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THE INVESTIGATION OF HORIZONTALLY AND VERTICALLY POLARISED DIRECTION FINDING ON FREQUENCIES OF THE ORDER OF 20 TO 70 MEGACYCLES PER SECOND.

SUMMARY.

Observations of the R.D.F. stations with a field intensity measuring set show that these field intensities are very variable. Sometimes, when intensity variations occur, bearings taken only half a minute later, with spaced horizontal frames, change by as much as 10°.

The spaced frame system is free from polarisation error, but is subject to Heiligetag error, due to the presence of two or more rays of different azimuths, one of which is almost certainly caused by very oblique reflection from refractive index discontinuities low down in the atmosphere. So far as we have made experiments, vertically polarised waves are much less affected. The fact that vertical polarisation is much less affected than horizontal polarisation can be explained by the theory of propagation of such waves over a curved and irregular earth's surface, so that there is theoretical as well as experimental evidence for the fact. The results are of practical importance in G.L. work, for if the target is low down, and horizontally polarized waves are used, there is a very considerable probability that the bearing obtained is not correct, and guns using this bearing will be pointed away from the target. The experimental evidence points to the existence of such errors in nearly horizontal transmission. They are probably less as the angle of elevation increases. If the theory is correct, they should be less over sea and over smooth ground, for the error is produced only if the ground ray is distorted by irregularities, and over sea there are no hills.

The results indicate that there is, for overland transmission, a very considerable effect produced by glancing incidence reflections from low-lying regions in the atmosphere, and that ultra short wave propagation over the surface of the earth may be very severely modified by such effects, and cannot be accurately calculated or allowed for unless the meteorological observations are sufficient to give the changes of refractive index in the atmosphere. These effects may produce excessive ranges, echoes at distances well beyond visual range, spurious echoes in R.D.F. work, and deviations in the bearings of the targets, which ought to be accurately determined by this radio location work.

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INTRODUCTION.

This research originated in an endeavour to find out something about ultra short wave propagation. It had always been assumed that when such a high frequency was used, there was no reflection from the ionosphere, and the transmission through the atmosphere would be perfect. This implies that the rays through the atmosphere would follow straight lines, and that there would be no errors in direction finding. I had considerable doubts about this - doubts which have since been amply justified. Meteorological observations show that the air is not of uniform refractive index, and that there are layers, roughly parallel to the earth's surface, in which there may be rapid changes of this, and these layers produce violent effects upon transmissions which are very oblique or nearly parallel to the earth's surface or the surfaces of discontinuity. These tropospheric discontinuities are often produced by temperature inversions, and although the changes are mainly in the vertical direction, there may also be clouds. A search for directional variations was therefore made, and in order to do this, a perfect direction finder had to be used, and one that was free from polarisation error, which may assume considerable importance in overland transmission on these waves. Suitable transmitters were found in the chain of R.D.F. stations, which send out horizontally polarised waves. The direction finder had therefore to be arranged for horizontal polarisation, and to obviate polarisation errors, had to be of the spaced aerial type. Two horizontal loops were therefore attached to each other by a rigid tube horizontal feeder, which rotated about a central vertical axis which was also a tube, and supplied a receiver below, the H.F. part of which rotated with the whole system. An appendix shows the complete instrumental make-up of the direction finding set. With this arrangement, bearing errors were sought, and in order to make the experiment more definite, field strength measurements were made simultaneously. These field strength measurements were made on a T.M.E. type 14 Marconi field strength measuring set, which covered the frequency range referred to. The R.D.F's were mainly on frequencies of 22 and 27 mc/sec, but measurements have also been made on local horizontally polarised G.L. stations, as well as on vertically polarised transmissions from Daventry and near Haslemere. All the transmissions were of the impulse type, and very high powers were usually used. Measurements of the field strength were compared with theoretical values, and the research therefore consisted of a comparison between the observed and calculated field intensities.

Bearings and field strengths could obviously be modified by tropospheric gradients and discontinuities, and very considerable changes were found. Many hundreds of observations were made by the W.R.N.S. personnel using this apparatus. Samples of the observations are shown in Figs. 1 - 9. These curves are rather striking, especially in the case of transmissions from the R.D.F. station at Colchester (Figs. 1 and 2) and perhaps this will be considered as a good example for the purposes of explanation. On quite a number of occasions during the periods in which the observations were made, i.e. between the hours of 8.30 to 5.0 B.S.T. in the daytime, sudden changes in the bearing were associated with sudden changes in the field strength, which, in the case of Colchester, were practically always a sudden increase of bearing associated with a sudden decrease of field strength. The curves of field strength and bearing were therefore almost complete mirror images of each other. These sudden changes may occur in a period of half a minute or so, and are therefore very sharply defined.

Observations were taken every half minute, so that there may be as much as 10° difference between one observation and the next, as well as a difference of the order of 20 decibels in the field strength. The observations have covered a period of about six months, and during certain times, the discontinuities or irregularities were much more marked than at other times, and these were generally in disturbed meteorological conditions.

(Disturbed conditions Figs. 1 - 7; normal conditions Figs. 8 - 9). Simultaneous observations were made on the bearing of two different R.D.F. stations, together with the field strength of one of them, to see if the changes in the two were associated. (Figs. 1, 3, 4.) About ten R.D.F. stations were observed, and all these showed the same effect in varying degrees. Usually the effect on the more distant stations was less than that on nearer ones. The mean bearings of the stations were usually fairly correct, and could be used as a means of identification, but the site was not ideal, and the instrument was probably not perfect, so that some systematic errors were no doubt present. Similar effects were observed in the short distance transmissions from the G.L. station at Writtle and one a few miles due north of us. These also used horizontally polarised transmitters and frequencies between 55 and 70 mc/sec. These higher frequencies also showed the effect (Figs. 5, 6, 7). On August 3rd, 1942, the aerials were changed from a horizontal position to a vertical one, and observations were made on the 49 mc/sec vertically polarised G transmissions from Daventry and Nr. Haslemere. These transmissions do not seem to show the sudden and large changes of bearing that the horizontally polarised transmissions do, and so far, with vertical transmission, we have not observed the anomalies which are associated with horizontal transmission. But we have not yet had a vertical transmission over a short distance, where the effects are likely to be at their greatest, at least by analogy with the horizontal polarised transmissions. We therefore intend to supplement the experiments by having a vertically polarised transmitter at Stock which will be similar to the horizontally polarised transmitter at Writtle, and only differ from this in its polarisation. It is also desirable that the research should be extended to the shortest waves usable, and 10 centimetre measurements of the same type will be made in the near future. There is evidence that such transmissions do not suffer from the big lateral deviations that the longer waves suffer from, but this should be checked experimentally. The result obtained will be of considerable importance for G.L. work, because if large errors are obtained in nearly horizontal transmissions, the G.L. receivers will not be able to determine the position of the targets, especially if these are low-flying aeroplanes and the ray path is nearly horizontal.

EXPLANATION OF THE SUDDEN CHANGES OF BEARINGS AND FIELD STRENGTHS.

The station at West Bromley, near Colchester, which may be used for purposes of explanation, is 42 Kms. from the receiver at Baddow, and even though the transmitter may be at a height of 100 metres, the receiver at 5 metres height is beyond the visual range. Anyhow, it cannot be seen from Baddow, so that hills at least will put it in the shadow. A transmission from such a station probably consists of two parts: (a) the direct ray over the surface of the earth which probably passes along a geodesic between Colchester and Baddow, and (b) a possible reflection from a tropospheric layer. The geodesic between the two stations may not, on account of hills and irregularities, remain in the vertical plane containing the transmitter and receiver. If the tropospheric layer is uniform, and parallel to the mean earth's surface, the reflected ray path will lie in this vertical plane. The direction in which the geodesic arrives at the receiver and in which the reflected ray arrives may not be the same, especially if the geodesic, like a thread, has to pass round hills. There is indication that in this transmission from Colchester, the geodesic, which has to pass south of Danbury Hill, is deviated from the straight path, so that the bearing of the ground ray is considerably greater than the true bearing. Two simultaneous signals will arrive at the receiver by two different paths which have not the same azimuth, and since the two signals are derived from the same station, they are synchronised, of course, in frequency. We have, in this case, therefore, a similar state of affairs as that discussed in "Synchronous Stations", which was that of two synchronised stations of different azimuths. It was shown, in this paper, that in such conditions, very large bearing errors may be produced, owing to the interference of the two rays, and that when these two rays do interfere, producing a change in field strength, they will also produce a change in bearing. This accounts for the fact that changes of bearing and changes of field strength occur simultaneously.

A rather vague qualitative theory like this needs a numerical backing before any certainty is achieved. The bearing of the station at Colchester (nearer Great Bromley) is 59°. The direct or geodesic ray is distorted, and has a bearing nearer 72°. This has been checked roughly with the help of a relief map of Essex, which shows that the geodesic ray has to pass round the south of Danbury Hill, and is therefore considerably distorted. The actual bearing of the station when there appeared to be no tropospheric reflections, (or these were small so that the mean strength and bearings were undisturbed), was about 72°. This deviation is not instrumental. A check on the instrumental behaviour was made on a small transmitter with a horizontal aerial, and it was found that at short distances the directional aerial receiver gave the correct bearing. There seems therefore, to be evidence that the ground ray over the surface of the earth is actually distorted about 13°. The undistorted condition from which the true direction of the bearing was obtained was judged in the following manner. It was observed that in the records of the bearings, these remained steady for a considerable period, and that then, suddenly, in the course of half a minute, there were large deviations of bearing and strength which lasted for a minute or two, or sometimes up to ten minutes. It was judged that the steady bearing represented the undisturbed condition. This bearing was not quite steady, probably owing to minor reflections from the troposphere, but a well defined average of 72° could be obtained, which therefore probably represented the actual bearing of the geodesic. We therefore have two rays from the transmitter, one with a bearing of 59° and the other, probably stronger, of 72°. The median line is in a direction of $65\frac{1}{2}^{\circ}$, and since the geodesic ray is probably stronger, all the bearings, as shown in my paper on Synchronous Stations, will be between $65\frac{1}{2}^{\circ}$ and $155\frac{1}{2}^{\circ}$, i.e. in the quadrant of a dominant ray. When these rays interfere it must be that the reflected ray is in opposite phase to the ground ray, so that the signal in these sudden irregular conditions is much reduced. In these conditions the bearing tends to a definite limit, which is actually greater than the mean bearing and even greater than the geodesic bearing. The value of this limiting angle, which occurs when the two rays are in opposite phase, is given by the formula:-

