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THE HISTORY OF THE FIRST TWENTY-FIVE YEARS OF RADAR METEOROLOGY IN THE UNITED KINGDOM

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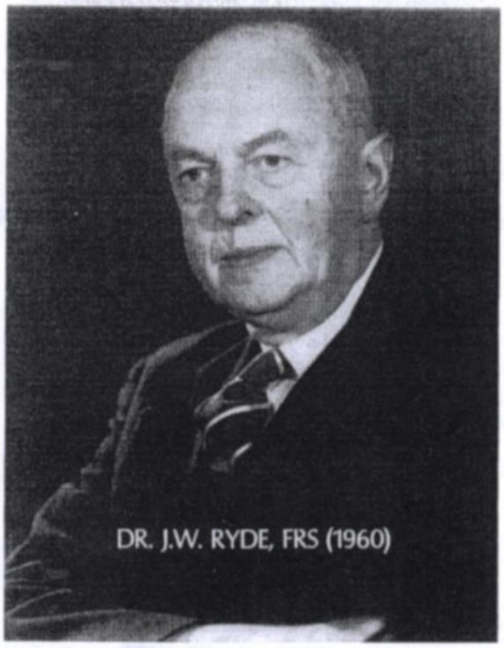


Dr. J.W. Ryde
Father of Radar Meteorology

CONTENTS

1. Introduction

This history describes all the research carried out in radar meteorology in the United Kingdom between 1940 and 1965, together with a complete bibliography. It is hoped that this will provide a useful reference source for anyone interested in the subject.

After the introduction of pulsed radar by Robert Watson-Watt in 1936, the imminence of war led to rapid developments. 10cm wavelength radars were installed at the General Electric Company Research Laboratory, GEC, in Wembley, Middlesex in July, 1940, and at the Air Ministry Research Establishment in Swanage, Dorset, in August, 1940. Both radars would have had the capability to detect weather echoes at close range, but the first report is of the Swanage radar following a thunderstorm over the English Channel for half an hour up to a range of seven miles on 21 February 1941 (Ligda 1951). This can be said to mark the beginning of observational radar meteorology. During the war of course radar was top secret and the only studies specifically related to radar meteorology were Ryde's theoretical work detailed in Section 2, investigations into anomalous propagation by e.g. Booker at TRE (Section 4), and a study by Ross detailed below. Otherwise, echoes from meteorological phenomena were simply regarded as interference.

Research was carried out during the war at the General Electric Company Ltd at Wembley and at the Telecommunications Research Establishment, TRE. Once the war was over the ability of radar to be used as a meteorological tool began to be investigated. Four establishments were involved at various times during the period under review. The Meteorological Office formed a radar research station at East Hill, near Dunstable, Bedfordshire. Several scientists worked each for two or three years at the TRE, which in 1953 became the Radar Research Establishment and in 1957 the Royal Radar Establishment, RRE, in Malvern, Worcestershire. At the Cavendish Laboratory, Cambridge University, two successive research students produced theses on radar meteorology using radars on loan from TRE. The Department of Meteorology, Imperial College, London had a radar for a short time and occasionally collaborated with East Hill. All the work done at each establishment is described in separate Sections.

The only practical use of radar in meteorology during the war that is known was carried out by Ross (1946). Ross was a Lieutenant-Commander in the Royal Navy; in 1944 from early summer until the end of the year he was able to collect very interesting weather data from high-power coastal radars operating on a wavelength of 10cm in the Orkney area. He considered one rather good example of the detection of the rain belt associated with a cold front moving in from the west over the Orkneys on 10 October 1944. Figure 1 shows the synoptic chart for 1200GMT together with the radar observations. He noted that the echo belt expanded as it approached Orkney. This could be explained by the front intensifying, and eventually slowing up, as the result of the development of a secondary disturbance to the southward. Ross made some very pertinent and prescient comments. He wrote "I should like to stress the need for correlation of the radar observations with the usual synoptic chart and other relevant weather information". Unbelievably, there is almost no evidence that this was ever done in the following twenty years, the only other being a synoptic chart showing a frontal system over the British Isles with some radar echoes marked (Ludlam and Mason 1957).

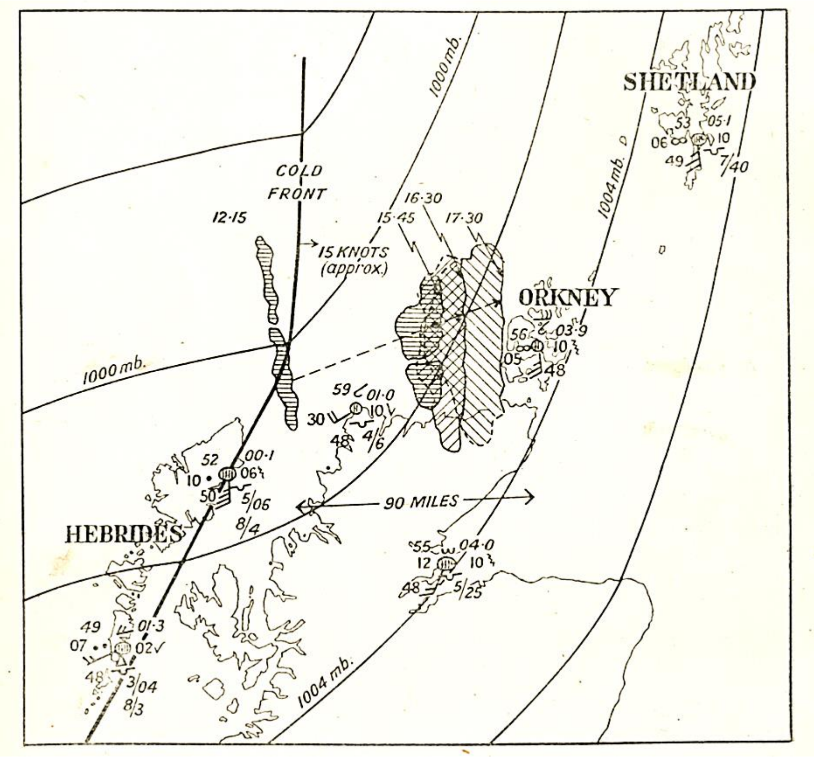
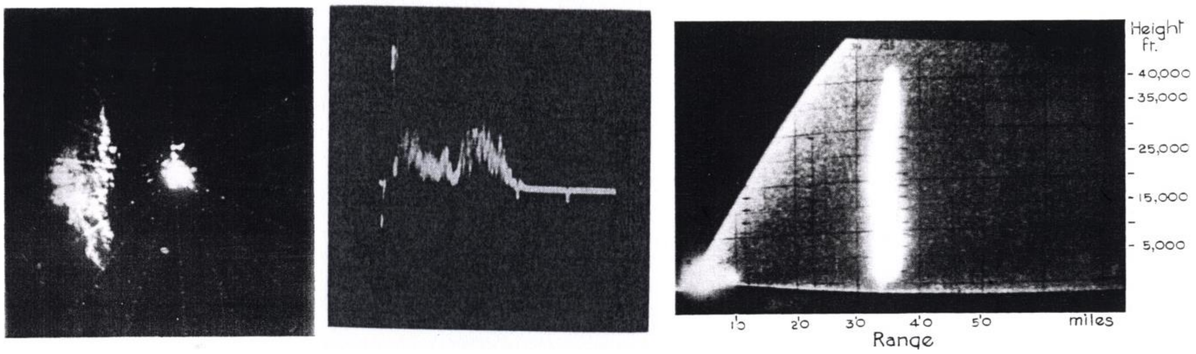


Figure 1. Synoptic chart, 1944, October 10, 1200GMT. Radar weather responses indicated by shaded areas for 1215, 1545, 1630 and 1730BST. Note increase in extent of response from a depth of approximately 7 miles at 1215 to 20-30 miles at 1730. From Ross (1946).

He noted that fog formations, haze tops and stratocumulus cloud layers did on occasions give echoes on radar. He had the remarkable foresight to suggest that they must be caused by a very sharp atmospheric discontinuity of temperature and humidity, something that was only investigated and confirmed several years later. He also suggested the installation of a skeleton network of radars at major airports, providing accurate information of the position, extent and intensity of storms or storm belts within a range of a hundred miles or so.

During the period under review the radar echo was displayed on a cathode ray tube of diameter 12in or so. Because the returned signal contains four parameters, three space and intensity, whilst the cathode ray tube can only display two, choices had to be made. Three methods of display were used; PPI, RHI and A-scope. For the PPI the aerial was rotated about a vertical axis at as low an elevation as was possible to avoid ground clutter; it provided a map of the echoes near ground level. The RHI display was obtained by keeping the azimuth of the aerial fixed and scanning from an elevation of 0^o usually to around $20^{o;}$; this gave a section through the echoes. It should be noted that early on the RHI was called the HRT. For the A-scope display the aerial was kept fixed; the display gave intensity as a function of range. This enabled quantitative calculations to be made. Examples of these three formats are shown in Figure 2. The large-amplitude, very rapid oscillations of the A-scope are clearly shown. These are discussed by Browne in Section 6. Displays for the Doppler radars were different and are explained when the radars are discussed.



(a) (b) (c)

Figure 2. Examples of radar displays. (a) PPI; (b) A-scope; (c) RHI. (a) and (c) from Jones (1950c), (b) from Battan[1]

In all cases data was obtained by photographing the cathode ray tube; when a succession of pictures were taken at short intervals throughout the duration of a system the analysis could be somewhat lengthy.

It should also be emphasised that during this period it was customary to list the authors of papers and reports in alphabetical order rather than with the lead author first.

2. Theory

Since work on the theory of radar meteorology was carried out at several establishments it is convenient to discuss it all in this Section. Even before any centimetric wavelength radars were tested, the possibility of meteorological phenomena such as rain interfering with the detection of targets such as enemy aircraft had been raised. GEC asked one of its scientists, Ryde, to investigate. There were two parts to the problem; calculating the intensity of the echo from the precipitation itself and calculating the reduction in the intensity as the signal passes through the precipitation to the target and back, called the attenuation. The first requires calculation of the backscattering cross-section of the particles, assumed by Ryde to be either water or ice spheres, and the second their total scattering cross-section and absorption. The complete theory of scattering by dielectric spheres had been obtained by Mie in 1908; his solution was in the form of a series whose variables are the ratio of the diameter of the sphere to the incident wavelength, D/λ, and the refractive index. The number of terms required in the series increased with D/λ, and each term contained complex mathematical functions. Since it was uncertain which wavelengths in the centimetre band might be used, Ryde made calculations appropriate to the whole band. Assisted by his wife he was able to transform the terms in the Mie series into ones for which calculation was less difficult. In 1940 only very approximate values for the refractive index of water and ice at centimetric wavelengths was available, nevertheless Ryde was able to produce graphs of both the backscattering cross-sections and the attenuation by the middle of 1941 (Ryde 1941). As more accurate values of refractive index

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[1] Battan LJ.1959. *Radar Meteorology*. University of Chicago Press. 5.

became available he refined his calculations (Ryde and Ryde 1944, 1945). After the war he was able to publish all his wartime work (Ryde 1946a, 1946b), including a graph of the backscattering cross-section of water and ice spheres for the values of $D/\lambda \leq 1.3$. This is reproduced as Figure 3.

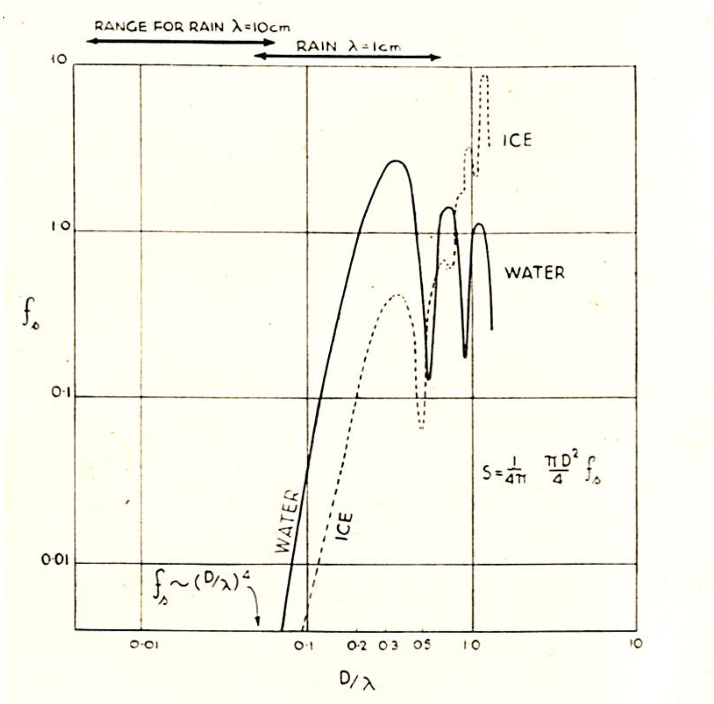

Figure 3: The normalised radar cross-section $f_s.\pi D^2/4$ (σ: backscattering cross-section) of water and ice spheres, each with constant refractive index, versus the particle diameter in wavelengths. From Ryde (1946a).

Ryde began by considering clouds and fog with $D/\lambda \leq 0.015$, showing that the attenuation was negligible for 10cm wavelength. It increased by a factor of 10 as it decreased to 1cm, reaching, for a liquid water content of $1\mathrm{gcm}^{-3}$, $0.9\mathrm{dBkm}^{-1}$. As for the ability of radar to detect these phenomena, Ryde showed that only with favourable drop-size distributions might clouds and fog be detected with 1cm wavelength radars, whilst at 10cm wavelength the echoes would be 10^4 times weaker. For rain, using drop-size distributions that had become available, he calculated that the attenuation was simply proportional to the rate of rainfall, the constant of proportionality being a function of wavelength, ranging from 0.2 at 1cm wavelength to 0.0004 at 10cm, in units of $(\mathrm{dBkm}^{-1})(\mathrm{mmhr}^{-1})$. For ice crystals and snowflakes he made further calculations using the theory of Gans for oblate spheroids. He found that for high altitude ice crystal clouds the attenuation at all wavelengths was negligible and detection doubtful at 1cm wavelength.

There had been a few reports from those using RHI radars of an enhancement of the echo at a height around the freezing level. Ryde (1946a) used his calculations of backscattering intensity for ice and water to examine how the echo intensity would vary as ice crystals aggregated to form snowflakes and then melted. He found that aggregation could increase the intensity by a factor of up to 40 (16dB); on melting, because water drops had five times the cross-section of ice, there would be a further increase to a factor of 200 (23dB). However, once melting was complete the melted flakes would acquire the fall speed of raindrops, thus their concentration would fall by a factor of five and the intensity would fall back to 40 (16dB). He showed that the same result would occur if there were no aggregation. Thus in a narrow layer just below the freezing level the signal intensity would be five times that above and below the layer. There can be no doubt that Ryde's calculations, particularly of the backscattering shown in Figure 3, established the foundations of theoretical radar meteorology. Amongst the most significant of his original work are the following:

1) the backscatter and extinction cross-sections of spherical ice and water particles out to $D=1.3\lambda$;

2) the reflectivity and attenuation of rain and hail as a function of precipitation rate and wavelength;

3) the reflectivity of snow and the theory of the 'bright band' just below the melting layer.

Considering the remarkable theoretical predictions of Ryde and their far-reaching implications for all of radar meteorology, his work must be placed first in terms of its historic importance.

