges, durations and amplitudes of 1836 echoes are discussed.

(4) Data are given for the daily rate of occurrence.

(5) An approximate quantitative relationship is given between meteoric ionization and amplitude of the echo, and the extent of the correlation with visual meteors is discussed.

1. *Introduction.*—The use of radio waves of frequencies between 1 and 20 Mc./sec. for investigating the ionized layers of the upper atmosphere is a well known technique. At some critical frequency in this range, dependent on time and place of observation, the reflected wave usually disappears, and waves of higher frequencies penetrate the E and F ionized layers and are not reflected. Abnormal reflections exist at frequencies well above the normal critical frequency, originating at approximately the level of the E-layer of the ionosphere. There are two types of abnormal reflection: (1) that from the abnormal ionization known as "abnormal E" persisting for periods of several minutes or hours at a height below the normal maximum of the E-region, and (2) transient echoes of durations generally a fraction of a second but lasting in certain cases to upwards of 60–100 sec.* These transient echoes exist for much higher radio wave frequencies than "abnormal E", and are now known to be associated with the passage of meteors through the upper atmosphere.†

Work on the transient echoes has been in progress at the Jodrell Bank Experimental Station of the University of Manchester since 1945 October and an account is given in this paper of the results obtained from 1836 echoes recorded between 1946 June 13 and August 14.

2. *Apparatus.*—The transmitter worked on a frequency of 72·4 Mc./sec. ($\lambda = 4{\cdot}2$ m.) and radiated 150 pulses per second each of 8 microseconds duration. The peak power in the pulse was 150 kW. The transmitter and receiving aerials were identical Yagi's and were directed vertically. In the N/S direction the beam width was ±22° down to half intensity and ±45° down to zero intensity. In the E/W direction the beam width was ±20° down to half intensity and ±35° down to zero intensity. There were side lobes as follows: in a N/S direction a small side

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* For a review of the work on abnormal ionization in the E-region see Lovell, *Rep. Progr. Phys.*, **11**, 1948.

† Skellett, *Proc. Inst. Radio Engrs.*, N.Y., **23**, 132, 1935; Pierce, *Proc. Inst. Radio Engrs.*, N.Y., **26**, 892, 1938; Appleton and Naismith, *Proc. Phys. Soc.*, **59**, 461, 1947; Hey and Stewart, *Nature*, **158**, 481, 1947; *Proc. Phys. Soc.*, **59**, 858, 1947.

lobe of intensity 5 per cent of maximum between 60° and 70° from the vertical; in an E/W direction a large side lobe with an intensity 40 per cent of the maximum with its peak at 65° from the vertical. The power gain of each aerial was 7·5 compared with a half wave dipole. The receiver was of conventional superheterodyne design using an intermediate frequency of 9 Mc./sec. and band width of $2{\cdot}5 \times 10^5$ c.p.s. The sensitivity was such that a power of $2{\cdot}0 \times 10^{-14}$ watts at the receiver input gave a detectable signal. The echoes were observed visually on a cathode ray tube using a linear time base calibrated so that the range of the echoes could be read directly. A master oscillator controlled the initiation of the transmitter pulse and of the time base.*

If the passage of a meteor through the atmosphere scatters back sufficient energy from the radiated transmitter pulse to the receiver an echo will be observed on the cathode ray tube at the appropriate range.† In addition to the range, the amplitude (vertical deflection) and duration were measured. In the present investigations these observations were made visually and hence the durations given for echoes lasting less than 0·5 sec. are estimates only.

3. *Correlation with visual observations.*—Between the nights of July 29 and August 14 inclusive a simultaneous visual and radio watch was arranged in order to establish coincidences between the visible meteors and the echoes appearing on the cathode ray tube. The visual observations were made by the Meteor Section of the British Astronomical Association. Weather conditions prevented effective combined work, except on part of the nights July 31, August 8, 10 and 14 so that less than one-fifth of the expected number of visual observations was obtained. Table I contains details of the combined watches and of the coincidences.

TABLE I

Date	Details of Combined Watch		Numbers		
G.M.A.T.‡	Limits	Duration h m	Echoes	Visual	Coincidences
July 31	1030–1400	2 15	45	15	4
Aug. 8	1011–1044	0 28	7	5	2
10	0900–1430	4 35	35	29	6
14	0845–1055	2 0	20	8	5

There is a wide divergence between the total number of echoes and the coincident visual meteors, but when the echoes are analysed according to their duration better agreement is found for the long duration echoes. The results of such analysis are given in Table II.

