METEOROLOGICAL OFFICE RADAR RESEARCH LABORATORY

RSRE MALVERN ENGLAND

RESEARCH REPORT

October 1977, No.3

METEOROLOGICAL OFFICE RADAR RESEARCH LABORATORY, MALVERN

RESEARCH REPORT

ASSESSMENT OF A REAL-TIME METHOD FOR REDUCING THE ERRORS IN RADAR RAINFALL MEASUREMENTS DUE TO THE BRIGHT-BAND

by J L Clarke, Royal Signals and Radar Establishment, Malvern

and C G Collier, Meteorological Office Radar Research Laboratory, Malvern

SUMMARY

The results of a series of experiments with a computer procedure for reducing the errors in radar rainfall measurements due to the effects of the bright-band are described. This procedure, originally developed at the Meteorological Office, Bracknell using a high-level computer language (FORTRAN) has been converted to a low-level computer language (PSEUDO, based on PDP assembly language) for possible eventual use within a real-time radar data processing system. This conversion has been successful and, although truncation errors have been introduced, it is felt that these are of an acceptable magnitude. The present procedure does not appear to be well suited for use with instantaneous radar data, but existing data are too limited for further investigation. Recommendations for future work are made.

1. INTRODUCTION

The presence of sleet within the radar beam causes the power received at the aerial to be greater than that from rain of the same rate of precipitation. For a radar scanning in azimuth at a low elevation angle (the normal PPI scan), a roughly annular band of enhanced radar echo (known as the "bright-band") is observed at ranges from the radar where the radar beam intersects the sleet. The result is the introduction of an additional error into the radar estimate of the surface rainfall. For a given radar beamwidth and elevation angle, the size of this error depends upon the height and the reflectivity and thickness of the melting layer.

As part of the work carried out during the Dee Weather Radar Project (see Harrold et al, 1973), an objective procedure for reducing the errors in radar rainfall measurements due to the presence of the bright-band was developed by Harrold and Kitchingman (1975) (see Appendix 1 to this paper). The method involves calculating the radar reflectivity factor at each range element, averaged over several degress of azimuth, and then deriving the ratio of reflectivity factor measurements at elevations of 0.5^{o} and 1.5^{o}, referred to as "lambda" ratios, together with an off-line assessment of this procedure. Harrold and Kitchingman (1975), revealed that out of 193 radar estimates of hourly rainfall totals in various subcatchments of area typically $60km^2$, using one raingauge calibration site, the average percentage difference, regardless of sign, between the radar and raingauge estimates was found to be 34% when the correction procedure is applied, but 38% when the procedure is excluded. It was suggested that the procedure removed the grosser errors over the area of radar coverage as a whole, but did little to improve the accuracy near raingauge calibration sites.

In order to investigate the performance of the correction procedure within an operational environment, the procedure was adapted for inclusion within a "real-time" radar data processing system developed by a team at the Royal Signals and Radar Establishment (Ball et al, 1976). This system had been used during the last eighteen months of the Dee Weather Radar Project, but unfortunately it had not been possible to incorporate the correction procedure before the Project was terminated. However, between March 1976 and September 1976 a large number of recordings of the raw radar video were made at the Llandegla Research Station in North Wales, in anticipation of the future testing of the bright-band correction procedure.

Extensive pruning of the original real-time data processing system was necessary to accommodate the new correction procedure within the minicomputer used to process the radar signals. In fact the procedure was found to require 7K words of core space in the PDP 11-40 computer in use, and the free core normally available in the computer, when the rest of the system was in residence, was 2K words. Software controlling the real-time calibration using raingauges, the calculation of integrated subcatchment rainfall totals, and several other facilities had to be removed from the system for the purposes of the tests.

The basic correction procedure was written in the low-level computer language necessary for the PDP computer at the Minicomputer Laboratory, Bracknell Met Office. No efforts were made by the present authors to optimize this software, except where incompatabilities were found to exist between the procedure and the interface software linking it to the rest of the system. The correction procedure was known to be very sensitive to minor software modifications. Such changes had led to numerical instabilities during the initial development by Harrold and Kitchingman.

The original concept of the correction procedure had been that it should be operated at a radar network control site, upon data transmitted via GPO telephone lines from a remote radar station. This would have proved difficult to implement as the procedure, in the form developed by Harrold and Kitchingman, requires data in polar coordinates which is not saved in the radar site computer, as core space is limited. Also, after the termination of the Dee Weather Radar Project no remote site existed for the tests. Therefore the procedure was implemented on a single minicomputer with video tape or manual data input, thereby simulating an on-site correction procedure.

2. RESULTS

Three types of tests have been performed on the RSRE correction procedure:-

TEST 1: A comparison, using as input the same set of hourly-integrated data derived from actual meteorological situations, between the performance of the correction procedure operated in simulated real-time in the RSRE computer, and the performance of the procedure off-line in the minicomputer at Bracknell as reported by Harrold and Kitchingman (1975). The data consisted of hourly integrated lambda values, averaged over a ten degree azimuth interval, with one value every 3km in range to a maximum range of 90km.

TEST 2: An examination of the performance of the RSRE correction procedure using a bright-band simulation (ie lambda ratios calculated from a horizontally homogeneous bright-band at various heights and with various thicknesses).

TEST 3: An examination of the performance of the RSRE correction procedure operated in simulated real-time, using as input raw radar video data from tapes recorced at the Llandegla Research Station. This test uses calculated instantaneous lambda ratios as input to the correction procedure, as opposed to the hourly-integrated values used in Test 1.

The first test was necessary to investigate any changes in the model performance which may have been produced by the conversion from an off-line procedure to one operating in real-time. In fact, the off-line procedure had been written in the FORTRAN computer language, and the results reported by Harrold and Kitchingman (1975) were produced using the facilities, such as floating point arithmetic, available with this computer language. The low-level computer system used for the real-time procedure does not have a floating point arithmetic option, and it was expected that some truncation errors might be introduced into the computations.

The second test was intended to reveal the characteristic behaviour of the correction procedure for different idealized bright-band configurations. It was hoped that the physical implications of the numerical constraints used in the procedure could be clarified.

In the final test the performance of the procedure using actual raw data in simulated real-time was to be examined. This would reveal any problems that might exist using data collected under operations conditions.

Wherever possible only the low beam (0.5° elevation) correction factors are discussed as it is probably low beam data which would be corrected in any operational system. This is because low beam data are used in order to minimize errors in derived surface rainfall estimates due to low-level growth or evaporation beneath the radar beam and wind drift effects (see Harrold et al (1974)).