In 1950 Browne, a research student at the Cavendish Laboratory, Cambridge, carried out experiments to verify the prediction from Ryde's theory that the echo intensity should be proportional to ΣND^6 where N is the concentration of drops of diameter D (Browne 1952a). He used a 3.2cm wavelength vertically-pointing radar; the radar specification together with the method of obtaining drop-size distributions are given in Section 6. The radar was calibrated both at TRE and at Cambridge using a fixed target of known reflectivity. During a shower on 6 May 1950 measurements of drop-size distribution and echo intensity were made when the rainfall rate was 5.4mmhr^{-1}; the calculated and observed values of ΣND^6 varied by only 0.4dB. Two measurements were made during a shower on 21 May 1950. In the first, with a rainfall rate of 2.1mm hr^{-1} the discrepancy was 0.1dB, whilst in the second with a rate of 4.2mm hr^{-1} it was 0.6dB, in each case within the experimental error. A similar experiment was carried out during a snowstorm on 18 December 1950. For snow, the equivalent function is ΣNm^2 where m is the mass of flakes of concentration N. Snowflakes were collected at the ground from which values of this function were obtained. Two measurements were made with equivalent rainfall rates of 1.5 and 1.3mm hr^{-1}. In the first the difference was 0.1dB and in the second 2.2dB.

During 1954 Robinson, who was at RRE, carried out experiments to investigate the attenuation and radar reflectivity at a wavelength of 8.6mm (Robinson 1955) in order to compare the results with the theoretical predictions of Ryde. The radar had a peak power output of 15kW, a pulse length of 0.15μs and a beamwidth of 1½°. Two Bibby raingauges were used to measure the rate of rainfall, one at the radar site and one 1¾ miles distant. The attenuation caused by rain was calculated by measuring the echo intensity at different ranges of ¼-mile intervals up to 2 miles and of ½-mile intervals beyond. 51 sets of readings from 16 storms were obtained when all factors were sufficiently uniform, in rainfall rates from 1 to 12 mmhr^{-1}. When the derived attenuation was plotted against rate of rainfall the points all lay fairly close to the straight line representing Ryde's prediction. Attenuation in fogs was determined by installing a corner reflector at a distance of 8¼ miles and comparing the received intensity during and after the fog. Visibility in the fog was related to liquid water content, which enabled calculation of the attenuation given by Ryde's theory. Agreement was reasonably good except when the temperature was below 0°C. In order to compare measured echo intensity with theory, Robinson obtained readings of signal intensity from a range of 1¾ miles correcting the values for attenuation. Twelve measurements were made on six occasions between October 1952 and February 1953; signal power was plotted against precipitation rate and Ryde's theoretical straight line superimposed. The results were in good agreement with the theory. By elevating the aerial so that echo was obtained from the melting band together with the rain below and the snow above, it was found that the echo intensity from the melting band exceeded that from the snow by 14 to 19dB, and from the rain by 2 to 8dB; values consistent with Ryde's theory of the melting band.

During the second half of the 1950s there were reports from the USA of anomalously high echo intensities from severe storms; it was suggested that these were caused by large hail. Although the calculations by Ryde (Figure 3) showed that the backscattering cross-section of ice exceeded that of water for D/λ>0.8 and is greater by a considerable margin when D/λ>1, providing an explanation for the high intensities, it is counterintuitive and had been questioned. A programme was therefore designed by Ludlam from Imperial College and Harper from East Hill which would measure these cross-sections experimentally. They were assisted by Atlas, on a Fulbright Fellowship from the Geophysical Research Directorate, USA, and Mossop, from CSIRO, Australia. The work took place at East Hill, using two radars of 3.3cm and 4.7cm wavelength. Ice spheres were suspended from a tethered balloon at a suitable range and the backscattered intensity measured. The signal was calibrated by flying a 12in diameter metal sphere, whose absolute backscattering intensity is known, at the beginning and end of each experimental run. Spheres of plexiglass, which has a refractive index fairly close to that of ice, were also used. Their results (Atlas et al 1960) confirmed the calculations of Ryde, showing that the backscattering cross-sections of ice spheres exceeded those for water when D/λ>0.8. Their measurements continued the curve to D/λ=2.3 and showed that for 1.2<D/λ<2.3, ice cross-sections exceeded those for water by a factor of 10 or more. Their results showed large-amplitude, short-period oscillations that were beginning to appear in Ryde's graph; these were eventually proved to be caused by resonance (Probert-Jones 1984). Atlas et al also measured the scattering as the spheres melted. The maximum liquid coat was found to be about 0.01cm; this had a major effect at 3.3cm but only a minor one at 4.7cm. Liquid continued to collect in sub-surface cracks and cavities; the final cross-sections were within 2dB of the all-water values after 7 to 10 minutes at 3.3cm and after 15 to 20 minutes at 4.7cm. It may be noted that computer calculations have confirmed that all Ryde's work was absolutely correct.

Evidence from large hailstones at the ground suggested that within severe storms hailstones had the form of oblate spheroids. Harper, now with the Meteorological Office at RRE, had the opportunity to use a test range to measure the cross-sections of plexiglass spheroids, expected to be similar to that of ice. The range produced a horizontally-polarised signal of 3.2cm wavelength. Five spheroids were used, of diameter 4.2cm and diameter to thickness ratios of 0.94 to 0.45; they were mounted on edge and the backscattering cross-section measured as they were rotated. Harper (1962) found that the effects of orientation increased as the axis ratio increased from 0.94 to 0.76 and then decreased. In all cases the cross-section was a maximum when the spheroid presented a minimum cross-section to the transmitter, the ratio of maximum to minimum cross-section reaching 14.4dB for an axis ratio of 0.76. The cross-section was also 6.2dB greater than that for a sphere of equivalent volume and 7.5dB greater than when the spheroid was placed on its edge. It was deduced that the maximum cross-section would be seen when using an RHI radar with a vertically-polarised quasi-horizontal beam, whilst the edge cross-section corresponds to that with a PPI radar. It was suggested that these results could explain the exceptionally strong radar echo intensities from thunderstorms containing large hail.

The signal intensity at the radar receiver is dependent not only on the echo intensity of the precipitation but also on the parameters of the radar set; these are the peak power output, the pulse duration, the wavelength and the aerial beamwidth. During 1947-48 Hooper and Kippax (1950a) at TRE carried out experiments to verify the theoretical predictions of the second and third of these. They used three radars of wavelengths 9.1, 3.2 and 1.25cm with identical aerial beamwidths, with the beam directed vertically. The 3.2cm radar had two alternative pulse durations of 0.5 and 2µs; this radar was used to test the theoretical prediction that the received power is directly proportional to the pulse duration; the ratio of the pulse energies was found to be 6.84±0.2dB. By observing the echo intensity from rain at a height of 9,000ft using each pulse width alternately, and only using data when an adjacent radar showed uniform conditions, they obtained a ratio of 6.9±0.2dB, in excellent agreement and confirming the theoretical dependence on pulse duration. In the next experiment they measured the received intensities at the three different wavelengths from precipitation. The intensity is theoretically proportional to $f(\kappa)_\lambda \lambda^{-4}$ where $f(\kappa)_\lambda$ is a known function of the permittivity κ and varies with wavelength. By making assumptions about the attenuation through the wet radome and other factors they found reasonable agreement with the theoretical ratios of the intensities. By using Dines and Bibby raingauges Hooper and Kippax were able to calculate the value of ΣND^6 and hence compare the calculated intensity with that observed, obtaining good agreement.

Roberts (1959), working at the Decca Radar Research Laboratory, Hersham, Surrey, used radars of wavelength 3.2cm and 8.6mm during 1957 and 1958 to compare observed and theoretical intensities in rain. In rainfall rates of 0.5 to 20mm hr^{-1} he obtained ratios of: -7±8dB from 200 measurements at low resolution 3.2cm, -16±10dB from 60 measurements at high resolution 3.2cm and -5±6dB from 80 measurements at 8.6mm. No explanation could be found for the discrepancy at high resolution 3.2cm. He also measured the ratio of echo intensity in and below the melting band. He found values of 7±4dB from 54 observations in rainfall rates of 0.5-6mmhr^{-1} at low resolution 3.2cm, 5±2dB from 36 in 2.5-6mmhr^{-}1 at high resolution and 1.5±0.5 from 24 in 0.5-1.5mmhr^{-1} at 8.6mm wavelength.

Hooper and Kippax in comparing the observed with the calculated intensity had used the average peak power which exceeds the average power by about 5dB. Other attempts to relate the observed power to the theoretical value had found large discrepancies, so that Marshall et al[2] suggested that the discrepancies should be taken into account by the inclusion of a correction factor *F*; for 10cm radar sets, a value of *F* of about 0.2 (7dB) was suggested. The symbol *F* was used since the colloquial name was fudge factor. Probert-Jones, in the Meteorological Office at RRE, applied a more extensive and more mathematical treatment of the problem; he showed that the original form of the radar equation overestimated the solid angle of the equivalent cone of received power and overestimated the antenna gain. This enabled him to bring the reported measurements in line with the theory (Probert-Jones 1962). The equation he produced is still regarded as the classic meteorological radar equation.

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[2] Marshall JS, Hitschfeld W, Gunn KLS. 1955. Advances in Radar Weather. *Advances in Geophysics*, Academic Press Inc., New York. 1-51.

3. Meteorological Office Radar Research Station, East Hill

Towards the end of 1946 an existing radar station at East Hill near Dunstable, Bedfordshire, was taken over by the Meteorological Office and a small staff of four including just one scientist, R.F.Jones, was appointed to investigate the value of the existing equipment as a research tool. The equipment available was an A.M.E.S. Type 21, consisting of a Type 13 RHI and a Type 14 PPI 10cm wavelength radars. The PPI had a peak power of 500kW, a pulse length of 1.9µs, a p.r.f. of 500s^{-1} and an aerial with half-power beamwidths of 1¼^{o}and 6^{o}. An upper aerial of half-power beamwidths of 1¼^{o} and 6^{o} was mounted at an angle of 3½^{o} in elevation to the lower aerial and was used when working with aircraft. The Type 13 RHI radar was similar but with aerial half-power beamwidths of 1½^{o} and 7½^{o}. In 1949 an AN/TPS-10 RHI radar of wavelength 3.3cm was acquired. This had a peak power of 65kW, a pulse length of 1µs, a p.r.f. of 1000s^{-1} and aerial beamwidths of 0.7^{o} and 2^{o}. This radar had two displays, an RHI and an A-scope for making absolute intensity measurements. In 1953 a 10cm wavelength GL3 precision radar with a peak power of 250kW, beamwidths of 6^{o}, a pulse length of 1µs and a p.r.f of 420s^{-1} was added.

Two major research projects were undertaken soon after some experience had been gained in operating the radars and interpreting the displays. The first was to compare the temperature at the top of a weather echo with an indication of the relative strengths of the vertical currents within the echoes (Jones 1949a, 1950a). The Type 13 was employed in both RHI and A-scope modes, the aerial scanning from -1^{o} to 19^{o}; in the latter the intensity was measured as a signal to noise ratio with the aerial sweeping giving the maximum intensity in a vertical plane. Photographs of the display tube were taken as required on 35-mm film; a written record was also made. Readings were not considered for ranges of less than 11 miles since even at that range the maximum observable height was 20,000ft. For analysis the ranges at which observations were made were split into 10-mile sections and from the 1,200 photographs the maximum top on each day, together with the weather type, were noted. The most suitable radiosonde ascent enabled the temperature at the echo top to be estimated, probably to within ±3^{o}F. All intensities were normalised to a range of 20 miles with the echo filling the beam. Those occasions when the echo came from a thunderstorm were separated. It was found that the temperatures at the tops of echoes from thunderstorms were, or might well have been, all below -40^{o}F. Conversely, echoes with top temperatures above 15^{o}F came from layer type clouds or those topped by an inversion. The remainder could be associated with fronts or troughs in which the intensity of the convection increased as the temperature decreased. Signal intensities on occasions of thunderstorms were compared with no thunderstorm occasions; the intensity was generally greater for the former than the latter. Consideration of all this information enabled Jones to make some deductions about the types of particles giving the radar echoes. He suggested that in clouds of limited thickness with very weak vertical currents probably less than ⅓ms^{-1} and tops warmer than 15^{o}F the echo was due to the aggregation of wet ice crystals or to the melting of small ice crystals not big enough to give an echo on their own account. In frontal systems with great depth of cloud and tops colder than 10^{o}F and with stronger vertical currents but still less than 1ms^{-1}, the echo was caused by the ice crystals themselves having grown to the requisite size due to their small rate of fall through a considerable depth of cloud. Finally, there were cumulonimbus with tops colder than -10^{o}F, with the characteristic of a columnar echo. The strongest intensity was not a horizontal band but a series of points in the column and more importantly there was no bright band. One possibility was the existence of hail of sufficient size and concentration to explain the intensities since dry hail has one-fifth the echo intensity of rain. The infrequency of such hail at the ground made this explanation unlikely. If the hail were wet by accreting so many supercooled water drops that the surface became wet the concentration of hail would satisfy the observations but would still require hail at the ground. It was therefore suggested that cumulonimbus echoes were principally, and perhaps often entirely, due to supercooled water drops of raindrop size. It was significant that almost all thunderstorms had much lower top temperatures and much greater maximum signal intensity than from other weather echoes. These greater intensities could be explained either by a substantial increase in drop concentration or a lesser increase in drop size. The paper (Jones 1950a) was read at a Discussion meeting of the Royal Meteorological Society (Hooper et al 1950).

Jones (1949b) discussed the probable significance of these results in relation to aircraft icing. He noted that radar echoes from above the freezing level indicated either snowflakes of large enough size formed by the aggregation of wet ice crystals, very large ice crystals or supercooled water drops of raindrop size, all in sufficient numbers. The first and second were likely to give horizontal bands on the radar display, whilst the third would give vertical columns. The first and third would give rapid ice accretion whilst the second might not lead to ice accretion if both crystals and aircraft are dry. All these conditions might occur in clouds giving no radar echo, but the worst icing would occur within the location of echoes. Jones then considered the use of aircraft radar to detect such echoes.

A major research programme was run between 1947 and 1949 with the intention of relating areas of turbulence to the RHI display from convective clouds. The PPI display enabled the RHI to be turned to the bearing of a suitable echo. The problem was to determine whether the radar echo is the most turbulent portion of the cloud and whether any characteristics of the echo gave an indication of the degree of turbulence to be expected and the places within the echo where turbulence was greatest. A Spitfire aircraft from the Aero Flight of the Royal Aircraft Establishment at Farnborough, Hampshire, was equipped with a vertical acceleration recorder with a time base. The aircraft was controlled by radio telephone from East Hill; the aircraft flew on a course either directly towards or away from the radar, the pilot switching on the accelerometer immediately on entering the cloud and off on exiting it, this being communicated to East Hill. Flights were made through each cloud at different levels. On some occasions the pilot flew through the best developed cumulus which was not giving a radar echo. Analysis of the accelerometer record was expressed in the form of a table for each cloud traverse giving the number of gusts encountered of a specific magnitude in increments of 0.1g. Between August 1947 and October 1948 26 sorties were flown involving 139 traverses (Jones 1949c). By carrying out a statistical examination of all the data, together with the detailed examination of two individual traverses, Jones was able to reach a number of conclusions. He found that not all turbulent clouds produce a radar echo, but gusts of 1g or more will always occur within an echo and are associated with the edges of strong and sharply defined columns; however, turbulence may extend to some distance on either side of the echo. There was some evidence that turbulence increased upward in the cloud to 0.4 of its vertical extent and thereafter remained constant. A second programme was arranged for the period December 1948 to June 1949 (Jones 1950b). The year was not a good one for cumulonimbus development and only eight sorties were made involving 38 traverses. The accelerometer records could be integrated to yield the upward and downward velocities; this required tracing the curves and integrating it, a lengthy and laborious process. Nevertheless, this was carried out by RAE for five traverses. These analyses showed that the turbulence is associated with the existence within the cloud of neighbouring up and down currents of comparable magnitude. Speeds of these currents were found to exceed 50fts^{-1} on some occasions, although the effect of cumulative errors made these values doubtful. Results from all the traverses produced results which agreed with those previously obtained. A summary of all the experiments and conclusions was given by Jones (1952a). Further flights must have taken place since Jones (1954a) referred to the programme continuing to November 1950 with a total of 30 traverses. His conclusions were similar to those previously obtained. In 1952 it was possible to replace the Spitfire with a Meteor VII, carrying an observer and equipped with more instrumentation that allowed the integration to obtain vertical speeds to be more accurate. On 13 July 1952 five flights were made through a belt of thunderstorms lying to the north-east of East Hill; the radar echo heights reached to 35,000 to 36,000ft, approximately the height of the tropopause (Jones 1953, 1954b). The most striking feature of the results was the change in frequency and intensity of gusts on entry into cloud with the biggest gusts all occurring within the radar echo. Upward and downward air currents of comparable magnitude, often exceeding 20fts^{-1}, occurred close to each other in the clouds, which were mature cumulonimbus; downcurrents, but not upcurrents, approaching 20fts^{-1} might occur outside cloud.