The direct analysis shows that 50 per cent of the echoes with durations $>0{\cdot}5$ sec. were coincident with visual meteors, and if we exclude seven echoes at very long range (which must have occurred in side lobes, outside the area of visual watch) the correlation improves to 65 per cent. On the other hand,

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* More detailed descriptions of the principles of operation and circuit details of these types of transmitters and receivers can be found in the special Radiolocation Convention issue of the *Institution of Electrical Engineers*, **93**, Part III A, Nos. 1 to 9, 1946–7.

† The appearance of a typical meteor echo is illustrated in Fig. 3 (Plate 3), p. 168 from a photograph of the cathode ray tube taken during another series of observations.

‡ To avoid change of date at midnight in these observations Greenwich Mean Astronomical Time (G.M.A.T.) has been used. To convert G.M.A.T. to U.T. add 12 hours.

TABLE II

Date		Duration of Echoes (secs.)				
		$=0{\cdot}1$*	$=0{\cdot}2$*	$>0{\cdot}2$ $\leqslant 0{\cdot}5$	$>0{\cdot}5$ $\leqslant 1{\cdot}0$	$>1{\cdot}0$
July 31	E	24	11	3	3	3
	C	0	1	1	2	0
Aug. 8	E	5	0	2	0	1
	C	0	0	1	0	1
10	E	19	4	1	1	10
	C	0	0	0	0	6
14	E	3	3	5	3	6
	C	0	0	1	2	2
Total	E	51	18	11	7	20
	C	0	1	3	4	9

E=*Echoes.* C=*Coincidences.*

* *Durations estimated.*

coincidences for echoes $\leqslant 0{\cdot}5$ sec. were infrequent and there was no correlation at all with echoes of the shortest duration. The extent of this correlation is discussed in Section 5 (a).

For fifteen of the coincident meteors the approximate apparent position was recorded by the visual observer, and the heights can therefore be calculated from these data and from the range of the radio echo, free from any ambiguity due to the spread of the radio beam. Details of these coincidences and of the observed heights are given in Table III. These heights are however subject to errors of the order of 10–15 km., due to (1) an ambiguity as to the exact point upon the meteor's path from which the echo was returned and (2) abnormal casual errors in the visual observations due to the strong moonlight; but they are generally in good agreement with the heights of the Perseid meteors determined by triangulation *, except for No. 12 which is at present an isolated discordant result.

4. *Characteristics of meteor echoes.*

(a) *Range distribution.*—The range distribution of the echoes will vary with the type of aerial system used and the sensitivity of the apparatus, and the data here given are intended merely to illustrate the type of results obtainable with this apparatus. A typical plot of the distribution in range is given in Fig. 1 which contains the measured ranges of all echoes observed between August 12^{d} 01^{h} 00^{m} and 08^{h} 40^{m} G.M.A.T. This shows a sharp peak between 90 and 110 km.; the cut-off is sharp on the shorter range side, but at long ranges occasional echoes are observed out to 500 km. Since the transmitter and receiver arrays were vertically directed Fig. 1 can also be taken as a close approximation to the distribution in heights at the short range end, but not at long ranges because the width and side lobes of the aerial beam introduce a considerable uncertainty in the heights of the longer range echoes.

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* J. G. Porter, *M.N.*, **104**, 262, 1944.

TABLE III

Coincidences

No.	G.M.A.T. 1946	Radio Echo			Visual			*H*
		R km.	*A*	*D* secs.	Mag. (obs.)	*h*	*D* secs.	km.
	July d h m					°		
1	31 10 51	95	S	1·0	1	75	...	92
2	54	112	3	0·5	4	90	...	109
3	13 36	108	3	0·2	0½	75	...	105
4	39	105	3	1·0	0½	75	...	102
	August							
5*	8 10 23	135 128	2 3	35·0	2	57	1·0	109
6	39	105	3	0·3	5	86	0·5	105
7*	10 09 12	105 95	2	20·0	0	...	0·9	...
8	11 50	275	3	30·0	1½	...	0·7	...
9	13 13	120	2	12·0	1½	54	0·4	97
10	35	270	2	12·0	0	24	0·4	111
11	45	200	2	12·0	1½	32	0·6	106
12	14 18	400	3	6·0	3	39	0·4	252
13*	14 09 25	138 141	3	1·5	2½	62	0·7	123
14*	35	135 128	3	1·0	2	51	0·7	101
15*	10 12	128 131	5	1·5	1	57	0·5	109
16	24	152	2	1·0	2	50	0·5	117
17	29	130	1·5	0·5	2½	40	0·4	83