$$\tan\theta = \frac{1+r}{1-r} \tan\alpha$$

where θ is a deviation of the bearing from the median line, 2α is the angle between the true direction and the geodesic direction, and r is the ratio of the reflected to the direct signal. Since the signal is suddenly decreased by 10 to 15 dBs or so, so that $(1 + r) \div (1 - r)$ lies between 2 and 9, the limiting bearing which must always increase at the moment of reflection or discontinuity must lie between 78° and 130° if the phases are correct. This actually is what almost always does happen, a sudden decrease in the strength being associated with a sudden increase in the bearing which may increase ten or more degrees from the normal bearing 72°, although a range as great as 130° has not been observed. It therefore seems that this is an adequate explanation, since it agrees numerically with the results observed. Since it appears probable that the reflected ray is in opposite phase to the direct ray, the height of reflection must be small. If the tropospheric layer has a sufficiently big change of refractive index, then on reflection the phase is unchanged, and it requires that the path on reflection should not be appreciably different (about $\lambda/2$ from the geodesic path) which only occurs when the height of reflection is very small. Although a decrease of strength is, in the majority of cases, associated with an increase of bearing, it has been observed that on a few occasions there is a decrease of bearing associated with a decrease of signal strength. This will happen when the phase of the reflected ray is not too far from the phase of the geodesic ray. At greater distances, the relation between the sudden changes of bearing and the change in field strength becomes less marked, because the transmission is of a more complicated nature and changes of phase are not definite and are almost accidental. Similar changes occur in transmission on about 65 mc/s, in which again there are occasions when the sudden increases of bearings are associated with sudden increases of signal intensity.

There are some occasions on all frequencies when the bearings are quite steady within the limits of experimental error, and other occasions when the bearings and the field strength are both very unsteady or variable, but in which there seems very little relation between the field strength and the bearing. A statistical analysis of the large amount of material that we have obtained shows that irregularities occur during 43% of the time, and seem to be more or less equally prevalent on the 65 mc/sec transmission and the 22 and 27 mc/sec transmissions. The evidence we have obtained so far, although incomplete, suggests that vertical transmissions do not suffer from these sudden changes of bearing in the same way that horizontally polarised transmissions do. The evidence is obtained from the observations of the 49 mc/sec transmissions from Daventry and Haslemere, in which the changes of bearing are more or less confined within the experimental error. These changes do not seem to me to be significant. But this is a long distance transmission, and is difficult to compare directly with the short distance horizontally polarised transmissions, and it may be that the failure to observe sudden large changes of bearings is due to the large range. Observations on short range vertically polarised transmissions on the G.L. wave-length of 65 mc/sec or so, with the help of the proposed transmitter at Stock, will help to clarify the situation.

RELATIONS BETWEEN THESE RESULTS AND METEOROLOGICAL OBSERVATIONS.

This type of transmission varies a great deal from time to time. Sudden changes on Colchester bearing and field strength were particularly marked in the period between 13th and 20th April, 1942 (Fig.2). In this period, the meteorological charts showed rather excessive temperature inversions, at a low height, and there were many reports of spurious echoes from G.L. and C.H.L. transmitters. It seems probable that during this period there were well defined layers and clouds of variable refractive index, and that these clouds, possibly produced by temperature inversions, were sufficient to give spurious echoes. The meteorological information given by these directional measurements is very much more comprehensive than the information given on the ordinary charts, which does not allow for the rapid changes which may occur in other localities and at other times of the day. Our results, therefore, may be of use to meteorologists, indicating as they do, in greater detail, the changes in the atmosphere that may occur. There may be some difficulty in interpreting the results, as they do not give directly the qualities, such as temperature and pressure, which the meteorologist likes to play with; yet they may be of value.

There is also a sound theoretical reason why the vertical transmission should be less erratic than the horizontal transmission. This is connected with the attenuation of horizontally and vertically polarised rays. Thus, as a rule, the horizontally polarised ground ray is more attenuated than the vertically polarised one, and the reflection at the tropospheric layer is likely to be the same for both. It therefore follows that the horizontally polarised ground ray is smaller in proportion to the reflected ray than the vertically polarised ray is. The result is that the reflected ray, which produced the erratic bearings, is more prevalent in the case of horizontal than in the case of vertically polarised transmission. We have therefore to consider in what cases the horizontally polarised ray is more attenuated than the vertically polarised one. This ratio is a function of many quantities, in particular the wavelength, the heights of the transmitter and receiver, the ground constants and irregularities such as hills.

In the particular case we are considering, which is a transmission over land on 22, 27, and 65 mc/sec. there is practically no difference between horizontally and vertically polarised rays for transmitters and receivers which are more than 5 metres above the ground, (on the assumption that there are no hills). The same is true of over-sea transmission if the frequencies are greater than 600 mc/sec. or so, Thus in the case of overland transmission, there is really no descrimination between horizontally and vertically polarised rays, unless irregularities are taken into account. Hills with a radius of curvature of the order of 50 Km. can produce a profound effect. Thus, such a hill will produce a difference between horizontal and vertical polarisation the same as that in transmission over the earth of frequencies of 0.6 mc/sec., (or wavelength of 500 metres). In this latter case, the difference in transmission of horizontally and vertically polarised waves is very significant. On the whole, on short waves hills favour vertically rather than horizontally polarised waves, and this is borne out by the observed facts.

ANALYSIS OF THE PROPAGATION OF HORIZONTALLY POLARISED WAVES.

Horizontally polarised waves on frequencies between 22 and 70 mc/sec. have been observed, and their directions determined by means of the spaced frame apparatus, their field strengths being measured by the T.M.E. 14. The stations observed were all of the pulse type. Some were the R.D.F. stations on 27 and 22 mc/sec, others were the R.D.F. stations on 50 to 48 mc/sec. and finally there were G.L. stations between 55 and 66 mc/sec. Two of these latter, anyhow, were within a few miles of us. The R.D.F. stations were all within about 150 Kms of us, and belonged to the chain of big R.D.F. stations round the east and south coast. About eight of these were observed on the longer waves, and three or four on the shorter waves, and it was always possible to identify them by means of their bearings and frequencies. The G.L. transmitters could be separated from the others in virtue of the fact that their repetition frequency was very much higher than that of the R.D.F's, which had a repetition frequency of 25 cycles per second.

THE PROPAGATION OF THE LONGER R.D.F. WAVES.

We now have information as to the position of the R.D.F. stations that we have measured, so that we can compare the measured bearings with the true bearings, and the measured field intensities with the calculated ones. Table 1 shows the positions of the stations observed, the frequencies they use, their true bearings, and the field strength computed on the assumption that the aerials use 200 K.W. that they are 100 metres high and that the receiver is about 5 metres high. The first set of observations was made from Nov. 20th 1941 to Feb. 1st 1942, but field strengths were not measured. It will be observed that we received about eight out of the 12 stations within 100 miles of us. The bearings are relatively correct, except for the more distant stations, and for West Bromley, near Colchester. On the stronger stations, excepting West Beckham and High Street, near Halesworth, they are within about 3° of their true bearings. The true bearing of West Bromley, is 59°. The average observed bearing, undisturbed by tropospheric reflections, is 72°, and this is probably, as suggested previously, the geodesic bearing. It is in virtue of the two rays with different azimuths, that we get the sudden changes in the bearing of Colchester associated with sudden changes in strength.

Later simultaneous measurements of field strengths and bearings were made, and records of these have been obtained up to June 1st, 1942. During this period, the bearing and the field strength of Colchester have again been found to be particularly variable, but this is not the only station that is variable, and the results of these measurements are given in table II. Here the strengths, as well as the bearings, of the stations are recorded. In these observations, attention has mostly been centred on West Bromley and Rye, although a few bearings and field strengths from other stations have been obtained.

The results of the mean bearings show, again, that Rye is very nearly its calculated value, that West Bromley has a bearing of 72°, and that the field strengths, although very variable, compare very favourably with the calculated values. Thus the field strength of Rye, of which we have many values, although varying over a large range, is, on the average, 27 dB/μV/m. Moreover, its calculated value is, again, of the same order, viz: 29.5 dB/1 µV/m. The mean value on Colchester of the field strength is rather less than what it should be, but I think that if the upper limiting values are taken for the undisturbed periods, it will be found that the measured field strength is close to the calculated value. It is thus as if the correct value were given in undisturbed conditions, and the disturbance, on account of the interference of the two waves, is always less than the true value for short distances.

Sudden changes, which made the bearing curve almost exactly a mirror image of the field strength, were especially marked between the 13th and 20th of April. We have reports on the C.H.L. systems that spurious echoes from supposed clouds in the troposphere were particularly marked also in this period. An examination of the meteorological charts shows temperature inversions at rather low heights, but an analysis of the M charts alone would not indicate when these disturbances were to be expected.

It is therefore probable that clouds and atmospheric discontinuities at a low height were prevalent during this period. Even though the correspondences and the sudden variable bearings are particularly marked, then they are not confined to this period alone; and it would appear that about 43% of the runs, which each took about 40 minutes, were disturbed. There seems to be always a fairly high probability that the bearings from Colchester will be distorted. No observations have yet been made at night time, and there is no reason to believe that they will be essentially different from those made during the day. It was thought possible that the simultaneous changes of bearing and field strength might have been produced by bad contacts in the hut in which the measurements were made. Observations were therefore made with a local transmitter, which showed no sudden changes, and therefore suggested that the changes were a real, and not an instrumental, effect. Observations were also made, as nearly as possible at the same time, of the bearings of two different R.D.F. stations, and the field strength of one of them, to see if there was any correlation between the bearings observed and this field strength, i.e. whether a cloud affected the two stations simultaneously; and on a certain number of occasions, of which examples are shown, the two stations underwent a sudden simultaneous change of bearing. Such a simultaneous change (Figs.1, 3, 4) of bearing of two different stations, is, however, rather a rare occurrence, but it does suggest that there are occasions when a tropospheric cloud covers both paths, and can produce a simultaneous bearing change. A great many observations would be required to determine the size of these tropospheric clouds.