Two phenomena which produced echoes which were not caused by precipitation were investigated by Jones. From 29 November to 1 December 1948 echoes were frequently received from high ground at ranges up to 145 miles compared to the normal 10-15 miles (Jones 1949d). This is known as anomalous propagation, discussed more fully in Section 4. It was known that the atmospheric conditions necessary were, for temperature alone an inversion of about 1^{o}F in 17ft, or for water vapour a lapse rate of 1mb in 100ft (Appleton 1946). Jones used the ‘Balthum’ kite balloon ascents at Cardington, Bedfordshire. At 1200GMT on 29 November there was a temperature inversion of 10.2^{o}F and a vapour pressure decrease of 2.8mb between 500 and 700ft., more than sufficient for super-refraction or anomalous propagation. On both 30 November and 1 December the inversion layer had lifted to above 1,000ft, but its existence could be inferred from the Downham Market radiosonde ascent.

Secondly, during the early months of 1952 radar echoes were received in conditions when precipitation was absent. These echoes took the form on the PPI display of a number of small dots which from the RHI display were confined to a horizontal belt mostly at 5,000ft or below. Their speed of movement was from the direction of the wind but at greater speed. Possible causes suggested by others, including birds, insects, second trace echoes, side-lobes and anomalous propagation were rejected, and Jones (1952b) postulated that the echoes were due to atmospheric inhomogeneities. He calculated that temperature changes of a few degrees Centigrade and of a few millibars in vapour pressure over a height of 2.5cm would be required, but that since the echoes were usually at the height of an inversion these lapse rates were not implausible.

By the end of 1949 Jones had acquired sufficient data from both PPI and RHI radars to be able to classify the displays according to the weather situation. In four articles (Jones 1950c) he gave examples of the displays associated with particular synoptic situations. In the case of cold fronts the PPI display showed a long and generally very narrow band of echo, rarely continuous but which was formed from a large number of small cores of quite high intensity. These showed up on the RHI as strong vertical columns of echo, probably from cumulonimbus clouds embedded in the frontal cloud system. The arrival of a warm front on the PPI display was marked by weak, diffuse echoes which gradually increased to one mass of echo around the station. Finally a straight edge, not clearly defined, indicated the position of the surface front. The most notable feature of the RHI was a bright band in the vicinity of the freezing level. The echo was diffuse and free of marked columns. Occlusions were visible on the PPI display as a single belt, wider than that from cold fronts and without the cores of high intensity; there was usually a clearly defined rear edge. Occasionally the structure was considerably more complicated. Finally Jones gave some examples of unusual echoes from which deductions could be made about details not apparent on synoptic charts.

An article by Whalley and Scoles (1949), using a 3cm wavelength radar with a pulse length of 1µs in the Research Department, Metropolitan-Vickers Electrical Co. Ltd., Manchester illustrated PPI records of a belt of heavy rain passing over the Manchester district. In reply Jones (1949e) reported that radars had been used for some time at East Hill, and gave illustrations of radar displays from a moving cold front. The records collected at East Hill enabled Jones (1950d) to reply to a correspondent who wondered if the intense but short-lived storm which occurred over Evesham was the same one that hit Birmingham some time later. Jones replied that the Evesham storm dissipated quite quickly and it was a new development that moved over Birmingham.

On 5 June 1950 isolated thunderstorms developed over southern England; five storms were followed from their first detection at 1403GMT until observations stopped due to an equipment fault at 1615GMT (Jones 1951a). The first developed over the river Blackwater three miles west of Sandhurst, Berkshire, travelled west at 8kt and had disappeared from the radar by 1511GMT; it appeared to be an isolated storm. The second appeared at 1459GMT as two narrow columns near Uxbridge and Hayes, Middlesex; around 1507GMT these amalgamated and the echo grew considerably. From 1541GMT it moved from 113° at 10kt and by 1607GMT had decayed considerably. The third storm appeared as a centre of activity on the western edge of the second at 1541GMT, 3 miles NNE of Maidenhead, Berkshire; this one became more marked as the second declined. The fourth developed between 1515 and 1541GMT 2 miles south of Wallingford, Berkshire and 28 miles from the origin of storm two. It had disappeared by 1558GMT. Finally a fifth storm appeared between 1541 and 1558GMT 2 miles north of Henley-on Thames, Berkshire, halfway between the second and fourth. It grew rapidly in 9 minutes and was the dominant storm by 1615GMT. During this period no other storms were observed within the coverage of the radar. All the storms other than the first began, and remained, in the Thames valley, and the locations of their initial development lay on a straight line which when extended eastward passed over London to the Thames estuary; the low-level wind was generally light and easterly. Jones suggested that all these factors were especially favourable for the initiation of convection at the time of maximum diurnal heating. The time from the first observed echo to that of maximum development, when most echoes reached the tropopause, was 20-30 minutes.

It had been established that in the tropics rain could fall from clouds that did not extend above the freezing level. For the first time Jones (1951b) was able to observe the same phenomenon in England. On 18 July 1951 numerous echoes were observed on 10cm wavelength radar, with a maximum top of 8,500ft. An example of the radar displays is shown in Figure 4. The echoes frequently showed a column-type structure. A Hastings aircraft of the Meteorological Research Flight found that the echoes were produced where there were domed tops rising above a layer of stratocumulus; the free-air temperatures were measured to be 45.7°F at 7,500ft and 44.6°F at

8,800ft. Reports made it clear that slight rain in moderately sized drops reached the ground, and there was no doubt that the rain observed fell from non-freezing clouds.

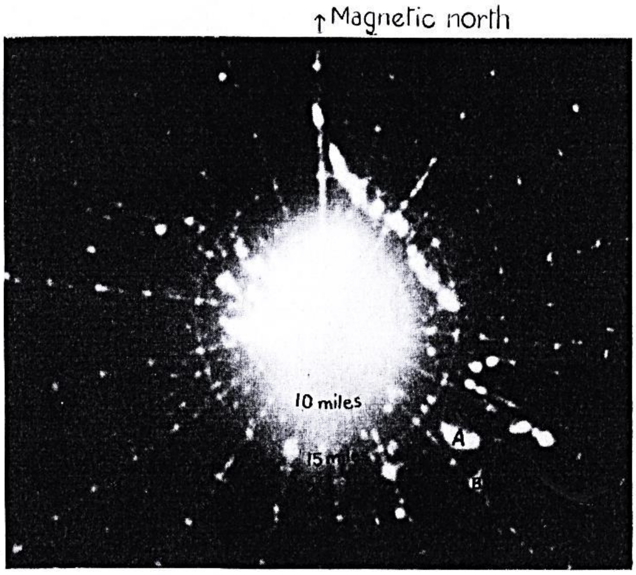

FIG. 1—P.P.I. PHOTOGRAPH OF RAIN ECHOES FROM CLOUD NOT REACHING FREEZING LEVEL.
Time of observation: 1501 G.M.T., July 18, 1951
(see p. 273)

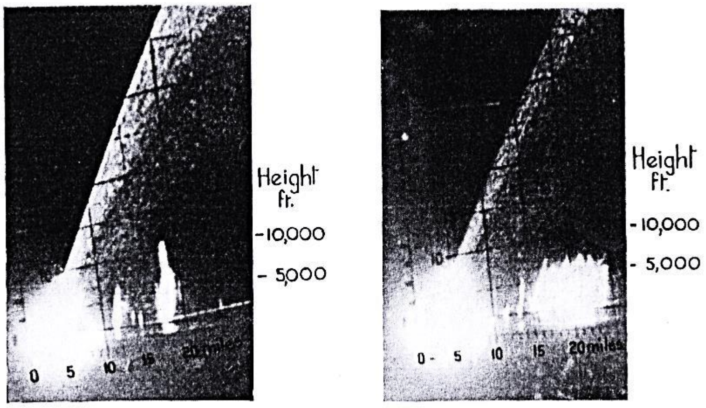

FIG. 2—VERTICAL CROSS-SECTION ON BEARING 134° MAGNETIC
Time of observation: 1459 G.M.T.

FIG. 3—VERTICAL CROSS-SECTION ON BEARING 125° MAGNETIC
Time of observation: 1346 G.M.T.

Figure 4. Photographs of the East Hill PPI and RHI radars on 18 July 1951, showing echoes of rain from clouds not reaching the freezing level. From Jones (1951b).

In the same year, on 31 December 1951, radar echoes from medium-level precipitation were observed from East Hill; they were strong in the middle of the day, became very weak by mid-afternoon; about dusk the intensity increased rapidly. The PPI display suggested the presence of very many tiny cells in lines oriented along the wind direction at the layer top. Jones (1952c) suggested that cooling of the top of the layer by radiation after sunset could produce cells of the Bénard type; the spacing and the depth of the cells satisfied this theory.

Radar echoes attributable to lightning flashes were obtained during thunderstorms on 20 and 21 August 1953 (Jones 1954c). It was found that lightning flashes only occurred where the temperature was -29°C or lower. Many strokes originated in the boundaries between the strong echo columns and the surrounding echo-free region but still within the cloud, the flash propagating through the anvil.

Harper joined Jones at East Hill in 1954. He presented a description of the facilities available and the uses to which radar could be put (Harper 1955). Jones left East Hill in 1956, but before he left Jones (1957) provided an assessment of the present and future research programme. He wrote "the present equipment is approaching the end of its useful life and the present site must be abandoned very soon…the limit of what can be done has already been approached". He listed the work already being investigated: the relation between radar echo intensity and rate of rainfall; the movement of belts of precipitation; movement and life of showers and thunderstorms; 'angel' echoes; aircraft co-operation; studies in short-period forecasting. After taking over, Harper (1956a) produced a summary of the problems to which attention would be devoted during the next two years. These were: the relation between radar echo intensity and rate of rainfall; movement of belts of precipitation; movement and life of showers and thunderstorms; short period forecasting. In anticipation of the eventual closure of the East Hill site, Harper also discussed possible alternative locations. He also mentioned possible cooperation in cloud seeding experiments by Porton. One such had already occurred on 9 March 1951 (Shellard and Grant 1951) in which both PPI and RHI radars had observed the results of seeding the top of two well-defined layers of stratocumulus by dry ice pellets.

An examination of the movement of precipitation belts begun by Jones was completed by Harper and Beimers (1956, 1958). During the period 1947-1952 82 belts of precipitation observed on the 10cm wavelength PPI display in which the belt movement could be clearly defined were examined to determine the direction and speed of movement of the belt normal to its length. All the belts could be loosely associated with cold fronts or occlusions. Upper air winds at 50mb intervals between 950 and 500mb were estimated from the nearest two radiosonde ascents. The best correlation between these winds and that of the movement of the radar belt, with a correlation coefficient exceeding 0.9, was found to occur at 700mb. The same result was obtained when individual data for cold fronts and occlusions, and for echo tops above and below 18,000ft, was examined. The paper (Harper, Beimers 1958) was read and discussed at a meeting of the Society (Harper, Beimers 1959). It was emphasised that the results applied only to the rain belts and not to any features on synoptic charts.

In the summer of 1956 a joint observational programme was organized between the Department of Meteorology, Imperial College and East Hill to study cumulus development (Harper et al, 1956, 1957). The results involving cumulus development are described in Section 5. Echoes from cumulus not containing precipitation were studied by Harper (Harper et al 1957). A type of echo which was observed on the 10cm RHI radar commonly at ranges up to 10 miles were typically persistent, diffuse and weak in the form of an inverted U or V; they were named mantle echoes. Simultaneous theodolite measurements established that the echo was received from the sides of cumulus or stratocumulus cumulogenitus, the lower part of the echo lying near the cloud base and its top at the cloud summit. It was thought that these were refractive effects associated with abrupt gradients of vapour pressure at the edges of clouds. A different type of echo was observed near the ground, thought to be due to refractive effects of strong temperature gradients at the caps of rising thermals. Other results from this observing programme are given in Section 5.

Results from the joint observing programme of 1957 were reported by Harper in Evans and Harper (1959), and was devised to study the relationship of hail to the stage of development of cumulonimbus clouds and the occurrence of lightning. PPI records were maintained at three-minute intervals and as many storms as possible were studied on RHI. A network of voluntary observers was recruited to note times and sizes of hail; they reported 330 occurrences on twelve days. Of these 298 were of hail of diameter 1cm or less; five were of between 2cm and 4cm, which all happened on one Sunday when radar data was not available. The duration of the hail fall was reported on 251 occasions; for indivual falls the average was 7 minutes. In many cases the echoes from storms producing hail could be traced back to the initial echo, enabling the time from the appearance of the first raindrops to hail in the storm to be found. It was found that the time from drops of 1mm diameter to hail of 1cm diameter was very close to 17 minutes. A study was made of a particular case on 19 July 1957. Storms with tops reaching or exceeding the tropopause at 30,000ft had been observed all day but had greatly decreased by 1800GMT, but just after 1900GMT a very active development took place within a mile of Elmdon, Birmingham. The first echo appeared at 1906GMT and within twelve minutes had attained its maximum size of about 20 square miles. The first lightning was recorded at 1915GMT; hail of 1.5cm diameter reached the ground at 1916GMT and lasted for 19 minutes. The highest echo top of 32,500ft was also recorded at 1916GMT. Allowing two minutes for the first echo to have appeared before 1906GMT (the PPI scans were at 3-minute intervals) and two minutes for the hail to reach the ground this implies that hail of 1.5cm diameter formed within ten minutes of the first millimetre-sized drops. Some observers also recorded thunder; from these it was deduced that on average thunder was heard at the same time that the hail reached the freezing level. However there was no evidence that hail was necessary for the generation of lightning. Conversely there were a few occasions when observers were definite that no thunder had occurred during a hailstorm.

Reports of hail damage to Meteor aircraft over the Channel on 3 July 1957 (Pavely[3]) together with reports of hail in south-east England led Harper (1958) to examine available PPI records from East Hill. The first at 0924GMT, 19 minutes after the aircraft report and when the range of the radar had been extended to 130 miles, showed very heavy storms in the Straits of Dover, the most severe of which at a range of 125 miles was almost certainly the one into which the aircraft had flown.