2.1 TEST 1

Several examples of radar data showing the effects of a bright-band, initially analysed by Harrold and Kitchingman, have been examined. Hourly averages of the value of lambda (the ratio of the reflectivity measured by the 0.5° elevation radar beam to that measured by the 1.5° elevation radar beam over 'bins' 10° wide in azimuth and 1.5km in range) were used as input to the procedure. Examples of the variation with range of the correction factor for the off-line anaylysis and the simulated real-time procedure are shown in Figures 1 and 2. Only the low beam correction factors are shown in the figures for clarity (see above).

The results from the two version of the correction procedure are generally similar with values of the correction factor which diminish the echo intensity in the bright-band and enhance it in the area of snow at the appropriate ranges. However, the two versions of the correction procedure do depart from each other by up to a factor of 1.5 at ranges beyond the range at which the bright-band first intersects the radar beams. In each case examined the correlation between the high beam correction factors (not shown in Figures 1 and 2) derived from the two versions of the procedure was significantly better than for the low beam (shown in Figures 1 and 2).

One possible explanation of the differences in performance between the results obtained for the low and high beams is that, for these cases, the height of the bright-band is only about 200-300 metres above the radar station, and therefore the high beam reflectivity is enhanced over only a small range increment. In this situation the bright band intersects the low beam at near ranges and produces an enhancement over a much larger range increment. This occurs in the examples shown in Figures 1 and 2.

The small truncation errors inherent in the RSRE procedure are known to produce instabilities in the procedure (section 1), which alter the calculated vertical reflectivity profile in the presence of the bright-band. Such instabilities are held in check by the physical contraints applied to the calculation. Nevertheless their cumulative effects in range would be manifest, particularly at ranges beyond the ranges where enhanced bright-band reflectivity occurs. This is the likely explanation of the differences between the two procedures.

These results give the authors sufficient confidence to assume that no <u>excessive</u> irregularities in the performance of the model have been introduced by the RSRE software interface, the different computer environment or the software conversion from FORTRAN to the low-level computer language PSEUDO. However other studies, which are recommended later in this paper, will be helpful in defining more clearly the seriousness of the additional errors introduced.

2.2 TEST 2

Four different bright-band configurations have been considered, based on the measurements reported by Lhermitte and Atlas (1963) (see also Battan (1973))

It was assumed that the height (either 500m or 1000m above the radar) and thickness (either 100m or 200m) of the bright-band were variable, but its vertical reflectivity profile was otherwise as shown in Figure 3. The apparent rate of rainfall in the bright-band was taken as five times greater than the surface rainfall, where as the reflectivity of the snow was taken as five times less than the surface rainfall because of its smaller dielectric constant.

Figures 4 to 7 show the assumed bright-band configurations, the resulting variations of lambda used as input to the procedure, and the corresponding variation of the correction factor with range for the low (0.5°) and high (1.5°) beams. Also shown on the Figures is the variation with range of the correction factor for the low beam that would have been required for perfect suppression of the bright-band. These results demonstrate that the correction procedure does reduce the reflectivity enhancement produced by the bright-band, and, where snow is in the beam, the reflectivity is increased. The figures also show that for two bright-bands at the same height, one half as thick as the other, the correction factor for the thinner bright-band is reduced by about a factor of 1.3 compared with that for the thicker bright-band.

These tests confirm that the formulation of the correction procedure is such that it does diminish the enhancement produced by idealized bright-bands at different heights and with different thicknesses. However, the overall performance of the procedure appears to be somewhat erratic, being more realistic for low, thin and high, thick bright-bands. (Figures 4b and 7b) In some cases the correction was in the wrong sense at some ranges, thereby causing a deterioration in accuracy. The physical constraint of not allowing the calculated reflectivity in any layer to exceed that in the layer beneath it by a factor of two or more (see Appendix to this paper), appears to be realistic at ranges where the bright-band occupies about 10% or more of the radar beam. At far ranges, where most of the beam is filled with snow, some relaxation of this constraint might be more realistic. This would allow an increase of the correction factor applied to the measurements of the reflectivity of snow, giving a closer approximation to the surface rainfall rate.

2.3 TEST 3

Harrold and Kitchingman (1975) concluded their work by pointing out the desirability of including the correction procedure in a real-time system. Therefore, since the procedure could not be implemented during the Dee Project, it was decided to record raw radar video from the Llandegla radar between March 1976 and September 1976, so that the procedure could be tested later in simulated real-time. Unfortunately only a few examples of bright-bands occurred during this period.

Tests have been carried out on instantaneous radar patterns of surface rainfall data, since there is insufficient capacity in the present computers to store entire fields of time-integrated data in the required detail. The results demonstrate that the procedure does attempt some suppression of the bright-band. However, the corrections are not applied in a consistent way, adjacent data points receiving quite different modification, although the absolute changes to the data were usually very small. The reason for this may lie in the observation made by Harrold and Kitchingman, that, if lambda ratios were calculated over too short a time period, then factors other than the bright-band, namely wind shear or movement of echoes between the times of the high and low beam observations, may obliterate the simple profile adhered to for the horizontally homogeneous bright-band situation. The present work confirms this situation, and suggests the need for some for of time integration of the input data to the correction procedure, or some increased spatial averaging of the lambda values, perhaps in the radial direction.

3. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The conclusions drawn and recommendations resulting from the present work are as follows:-

1. A correction procedure which goes some way to modifying the surface rainfall field derived from radar data, in a way which removed the grosser errors produced by the effects of the bright-band, can be incorporated into a "real-time" system which processes the radar data, if the input data are in the form of hourly integrated fields. However, this cannot be achieved with the existing on-site computer system due to computer core limitations.

2. Small truncation errors, probably introduced into the real-time procedure during its conversion from a high level to a low level computer language, have introduced small, but noticeable, effects.

3. The procedure tends to react to different bright-band configurations in quite different ways. It is felt that further studies are needed to identify the characteristic behaviour of the procedure for many different forms of input data. In some cases the correction procedure actually causes a deterioration in the data at some ranges.

4. The use of lambda ratios calculated from instantaneous rainfall data does not appear to be satisfactory, this result confirming the earlier work of Harrold and Kitchingman (1975). Thus, before a real-time scheme can be implemented, further work is needed to examine the possibility of using time integration or spatial averaging techniques to provide the data for the correction procedure when operated within a real-time radar data processing environment.