SHORTER WAVES.

Higher frequencies than those already observed have been subjected to tests. These include R.D.F. transmissions, mainly on 48 mc/s, local G.L. transmissions on 55 and 66 mc/s, and vertically polarised waves from transmitters at Daventry and Haslemere. These measurements were made on vertical transmissions from G stations. The horizontally polarised waves on these frequencies showed the same characteristics as those of lower frequencies, which have already been discussed. That is to say that the nearer stations show sudden changes of bearing associated with sudden changes of field strength. This was particularly marked on the G.L. stations, one of which was at Writtle and another at New Hall, Nr. Boreham, which is only a few Km. from our receiving station at Great Baddow. These stations, as stated before, show just the same features as were so marked in the transmissions from Colchester, but the effects were most marked on the short distance transmissions - a good deal shorter, in fact, than the previously discussed transmission from Colchester. The ranges were only a few Km., and the mechanism by which these simultaneous changes in bearing and field strength were produced is, no doubt, similar to that mechanism by which the Colchester variations were produced.

As in the previous case there were periods during which the deviations were much more violent than usual. Thus, on the 25th of June and the 24th of July, 1942, the variations were particularly marked. Meteorological observations show no essential difference on these days. A careful local examination of the atmosphere up to heights of a few hundred feet is required, and this should be made so that sudden changes coincident with the D.F. changes will be recorded.

The station mainly observed was the G.L. station due north of us, of which 72 observations were made, and a really well defined mean bearing of 180.8° was obtained. The field strength on this station was very variable, and changed at times as much as 20 dB. The mean upper limit of all the readings was 58.5 dB, the mean and lower limit being 50 dB and 40 dB respectively (See table III).

Two R.D.F. stations were also observed, one at Rye, near Winchelsea, and one at Bawdsea, and these gave, for Winchelsea, a mean bearing of 164.7° and for Bawdsea 58°. Table III gives the bearings and field strengths observed. It is probable that there is a correction of about 3°, and that on this frequency the D.F. reads 3° low.

Vertical polarisation results are rather in contrast with those for horizontal polarisation, but as these are for long distance transmissions, it may be that the steadying of the observations is the result of this long distance rather than the result of vertical instead of horizontal polarisation. Anyhow, the field strength did not vary more than 4 or 5 dB and the bearing variation was only 2 or 3 degrees, and was probably within the errors of experiment. The previous results show that bearing deviations are just as prevalent on these higher frequencies of 40 to 70 mc/s as on the lower frequencies of the order of 22 to 27 mc/s and are due, almost certainly, to reflections from layers of discontinuity in the troposphere. They also indicate that vertically polarised transmissions are less affected than horizontally polarised ones.

Further experiments are required to make these conclusions quite definite because, for example, short distance vertical transmissions have not yet been observed. Nevertheless, it is quite certain that horizontally polarised rays are badly distorted, so that transmissions along the surface of the earth may be very much in error. It is probable that higher angle transmissions are less affected, but what the law of error with angle of elevation may be cannot be exactly stated until we know more about the variation of refractive index with height. It is, however, probable that even low angle G.L. observations will be somewhat in error, and it is essential that vertical polarisation transmissions should be tried, to see if they are less subject to error.

GENERAL.

These researches have indicated that transmission on short waves is difficult to D.F. and probably does not take place along straight lines, as it would do if the lower atmosphere were uniform and ideal.

Direction finding is difficult because of the interference of waves over the earth by waves reflected from tropospheric discontinuities or clouds. The results are of considerable practical importance, because they show that accurate D.F. of nearly horizontal rays is very difficult.

The practical conclusion we may draw is that a G.L. system may not indicate the true direction of the target, especially when this target is an aeroplane flying very low, so that the path between the G.L. and the aeroplane is very nearly horizontal. Errors of 10° or more take place when the ray is completely horizontal, and there is certain to be some error even when the ray is not quite horizontal and the target is well above the earth. How this error varies as the angle of elevation of the ray increases, cannot be deduced unless we know the vertical change of refractive index, but there can be no doubt that some error will remain when the angle is small but not zero. The errors occur if the direct ray over the surface of the ground is not **straight, or if the reflection from the cloud is, again, not straight.**

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These errors only occur if the two rays have not the same azimuth, and we cannot be sure, from these experiments, whether all the curvature is produced in the ground ray, or whether the tropospheric clouds are irregular enough to produce curvature in the reflected ray. In the latter case, there would still be some error, even if the ground were not there, or if the ground were perfectly smooth. Thus, oversea, for instance, an error would be possible in this case, but it would not be present if the reflecting surface were perfectly uniform and had no horizontal gradients. In any case, it is probable that the errors in oversea transmission are very much less than those over irregular ground, but it is still quite possible that they may be appreciable. Further experiments are required to settle this point.

If the explanations are correct, and I think that there is very little doubt that they are so, the observations give us a clear understanding of very short wave propagation. The results show that in overland propagation there are very large variations of both intensity and bearing. From the simultaneity of these changes, we can deduce, with a fairly high degree of probability, that the waves do not behave, in the region above the ground, as if they were propagated in straight lines in the free ether but as if they were reflected from regions where vertical discontinuities in the refractive index of the air are sufficient to make a good reflecting surface when the ray angle of incidence is small.

Unfortunately, it is not easy to deduce what these changes of refractive index must be in order to produce the effects observed. Alternative explanations are possible, but it is suggested that the regions of reflection are low (possibly a few hundred feet). Otherwise, in short distance transmissions, the angle of attack of the rays at the tropospheric discontinuities would be too large for appreciable reflection, and if the earth were smooth (no hills) and the distances 8 km, and $< 1/2^{\circ}$ were needed for appreciable reflection, h would be about 20 metres or less. In any case it would be low. The observations also show that horizontally polarised waves are much more subject to variations than vertically polarised waves, and the cause of this is the irregularity of the earth.

If there are hills or irregularities which cast shadows onto the receiver, the ground intensity at the receiver is considerably less for horizontal than for vertical waves. The reflected waves which cause the variability in signal intensity and bearings are relatively greater for horizontal than for vertical waves, hence the greater variability of horizontal waves.

If the ground irregularity is the major factor in bearing distortion - as is suggested by the Colchester transmission, where the bearing of the ground ray is 13° too high, - these effects should be very considerably reduced in oversea transmission and may not even be appreciable. The use of very much higher frequency waves than those investigated in this report makes the difference between H. and V. waves less, and probably reduces the irregularities, because the reflecting surface is rather rough for these very short waves, with little reflection, and relatively smooth for the longer waves.

The bearing errors are very much exaggerated by the interference of two waves of different azimuths.

In oversea transmission, the ground wave azimuth is probably very nearly correct. This exaggerated error effect can then only be due to horizontal irregularities in the tropospheric reflecting surface. As yet we have very little information about this. Further experiments are required, and we need to translate the radio results into meteorological results, which are sadly deficient in giving the local low level changes, which greatly affect the radio transmissions.

The possibility of long distance transmissions, that is transmissions beyond the visual range, can easily be calculated when the vertical gradients of refractive index are known.

The phase integral method is exactly applicable in this case when the vertical gradients are known, and if the change of phase at a sharp gradient is also known, it will then be only a matter of rather laborious mathematics to calculate how energy trapped between the earth and an upper layer in the troposphere will travel. But a good deal of guesswork is required to make the calculation definite, for the distribution of refractive index must be fairly exactly known, and can now only be roughly guessed.

The results obtained might be used for indicating when spurious echoes are likely to be present, but certainty cannot be achieved, as local conditions here are unlikely to be identical with the conditions at the G.L. and C.H.L. stations.

Thus it seems that there are likely to be clouds which give spurious echoes, but the existence of a cloud here (which we can deduce from our D.F. experiments) will not tell us, for example, whether or not there is a cloud giving spurious echoes at Happisburgh, say.

APPENDIX.

DESCRIPTION OF EXPERIMENTAL U.H.F. SPACED LOOP DIRECTION FINDER.

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General.

The spaced loop direction finder, whose salient features are shown diagramatically in the accompanying drawing, was designed to work from 20 mcs. upwards, to assist research in U.H.F. wave propagation. It will be seen from the drawing that the aerial and input circuits are quite simple. (Fig.1A).

The two loops, which can be fixed vertically or horizontally, are paralleled at the centre of the spacing feeders, in such a way that their outputs oppose each other when they are equally phased. The resultant output is taken to a closely coupled screened and balanced transformer, across whose tuned secondary is connected an acorn pentode amplifier. The latter has a tuned anode feeding an X.62 frequency changer modulated by an acorn triode oscillator. The frequency changer supplies a 10 mc. wide-band intermediate frequency amplifier, followed by a diode detector and K.T.61 output stage working phones and a small cathode ray tube. The latter is connected to a 25 c.p.s. timebase locked to the supply mains.

The input transformer, H.F. amplifier, local oscillator and frequency changer are enclosed in a screening box rotating solidly with the aerial. The necessary supplies and I.F. output are taken through flexible cables to a stationary power pack and I.F. amplifier respectively.

Technical Details.

The spacing of the loops when vertical is 3.8 metres, and when horizontal, effectively 4.8 metres. Thus secondary minima occur at frequencies higher than 79 mcs. when loops are vertical, and at frequencies higher than 62.5 mcs when loops are horizontal. The loops are 1 metre square and made of 3/8" diameter copper tube.

The horizontal feeders connecting the frames consist of a 1.7/8" diameter outer copper screen enclosing two conductors of narrow copper braiding spaced 5/8" apart and tensioned by small springs. The feeders have a characteristic impedance of about 415 ohms., and terminate in a screened paralleling box on the central supporting pole. The latter is a steel pipe of about 2" internal diameter containing a two-wire feeder connected as shown in the drawing, and similar to the feeders already described.