In an investigation to assess the variation with height of rainfall below the melting level Harper (1956b, 1957a,b) used the 3cm wavelength RHI radar in A-scope mode to measure the intensity at a range of 3 miles. The aerial was scanned in 2^{o} steps corresponding to height intervals of 500ft down to 500ft above the ground. Results were obtained on three days of widespread continuous rain in warm-frontal conditions; the PPI radar showed reasonably uniform conditions over a wide area. He presented detailed results from eight scans made on 20 October 1955 between

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[3] Pavely TA, Harding J, Harper WG. 1958. Hail damage of aircraft at nearly 30,000 feet on 3 July 1957. The extent of the damage. *Meteorol.Mag.*, 87, 23-25.

1159GMT and 1227GMT. The bright band at a height of 4,500ft was uniform in intensity and height, having a thickness of 1,000ft; intensities below also showed considerable uniformity. Of the total of 32 scans, 24 showed no obvious trend towards increase or decrease of intensity with height; variations in the remainder being attributed to lighter or heavier rain moving into the beam. These results implied that there was no drop growth below the melting band, either by accretion or aggregation; the reported cloud with a base of 1,500ft to 2,000ft must have been a layer of turbulence cloud of small liquid water content. It was deduced that radar measurements at 2,000ft are an accurate measure of the rainfall at the ground.

Harper[4][5][6][7][8] became convinced that radar 'angels' were caused by flocks of birds; that for example the mantle echoes previously described were due to swifts feeding on insects carried up by thermals. Jones was not prepared to accept Harper's categorical assertion "that all widespread displays of 'angels' on centimetric radar in southern England are caused by birds" (Harper[9]). He therefore carried out a thorough theoretical investigation into the possibility that radar echoes from atmospheric inhomogeneities were the explanation of such echoes (Jones 1958). He found that reflection of the main or side-lobe energy at a limited quasi-horizontal surface was the most likely explanation but required changes of 2×10^{-5} in refractive index over heights of 25cm; no attempts to measure such changes had been made. However the noticeable increase in the number of echoes in the evening, failure to detect such echoes at temperatures below 0°C, the greater likelihood of echoes being detected by high-powered and narrow beamwidth radars and the greater ability to detect echoes on long wavelengths than on short, all of which were predicted by the theory and observed in practice, lent great weight to the hypothesis that such echoes are meteorological in origin. In subsequent correspondence (Harper, Jones 1959) Harper produced arguments to counter Jones, who in his reply maintained that at least not all 'angels' could be caused by birds and that atmospheric inhomogeneities could be responsible.

In 1956 a Type 41 3cm wavelength radar was installed on the roof of Victory House, Kingsway, London, the location of the London Forecast Office. In conjunction with this Caton (1958) presented a review of an experiment to predict the onset and duration of precipitation at three locations: Dunstable, Bedfordshire; Cardington, Bedfordshire; and Victory House using the East Hill PPI radar. Situations were divided into showers and rain belts; forecasts were divided into half-hour intervals and verified using the autographic rain-gauge record from each station, rain beginning in the relevant half-hour interval or the subsequent one being judged correct. The velocity of the observed echoes was derived either from the 700mb wind or preferably from the motion of the echoes themselves; however an error of as little as 10° in direction could have a disastrous effect on the accuracy. Caton considered that detailed forecasts of a useful standard of accuracy were possible for two hours ahead, both for showers and precipitation belts. In the discussion mention

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[4] Harper WG. 1957. 'Angels' on centimetric radar caused by birds. *Nature*, 180. 847-849.

[5] Harper WG. 1958. An unusual indicator of convection. *Proc. 7th Weather Radar Conf.*, Amer.Meteorol.Soc., D9-D16.

[6] Harper WG. 1958. Detection of bird migration by centimetric radar – a cause of radar 'angels'. *Proc.Roy.Soc. B*, 149. 484-502.

[7] Harper WG. 1959. Roosting movements of birds, and migration departures from roosts, as seen by radar. *Ibis*, London. 101. 201.

[8] Harper WG. 1960. An unusual indicator of convection. *Marine Observer*. 30. 36-40.

[9] Harper WG. 1957 *loc.cit.*

was made of investigations at East Hill which had found that the lifetime of small shower echoes was about one hour; that of a complex of heavy showers or thunderstorms could be considerably more.

4. Telecommunications Research Establishment, Radar Research Establishment, Royal Radar Establishment; Malvern

Anomalous propagation, whereby the structure of the atmosphere can on occasion cause radio waves to be propagated non-linearly, had been known before the war. Very soon after the start of the war it was found that the phenomenon could affect centimetric radar; the set at Swanage reported on occasions detecting echoes from the French coastline, well below the line of sight. For example during 5-26 July 1941 echoes were obtained at ranges up to 170km when a maximum range of 40km would have been expected (Appleton 1946). A considerable amount of research into the problem was carried out during the war; none could be published until afterwards for security reasons. A conference was therefore organized in 1946 jointly by the Physical Society and the Royal Meteorological Society at which all the results were brought together and published as Meteorological Factors in Radio-Wave Propagation. Most of the papers dealt with the theoretical problem of propagation related to atmospheric structure and made no distinction between long (radio) and short (radar) wavelengths. Booker, of Christ's College and the Cavendish Laboratory, Cambridge University, was appointed head of research at TRE for the duration of the war. He conducted radio meteorological investigations both in England and abroad on anomalous propagation, also known as super-refraction. In Booker (1948a) he shows examples of super-refraction with sketches of PPI displays, mostly from overseas. Super-refraction was shown to be particularly striking when both radar and target are close to the surface. An example shown was of substantial echoes from the Dutch coast seen by a radar of 50cm wavelength located on the coast of East Anglia, despite the fact that this coast is only a few feet high. It was clear that under certain meteorological conditions radars could see great distances beyond the geometrical horizon.

A comprehensive theoretical study of anomalous propagation was given by Booker and Walkinshaw (1946). Anomalous propagation requires the existence of a duct, a region extending from or close to the surface through which the refractive index decreases, the top of the duct being at the minimum of the refractive index. The depth of the duct determines the wavelength that can be contained within it; 100ft can produce strong super-refraction at a wavelength of 10cm, whereas a wavelength of 1m requires at least several hundred feet. The refractive index depends on potential temperature and specific humidity; an increase in the former and a decrease in the latter produces a fall in refractive index, in other words an inversion is a necessary requirement for super-refraction. Booker (1946) investigated the synoptic and climatological conditions under which super-refraction would occur. He suggested that an increase in potential temperature of 5^{o}/100ft or a fall in specific humidity of 0.5g/100ft to the top of the duct would produce super-refraction for wavelengths depending on the depth of the duct. Such conditions are likely to occur in fine, anticyclonic weather and not in stormy or cloudy conditions. However even in the presence of an anticyclone it will only happen over land at night. In his Symons Memorial Lecture (Booker 1948b) Booker addressed the meteorological problem of predicting the profiles of temperature and humidity with sufficient accuracy to state whether the above gradients were exceeded. He suggested that a theory was required in which the coefficient of eddy-diffusion increased linearly from ground level to a maximum at no great height, and then decreased again.

Clearly the profile of atmospheric refractive index is fundamental in predicting the existence of anomalous propagation. Macfarlane (1946), publishing work done at TRE during the war, showed that this could be deduced from radio observations alone, without the need for meteorological information. It could be done with one set of height-gain measurements at a fixed range and a few observations of field strength at a constant height and different ranges, or from two sets of height-gain measurements at different wavelengths. This could not be verified since no simultaneous observations of radio and meteorological soundings were available.

Observations of anomalous propagation were reported by Jones (1949d), see Section 3, and by Browne (1952a) and Barratt (1957), see Section 7. All the research was directed towards explaining anomalous propagation in terms of atmospheric structure. The only experiment designed to do the reverse was carried out by Barratt.

Whilst engaged on their experiments to verify the effects of varying the parameters of the radar set on the received intensity, discussed in Section 2, Hooper and Kippax (1950a), they also detected the ‘bright band’, a narrow horizontal region of considerably increased intensity (Hooper and Kippax 1950b). It had been suggested by Ryde (1946a) and others that as ice crystals and snowflakes fall below the freezing level the change from ice to water will lead to an increase in the backscattering cross-section. As they melt they will acquire the greater fall speed of water drops and so the number per unit volume will decrease. Hooper and Kippax took a vertically-pointing radar of 3.2cm wavelength to the radiosonde station at Larkhill and made observations to coincide with radiosonde ascents. They found that on average the bright band lay 330±150ft below the freezing level with an intensity of five to nine that from the rain below. The theory of Ryde suggested that this should be the ratio of the fall speeds of the ice crystals to that of the raindrops. Hooper and Kippax carried out some experiments during the winter of 1947 to measure the fall speeds of snowflakes and the drop size into which they melted. By using a relation provided by the Meteorological Office this size was converted to a fall speed. They also used some previously published data on the fall speeds of crystals and flakes. The ratios obtained fell within the range of five to nine, providing support for Ryde’s hypothesis. To the accuracy available with the radar, it was found that the average depth of the bright band was 750ft. The paper was read at a Discussion meeting of the Royal Meteorological Society (Hooper et al 1950).

During the period 1950-1953 experiments on polarisation were made using two radars, 3.2cm wavelength or X-band and 8.6mm or Q-band (Gent 1954, Hunter 1954, Gent et al 1963). Each radar had two aerials, the transmitter radiating and receiving right-hand circularly polarised waves, and the second receiving left-hand polarised waves. The ratio of the left-hand to the right-hand intensity is known as the depolarisation ratio or cross-polarisation. Theoretically, if the scatterers are perfect spheres this ratio will be zero; in practise for the X-band it was found to be -30dB and for the Q-band to be 32dB. In steady rain the X-band found cross-polarisations of -28dB to -30dB, degenerating in thundery conditions to -25dB, probably due to the presence of appreciably distorted very large drops. In the melting band the cross-polarisation varied from -20dB when the precipitation was drizzle to -15dB in thundery conditions. Only one measurement was made in snow, when the figure was -26dB. The results from the Q-band radar were similar to those obtained at X-band, but differed in magnitude, almost certainly because the shorter wavelength was more sensitive to the shape of the drops. The values for rain were -17db, for the melting band -6dB to -11dB and for snow, for which the values may have been unreliable, -12 to -16dB. In 1952 Robinson, using the Q-band radar, carried out a joint experiment with Browne at the Cavendish Laboratory, Cambridge University, who used an X-band set (Browne and Robinson 1952). They obtained cross-polarisation values for rain of -21.8±0.4dB at X-band and -15±1dB at Q-band; however these ratios were not reliable and probably indicated similar values introduced by the aerial system. For snow and for the melting band the values were -19.9±0.4dB and -15.9±0.3at X-band and 12±2dB and 7±1dB at Q-band. It was deduced that particles in the melting band preserved their non-spherical shape until melting is almost completed.

In the mid-1950s RRE developed a pulsed Doppler radar of advanced design for military use. It is not known if it was found unsuitable, but in late 1956 it became available to Boyenval to carry out a limited programme to assess its possible meteorological use. The radar was located not at RRE Malvern but at Throckmorton airfield near Pershore, Worcestershire, some sixteen miles from Malvern. Thus observations could not be made spontaneously; a day had to be set aside, relying on the weather forecast, for a scientist and a technician to travel to Throckmorton.

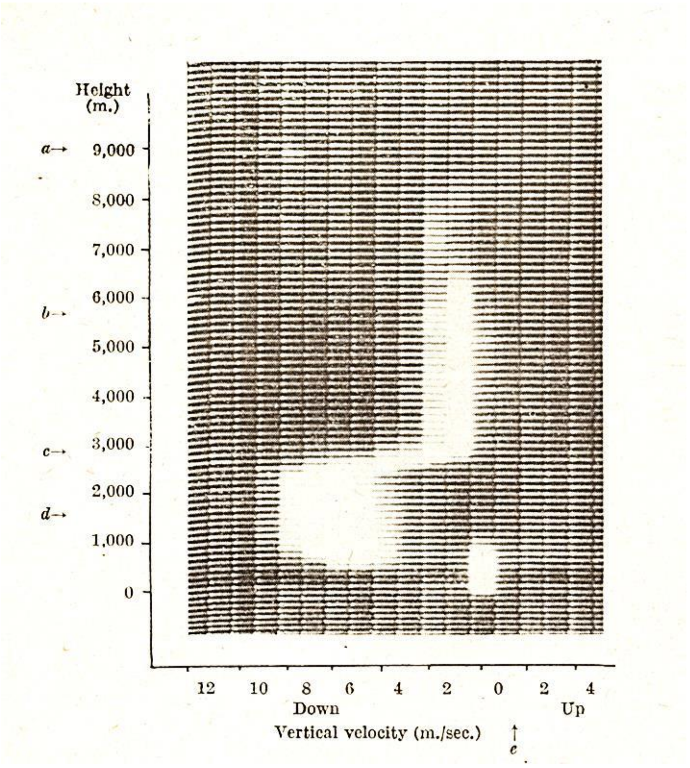

Figure 5. Photograph of a typical display from the vertically pointing Doppler radar during warm frontal precipitation. *a*, range marker; *b*, echo from ice crystals and snow; *c*, acceleration zone as snow melts (melting band); *d*, echo from rain; *e*, transmitter pulse and ground break echo. From Probert-Jones (1960b)

The radar had a special facility for measuring the Doppler frequency shift of the returned echoes, which is proportional to the radial velocity of the scatterers. A full specification of the radar is given by Boyenval (1960); the wavelength was 3.2cm, peak power 10kW, and the aerial beamwidth to half-power points 3½° by 2½°; in 1960 a larger aerial was installed with a beamwidth of 1.7°. The radar was used with the aerial pointing vertically. The information from the radar was displayed in the form of an array having twenty columns and about eighty rows. An example of the radar display is shown in Figure 5. Each column corresponded to a velocity channel of width 1ms^{-1}; it was possible to arrange for the channel width to be ½ms^{-1} or ¼ms^{-1}; however it was an inherent feature of this type of radar that a target with a velocity outside the velocity range is not lost but folds over. Each row corresponded to a height interval of 500ft. The intensity displayed in each velocity and range segment is the combined intensity of all the scatterers having velocities and ranges within the limits of that segment. This can all be seen clearly in Figure 5. The problem of receiver paralysis, which prevents satisfactory reception within about 3,000ft of the transmitter, was solved by delaying the received signals by 63μs; the delayed break-through from the transmitter pulse provided a convenient range marker at 9,500m. The display was photographed by a specially modified Vinten cine camera, either with single exposures or, for an effectively continuous record, with an exposure every five seconds.

Boyenval (1960) conducted two experiments, the first to determine drop size distribution. By assuming negligible vertical air motion and using the known fall speeds of raindrops the velocity channels correspond to channels of specific drop diameter ranges. By measuring the relative echo power in each range-velocity element and assuming a Rayleigh scattering law it is possible to calculate the relative number of drops in each element. To obtain the relative intensities of the echo the signal was attenuated at intervals of 3dB; a photograph of the display was taken at each attenuation and that at which the signal in each element was just disappearing into noise was determined. It will be realised that this analysis took a considerable amount of time. Full gain photographs were taken of the display before and after each attenuation run; only when there was good agreement was the data used. On 9 August 1957 during the passage of a depression several sets of readings were taken, of which two were analysed. Drop size distributions were obtained for the heights 1,600ft, 3,400ft, 5,200ft and 7,000ft; plotting the drop size against the logarithm of the concentration gave straight lines. Drop sizes at the ground were obtained using stained filter papers; from these the concentration N of drops of diameter d could be obtained and graphs of $10\log_{10}N/d$ plotted. The slopes of the approximately linear portion of these graphs agreed closely with the radar data. From these slopes the rate of rainfall R could be found. Jones (1948) had obtained the expression $N_d=Ke^{-ad}$ where N_d is the number of drops per unit volume of diameter d. Using this expression and the slope of the radar distribution curve a second value of R could be obtained. A third value of R was obtained directly from the filter paper results. It was found that on the two occasions the three values of R were 0.45mmhr^{-1}, 0.5mmhr^{-1}, 0.65mmhr^{-1}and 0.6mmhr^{-1}, 0.65mmhr^{-1}, 1.0mmhr^{-1} respectively.