5. In its present form the correction procedure occupies a large area of computer core, and uses input data in polar coordinates. If time integrated fields are required (see item 3 above) the core requirement will be even greater. Future work should investigate the possibility of reducing the core requirement by the use of data in cartesian coordinates. The data already exist in the processing system in this form for other purposes, and the expected saving is about 4K words. It is likely that the central processor unit timing required by the procedure could also be reduced significantly by the use of data in cartesian coordinates.

6. Several factors influence the location of the correction procedure within a radar network system. These include the amount of computer core available at a remote radar site, limitations on data transfer speeds produced by GPO telephone lines connecting remote sites to a network centre, and the practical problems associated with compositing data from several radars each with their own bright-band correction procedure. Consideration will have to be given to all these factors before a recommendation can be made.

7. Since only a very limited amount of bright band data are available on video tape, the above investigations require further data to be acquired, for example, from the Llandegla radar at the proposed Clee Hill (Shropshire) site. (This would be a suitable radar because the procedure uses data at two low elevation angles, which are not too widely spaced, yet are essentially independent. This requires the use of a radar with a 1° beamwidth, see Harrold et al (1974)).

REFERENCES

Ball, A P, Clarke J L, Davy, B D, O'Brien, M J, Trigg, S E, Taylor B C, and Voller, T A — 1976 "A system for the processing transmission and remote display of data from a weather radar", RRE Memo No 3020, unpublished.

Battan, L J — 1973 "Radar Observations of the Atmosphere" University of Chicago Press, Chicago and London

Harrold, T W, English, E J and Nicholass, C A — 1973 "The Dee Weather Radar Project: The measurement of area precipitation using radar", Weather, 28, pp 332-338

1974 "The accuracy of radar - derived rainfall measurements in hilly terrain", Quart J R Met Soc, 100 pp 331-350

Harrold, T W and Kitchingman, P G — 1975 "Measurement of surface rainfall using radar when the beam intersects the melting layer", Preprint Vol, 16th Radar Met Conf, Houston, Texas, April 22 - 24, pp 473-478

Lhermitte, R M and Atlas, D — 1963 "Doppler fall speed and particle growth in stratiform precipitation", Proc 10th Weather Radar Conf, Boston, pp 277-302

LEGENDS FOR FIGURES

Figure 1 : Comparison of the Bracknell and RSRE correction procedure with the lambda ratio input as a function of range for 1100Z to 1200Z, 7th January 1974, azimuthal sector 130° to 139°. The height of the bright-band above the radar is approximately 200m.

Figure 2 : As for Figure 1, 1900Z to 2000Z, 29th January 1974, azimuthal sector 110° to 119°. The height of the bright-band above the radar is approximately 300m.

Figure 3 : Vertical reflectivity profile used for Test 2 (after Lhermitte and Atlas (1963)).

Figure 4a : Bright-band configuration and the height of the 0.5° and 1.5° elevation beams. The bright-band is taken as 200m thick at a height of 1000m above the radar.

4b : The variation of correction factor for the low and high beams and input lambda ratio with range for the bright-band shown in Figure 4a. The variation of correction factor for the low beam required for perfect bright-band suppression is also shown.

Figure 5a : As for Figure 4a. The bright-band is taken as 100m thick at a height of 1000m above the radar.

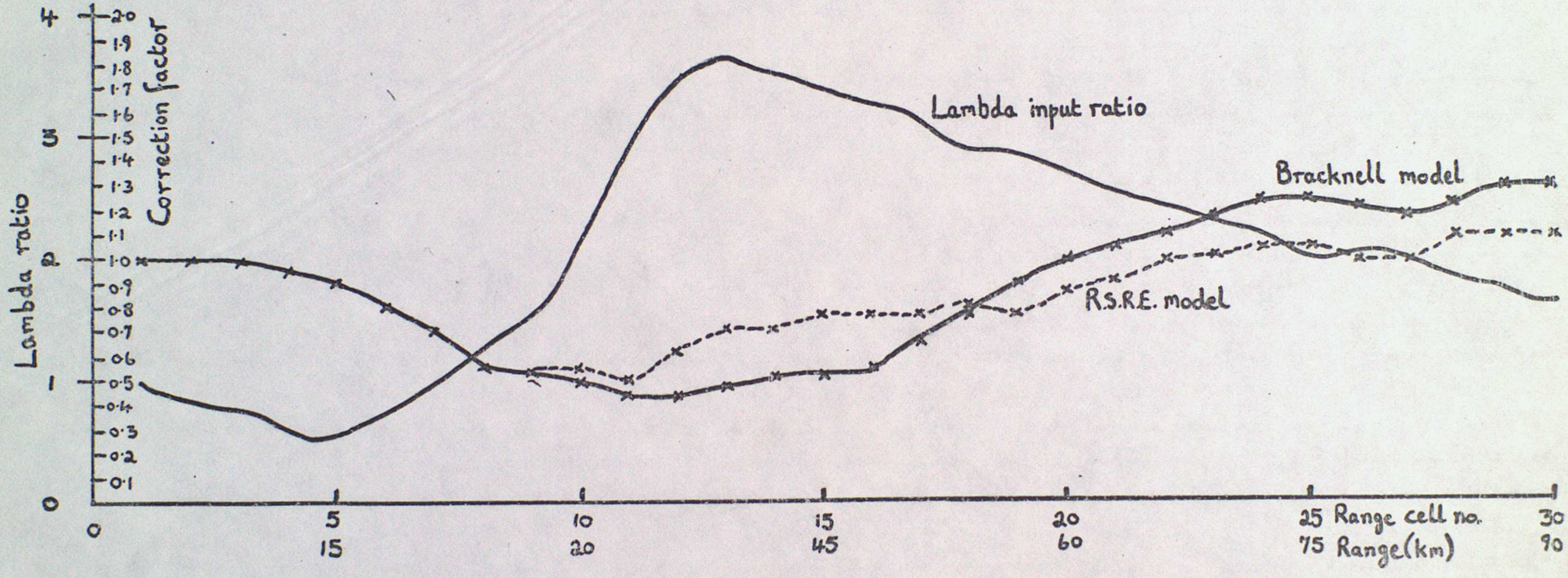
5b : As for Figure 4b using the bright-band configuration shown in Figure 5a.

Figure 6a : As for Figure 4a. The bright-band is taken as 200m thick at a height of 500m above the radar.