R=*range*. *A*=*amplitude*. *D*=*duration*.
Mag.=*observed magnitude*. *h*=*altitude*.
H=*height*. S=*saturation*. *=*a travelling echo*.

The range distributions measured from day to day and for different periods of the day show minor variations in the general form of Fig. 1, but the data are insufficient to determine whether these variations are significant.

(b) *Amplitudes*.—The distribution in the amplitude of the echoes is plotted in Fig. 2. The abscissa gives the ratio of the amplitude of the echo to the normal noise level of the receiver, and the power in watts at the receiver input which this represents. The ordinate gives the percentage of the total number of echoes which occur with a given signal-noise ratio. There were no significant changes in this distribution during the period of the observations. The curve is still rising sharply at the lowest level of signal detectable, thus suggesting that many more echoes could be obtained with a more sensitive apparatus. This expectation has been realized in more recent work.*

(c) *Duration of echoes*.—The distribution in duration of the 1836 echoes in this sample is plotted in Fig. 3, p. 160.

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* See Lovell, Banwell and Clegg, *M.N.*, **107**, 164, 1947.

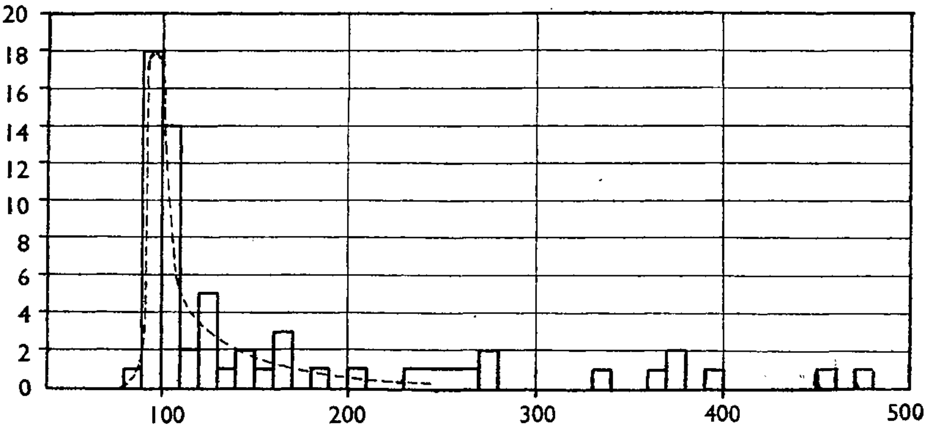

FIG. 1.—*Range distribution of echoes measured between* 1946 *August* 12^{d} 01^{h} 00^{m} *and* 08^{h} 40^{m} *G.M.A.T.*
Ordinates: Number of echoes in 10 *km. intervals.*
Abscissae: Range in km.

During 1946 June–July more than 80 per cent of the echoes were of durations less than 0·5 sec., most of them being estimated at 0·1 or 0·2 sec. During the Perseid epoch the proportion of long duration echoes increased, as shown in Fig. 4B (Plate 2), the proportion of very short duration echoes decreasing to 50 per cent. The echoes of very long duration were almost entirely confined to the epoch of Perseid maximum. The longest durations measured were 90, 80 and 50 secs., on August 12, 12 and 13 respectively.