Two input transformers are necessary to cover the frequency range 20 to 66 mcs., which is the successful working range of the apparatus up to the present time. Details of the transformers follow:-

Transformer Range.	Primary Inductance.	Secondary Inductance.	Coupling Coefficient.	Approx. Diameter.
(1) 20 - 37 mc/s.	.9 μH (6 turns)	2.1 μH (9 turns)	61%	1"
(2) 30 - 66 mc/s.	.3 μH (4 turns)	.6 μH (5 turns)	34%	3/4"

The above frequency ranges are obtained by shunting the transformer secondaries with auxiliary inductances when the desired frequency is higher than can be tuned by the secondary alone. Primaries and secondaries are separated by two overlapping insulated copper screens connected to earth, and the primaries are wound symmetrically relative to the earthed screens, while to facilitate quick removal, the transformers terminate in Whistlecroft sockets fitting into plugs at the base of the vertical feeder. The purpose of C_1 is to balance small asymmetries in frames, feeders and the transformers and thus to improve the quality of the minima. The setting of C_1 is frequency - dependent.

Receiver Characteristics. Receiver first-circuit noise predominates over other noise sources up to 60 mcs.

Over the frequency range 20 - 30 mcs. 1 uV. applied to the input transformer primary gives about 20 volts on the tube. This is twice the voltage produced by receiver noise. The H.F. gain between transformer primary and H.F. amplifier anode is about 100. The gain of the 10 mcs. I.F. amplifier is about 5,000, and the bandwidth 1 mc. The impedance of the K.T.61 output stage is 5,000 ohms.

The time-base makes 25 sweeps a second synchronised to the supply mains. It has the choice of an approximately linear slow sweep and a non-linear rapid sweep to assist observation of pulse echoes. The rapid sweep speed is about 1/3" in 100 u/secs. The start of the time-base is phasable relative to the mains, so that a locked pulse may be placed in a convenient position on the tube.

Performance of Direction Finder. Local oscillator tests over the frequency range 20 - 66 mcs. gave bearings within ± 3° of the true bearing, with the frames either horizontal or vertical. The range 29 - 33 mcs. is excepted because at 31 mcs. one frame is a short circuit on the other, causing large bearing errors and small sensitivity. The bad region can easily be shifted, however, by altering frame and/or feeder impedances. Sensitivity in the range 20 - 28 mcs. was about 20 uV. for 10° zone of silence. With vertical frames, tests on predominantly horizontally polarised 55 mcs. and 48 mcs. transmissions showed that the apparatus would deal satisfactorily with a 26 dB. excess of horizontal over vertical component. Tests with horizontal frames on 28 mcs showed that the apparatus was limited to a 10 dB. excess of vertical over horizontal component for satisfactory working. This is attributed to the increased coupling between feeders and frames in horizontal working.

T A B L E I

November 20th 1941 to February 1st 1942. 22 to 27 Mc/s.

	West Beckham	Stoke Holy Cross	High St. Halesworth	Bawdsey	West Bromley	Carnewdon	Dunkirk Kent	Dover	Hythe	Rye Winchel-Sea	Pevensey	Arundel
Average Bearing No. of obs.	11.9° 4	29° 8	50.4° 4	63.2° 12	70° 13	122.8° 5				171.2°	181.4°	
True Bearing	19°	3[illegible]°	47°	62°	59°	123°	143°	134°	155°	168°	185°	210°
Distance in kms.	148	107	94	72	42	19.2	57.8	85.6	83.2	81.6	92	120.2

T A B L E II

February 1st 1942 to June 1st 1942 22 - 27 Mc/s

	West Beckham	Stoke Holy Cross	High St. Halesworth	Bawdsey	West Bromley	Carnewdon	Dunkirk Kent	Dover	Hythe	Rye Winchel-Sea	Pevensey	Arundel
Bearing		35°	51°	69°	72°					170°		
True Bearing		30°	47°	62°	59°					168°		
Signal Strength dB/1μV/m		40 32 27	53 50 47	30 24 21	58 42 20					32 27 22		
Calculated Signal Strength		22	26	36	52					29.5		

T A B L E III

JUNE 1st to SEPTEMBER 1st, 1941

48 to 66 MC/S

		Haslemere G	GL North	GL Writtle	R.D.F. to Rye	R.D.F. Bawdsea.
Bearing		223.7°	180.8°	304.3°	164.7°	58°
True Bearing		231°	-	305.0°	168°	62°
Signal	max.	36	58.5	55	42	49
Strength	mean.		50	40	36.8	36
dB/1 μV/m	min.	34.2	40	34	28.0	31
Calculated signal strength					36	42
Distance in kms.		107.5	5	6	81.6	72.7

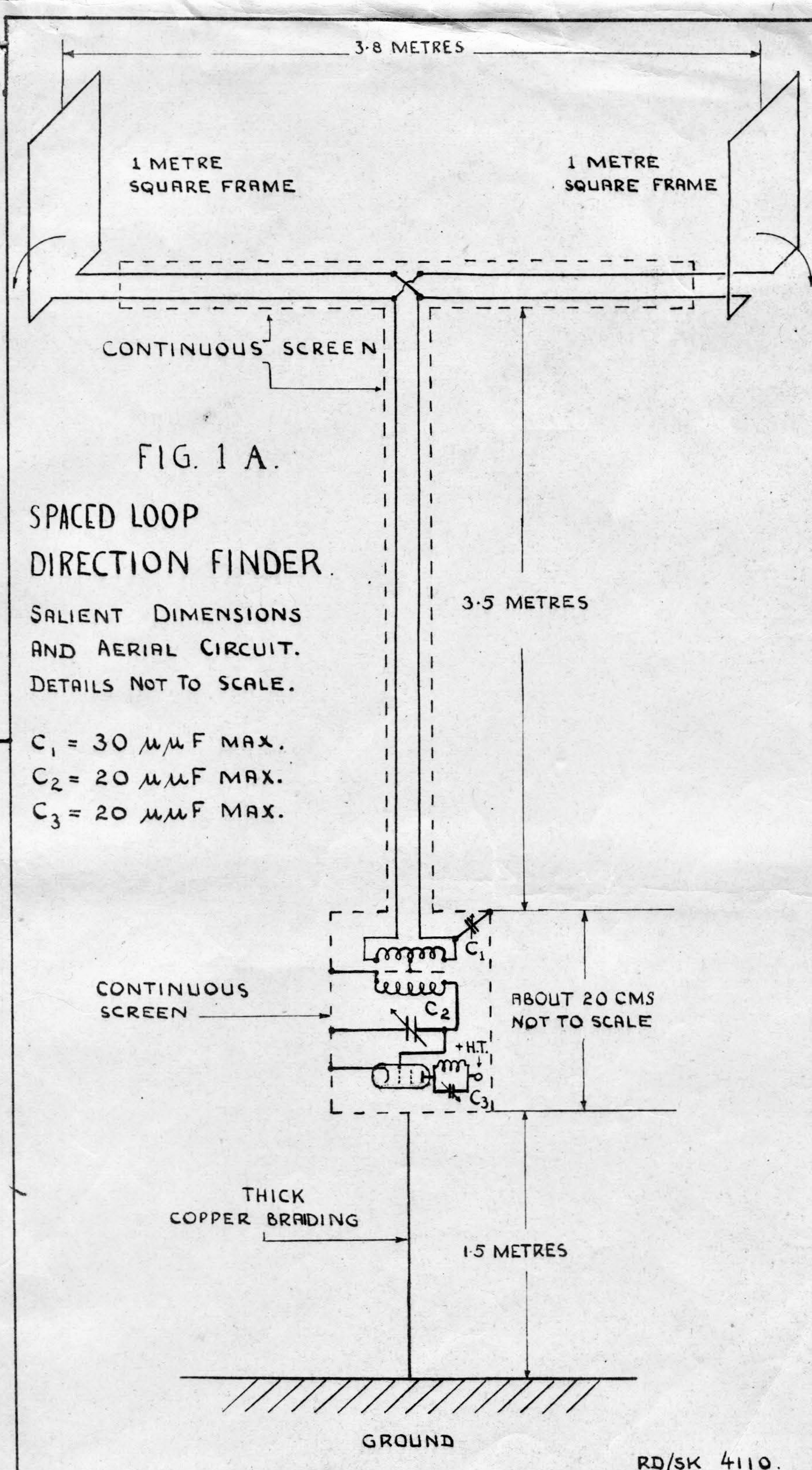
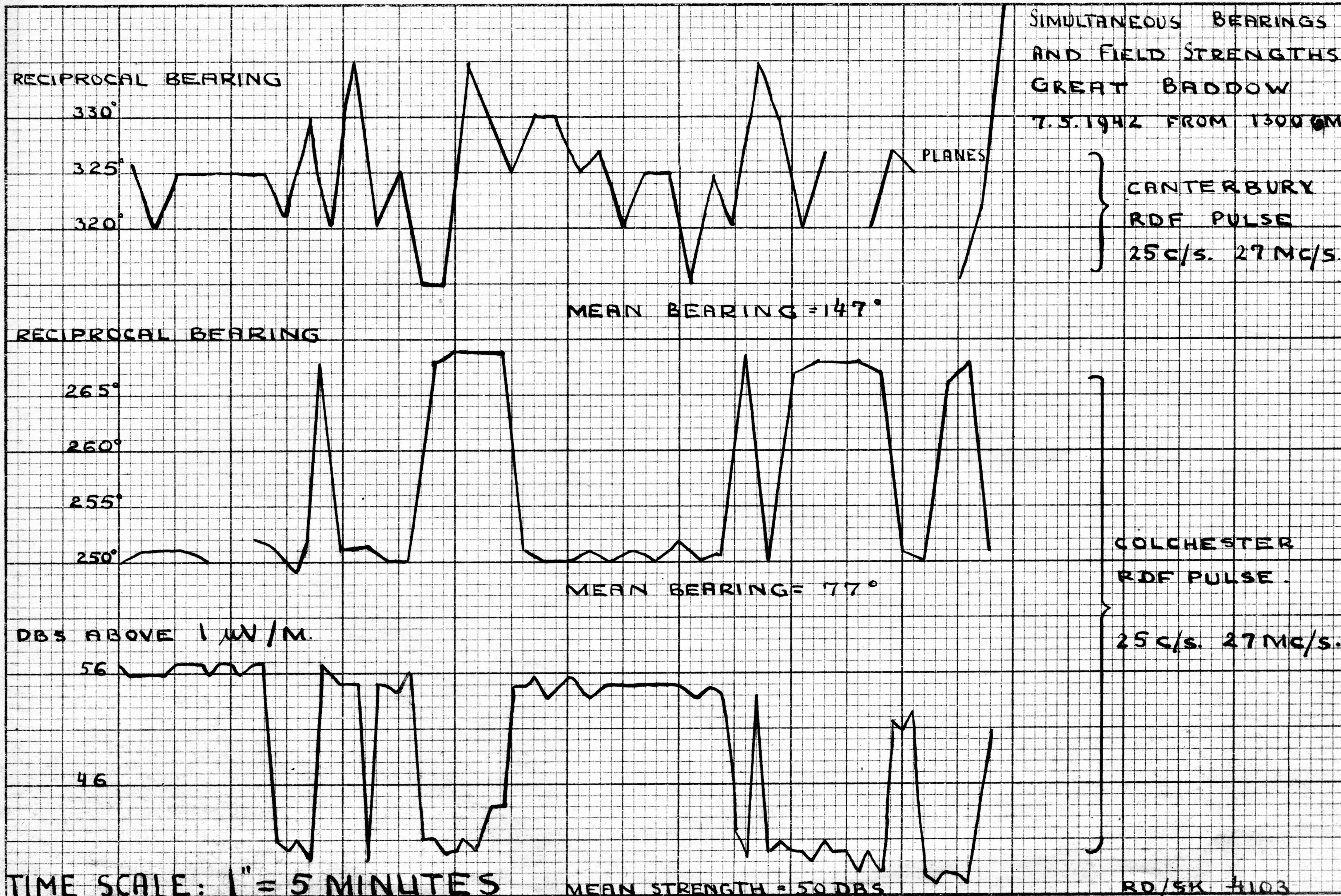