6b : As for Figure 4b using the bright-band configuration shown in Figure 6a.

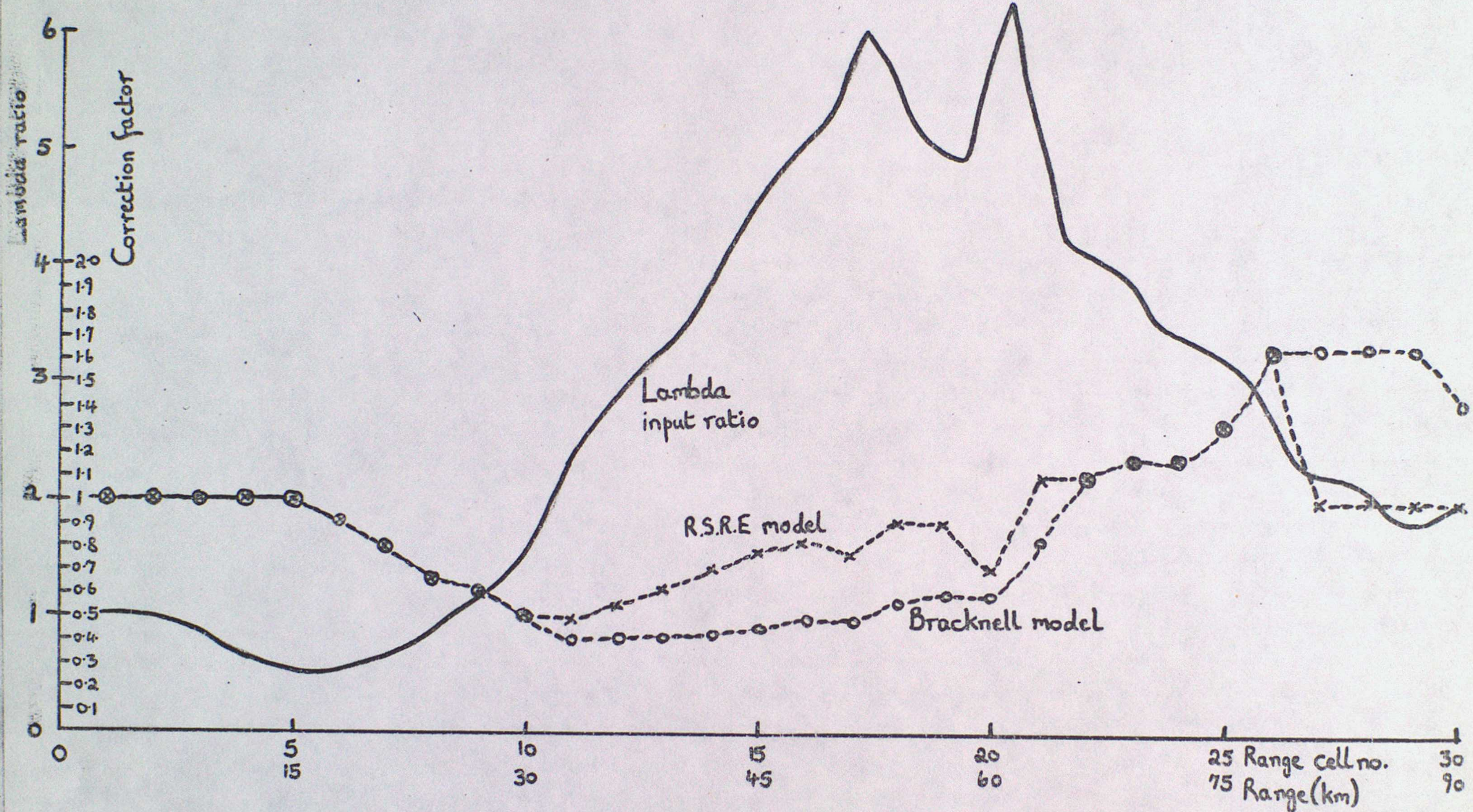
Figure 7a : As for Figure 4a. The bright-band is taken as 100m thick at a height of 500m above the radar.

7b : As for Figure 4b using the bright-band configuration shown in Figure 7a.



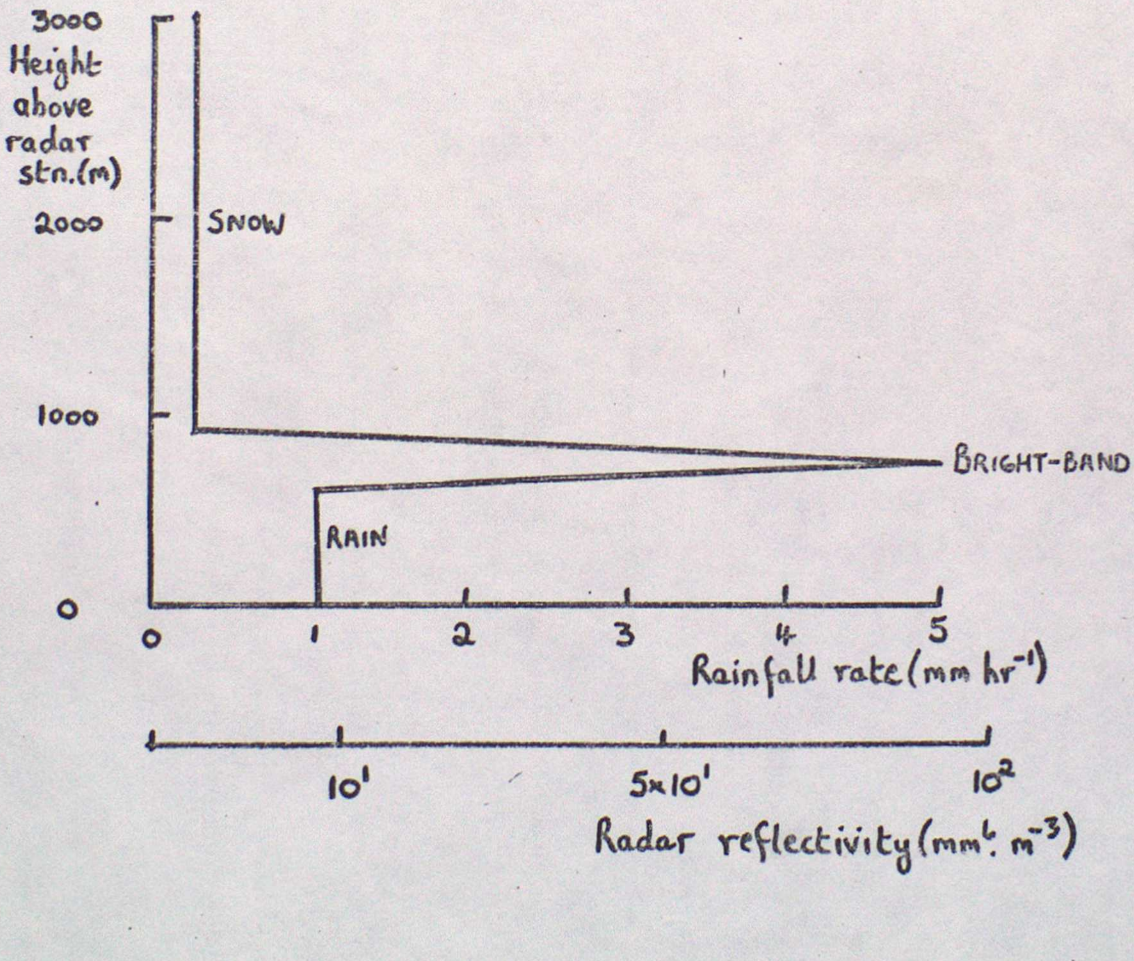
Lambda ratio
Correction factor
Lambda input ratio
Bracknell model
R.S.R.E. model
Range cell no.
Range (km)
0
1
2
3
4
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
1·8
1·9
2·0
5
10
15
20
25
30
15
20
45
60
75
90