(d) "*Travelling*" *echoes.*—The majority of the echoes appear as deflections of the time base which are stationary in range. Fifty-five of the echoes, however, were seen to travel in range, ten increasing in range and forty-five decreasing. The greatest movement observed was 50 km. but movements of 5 to 10 km. were

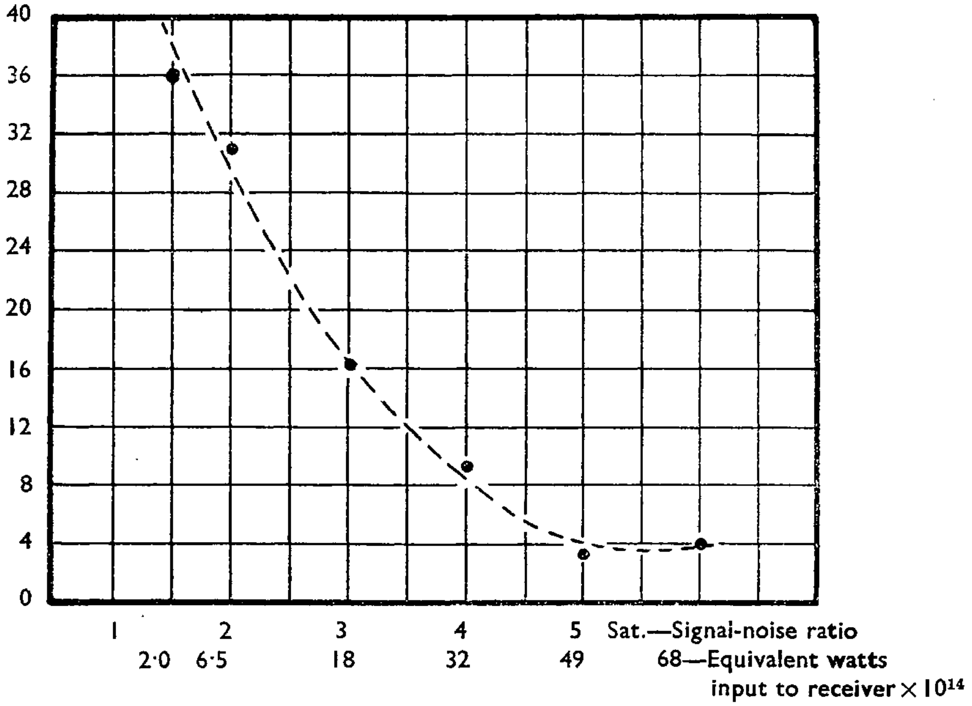

FIG. 2.—*Distribution of amplitudes (percentage of total signal-noise ratio)* 1946 *June, July, August.*
Ordinates: Percentage of total.

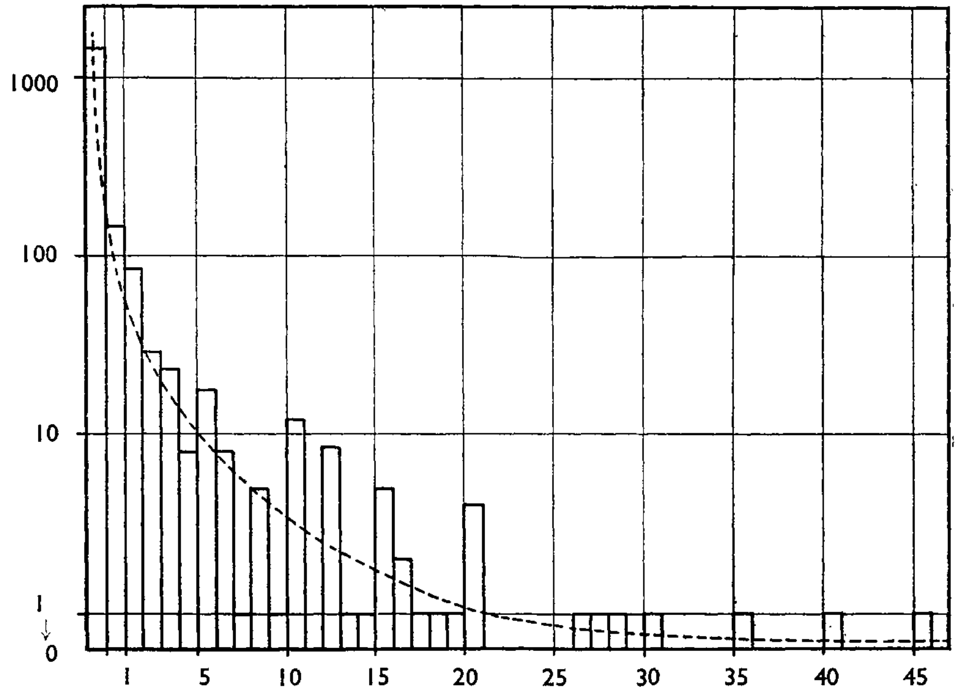

Fig. 3.—*Histogram of distribution in duration of* 1836 *echoes,* 1946 *June, July, August. (Logarithm of number of echoes in intervals* $<\frac{1}{2}$ *sec.;* $\geqslant\frac{1}{2}<1$; $\geqslant 1<2$; $\geqslant 2<3$; *etc.).*
Ordinates : Number of echoes.
Abscissae : Duration (seconds).