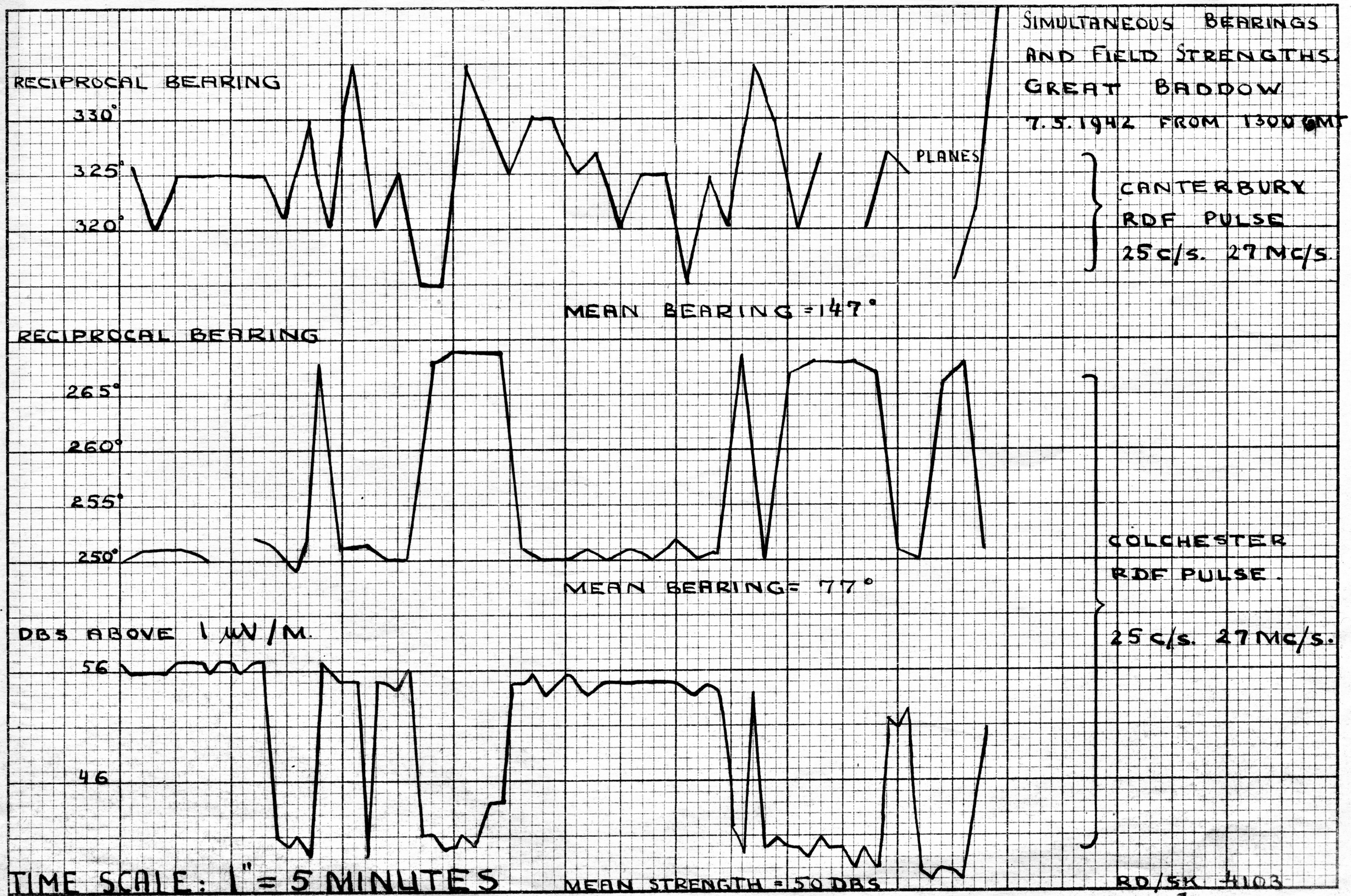
FIG. 1 A.

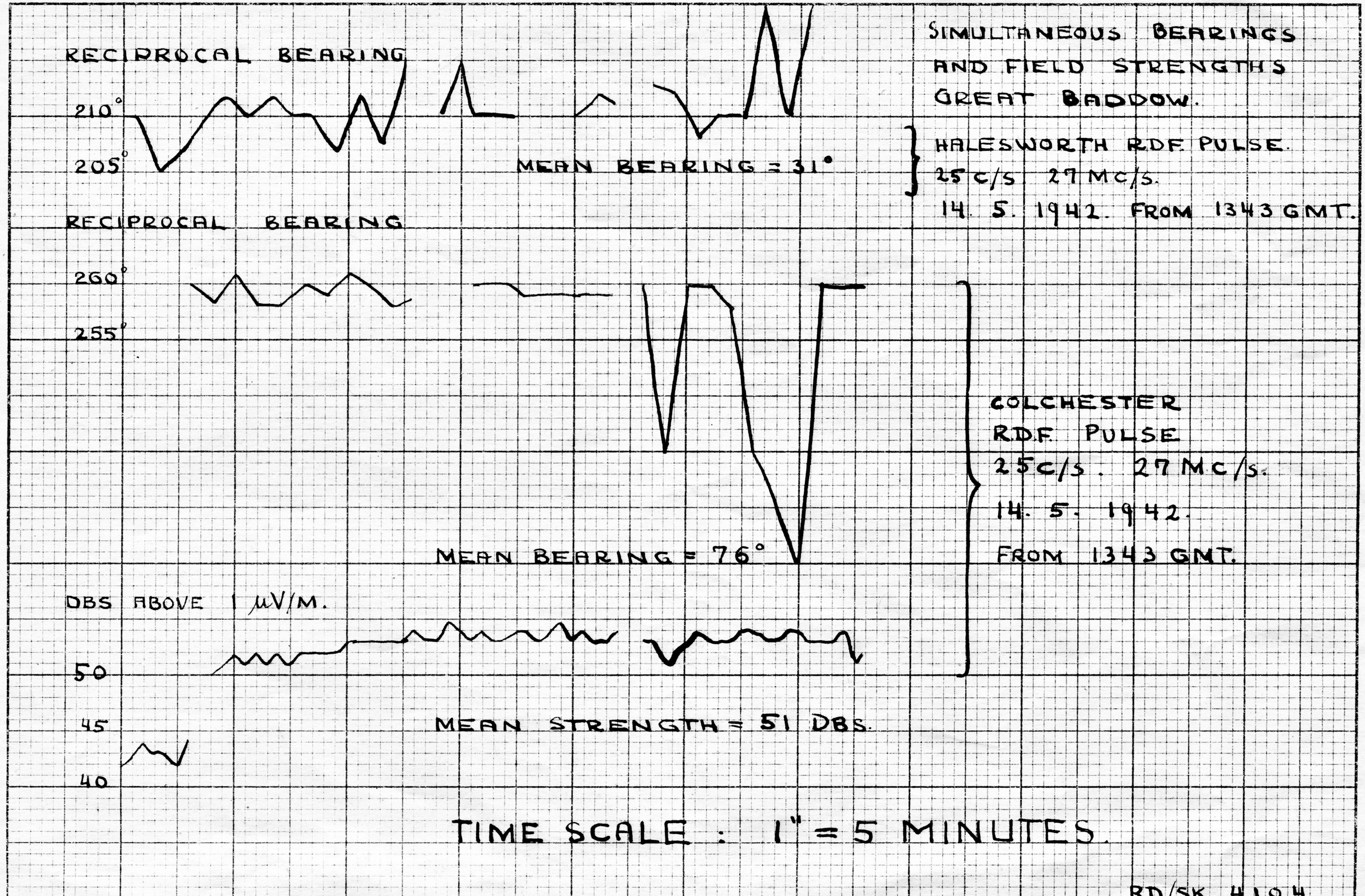
SPACED LOOP DIRECTION FINDER.