FIGURE 2

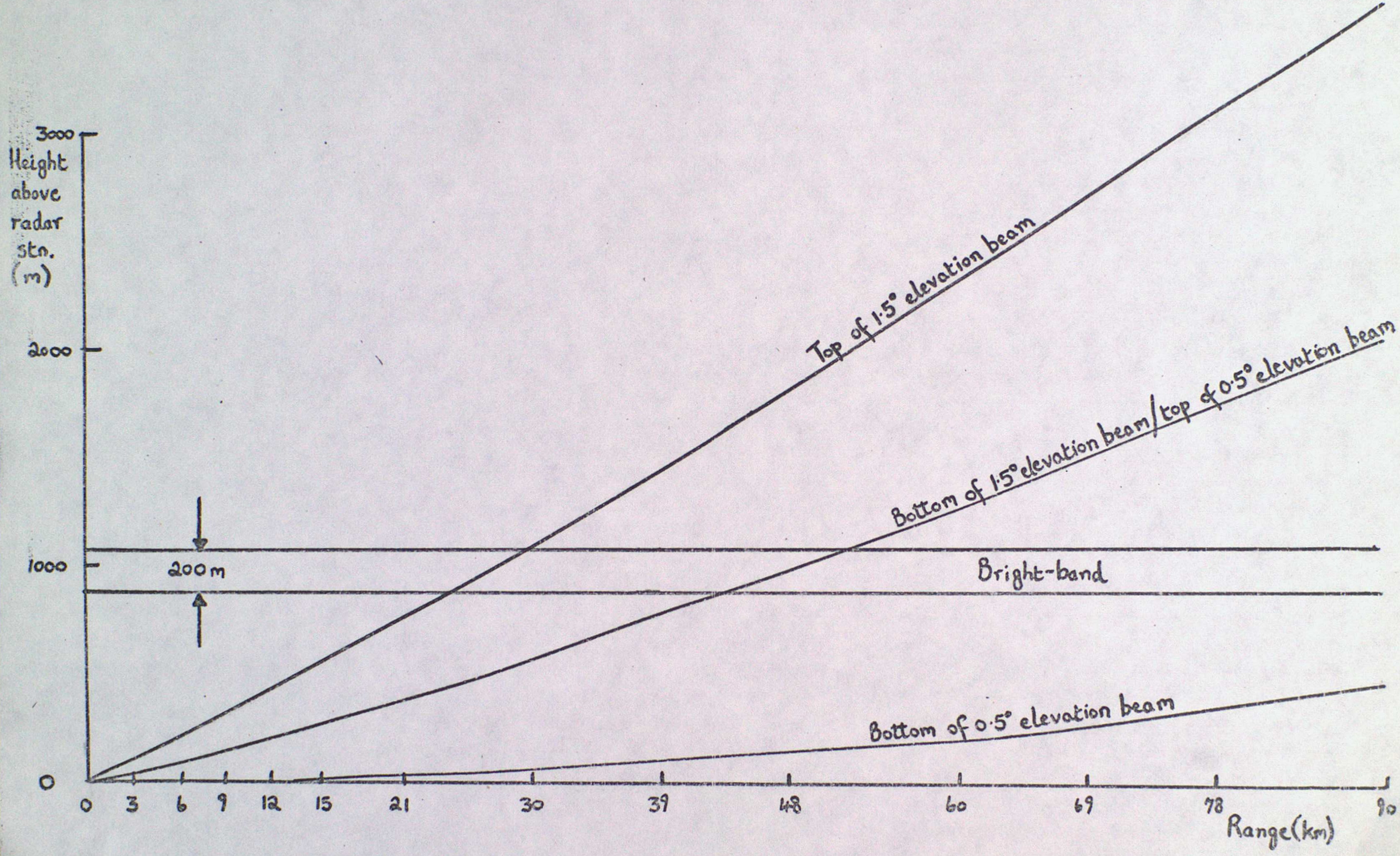


Lambda ratio
Correction factor
6
5
4
3
2
1
0
2·0
1·9
1·8
1·7
1·6
1·5
1·4
1·3
1·2
1·1
1
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
Lambda
input ratio
R.S.R.E model
Bracknell model
0
5
15
10
30
15
45
20
60
25 Range cell no.
75 Range (km)
30
90