The second experiment was made possible by the installation of a facility to film the display continuously at 5 second intervals for several hours. This was used on 6 September 1957 during the passage of a warm front followed by a warm sector. Upper air soundings at Hemsby, Crawley, Camborne and Valentia enabled a vertical section to be constructed and the radar echoes superimposed. This cross-section is shown in Figure 6. The whole section covers a period of several hours; the start of the record is on the right. Initially there were only patchy echoes. With the arrival of the warm front there was a period of light steady rain dying out behind the front. Later very much stronger echoes extending to 25,000ft were observed and some upward vertical velocities of up to 1ms^{-1} were detected.

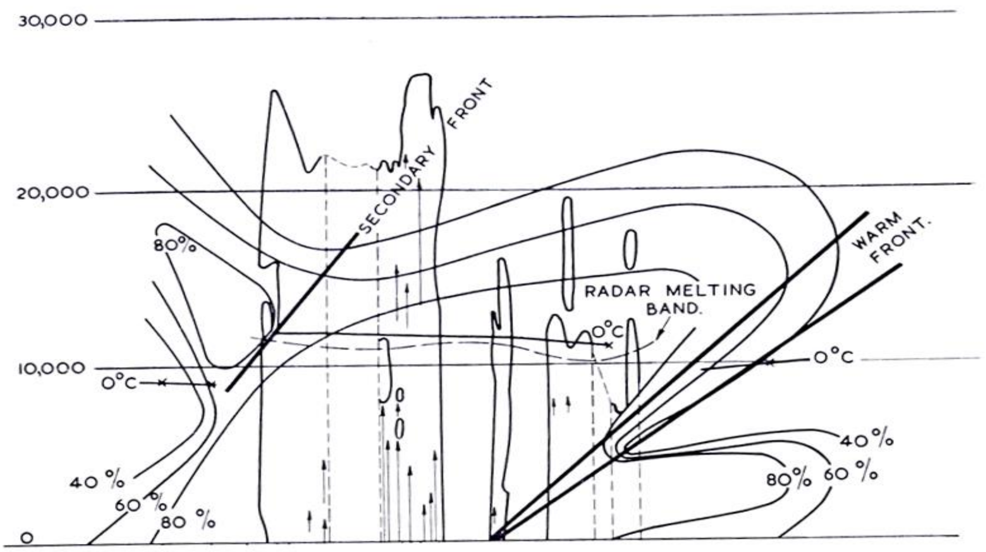

Figure 6. Section through warm sector. Arrows show regions of upward air motion. From Boyenval (1960).

Boyenval suggested that the Doppler radar could be used in two ways; first to study a small section of a meteorological situation in great detail, and second to study extensive situations over a period of time. However he noted correctly that the greatest problem would be one of interpretation; information is collected at such a great rate that a few hours of operation could provide material for many days of detailed analysis.

It is presumed that RRE approached the Meteorological Office with a presentation of Boyenval's results and an offer for the Office to use the radar and carry on the research. The Meteorological Office appeared disinterested; instead of sending someone from East Hill to appraise the radar and suggest a suitable scientist, they sent Probert-Jones on detachment for six weeks. He had only just completed his two-year Scientific Officer training period, he had no knowledge of radar meteorology and no research experience. He was given no contact with the radar meteorologists at East Hill. Nevertheless Probert-Jones' detachment was extended, and he remained at RRE, with some breaks, for three years. Initially both technical and clerical support were provided by RRE; it was only after some months that a technician and assistant from the Meteorological Office were posted to join Probert-Jones. A major disadvantage in the use of the Doppler radar was the lack of a PPI or RHI radar to provide a context.

Probert-Jones (1960a, 1960b) carried out four investigations during his first year at RRE. Ten sets of drop size distributions were obtained, using the technique described by Boyenval, between 2125 and 2300GMT on the evening of 1 November 1958 associated with the passage of the warm fronts of a complex low near Iceland. These showed an apparent decrease by a factor of 20 in the number of 1mm radius drops and a smaller increase in the number of small drops between 1,200m and 800m, together with an increase in the vertical flux of liquid water by a factor of two between these levels. The radar indicated a steady state below the melting level; this was an occasion when conventional radar observations would have been of use. Since vertical air motion appeared to be the only possible explanation, distributions and fluxes were computed for various values of vertical air velocity; downward motion of $1ms^{-1}$ at 1,500m and 2,200m relative to that at 800m was capable of eliminating completely both the variation in flux and the anomaly in drop concentrations. The effect lasted for at least 1½ hours; the most probable explanation was thought to be an orographic standing wave due to either the Malvern hills or the Welsh mountains, both of which lay directly upwind.

Later on the same occasion, between 2300 and 0100GMT, the precipitation became less uniform and the record showed several isolated echoes, originating well above the melting band and lying in comparatively high velocity channels, which were observed to fall towards the melting band. These were upper bands or precipitation streaks (Wexler 1952a, Browne 1952b, Barratt 1957); five could be analysed. All appeared initially at heights of between 4,500m and 5,000m occupying the $3ms^{-1}$ and $4ms^{-1}$ channels, and fell quickly. Using the upper winds, which were very uniform in direction, the shapes of the streaks were best fitted by assuming a generating level of 6,000m and a fall speed of $3ms^{-1}$; the particles must therefore have been graupel. One streak passed through the melting band and produced drops with fall speeds of $3ms^{-1}$ to $6ms^{-1}$. It was deduced that the graupel must have had densities and radii of between $0.9gm^{-3}$ and 0.35mm to $0.2gm^{-3}$ and 1.15mm. It was proposed that the proximity of the generating level to a level of potential instability together with the release of latent heat could have provided suitable conditions for the growth of the particles.

The Doppler radar could also be used to measure the horizontal wind. If the aerial was brought down to a low angle of elevation in frontal precipitation, the echo from above the freezing level could be assumed to be due to ice crystals with a fall speed of $1ms^{-1}$; knowing the radial velocity and the vertical velocity enabled the horizontal velocity to be calculated. Values from two azimuths at a separation of 20^o were averaged. Such an experiment was carried out on 6 January 1959 when a warm frontal zone lay over the radar at a height of between 800m and 1,400m. Winds were calculated at heights of 600m, 900m and 1,200m. Fifteen values of the wind at various azimuths were obtained at each level, the points covering an area of about $16km^2$. The results were consistent with the theoretical estimate of accuracy of $2ms^{-1}$. The objective was to calculate the divergence in the frontal zone. However the low accuracy and the small area made such a calculation impossible.

In order to verify the accuracy of the drop-size distributions obtained by the Doppler radar, a programme was devised to make use of an Instrument which had been developed at the Royal Aircraft Establishment in Farnborough, Hampshire for sampling raindrops from an aircraft in flight and hence to obtain the drop-size distribution (Bigg et al[10], Garrod[11]). Both radar and aircraft measurements were made on 16 April 1959 as a warm front moved north. The aircraft flew over the radar at height intervals of 300m, seven runs being made below the melting band; concurrently sets of observations at increasing attenuation from the radar were recorded. The radar signal intensities were measured relative to the noise level; this could be calculated theoretically. This enabled absolute intensities and thus the drop-size distributions to be obtained. To convert velocities to drop-sizes, the terminal velocities were corrected for atmospheric pressure, temperature and, for values of the Reynolds number greater than 10^3, the drag coefficient and the Reynolds number (Probert-Jones 1959, unpublished). The instrument on the aircraft could only sample a volume of

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[10] Bigg FJ, McNaughton II, Methven TJ. 1956. The measurement of rain from an aircraft in flight. *R.A.E.Tech.Note Mech.Eng*. 223, Min of Supply, London.

[11] Garrod MF. 1957. Recent developments in the measurement of precipitation elements from aircraft. *Meteorol.Res.Paper* 1050. Meteorological Office, Air ministry, London.

0.2m^{-3} and therefore could not detect the larger drops. Comparison of the drop-size distributions obtained from the Doppler radar and from the aircraft instrument on 24 occasions produced excellent agreement with a standard error of 20 per cent. It was concluded that the Doppler radar could produce accurate drop-size distributions (Probert-Jones 1960a).

In late 1959 the Meteorological Office had to vacate its site at East Hill; with the agreement of RRE, Harper joined Probert-Jones to take charge of what became known as the Meteorological Research Unit, Royal Radar Establishment. The extra staff enabled analysis of the Doppler radar record from three showers, on 8 April 1959, 9 April 1959 and 8 June 1961, to be made to determine the profiles of vertical air motion. In all cases there was clear evidence of a melting band. It could therefore be assumed that the particles above the melting band had a terminal velocity of 1ms^{-1} and deviations from this were attributed to vertical air motion (Probert-Jones, Harper 1961, 1962). By assuming that this was unchanged across the narrow thickness of the melting band to the raindrops with the highest fall speeds and also by assuming their terminal velocity remained unchanged as they fell to the ground the complete time-height sections of air motion could be obtained. The results for 9 April are shown in Figure 7. General features of all three showers were an inflow at a low level at the front rising to a near vertical updraught in the centre and outflowing near the top at the front. Towards the rear there was a downdraught from middle levels outflowing near the ground.

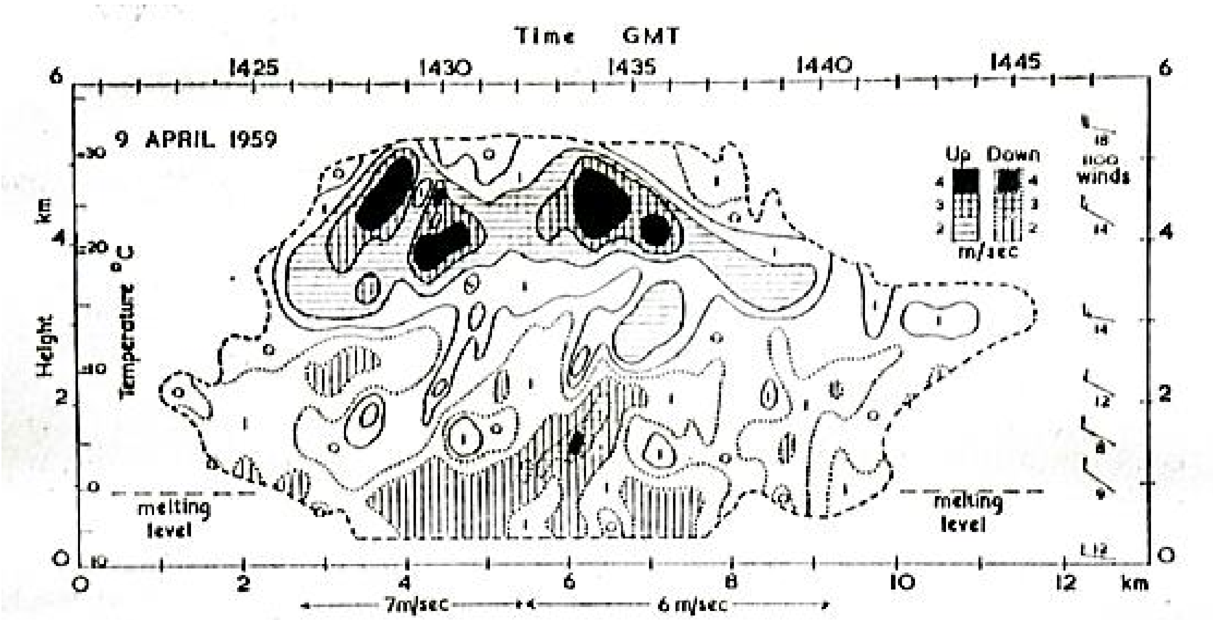

Figure 7. The pattern of vertical air motion in the shower of 9 April 1959. The left-hand side is the leading edge of the shower. Wind speeds are in knots (from Probert-Jones, Harper 1962).

By 1961 RRE had built a second Doppler radar and installed it in a large vehicle with an aerial mounted on the roof with the idea that it could be directed into the path of thunderstorms by a PPI radar, rather than hoping one would occur over the original radar at Throckmorton. Since it was thought that thunderstorms were more likely to occur over southern England than in the Vale of Evesham, the mobile Doppler together with a PPI radar were deployed to RAF Odiham, Hampshire in

July 1961. Unfortunately only two days after arriving and whilst all the staff were at lunch a valve left by a south-facing window in bright sunlight set fire to the papers it was on, and the vehicle was completely burnt out. Thus the first mobile Doppler radar was destroyed without having made a single observation.

Between August 1960 and December 1961 a total of 107 sets of observations, using the successive attenuation method described above, were obtained on 10 separate occasions; 83 sets were in sufficiently uniform conditions to be used. They were analysed comprehensively by Caton (1966), who had replaced Probert-Jones at RRE in 1961, to examine the variation of drop-size distribution with rainfall rate and with height. An absolute scale was obtained by equating the calculated flux at the lowest level of analysis, 750m, with the open time-scale rain record from Pershore. The 83 distributions showed substantial variation not only from day to day but even over 15-minute intervals. This variability persisted even when the data was grouped by rainfall rate. A clear distinction was found for rainfall rates of less than 0.15mmhr^{-1} when there was a preponderance of small drops and exceptionally few large drops, typical of drizzle. Caton divided the rainfall rate into ranges and presented graphs of mean drop-size distribution and their 90 per cent spread. In all cases there were fewer large and fewer small drops than in an exponential distribution. Vertical air motions were diagnosed at some or all levels in 30 of the analysed observations, predominately downward of between 0.5 and 1ms^{-1}; this was ascribed to gravity waves induced by hills. The 83 drop-size distributions enabled a relation between $\mathbf{Z}_e$ and **R,** where $\mathbf{Z}_e$ is the equivalent reflectivity factor and **R** is the rate of rainfall, to be obtained for two heights which when extrapolated to the ground gave $\mathbf{Z}_e=285\mathbf{R}^{1.30}$. The distributions showed a significantly lower concentration of small drops of diameter less than 0.6mm than found by other researchers, but no reason could be found and it was concluded that the Doppler radar results were valid. The variation with height of the distributions was examined in detail to find evidence of coalescence, accretion and evaporation. There appeared to be some indication of coalescence, but that accretion and evaporation were too small to be resolved by the resolution of the data.

Caton (1963a, 1963b) refined the technique used by Probert-Jones to increase the accuracy to which the horizontal wind could be measured. By keeping the aerial elevation at 30^{o} and measuring the radial velocity at azimuths at 10^{o} intervals over a range of at least 60^{o} either side of the assumed wind direction Caton was able to obtain the horizontal wind with a standard error of ¾ms^{-1} below the freezing level and ¼ms^{-1} above; the direction was obtained with a standard error of 1.5^{o}. Winds could be obtained at height intervals of 300m. Observations at approximately hourly intervals were made on two occasions, 8 December 1961 and 28 March 1962, on both dates through frontal zones. In both cases a vertical region of frontal shear could be identified which descended slowly with time. An attempt, in an initial test, to devise an experiment to calculate divergence was not successful but showed promise.