most common. The velocity of movement which could only be estimated very approximately varied considerably; some moving at only a few km./sec. and others up to velocities of the order of 60 km./sec. Small movements of 1 or 2 km. in range would not be detected by us and the possibility that many more echoes show such small movements cannot therefore be excluded. Some of these travelling echoes may be due to the motion of a meteor trail of high ionization scattering back a weak deflection before it reaches the broadside position.*

(e) *Complex echoes.*—Normally the echoes are clear-cut in appearance but occasionally complex echoes are observed. Thirteen were recorded with abnormal breadths of from 3 to 10 km., seven of which were travelling echoes. Three cases of apparently related but distinct echoes were observed.

(f) *Rate of occurrence (hourly rates).*—The rate of occurrence of the echoes in this sample throughout the period 1946 June 13 to August 14 is plotted in Fig. 4A (Plate 2). The number of echoes observed on apparatus of this type will depend on the parameters of the receiver, transmitter and aerial system. Echoes are in general only observed when the meteor passes at right-angles to the radio beam, and care is therefore necessary in interpreting the echo rates plotted in Fig. 4A (Plate 2). The beam was vertically directed throughout these observations, and variations of the altitude of the radiant at the time of special streams such as the Pons-Winnecke meteors, the δ Aquarids and the Perseids may be expected to cause considerable fluctuations in the observed echo rate. The following broad conclusions may however be drawn:

(*a*) The remarkably high rate of occurrence between June 19 and July 5 may indicate the presence of the Pons-Winnecke shower, though this cannot be stated

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* Hey, Parsons and Stewart, *M.N.*, **107**, 176, 1947.

with certainty from this set of observations. On other dates in June and July a rate of 15–20 an hour was frequently observed, which is far higher than the rate obtained on ordinary dates in the following autumn and these June–July observations, being made during daylight hours, may be of streams not observable at night.*

(*b*) The Perseids had a less noticeable effect than was expected; there was a sharp increase in the hourly rate about August 11^{d} 13^{h} G.M.A.T., but apart from this the stream did not cause a marked change in the rate such as was found by Hey and Stewart † for the 1946 Quadrantids and Lyrids.

(*c*) The Perseids, however, were accompanied by a very marked increase in the rate of occurrence of the echoes of longer duration. This is shown in Fig. 4B (Plate 2), where the percentage of echoes with durations >0·5 sec. are plotted.

5. *Discussion.*

(a) *Relation between meteors and transient echoes.*—Details of the observed correlation are given in Section 3. Two cases arise for discussion: (*a*) where a visual meteor does not give rise to any echo, (*b*) where an echo is recorded but no meteor is seen. The first case is explained by the critical dependence of echo strength on the angle between the meteor trail and the radio beam. The second case requires further discussion. It will be shown elsewhere ‡ that if a radio beam is directed at right-angles to a meteor trail the power ϵ scattered back to the receiver from the column of electrons created by the passage of the meteor through the atmosphere is given by

$$\epsilon = 3{\cdot}3 \times 10^{-28} \frac{\alpha^2\lambda^3}{R^3} P_0 G^2 \text{ watts,} \qquad (1)$$

where α = number of electrons produced per cm. path by the meteor,

λ = wave-length (cm.),

P_0 = peak transmitter power (watts),

G = power gain of the aerial system (assumed to be the same for transmitter and receiver),

R = range of echo (cm.),

and the numerical constant contains the cross-section for scattering by the electrons. This relation is derived on the assumption that the effective diameter of the ionized column is so small compared with the wave-length (4·2 m.) that phase differences across the column are negligible and that the scattering is by free electrons.