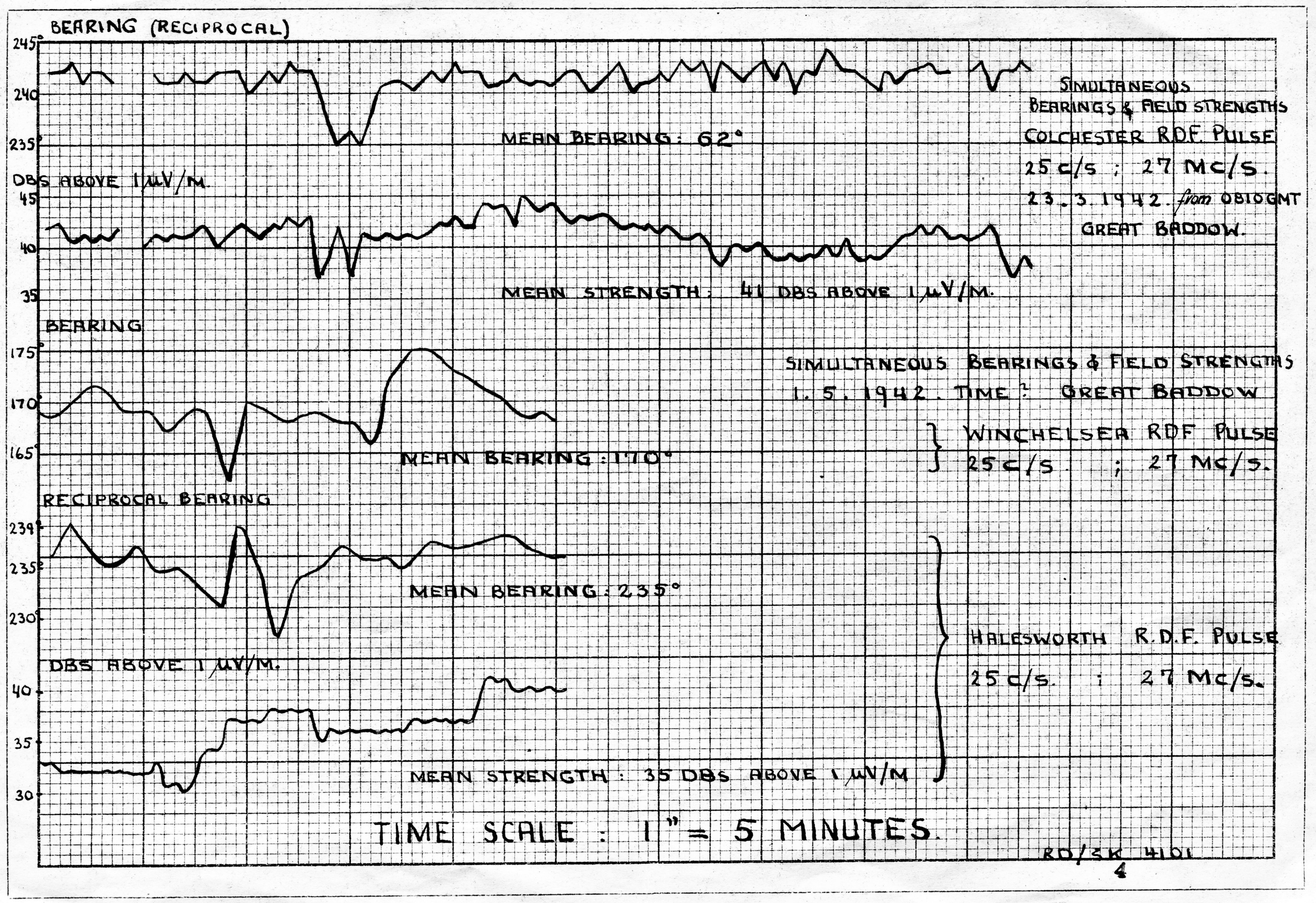
SALIENT DIMENSIONS AND AERIAL CIRCUIT. DETAILS NOT TO SCALE.

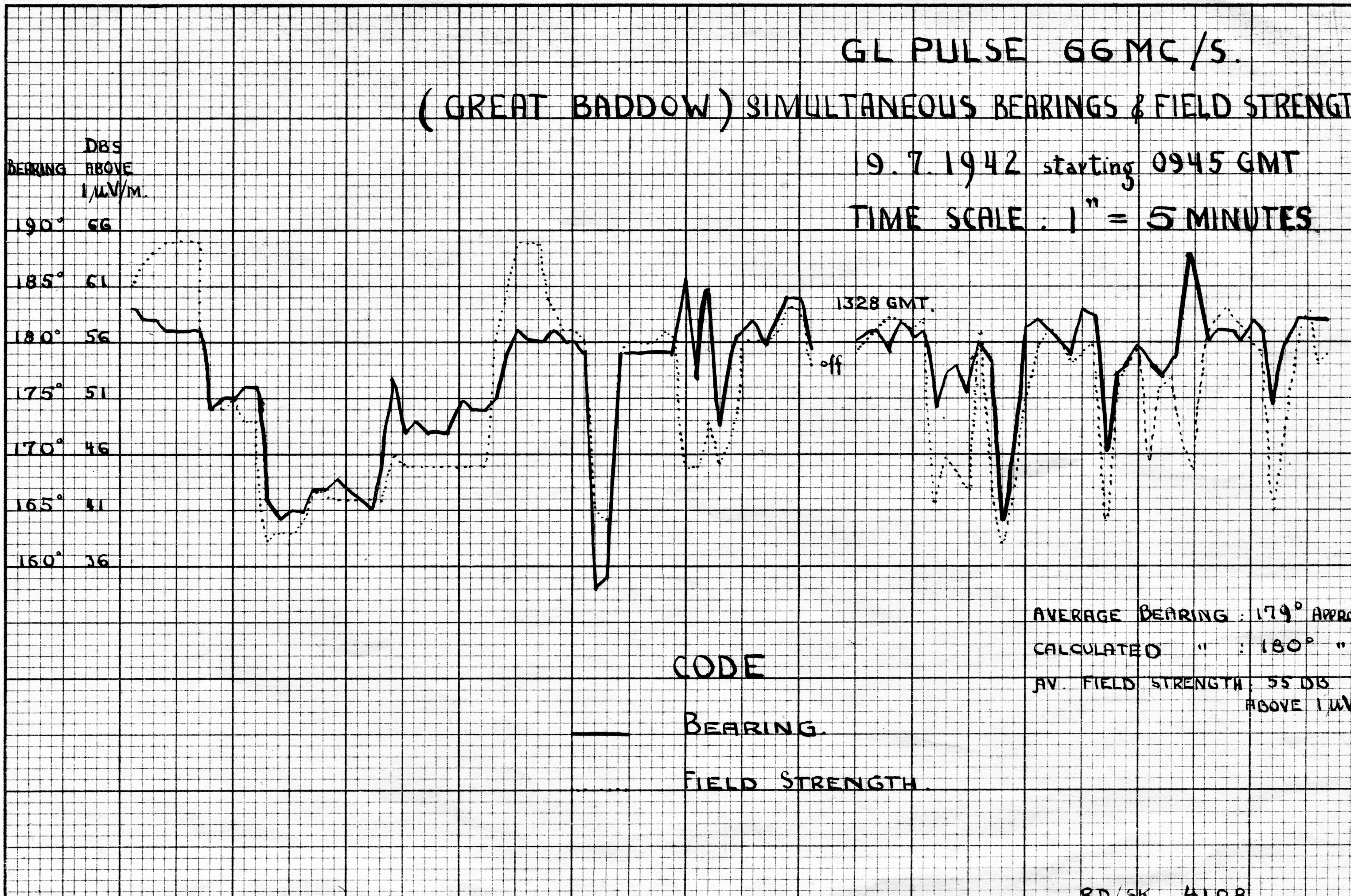
$C_1 = 30\ \mu\mu F$ MAX.
$C_2 = 20\ \mu\mu F$ MAX.
$C_3 = 20\ \mu\mu F$ MAX.