Harrold (1966), who joined the Group in 1964, extended Caton's method of analysis by using observations at 10^{o} intervals throughout a 360^{o} revolution of the aerial, using elevations of both 15^{o}and 30^{o} and making use of the facility to change velocity channels from a width of 1ms^{-1} to ½ms^{-1}. He showed that the errors in calculating divergence with this data decreased with decreasing aerial elevation and increasing height and were less in snow than in rain. Measurements up to a height of 4km were made during continuous rain on 1 June 1964. Calculations of the wind field showed the movement of a wind front or sloping shear zone across the area, which could not be related to any synoptic feature. Convergence below a frontal inversion was compensated by a pronounced divergence of about $50x10^{-5}s^{-1}$ immediately above the front. Computed vertical velocities showed ascent of $10^{-2}mbs^{-1}$during the rain.

In 1961 an 8.6mm wavelength radar became available for the use of the Group. The radar had an aerial of diameter 4.9m, giving a half-power beamwidth of 8´, and a pulse length of 0.2µs, equivalent to 30m. The radar was used with the aerial pointing vertically and the signal displayed on a cathode ray tube as an intensity-modulated line with height as the vertical coordinate, which was recorded on a moving film. The investigation was designed to assess the detectability of various cloud systems; an all-sky camera supplemented by observations provided records of cloud conditions at the zenith. Harper (1964) found that the detection rate ranged from 100 per cent for nimbostratus and cumulus congestus through about 90 per cent for cirrostratus and altostratus and two-thirds for altocumulus and stratocumulus to almost zero for other cloud types. Significant fallstreaks could be detected in 50 per cent of cirrus, 83 per cent of cirrostratus, 68 per cent of altocumulus but only 27 per cent of stratocumulus. These fallstreaks were interpreted as precipitation particles, either water drops of at least 200µm diameter or large ice crystals with the same fallspeed. Harper (1966) presented analyses of indivual occasions recorded in 1961 and 1962. On 24 September 1962 well-developed cirrus between 22,000ft and 24,000ft showed uniform closely spaced fallstreaks. A section of the record is shown in Figure 8.

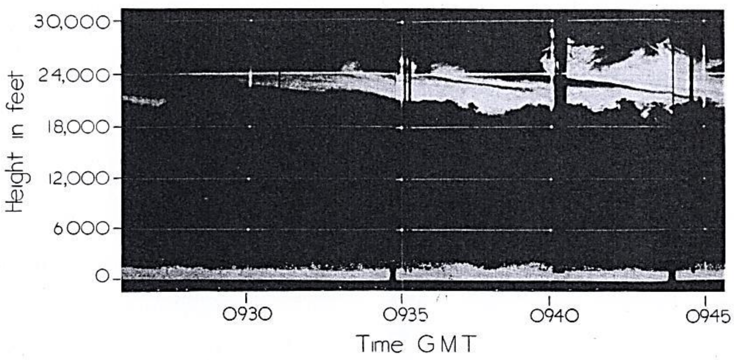

Figure 8. An example of a height-time record from the 8.6mm radar on 24 September 1962. The cloud was cirrus fibrates, becoming cirrostratus. There is clear evidence of fallstreaks.
From Harper (1964).

On 31 October 1961 cirrus and cirrostratus were observed at 1600GMT which showed closely spaced fallstreaks. By 1650GMT the echo had increased in thickness and intensity; a bright band had appeared at 9,000ft with fallstreaks of rain below. Two examples of the echoes observed from altocumulus showed that the high resolution of the radar enabled the bubbly echo from a water cloud to be distinguished from the fibrous nature of that from ice clouds. On 13 August 1962 the radar detected cirrostratus above 18,000ft producing fallstreaks which descended into echo from altostratus which had a base at 10,000ft. This case was analysed in detail by Stewart (1966) who found that the echo base only descended by 1,150ft over 65 minutes; the most likely explanation was the evaporation of the precipitation particles. Finally Harper provided photographs of echoes from precipitating cumulus and cumulonimbus, which were described as chaotic.

5. Department of Meteorology, Imperial College, London

At the beginning of 1950 Wexler joined the Department of Meteorology, Imperial College, on a Fulbright Fellowship from Harvard University and the Massachusetts Institute of Technology Weather Radar Unit to work with the cloud physicists Mason and Ludlam. His particular interest was the physical processes involved in producing radar echoes, particularly above the freezing level. Thus at a Discussion meeting of the Royal Meteorological Society at which the paper of Hooper and Kippax (1950b) on the radar bright band was read (Hooper et al 1950), Wexler pointed out that in order to produce a bright band the water of a melting snowflake must be mainly on the outside. Wexler carried out two investigations whilst at Imperial College. In the first (Wexler 1952a) he compared the theoretical growth rates of ice crystals in stratiform clouds above the freezing level with the variation of radar echo intensity with height. Assuming a model cloud with an updraught of 10cms^{-1} and a base at a temperature of 0^{o}C he calculated the growth of ice crystals at ice and water saturation, and hence the variation of relative radar intensities with height. He found that ice saturation best fitted observations obtained from Browne (1952a) and Hooper and Kippax (1950a). In the second (Wexler 1952b) he dealt with the theory of the upper band, a comparatively short-lived radar echo appearing at heights where the temperature was around -15^{o}C and which fell at about 2ms^{-1}. He showed theoretically that if there is a relatively high updraught speed in the upper portion of the cloud at a temperature near -20^{o}C, the ice crystals cannot grow by diffusion at a sufficient rate to consume all the water released by the updraught and will grow by coalescence with the cloud drops to form graupel. Initially the graupel will have a fall speed of 2ms^{-1} and in falling through the updraught will remove more liquid water than is being released, thus stopping the process. Browne (1952b) had also investigated upper bands, and both papers were read at a Discussion meeting of the Society (Wexler, Browne 1953); Wexler had already returned to the USA.

Mason (1955) suggested that by examining the ratio of the intensity of radar echoes from above, within and below the melting band it would be possible to estimate the amount of coagulation of snowflakes in the melting band, and their orientation. He used results from the experiments of Hooper and Kippax (1950a), Browne (1952a and unpublished) and Austin and Bemis[12] to obtain the three ratios I_m/I_w, I_m/I_i and I_i/I_w where I_i was the intensity above the melting band, I_m that within it and I_w below it. Although there were large variations in all ratios, I_i/I_w was almost always greater than 1. Using this and values of the other ratios Mason deduced that within the melting band a snowflake would coalesce with between one and six other flakes to produce water-coated horizontally oriented oblate spheroids with diameter/axis ratios of 2.5 to 7, these being extreme values.

Ludlam believed that coalescence could initiate showers. In August 1952 a collaborative programme was arranged to observe cumulus clouds in the vicinity of Cranfield, Bedfordshire. On 13 August the radar at East Hill observed echoes with tops at 9,000-11,000ft; aircraft found that cumulus which produced showers had tops where the temperature was -1^{o}C but with no evidence of ice crystals. It was deduced that the slight showers were produced by coalescence (Browne et al 1955).

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[12] Austin PM, Bemis AC. 1950. A quantitative study of the “bright band” in radar precipitation echoes. *J Meteorol.*, 7, 145-151.

By 1955 a radar set had been installed on the roof of the Department building in South Kensington, London. It was a modified airborne radar with a peak power of 10kW, a wavelength of 3.4cm, a pulse length of 1µs and a half-power beamwidth of 4^{o}, operating in RHI mode; the maximum useful range of the radar was 10 miles. The observing programme during June and July 1955 also used radar observations from East Hill together with information on lightning and hail given by a network of voluntary observers. To obtain proof of the coalescence theory initial radar echoes from showers whose tops were warmer than 0^{o}C were sought (Feteris and Mason 1956, Ludlam and Mason 1956).

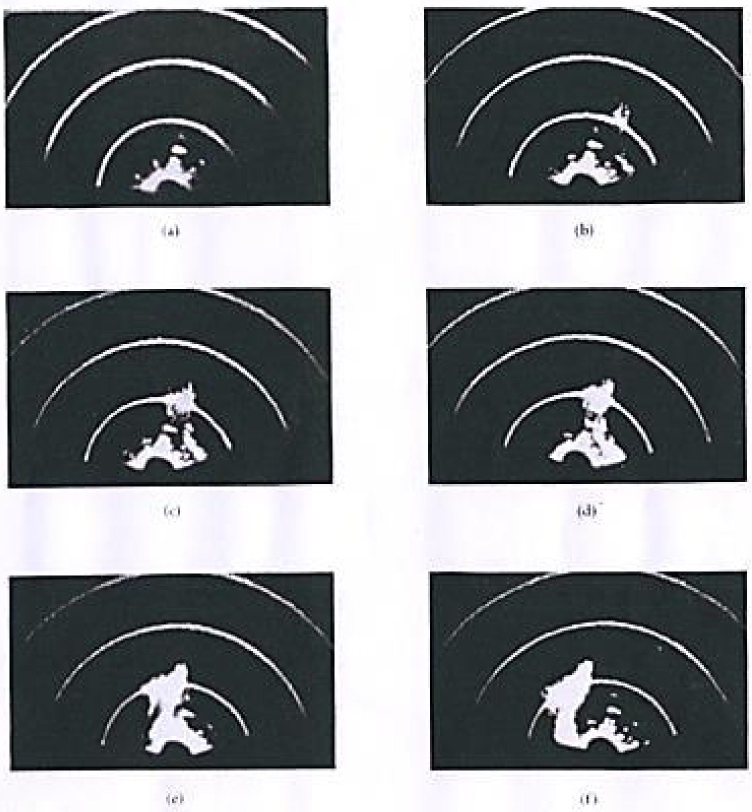

Figure 9. A sequence of photographs showing the development of coalescence showers on the Imperial College RHI radar display, scanning from horizon to horizon through the zenith, 11 August 1955. The range markers are 2 mi (10,500ft) apart.
(a) 1010.00hr Echo not yet apparent ; (b) 1013.30hr Initial echo top at 12,500 ft, -2°C ; (c) 1014.30hr Echo top at 13,000ft ; (d) 1015.00hr Top at 13,000ft but echo spreading downwards ; (e) 1016.15hr. Top still at 13,000ft but echo spreading laterally and downwards ; (f) 1019.00hr Echo at maximum state of development. Top at 14,500ft. -5.5°C. From Feteris and Mason (1956).

The procedure adopted was to select visually a suitable bulging cumulus, direct the aerial onto it and wait for the appearance of an echo. A typical sequence is shown in Figure 9. On 48 occasions on 13 days during May to September 1955 the tops of the first detectable echoes from shower clouds were found to be at or warmer than -2^{o}C, providing strong evidence for the coalescence theory.

Attempts were also made to detect initial echoes from, and follow the development of, thunderstorms. The display was photographed at two-minute intervals; in-between, attenuation was introduced in 10dB steps. Records from 8 storms were obtained between May and September 1955. When the initial echoes were detected the tops were only slightly above the 0°C level, suggesting precipitation was initiated by coalescence; in all storms the temperature at the cloud base was above 0°C. The interval between the appearance of the first echo and the occurrence of lightning was between 8 and 10 minutes; the echo top was always below -20°C. A patchy distribution of intensity was found to be typical of echoes associated with lightning, one such is shown in Figure 10; equally intense storms with a much more uniform distribution failed to produce lightning.

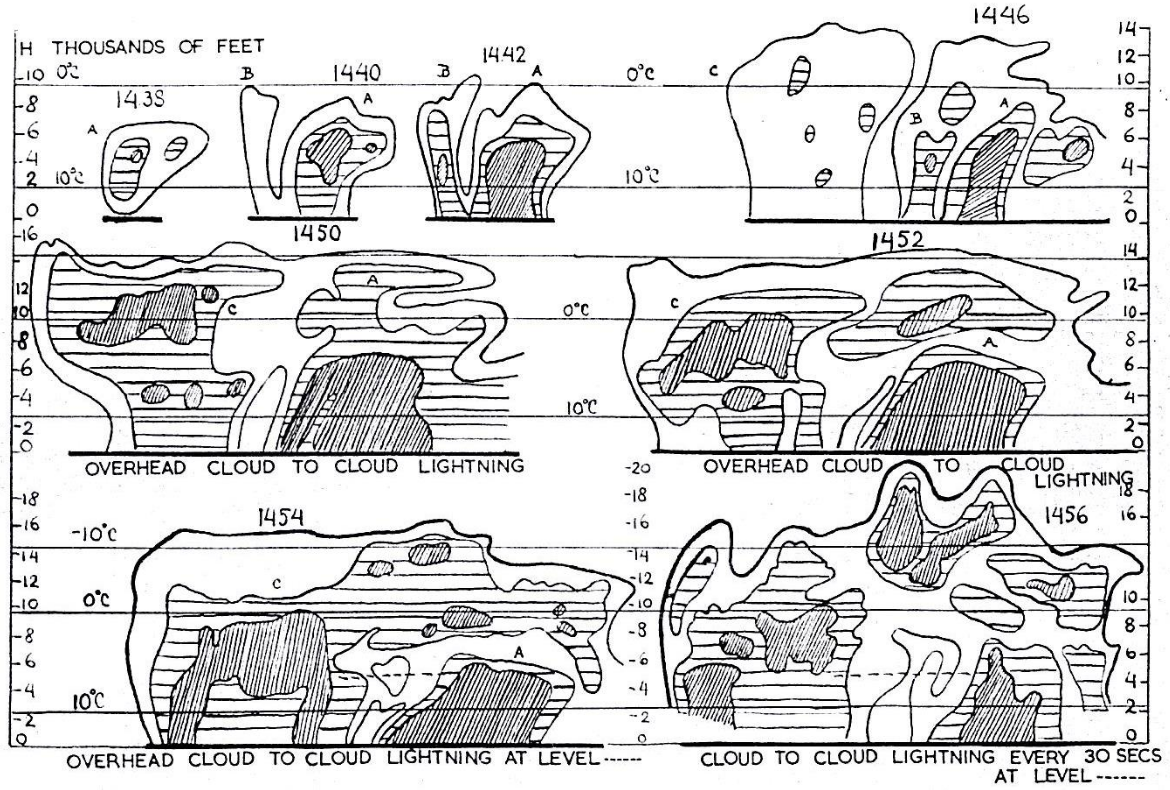

Figure 10. A sequence showing the growth and development of the radar echo from a thunderstorm first detected at 1438BST on 9 September 1955. The initial echo was blow the 0°C levl. Contours of intensity are at 10dB intervals, horizontal and vertical scales are equal.
From Ludlam and Mason (1956)

Radar observations were made during the passage of frontal systems; however no useful conclusions could be drawn.

The observing programme for 1956 was based at East Hill and took place between June and August 1956 (Harper et al 1956, 1957, Ludlam and Mason 1957). This involved the use of two radars: a 10cm wavelength PPI/RHI and a 3cm RHI, double-theodolite ground observations and flights by the Meteorological Research Flight and a light aircraft operated by Imperial College. In agreement with previous experience it was found that radar echoes developed in clouds whose visible towers exceeded a well-defined level. Where successive towers reached similar heights the echo column broadened and extended to the ground within a few minutes. The radar echo from maturing shower clouds was found to broaden and intensify throughout their height. It was observed that there was often a new surge in the growth of cumulus soon after glaciation; the radar display showed very tall and broad echoes whose upper parts, which corresponded with the anvils, were diffuse and weak but which contained stronger columns associated with newly-rising towers. Study of the radar echoes enabled the cloud physics of shower formation and development to be investigated. To supplement the investigations into frontal systems carried out at Imperial College in 1955, observations of cold fronts using the 10cm wavelength radar at East hill were made on 6 June and 5 July 1956. The results enabled some general deductions to be made, and it was suggested that such observations could lead to improved models of frontal structure. Other results from this programme are given in Section 3. A further observing programme took place during June and July 1957 and is described in Section 3.