FIGURE 3

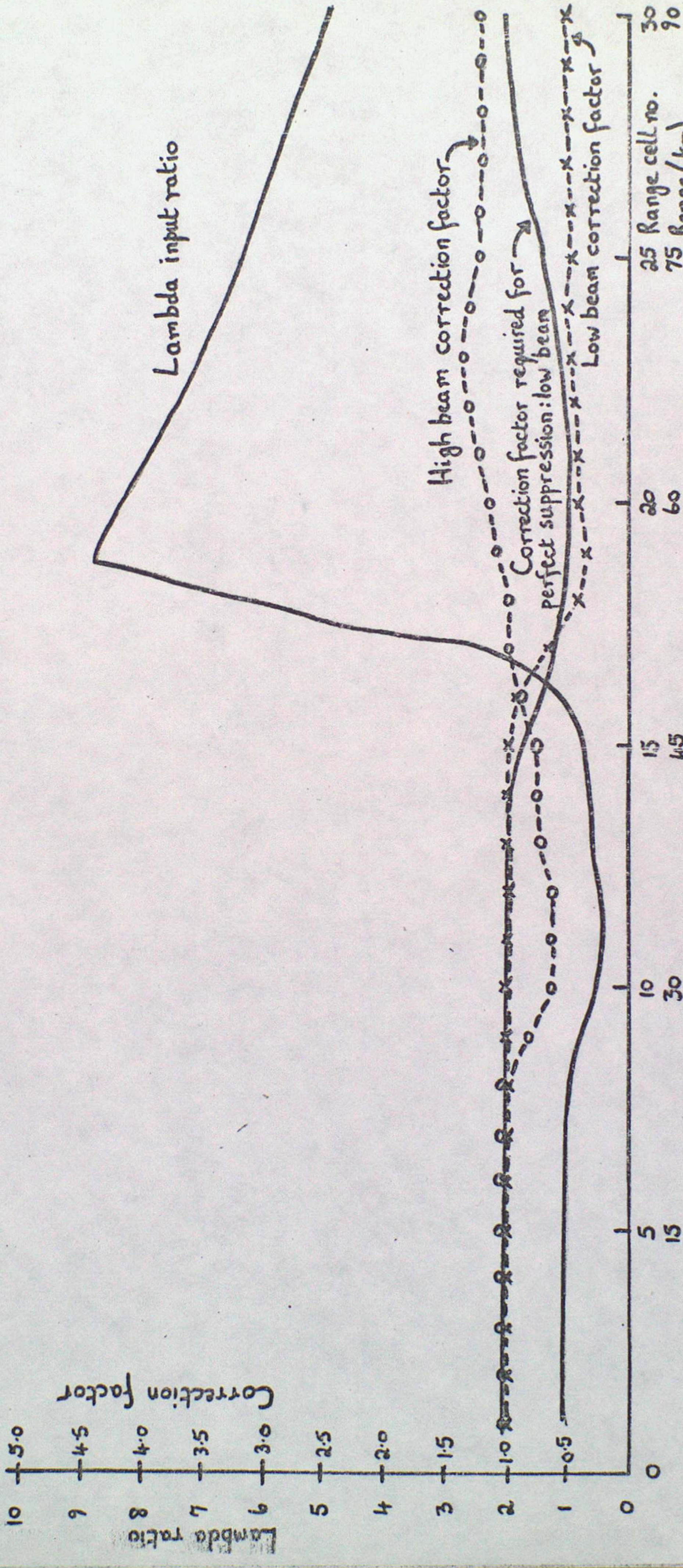


3000
Height above radar stn.(m)
2000
1000
0
SNOW
BRIGHT-BAND
RAIN
0
1
2
3
4
5
Rainfall rate (mm hr-1)
10'
5x10'
10²
Radar reflectivity (mm⁶. m-3)



3000
Height
above
radar
stn.
(m)
2000
1000
0
200m
Top of 1·5° elevation beam
Bottom of 1·5° elevation beam/top of 0·5° elevation beam
Bright-band
Bottom of 0·5° elevation beam
0
3
6
9
12
15
21
30
39
48
60
69
78
90
Range(km)

FIGURE 4b


Lambda input ratio
High beam correction factor
Correction factor required for perfect suppression: low beam
Low beam correction factor
Lambda ratio
Correction factor
10 9 8 7 6 5 4 3 2 1 0
5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5
0 5 10 15 20 25 Range cell no.
15 30 45 60 75 Range (km)
30
90