The dependence of α on size and velocity of the meteor is given in the theory of meteor ionization developed by Herlofson §, whose calculations indicate that for a meteor of velocity 40 km./sec. a meteor near the limit of visibility will produce

$$\alpha = 10^{10} \text{ electrons/cm.}$$

and that α is proportional to the size of the meteor for a given velocity. Now in

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* *Note added in proof.*—Observations during the summer of 1947 have shown that this high rate is due to an extensive daylight meteor stream which transits between $10^{h}{\cdot}00$ and $11^{h}{\cdot}00$ U.T.; see *British Astronomical Association Circulars*, Nos. 282, 285, 1947.

† Hey, Parsons and Stewart, *loc. cit.*

‡ Lovell, *Nature*, **160**, 670, 1947.

§ Herlofson, in publication; see also *Rep. Progr. Phys.*, **11**, 1948.

the apparatus described in this paper

$$\lambda = 420 \text{ cm.}, \quad P_0 = 1{\cdot}5 \times 10^5 \text{ watts}, \quad G = 7{\cdot}5.$$

Hence, taking $R = 95$ km. (the most frequent range—see Fig. 1) and substituting in (1) we obtain

$$\epsilon = 3{\cdot}0 \times 10^{-14} \text{ watts.}$$

Reference to Fig. 2 shows that a received power of this or greater amount was obtained for 64 per cent of the echoes, so that for 36 per cent of the echoes the ionization and hence the luminosity was insufficient for the meteor to be observed with the unaided eye. Furthermore, in considering the remaining 64 per cent account must be taken of the limitations of the eye in the perception of the fainter meteors, a large proportion of which are missed by a given observer.* An estimate of the probable number of meteors overlooked by the visual observer may be obtained from the experimental data derived by Öpik† for the Perseid shower. His investigation shows that for meteors of zenithal magnitude 4·0 the ratio of the number seen by a given observer to the total number of that magnitude appearing in a standard area is approximately 1:11, and similarly for meteors of zenithal magnitude 3·0 the corresponding ratio is 1:3. Assuming therefore a normal distribution of visual magnitudes in this sample we should expect that only about 13 per cent of the echo producing meteors would be seen by a single visual observer. The observations (Table II) show 17 coincidences in 107 echoes, i. e. the observed correlation is of the right order.

From the details of range and amplitude of the coincident echoes given in Table III it is possible to calculate the number of electrons produced per cm. path by the use of equation (1). The results are given in Table IV, in which the reference number corresponds to the reference in Table III and α is the calculated number of electrons per cm. path.

TABLE IV

No.	α	No.	α	No.	α
1	$5{\cdot}1 \times 10^{10}$	7	$1{\cdot}8 \times 10^{10}$	13	$4{\cdot}6 \times 10^{10}$
2	3·3	8	13·0	14	4·4
3	3·1	9	2·1	15	6·9
4	3·0	10	7·4	16	3·1
5	4·4	11	4·7	17	1·3
6	3·0	12	22·6		

There is an uncertainty in these results due to the spread of the aerial beam. The power gain G assumed in calculating α is 7·5, which would be correct for a meteor passing across the axis of the aerial beam. In most of the cases listed above, however, the range plots and the visual observations indicate that the meteor passed through the beam at a distance from the axis. Hence the values of α calculated above must be assumed to be *minimum* values. Even so, these values of α are greater than the value of α calculated for a meteor near the limit of visibility.

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* T. W. Backhouse, *Observatory*, **7**, 299, 1884.

† E. Öpik, *Publ. Obs. Tartu*, **25**, No. 4, 1923.

The theory is therefore capable of giving a quantitative explanation of the degree of correlation between radio echoes and visual meteors. Later experimental work with a directional aerial system during the Giacobinid shower of 1946 has shown* that echoes of whatever duration are correlated with the hourly rate of the shower, thus confirming that all these types of transient echo are associated with meteors.

6. *Acknowledgments.*—The authors are indebted to the Director and staff of the Jodrell Bank Experimental Grounds, University of Manchester, for facilities and help given during the development of this work; to the Director of Radar, War Office, for the loan of equipment; to the G.O.C. in C., A.A. Command, for assistance in the inception of this work, and to Mr J. S. Hey of Ministry of Supply, A.O.R.G., for his assistance and advice. Their thanks are also due to Professor P. M. S. Blackett, Director of the Physical Laboratories, for his encouragement and to Mr C. E. Young for technical assistance, and to the Meteor Section observers Messrs G. S. Hawkins and M. W. Ovenden for their visual observations.