At the invitation of Professor Vittori of Bologna University, Italy, Ludlam and Harper spent the summer of 1958 studying thunderstorms in the Po valley, Italy. As a consequence Ludlam decided that a thorough investigation of severe thunderstorms required several radars. For the observing season of 1959 he assembled five radars at East Hill. There were two of 10cm wavelength; the PPI radar took full-gain photographs every three minutes with some intermittent step-wise gain reduction; the RHI made manual searches for maximum echo heights and also made intensity measurements. A 4.7cm wavelength radar made step-wise gain reductions in PPI sweeps at successive elevations, taking 12 minutes for a complete cycle. One 3.3cm wavelength radar was employed to follow column tops and obtain their rate of rise, a second to follow and measure the intensity of the most intense echoes. Nearly two thousand ground observers had also been recruited. Such a huge observing system remains unique; Ludlam was optimistic in expecting the kind of severe thunderstorm he was hoping for, since in the previous year a particularly severe storm, the Horsham storm, had struck southern England and it was very unlikely that two such would occur in successive years. Nevertheless fortune was with Ludlam; on 9 July 1959 a storm system developed over the Brest peninsula and moved north-east across the Channel, crossing the Dorset coast at about 1030BST, passing just to the east of the radar site and reaching East Anglia at about 1500BST. It reached the most severe phase near Wokingham, Berkshire, giving 2-inch hail, and was hence known as the Wokingham storm. All the radars had been calibrated on the previous day using a method introduced by Atlas and Mossop (1959). They all performed perfectly throughout the time when the storm system was in range apart from an interruption due to an electricity failure between 1300 and 1415BST when the storm was close to the radar site and observation would have been difficult.

A comprehensive analysis of the radar data was carried out by Ludlam and his research student Browning (Browning and Ludlam 1960). The PPI observations enabled seven distinct storms within the system to be identified; but only one, the largest, was persistently intense and the only one producing hail. Using intensity measurements, expressed in terms of 10log$\mathbf{Z}$mm^{6}m^{-3}, from the 3.3cm and 4.7cm wavelength radars, the maximum reflectivities were generally found at heights between 20,000ft and 30,000ft and had magnitudes of greater than 65 after 1145BST, coinciding with the intense phase of the storm; reflectivies of over 70 occurred between 1200BST and 1230BST when hail greater than 1½in reached the ground. Echo tops were above the tropopause, which was at 37,000ft, from 1115BST and above 40,000ft from 1145, reaching over 44,000ft between 1150BST and 1220BST. Before 1145BST it was possible to detect rising towers on the right flank of the storm. When the storm was in its intense phase from 1145BST to 1230BST no such towers could be found; its speed dropped from 50kt to less than 35kt, and it appeared to be moving in a quasi-steady state. Using this assumption, the 12-minute scans of the 4.7cm wavelength radar could be used to construct the three-dimensional structure of the storm; this revealed three important features: the wall, the forward overhang and the echo-free vault. It was then possible to construct a range-height section displaying isopleths of intensity which, it was suggested, was typical of a steady-state severe storm. By considering the implications for the growth of precipitation including hail, the dynamics of the storm were discussed; this enabled a complete three-dimensional pattern of airflow in a steady-state storm to be proposed. This model has become of great importance in meteorology; it is now called a supercell and is typical of the storms which occur in 'tornado alley' in the USA. A further general analysis of severe storms with an emphasis on the Wokingham storm was given by Browning and Ludlam (1962).

The availability of intensity measurements at three different wavelengths led Atlas and Ludlam (1960, 1961) to investigate the possibility of deducing hailstone size distributions using the variation in backscattering cross-section with wavelength. New computer calculations and the measurements discussed in Section 2 for both dry and wet hail were available. These enabled Atlas and Ludlam to show that the variation of reflectivity with wavelength for monodisperse spectra of dry hail differed notably from that for any broad spectrum. They applied these results to the reflectivities from the Wokingham storm; the observed variation of maximum reflectivities was consistent only with a very narrow size distribution of hail of a specific size. The deduced diameters of 3.9cm at first and 4.6cm later agreed with those observed at the ground but the concentrations implied aloft exceeded those at the ground by a factor of 10 to 100; this was explained by the strong wind shear in the proposed airflow pattern. This, together with wetting which most strongly affected the reflectivity at 3.3cm, also explained the large decrease in intensity which was observed below the 0^{o}C level. They concluded that hail sizes aloft could be accurately determined with three calibrated radars of differing wavelengths, ideally 3.2, 5.6 and 10cm. They also found that in summer surface hail is unlikely unless $\mathbf{Z}>10^5$, for $\mathbf{Z}=10^6$ small hail is certain, as is large hail when $\mathbf{Z}=10^7$, using a wavelength of 3.3cm.

Ludlam (1960) examined the possible use of radar as a forecasting tool. He advocated a network of radars sufficient to cover the country capable of quantitative echo measurements. The intensity in every 10km square would be obtained and represented by a single digit, varying from 0 for $\mathbf{Z}\leq 25$ to 9 for $\mathbf{Z}\geq 76$. This would be plotted on a chart which could be very rapidly passed to a forecaster. A similar system was being introduced in the U.S.A.

Although Ludlam found that he needed five radars to examine fully a steady-state severe storm, he believed that a single radar could be of use in establishing the structure of showers and perhaps weak thunderstorms. He therefore acquired a radar of 4.7cm wavelength and intended to install it on the western edge of the Imperial College Field Station at Silwood Park near Ascot, Berkshire. Because of the wooded nature of the site, the radar would have to be mounted on a tower. However, because of very lengthy delays in obtaining planning permission and then problems with the components of the tower, by the time the tower was erected Ludlam had moved on to other research and the radar was never installed.

6. Cavendish Laboratory, Cambridge University

In 1948 Browne began three years as a research student in the Cavendish laboratory aiming to use a radar with a fixed vertical beam to study the growth of precipitation particles and to measure turbulence in clouds, producing a thesis on “Radar studies of clouds” (Browne 1952a). A second student, Barratt, continued his work from 1952 to 1955; he called his thesis “Studies in radar meteorology” (Barratt 1957). Both were supervised by Dr T.W. Wormell , an authority on atmospheric electricity[13] who worked at the University Observatory Field Station until 1950 when he was appointed University lecturer in Meteorological Physics and moved to the Cavendish Laboratory. It is not known what meteorologists there were in the Department; Browne thanks members of the meteorological section of the Cavendish Laboratory whilst Barratt makes no such reference. Both Browne and Barratt died young; Browne in 1957 at the age of 30 only two months after being elected to Council of the Royal Meteorological Society (Browne 1958); and Barratt in 1962 aged just 31 (Barratt 1962).

Browne spent November and December 1948 at TRE assisting Hooper and Kippax in their experiments to determine how the received power varied with wavelength and pulse length (Hooper and Kippax 1950a). In March 1949 he obtained on loan from TRE three radars, of wavelength 9.1cm, 3.2cm and 8.6mm; they were installed in the Observatory Field Station. He used mostly the 3.2cm wavelength radar for his investigations into the growth of precipitation particles and the 9.1cm to investigate turbulence; unless otherwise indicated the radars were used with the aerials pointing vertically. The 3.2cm wavelength radar had a peak power of 40kW, a p.r.f. of 1000cps, an aerial half-power beamwidth of 3.2^{o} and an A-scope display; the intensity below 3,000ft was unreliable because of receiver paralysis. Rainfall was measured using two Dyson tilting syphon raingauges and a Bibby rate-of-rainfall recorder. Drop-size distributions were obtained from an apparatus developed by L.G. Smith[14] of the Cavendish Laboratory in which the small drops were estimated from their terminal velocity whilst the size of large drops was found from the change in capacity of a parallel plate condenser when the drop falls between the plates. The equipment might have underestimated the concentration of small drops, but was accurate in obtaining that of the larger drops which contribute most to the backscattered intensity. Some values of the electric field at the ground were also available from Smith’s laboratory close to the radar site.

Browne first investigated the formation of precipitation. He used the observations from sixty individual occasions to assess the pattern of the received echo under various meteorological conditions. Echoes from warm frontal rain varied little in time or between occasions. The echoes from cold fronts were similar but the intensity had more vigorous fluctuations; upper bands were prominent. Showers and thunderstorms showed interesting patterns, sometimes fluctuating rapidly; the melting band was often weak. He extended Ryde’s theory of the melting band to cover the cases of vertical air motion and growth of particles in the melting band. He discussed the effect of the pulse length on the observed depth of the melting band.

For his investigation into the growth of precipitation particles in steady rain, Browne used data from sixteen occasions between April 1949 and August 1951 when both the rainfall rate and

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[13] Wormell TW. 1953. Reviews of modern meteorology-8. Atmospheric electricity, some recent trends and problems. *Q.J.R.Meteorol.Soc.*, 79, 3-38.
[14] Smith LG. 1952. New method to measure raindrop size. Urbana, Ill., State Water Surv., B.No 41, 299.

the radar echo intensity were reasonably constant over the measuring interval; the rainfall rate never exceeded 3mmhr^{-1}. He found first that the echo intensity did not vary below the melting band and growth by coalescence was undetectable; he deduced that the liquid water content in clouds below the freezing level varied from 0.4gm^{-3}in cold frontal rain with a rainfall rate of 3mmhr^{-1} to 0.05gm^{-3} in warm frontal rain of 1mmhr^{-1}. The peak of the melting band was found to occur 600±200ft below the freezing level compared to the 300ft found by Hooper and Kippax (1948), and the intensity at the peak of the band compared with that from the rain below was found to lie between 4 and 8, in good agreement with Hooper and Kippax who obtained values of 5 to 10. By developing a comprehensive theory of the melting band, which was sufficient to explain the observations, he deduced that in steady warm-frontal rain each snow particle coagulates with from one to three others, whilst in cold frontal rain as many as twelve crystals may coagulate to form a snowflake. This was in good agreement with Hooper and Kippax (1950b). Browne presented some of his early results at a Discussion meeting of the Royal Meteorological Society (Hooper et al 1950). He found that above the freezing level $\Sigma N_m m^2$, where N_m is the concentration of particles of mass m, decreased linearly for about 4,500ft then decreased more and more slowly. It was assumed that the growth of ice crystals was due to condensation and accretion. By making some reasonable assumptions a comprehensive theory of the growth was obtained and from this the variation of $\Sigma N_m m^2$ could be found; agreement with the observations was excellent. It was suggested that the close agreement was to an extent fortuitous in view of the assumptions made. This growth process could only produce rainfall rates of less than 3mmhr^{-1}, typical of warm fronts; almost certainly because it was assumed that there was no vertical air motion. In cold fronts, not only would there be vertical motion, but the liquid water content would be higher and greater growth rates would produce larger crystals so that coagulation might be involved; it was not considered worthwhile to attempt detailed calculation.

Browne made several observations of upper bands, narrow echoes first detected well above the freezing level which fell with velocities of about 20fts^{-1} and which decreased with time. Browne developed a theory which gave the apparent rate of fall in terms of vertical wind shear, the horizontal wind speed near the cloud top and the terminal velocity of ice crystals. Measured values gave good agreement. This work was published (Browne 1952b) and read at a meeting of the Society (Wexler, Browne 1953).

During 1950 the echoes from thirty-five showers and thunderstorms which passed over the radar were examined and a typical sequence of events deduced. The melting band was weak at the beginning, vanished during the intense phase and returned strongly in the later stages. The existence of a melting band in the initial stage posed a problem; it required there to be a very small vertical velocity, whilst the usual existence of a strong echo at higher levels and the absence of rain at the ground implied a significant updraught. It was not found possible to interpret quantitatively the echoes from shower clouds except on three occasions. In these, at the commencement of the most intense rain the absolute echo intensity increased exponentially with decreasing height in a region well below the freezing level. Over a height of 2,000ft the intensity increased by between 17dB and 30dB. Two hypotheses were put forward. First it was proposed that drops reached a critical size and broke into a few smaller drops which grew rapidly and repeated the process in a chain reaction. To fit the data this required an updraught of 4ms^{-1} and drops splitting at a diameter of 3mm, rather than the generally accepted value of 5mm. Alternatively it was shown that coalescence could produce the observed increase in intensity if the liquid water content was 4gm^{-3} and with an updraught of 1ms^{-1}.

Values of the electric field at the ground were available for the occasions when showers occurred; a connection between the fields and the echo patterns gave on the whole disappointing results. However a correlation was found between the magnitude of the negative field and the echo amplitude near the base of a hailstorm when the surface wind was 50mph and there was a fall of soft hail up to half an inch in diameter; the charge was found to be proportional to the square of the radius of the hail. The positively charged region sometimes found in the base of cumulonimbus clouds was found to coincide with the region of rapidly increasing intensity. The theory which could explain this required the existence of a significant updraught, supporting the chain reaction theory. This work was described in brief at Discussion meetings of the Meteorological Office (Browne 1951a, Wormell 1951).

On 12 July 1949, during routine maintenance, Browne detected a weak echo from a height of 4,560ft in the absence of any cloud or precipitation. The echo lasted for about 30 minutes and by tilting the beam from the vertical the echo was found to be coming from an extensive and continuous horizontal layer; the echo was classified as an ‘angel’. The radiosonde ascent from Downham Market showed a sharp change in lapse rate and temperature at the height of the layer. Browne (1953), using a simple model of a discontinuity, deduced that there must have been a very sharp change in both temperature and humidity. The absolute value of the intensity of the echo was measured, and it was calculated that a change in vapour pressure of 4mb would be required. Since the reflection was not specular the layer must have been turbulent. Thus these observations suggested the presence of a layer with a depth of some tens of metres in which there was small-scale turbulence. In spite of repeated searches in similar synoptic situations no similar echo was ever detected.

On 6 July 1950 during a thunderstorm a momentary strong echo was detected at a height of 12,000ft with a duration of 1-2ms. The estimated intensity was 2x10^{-6}W. A strong positive electric field change at the same time confirmed that the echo was due to a lightning stroke. Browne, after examining theoretically all the alternatives, found the only satisfactory explanation to be scattering from electrons and ions in the lightning channel, provided that the channel was narrower than the wavelength. From this he calculated that the electron density was about 10^{12}cm^{-3}. A brief note on this work was given in Browne (1951b).

The possibility of obtaining the vertical velocities of precipitation particles was examined theoretically by Browne. Whilst the requirements to obtain absolute velocity could not be met, the variation in intensity between successive pulses could give information about the relative velocities in the echoing volume and hence an indication of the turbulence. The autocorrelation of successive intensities would give a power spectrum equivalent to the probability distribution of the vertical velocities of the drops in the echoing volume. For this investigation, because of its greater stability, the 9.1cm wavelength radar was used. This had a peak power of 100kW, a pulse length of 1µs and a variable p.r.f. The aerial had a half-power beamwidth of 3^{o}. The necessary equipment was mostly designed and installed by Browne, who also adapted a camera to run film continuously at 2fts^{-1}, sufficiently fast to separate individual pulses. Measuring the intensities from the film and then calculating the autocorrelations was a lengthy process. Although the equipment was not in its final stage, some preliminary observations were made. In conditions where little turbulence was to be expected, and the rainfall rate was 1mmhr^{-1}, a root mean square velocity for raindrops of 80cms^{-1} was found. In the degenerate stage of a thunderstorm on 22 July 1951, with a melting band at 9,000ft, root mean square velocities were found of 120cms^{-1} at 600ft below the melting band and less than 20cms^{-1} at 600ft above. No further observations were made with the equipment, although Browne suggested that the power spectrum could be recorded on magnetic tape and electronically analysed to save the lengthy manual analysis.