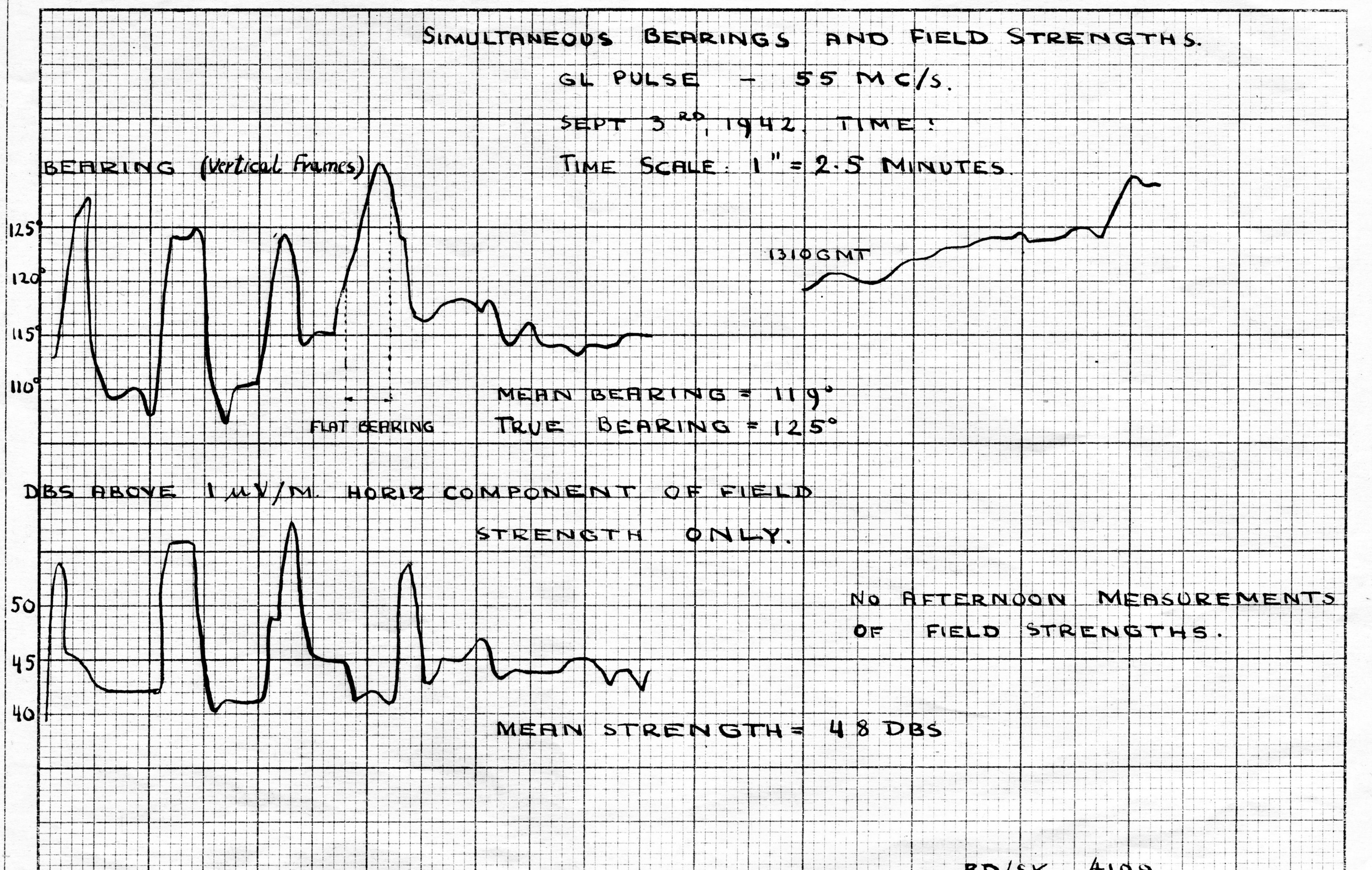

SIMULTANEOUS BEARINGS AND FIELD STRENGTHS.
GREAT BADDOW
7.5.1942 FROM 1300 GMT
RECIPROCAL BEARING
330°
325°
320°
PLANES
CANTERBURY RDF PULSE 25 c/s. 27 Mc/s.
MEAN BEARING = 147°
RECIPROCAL BEARING
265°
260°
255°
250°
MEAN BEARING = 77°
COLCHESTER RDF PULSE.
25 c/s. 27 Mc/s.
DBS ABOVE 1 µV/M.
56
46
TIME SCALE: 1" = 5 MINUTES
MEAN STRENGTH = 50 DBS
RD/SK 4103

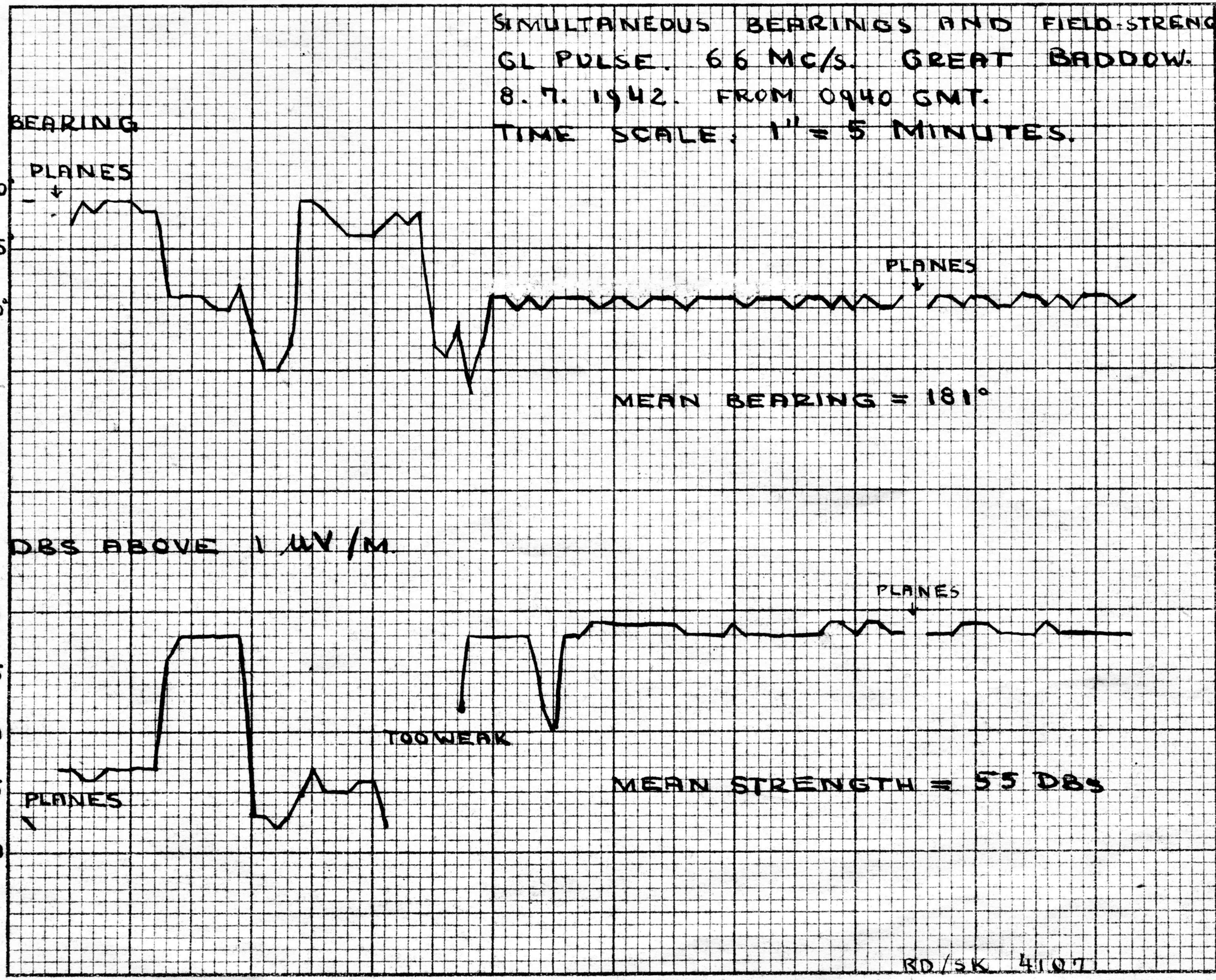

SIMULTANEOUS BEARINGS
AND FIELD STRENGTHS.
GREAT BADDOW
7.5.1942 FROM 1300 GMT
RECIPROCAL BEARING
330°
325°
320°
PLANES
CANTERBURY
RDF PULSE
25 c/s. 27 Mc/s.
MEAN BEARING = 147°
RECIPROCAL BEARING
265°
260°
255°
250°
MEAN BEARING = 77°
COLCHESTER
RDF PULSE.
25 c/s. 27 Mc/s.
DBS ABOVE 1 µV/M.
56
46
TIME SCALE: 1" = 5 MINUTES
MEAN STRENGTH = 50 DBS
RD/SK 4103


SIMULTANEOUS BEARINGS AND FIELD STRENGTHS GREAT BADDOW.
HALESWORTH RDF PULSE. 25 c/s. 27 Mc/s. 14. 5. 1942. FROM 1343 GMT.
RECIPROCAL BEARING
210°
205°
MEAN BEARING = 31°
RECIPROCAL BEARING
260°
255°
COLCHESTER RDF PULSE 25c/s. 27 Mc/s. 14. 5. 1942. FROM 1343 GMT.
MEAN BEARING = 76°
DBS ABOVE 1 μV/M.
50
45
40
MEAN STRENGTH = 51 DBS.
TIME SCALE : 1" = 5 MINUTES.
RD/SK 4104