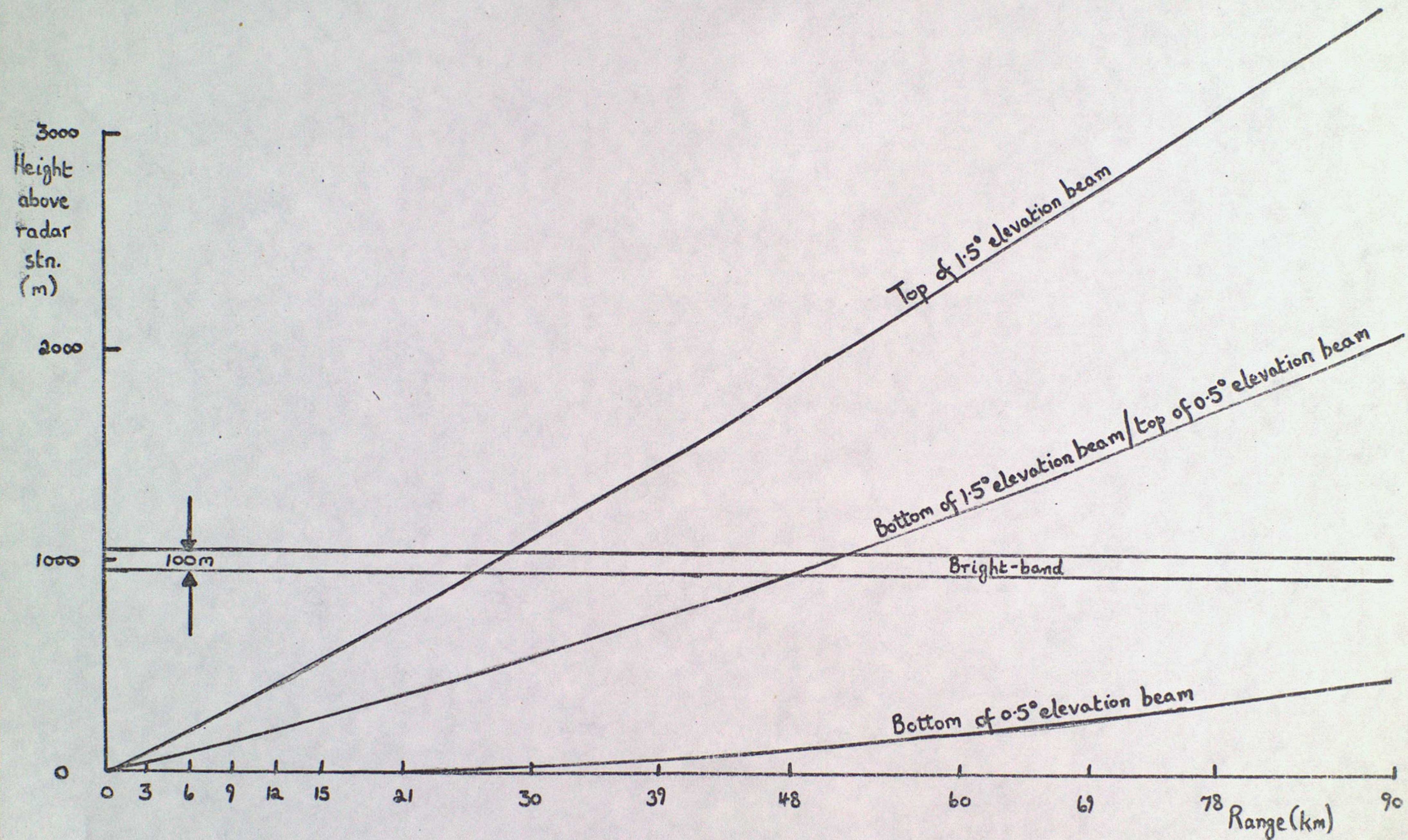
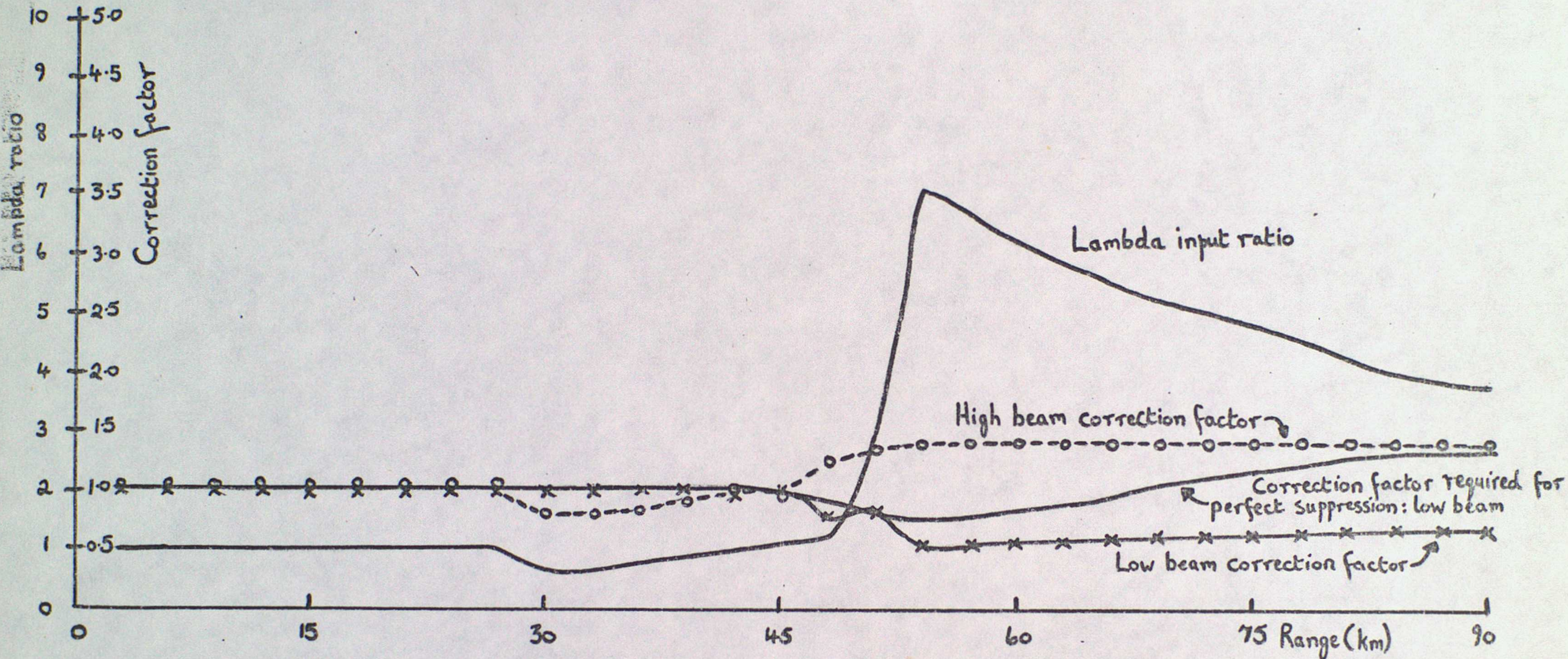
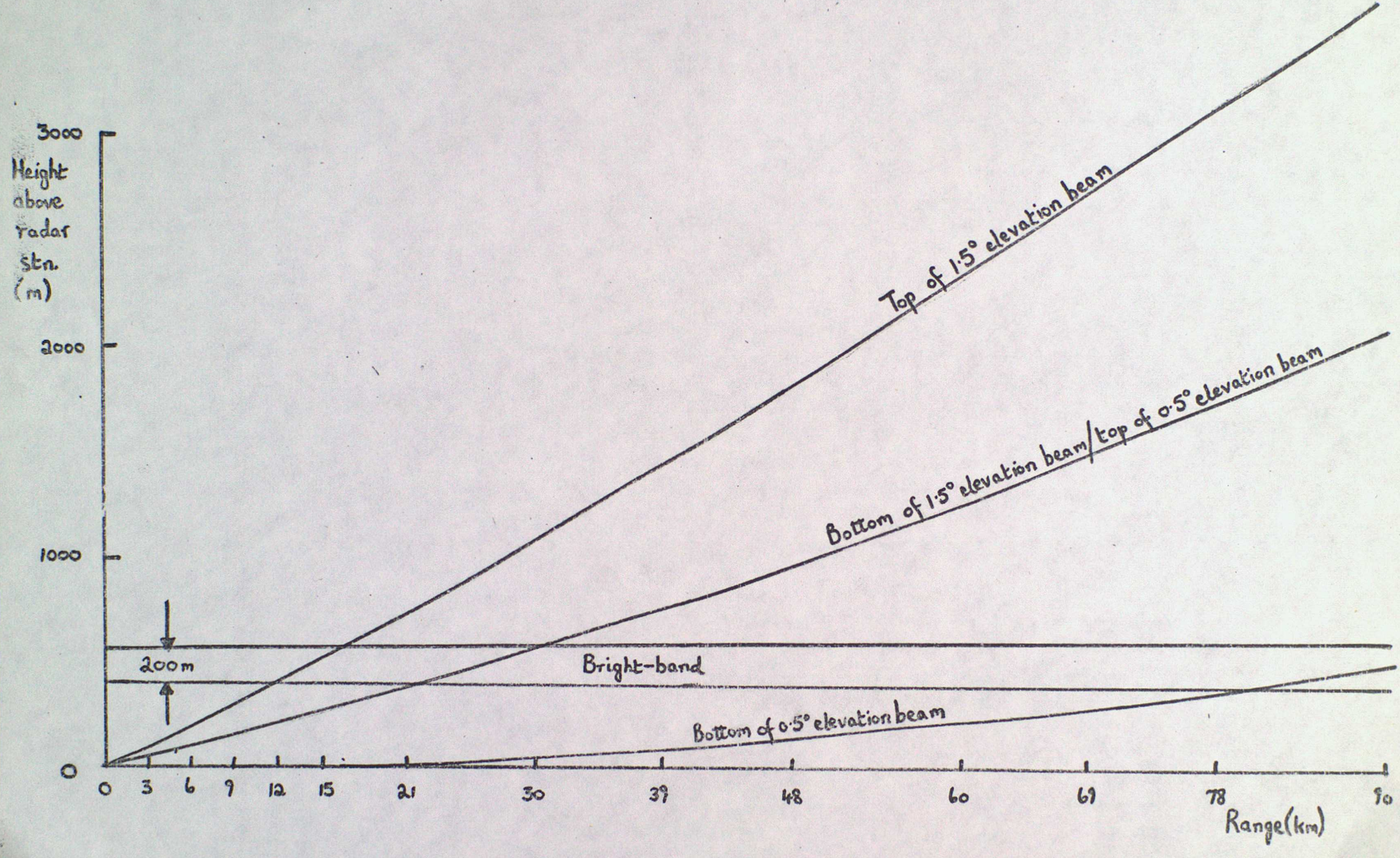