Meteor Section,
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1947 *January* 8.

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* Lovell, Banwell and Clegg, *loc. cit.*

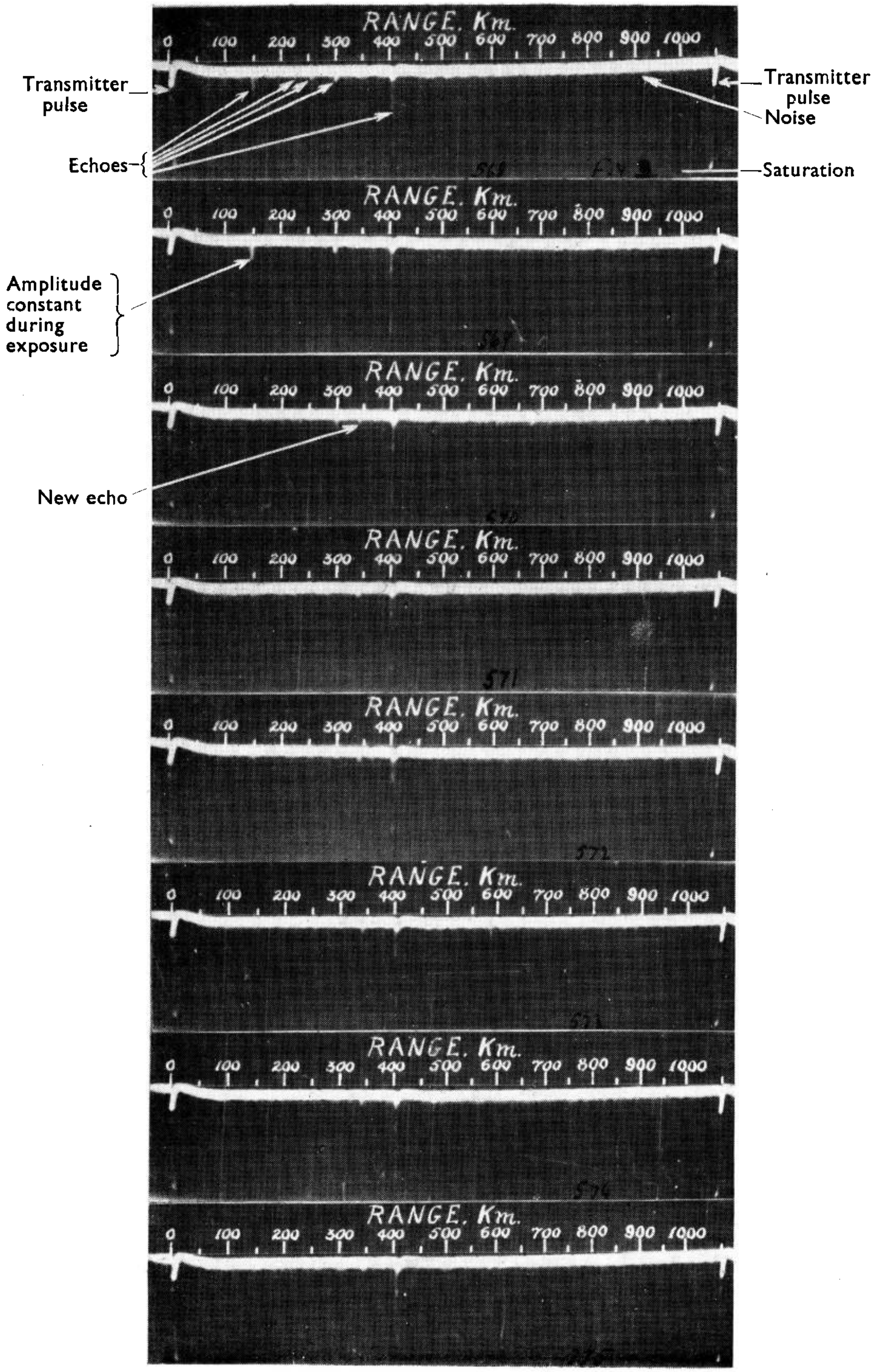

FIG. 3.