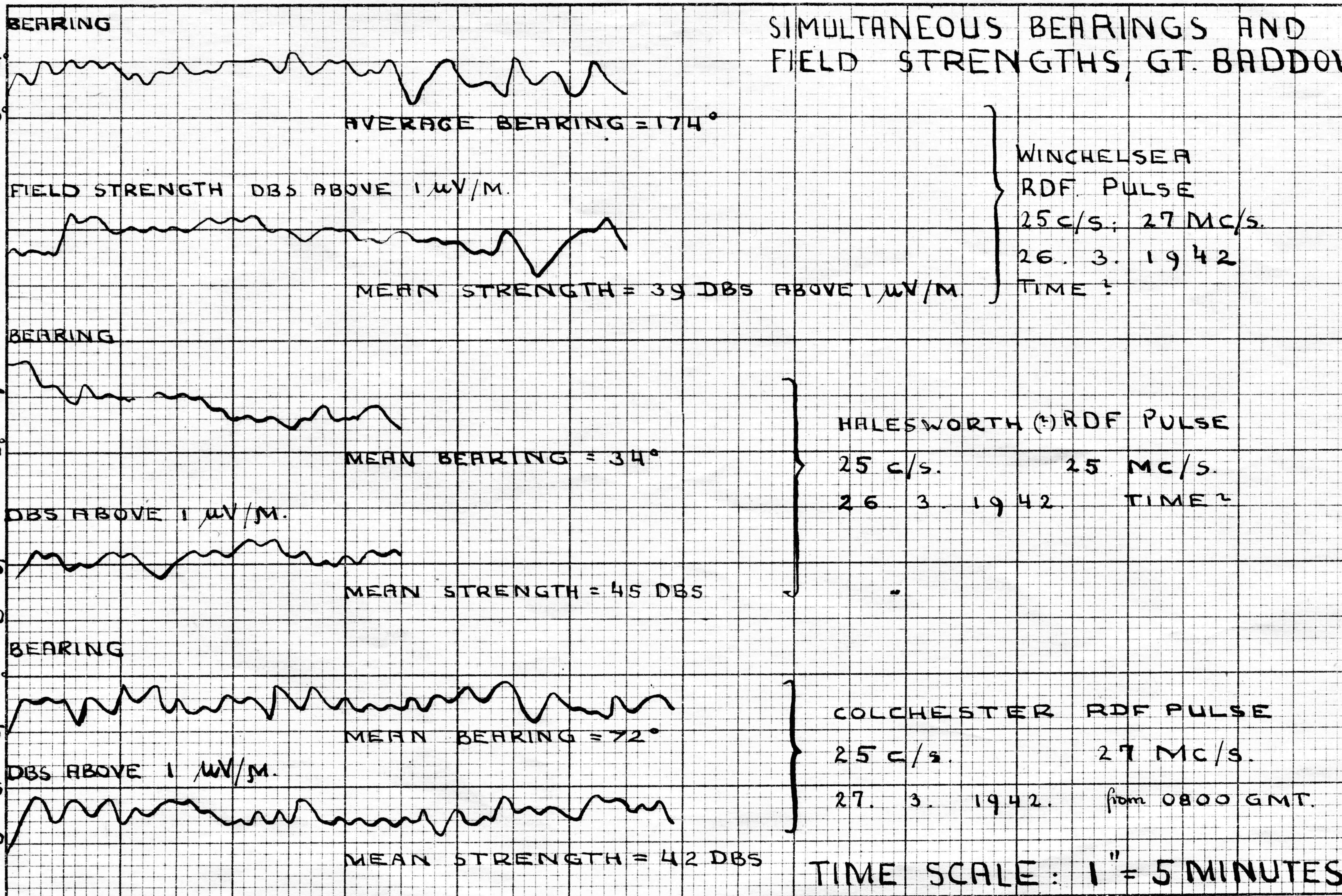

BEARING (RECIPROCAL)
245°
240
235°
MEAN BEARING: 62°
DBS ABOVE 1 µV/M.
45
40
35
MEAN STRENGTH: 41 DBS ABOVE 1 µV/M.
SIMULTANEOUS BEARINGS & FIELD STRENGTHS
COLCHESTER R.D.F. PULSE
25 c/s ; 27 Mc/s.
23.3.1942. from 0810 GMT
GREAT BADDOW.
BEARING
175°
170°
165°
MEAN BEARING: 170°
SIMULTANEOUS BEARINGS & FIELD STRENGTHS
1.5.1942. TIME ? GREAT BADDOW
WINCHELSEA RDF PULSE
25 c/s ; 27 Mc/s.
RECIPROCAL BEARING
239°
235°
230°
MEAN BEARING: 235°
HALESWORTH R.D.F. PULSE
25 c/s. ; 27 Mc/s.
DBS ABOVE 1 µV/M.
40
35
30
MEAN STRENGTH: 35 DBS ABOVE 1 µV/M
TIME SCALE: 1" = 5 MINUTES.
RD/3K 4101


GL PULSE 66 MC/S.
(GREAT BADDOW) SIMULTANEOUS BEARINGS & FIELD STRENGTHS.
19.7.1942 starting 0945 GMT
TIME SCALE : 1" = 5 MINUTES.
BEARING
DBS ABOVE 1 µV/M.
190° 66
185° 61
180° 56
175° 51
170° 46
165° 41
160° 36
1328 GMT.
off
AVERAGE BEARING : 179° APPROX
CALCULATED " : 180° "
AV. FIELD STRENGTH : 55 DB ABOVE 1 µV/M.
CODE
BEARING.
FIELD STRENGTH.
RD/SK 4108

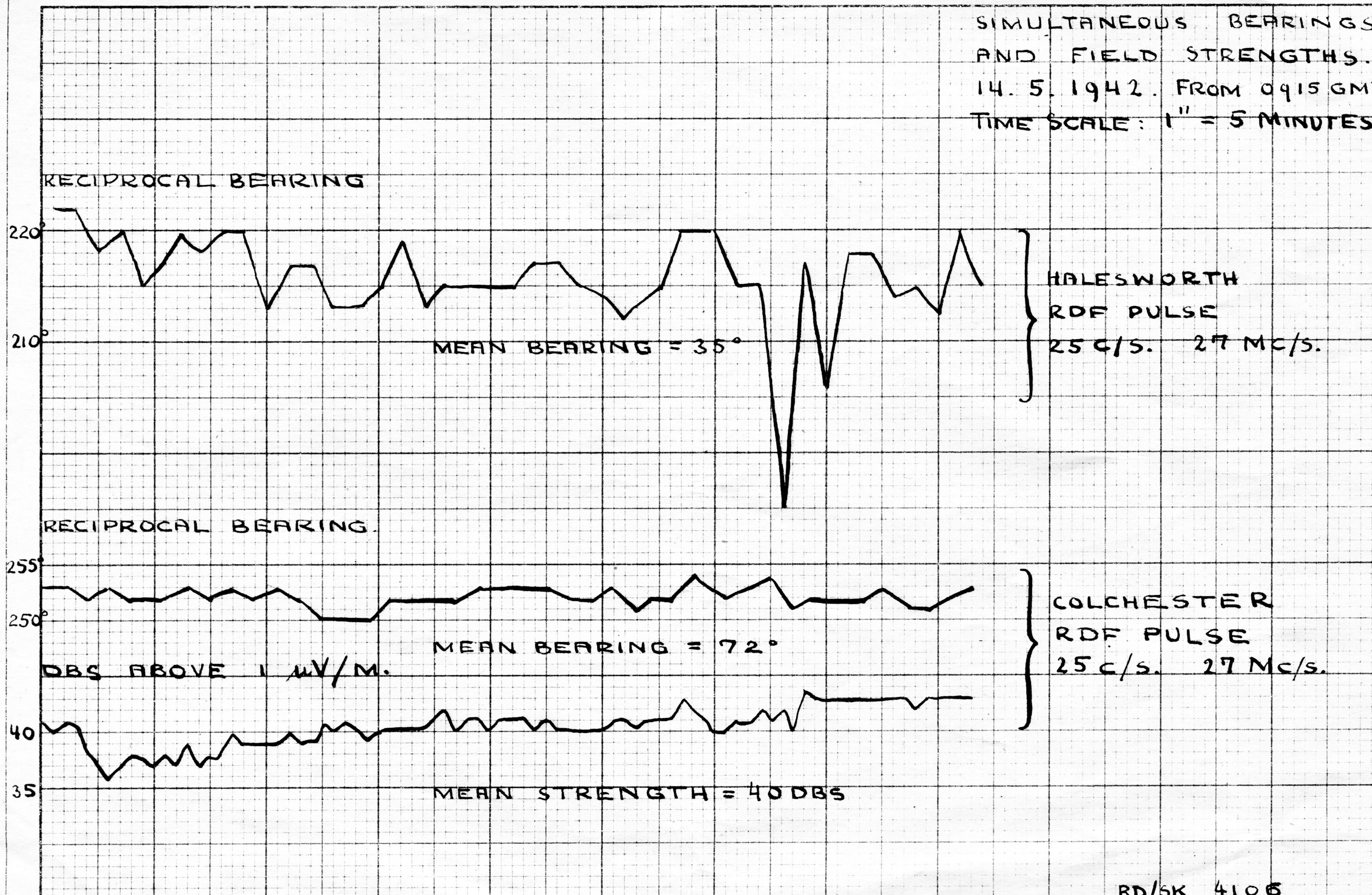

SIMULTANEOUS BEARINGS AND FIELD STRENGTHS.
GL PULSE - 55 MC/S.
SEPT 3RD, 1942. TIME:
TIME SCALE: 1" = 2.5 MINUTES.
BEARING (Vertical Frames)
125°
120°
115°
110°
1310 GMT
FLAT BEARING
MEAN BEARING = 119°
TRUE BEARING = 125°
DBS ABOVE 1 μV/M. HORIZ COMPONENT OF FIELD STRENGTH ONLY.
50
45
40
NO AFTERNOON MEASUREMENTS OF FIELD STRENGTHS.
MEAN STRENGTH = 48 DBS
RD/SK 4109


SIMULTANEOUS BEARINGS AND FIELD-STRENGTHS.
GL PULSE. 66 Mc/s. GREAT BADDOW.
8. 7. 1942. FROM 0940 GMT.
TIME SCALE: 1" = 5 MINUTES.
BEARING
PLANES
190°
185°
180°
PLANES
MEAN BEARING = 181°
DBS ABOVE 1 μV/M.
60
55
50
45
40
PLANES
TOO WEAK
PLANES
MEAN STRENGTH = 55 DBS
RD/SK 4107

7


SIMULTANEOUS BEARINGS AND FIELD STRENGTHS, GT. BADDOW.
BEARING
175°
170°
AVERAGE BEARING = 174°
FIELD STRENGTH DBS ABOVE 1 µV/M.
40
35
MEAN STRENGTH = 39 DBS ABOVE 1 µV/M.
WINCHELSEA
RDF PULSE
25 c/s. 27 Mc/s.
26. 3. 1942
TIME ?
BEARING
35°
30°
MEAN BEARING = 34°
DBS ABOVE 1 µV/M.
45
40
MEAN STRENGTH = 45 DBS
HALESWORTH (?) RDF PULSE
25 c/s. 25 Mc/s.
26. 3. 1942. TIME ?
BEARING
75°
70°
MEAN BEARING = 72°
DBS ABOVE 1 µV/M.
45
40
MEAN STRENGTH = 42 DBS
COLCHESTER RDF PULSE
25 c/s. 27 Mc/s.
27. 3. 1942. from 0800 GMT.
TIME SCALE: 1" = 5 MINUTES

RD/SK 4105


SIMULTANEOUS BEARINGS AND FIELD STRENGTHS.
14. 5. 1942. FROM 0915 GMT.
TIME SCALE: 1" = 5 MINUTES.
RECIPROCAL BEARING
220°
210°
MEAN BEARING = 35°
HALESWORTH RDF PULSE 25 C/S. 27 MC/S.
RECIPROCAL BEARING.
255°
250°
MEAN BEARING = 72°
COLCHESTER RDF PULSE 25 c/s. 27 Mc/s.
DBS ABOVE 1 µV/M.
40
35
MEAN STRENGTH = 40 DBS
RD/SK 4106