Browne made a contribution to a review paper (Browne et al 1954) putting some of his research into context. At the end of his thesis Browne included some suggestions for future work. The existing 3.2cm wavelength radar suffered from receiver paralysis below 3,000ft. A 3cm wavelength radar was built with separate aerials for transmitting and receiving with a minimum range of 1,500ft. This was used to measure cross-polarization, described in Section 4 (Browne and Robinson 1952). He also suggested that absolute values of velocity could be obtained by using a stationary target to provide a reference frequency. After the end of his research studentship Browne stayed on with a Twisden Studentship from Trinity College and together with Barratt, who had begun as a research student, developed equipment to measure the absolute Doppler spectrum of precipitation particles; the 9.1cm wavelength described above was used. An observation was made on 27 May 1953 during a shower when the precipitation rate was 10mmhr^{-1} was made to obtain the absolute Doppler spectrum at a height of 5,000ft. This spectrum agreed with that to be expected from the drop-size distribution apart from a frequency shift corresponding to a downward velocity of 2ms^{-1}. A brief notification of this work was given by Barratt and Browne (1953). No other description of this work is given in the theses of either Barratt or Browne.

Barratt found that the equipment used was unsuitable for repeated use. A complete redesign and rebuild was therefore required. The radar used was the 9.1cm wavelength radar described above. The echo from the precipitation was mixed with the echo from a steady ground target at the same range, via a plane plate fixed above the antenna at an angle of 45^{o}. Beat frequencies were developed in the radar receiver, leading to a fluctuating voltage in the video stages which was the resultant of components with all the possible frequencies from the mixing of the signals. A record was obtained of the magnitude of this resultant for each received pulse. This was displayed as a vertical line on an A-scope and recorded on a film moving at 2.5fts^{-1}, each line on the film corresponding to a single transmitter pulse. The usual recording time was 5 seconds, although Barratt established theoretically that the optimum number of pulses required to obtain a spectrum was 200. Analysis to recover the Doppler spectrum was laborious, taking about twenty hours. Absolute vertical air velocities were accurate to 20cms^{-1}.

The interpretation was made as follows. For observations made below the melting band the rate of rainfall at the ground was measured using either a Dines or a Bibby recording raingauge, and it was assumed that this was representative of the rainfall rate at the echoing level. This was then converted to a drop-size distribution using the formula given by Best[15]; knowing the terminal velocities of all drop sizes enabled the expected Doppler spectrum in the absence of vertical air motion to be obtained. An exhaustive examination of all the factors that could affect the spectrum was made and it was concluded that only a strong wind producing a radial velocity towards the

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[15] Best AC. 1950. The size distribution of raindrops. *Q.J.R.Meteorol.Soc.*, 76, 16-36.

edges of the beam could be significant; this would produce a widening of the spectrum. The theoretical spectrum was compared to that derived from the radar echo; any differences could be ascribed to vertical air motion and a horizontal wind. An example is shown in Figure 11; the observation was made on 23 March 1955 at a height of 3,000ft; the melting band was at 5,000ft. Synoptically, an occlusion was crossing East Anglia. The peaks of the spectrum correspond to velocities with respect to the radar of 325, 680and 900cms^{-1}. The observed precipitation rate implies a maximum in the corresponding spectrum at 630cms^{-1}.

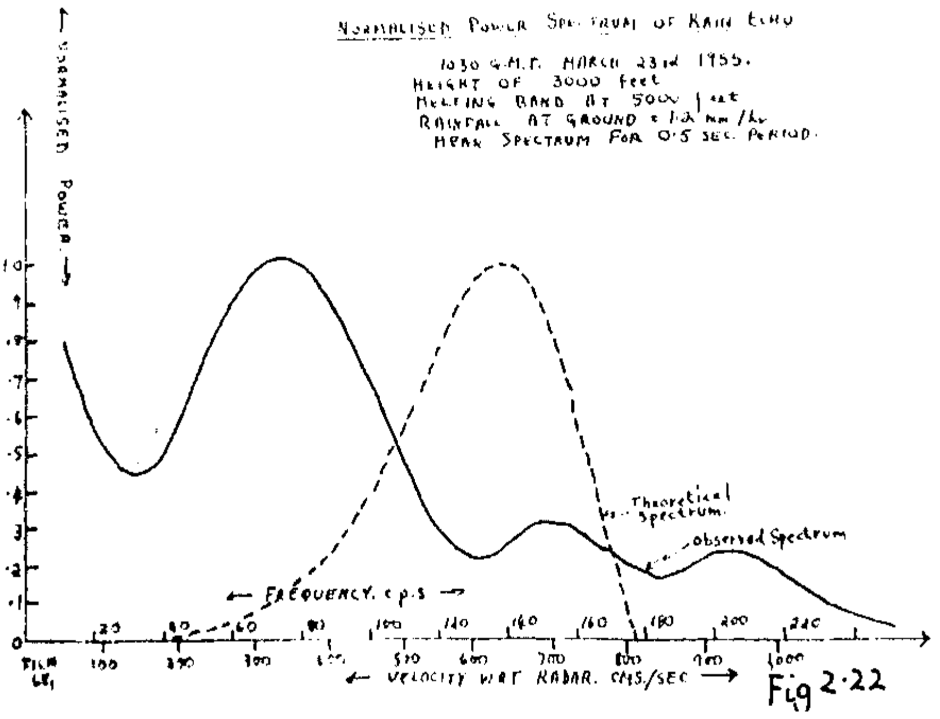

Figure 11. Normalised power spectrum of echo from rain, 23 March 1955 1030GMT at a height of 3,000ft. The melting band was at 5,000ft, the rate of rainfall at the ground was 1.2mmhr^{-1}.
From Barratt (1957).

Barratt made the assumption that the spectrum amplitudes were proportional to the volumes of air with those velocities; it was deduced that an updraught of 305cms^{-1} existed over an area of 25,000ft^{2} and downdraughts of 50cms^{-1} and 270cms^{-1} over 5,000ft^{2}. The film recording the A-scope display was typically run for five seconds, giving a total of 2,500 vertical lines, one for each transmitter pule, for a p.r.f. of 500s^{-1}. Since only about 200 were required to calculate the Doppler spectrum, several could be obtained from a single run. Whilst the main peaks gave consistent results for vertical air motion, the minor peaks such as those seen in Figure 11 showed considerable variation. This was interpreted as being due to gusts and values of a gustiness were obtained. Observations were made 25 March 1955 at 3,000ft and 45 minutes later at 11,000ft, the melting band being at 8,000ft. At the higher level five sets of measurements from the 5-second run were obtained. The greater part of the air in the echo region was found to have no appreciable vertical air motion, but downdraughts of 2.75ms^{-1} and 5.0ms^{-1} were detected with vertical accelerations of the order of 0.1g. At 3,000ft eleven sets were obtained giving mainly a downdraught of 70cms^{-1} but with additionally a downdraught of 250cms^{-1} and an updraught of 185cms^{-1}.

Time constraints and a lack of suitable meteorological conditions meant that only one more observation could be made, giving similar results. Nevertheless Barratt felt that both the equipment and the method of analysis had been validated. Unfortunately no one carried on his work.

Barratt had available an AN-APS 15 radar with a wavelength of 3.2cm, a peak power of 25kW, and a pulse length of 1µs, having an aerial of half-power beamwidth 3^{o}, scanning in an RHI mode; azimuthal scans could be made at 5^{o} or 10^{o} intervals. The aim was to use the radar to observe the three-dimensional form of showers, and hence to derive a simplified representation to which all showers might be fitted. When a shower was observed, the radar was operated to produce RHI scans at suitable azimuthal intervals to cover the horizontal width of the shower. It was first observed that the radar echoes from showers could easily be divided into a central region of high intensity surrounded by an outer region of low intensity, the difference being around 20dB. Only the regions of high intensity were used in the study. Showers were found to consist of a group of columnar cells about one mile in diameter separated by the same distance. From the RHI scans at the various azimuths horizontal sections of the echo could be produced at any required height. Also from the RHI scans the height of the highest cell could be obtained; this was found to increase as the shower developed, reach a maximum and then decrease. Seven showers were observed during the observational period of June 1953 to June 1954 and yielded sufficient information for the evaluation of the three-dimensional echo at thirty times. Each of these thirty sets could be used for the construction of sections showing the distribution of the echo in horizontal planes at various heights. At each height the area covered by the echo was measured. In order to compare the variation of this area with height for different showers and different times, both the height and the area were normalised. These were given by $\mathbf{H}=\mathbf{h}/\mathbf{h}_t$ where $\mathbf{h}$ is the height and $\mathbf{h}_t$ the top of the radar echo, both measured in feet; $\mathbf{r}=10^{-5}\mathbf{A}^{1/2}/\mathbf{h}_{t,}$ where **A** is the area covered by the echo in square feet. In general values of $\mathbf{H}<0.2$ could not be used since for such heights echoes from ground targets interfered. It was found that the maximum value of **r** occurred at $\mathbf{H}=0.4$ whilst the shower was developing and increased to $\mathbf{H}=0.5$ when the shower was at its maximum development. **r** was plotted against **H** for each individual observation, and it was found that the points could be fitted by parabolas of the form:

$$\mathbf{H}^2+2\mathbf{a}(1-\mathbf{H})=\mathbf{b}\mathbf{r}+1$$

a is the value of **H** at which **r** is a maximum, whilst **b** was found empirically to be given by:

$$\mathbf{b}=0.5\mathbf{a}+0.4.$$

These equations effectively defined the state of the radar echo from the observed showers at any particular time. By using the variation with time for each individual shower, it was found possible to obtain two equations expressing **t** as a function of **a** and $\mathbf{a}_{max}$ where **t** is the time measured from the time when $\mathbf{a}=\mathbf{a}_{max}$ either forward or backward, and $\mathbf{a}_{max}$ is the maximum value of **a**. The value of $\mathbf{a}_{max}$ was always close to 0.58, and this gave times of 30 minutes for the shower to develop to its maximum radar echo and 45 minutes for it to decay. An attempt was made to use these relations to investigate the liquid water budget of a shower. The conclusion reached was that this approach might prove of value in the further study of the mechanisms of showers.

RHI displays of, particularly, frontal precipitation showed a narrow horizontal band of high intensity, called the bright band or melting band. It had been established by e.g. Hooper and Kippax

(1950b) that the bright band was caused by the formation of a thin film of water on ice crystals giving them the higher backscattering cross-section of water drops before melting and accelerating to become raindrops. The melting band occurred at a distance below the freezing level; Barratt wished to investigate the physical processes involved in the melting of the ice particles and so establish theoretically the separation of the freezing level and the melting band. He realised from the start that large variations could be expected in the magnitudes which had to be assumed for some of the parameters. This was realised in practice. The height of the melting band was obtained accurately from the RHI radar and that of the freezing level from the Meteorological Office Daily Aerological Reports, from which also the lapse rate could be found. Surface observations of wet and dry bulb temperature were provided by the Station at the Botanical Gardens, Cambridge. A comprehensive theoretical and analytical study of the processes involved was carried out. These included condensation, accretion and aggregation which would change the mass, and the transfer of heat into the ice particle with its surrounding shell of water. The influence of external factors such as the air temperature, the humidity and any air motion had to be included. An expression was derived relating the separation between the melting level and the freezing level to the lapse rate, the ground temperature and various properties of the particles. This formulation necessitated various assumptions and approximations, and the results showed a considerable spread. An empirical expression was derived for the height of the freezing level in terms of the height of the melting band:

$$\mathbf{H}_t=4.16\log_{10}\mathbf{H}_m+2.68-\mathbf{H_m}$$

where $\mathbf{H}_t$ is the freezing level height and $\mathbf{H}_m$ that of the melting band, both measured in miles.

Upper bands and precipitation streaks had frequently been observed, and their theory had been investigated by Wexler (1952a) and by Browne (1952b). Browne used a vertically-pointing radar, and Barratt aimed to advance the theory by examining the streaks using an RHI display. This enabled the three-dimensional form of the upper band to be found; it was sheet-like in form and could be regarded as part of the surface of a parabolic cylinder with its axis horizontal. The results showed that the movement of upper bands could be explained by their observed form and the horizontal winds, the bands retaining their form with time and moving with a uniform speed. The fall speeds of the particles which were derived agreed with those for ice crystals and snowflakes; the alternative idea that the particles were graupel was shown to be untenable. For fallstreaks, theoretical expressions were obtained for their shape in terms of the horizontal wind speed at the top of the streak, the generating cell, the magnitude of the wind shear and the apparent fall speed of the particles, which may be affected by vertical air motion. It was also deduced that when streaks were observed below the melting band the wind shear was constant and there was little, if any, vertical air motion. Barratt noted that the measurement of another suitable quantity would have greatly enhanced the value of the streak analysis. Doppler radar would have been ideal; unfortunately it was impossible to operate the Doppler radar at the same time as the RHI radar.

The occurrence of a solar eclipse with a maximum obscuration of 75 per cent on 30 June 1954 enabled Barratt to investigate its effect on the propagation of 3.2cm wavelength radiation and to deduce its effect on the low level structure of the atmosphere. Five targets were selected at distances from 13,000yards to 25,500yards and the variation of their echo intensity measured throughout the duration of the eclipse. Large variations in echo strength were observed which were comparable to those previously known to occur in the presence of ducting. It was concluded that during the eclipse an inversion formed at a height of approximately 40 feet.

Barratt was able to reach some general conclusions. Upper bands occurred when there was a linear change of horizontal wind strength with height and negligible vertical air motion. Analysis of precipitation streaks, and results from the echo spectra, showed small but significant vertical velocities. Echo spectra below the melting band showed both updraughts and downdraughts but no evidence of a continuous velocity spectrum; the peaks were always well-defined. The model of a shower was a promising concept. In all cases there was a need for additional information if full advantage was to be taken of the methods. The technique for obtaining echo spectra was found to be very encouraging; the use of corner reflectors could overcome the absence of permanent echoes and the use of narrow band-pass filters was suggested, anticipating the method used in the RRE Doppler radar.

The above is a brief description of some very extensive theoretical and experimental analyses. There is no doubt that Barratt's 450-page thesis was a remarkable, but unknown, contribution to radar meteorology; he published nothing.

7. Concluding Remarks

Radar meteorology began in 1940; by 1965 it had become a fully developed discipline. The theoretical foundations had been firmly established by Ryde, by Hooper and Kippax and by Probert-Jones. The use of radar to investigate the structure of convective precipitation had been pioneered by Ludlam, culminating in his examination of the Wokingham storm enabling the full three-dimensional structure of a steady-state supercell to be obtained. The invention of pulsed Doppler radar by Browne and Barratt, and at RRE, preceded similar developments elsewhere by several years. As briefly detailed above, a considerable amount of other research, much of it original, was carried out during the period 1940-1965 by United Kingdom radar meteorologists. However, there is one aspect of the research during this period which has to be mentioned. There was no communication, let alone exchange of scientific ideas, between any of the four establishments during this period, and the only collaboration was between Imperial College and East Hill in the mid-1950s. This is particularly true for the Cavendish Laboratory where it would appear that Barratt worked in total isolation; his research was not made known to anyone.

I would like to express my thanks to Andrew Watt of the National Meteorological Library and Archive for his help and patience in providing copies of many of the references. The theses of both Browne and Barratt have been deposited in the National Meteorological Library and Archive.

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