A. C. B. Lovell, C. J. Banwell and J. A. Clegg, Radio Echo Observations of the Giacobinid Meteors **1946.**

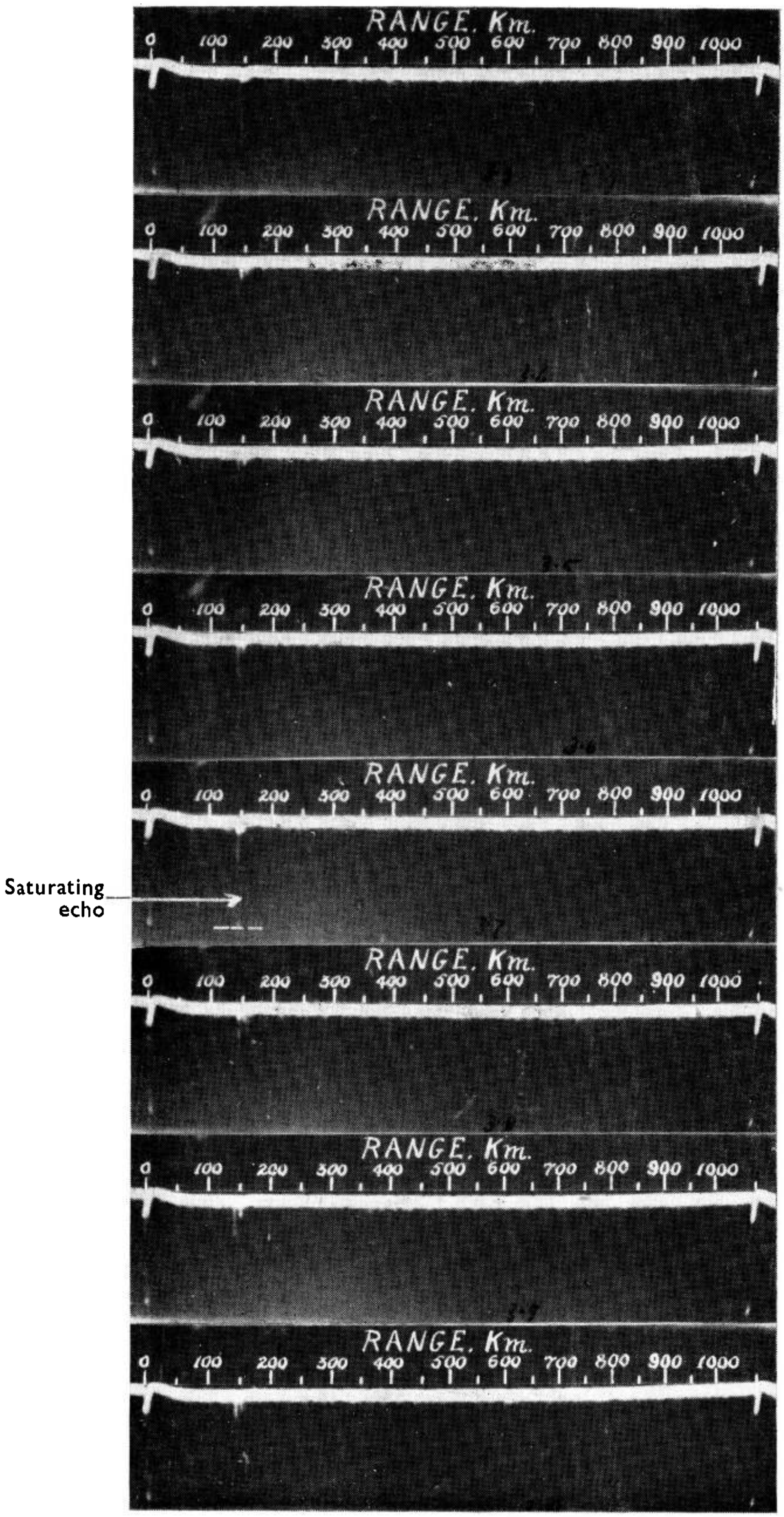

Fig. 4.

A. C. B. Lovell, C. J. Banwell and J. A. Clegg, Radio Echo Observations of the Giacobinid Meteors 1946.