3000
Height above radar stn. (m)
2000
1000
0
0
3
6
9
12
15
21
30
39
48
60
69
78
90
Range (km)
Top of 1·5° elevation beam
Bottom of 1·5° elevation beam / top of 0·5° elevation beam
Bright-band
100m
Bottom of 0·5° elevation beam

Figure 5a



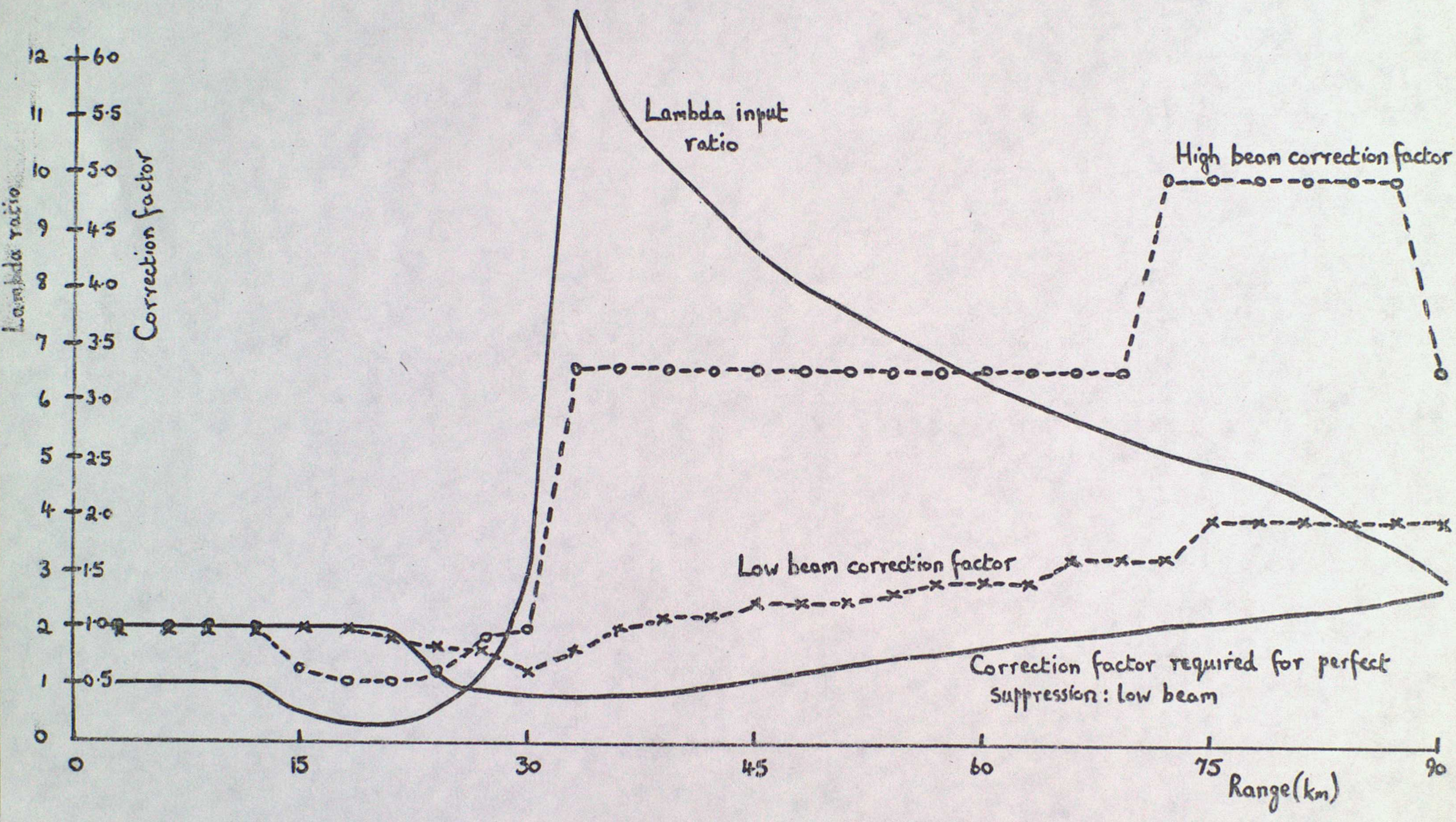
Lambda ratio
Correction factor
Lambda input ratio
High beam correction factor
Correction factor required for perfect suppression: low beam
Low beam correction factor
Range (km)
0
15
30
45
60
75
90
10
9
8
7
6
5
4
3
2
1
0
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5

FIGURE 6a



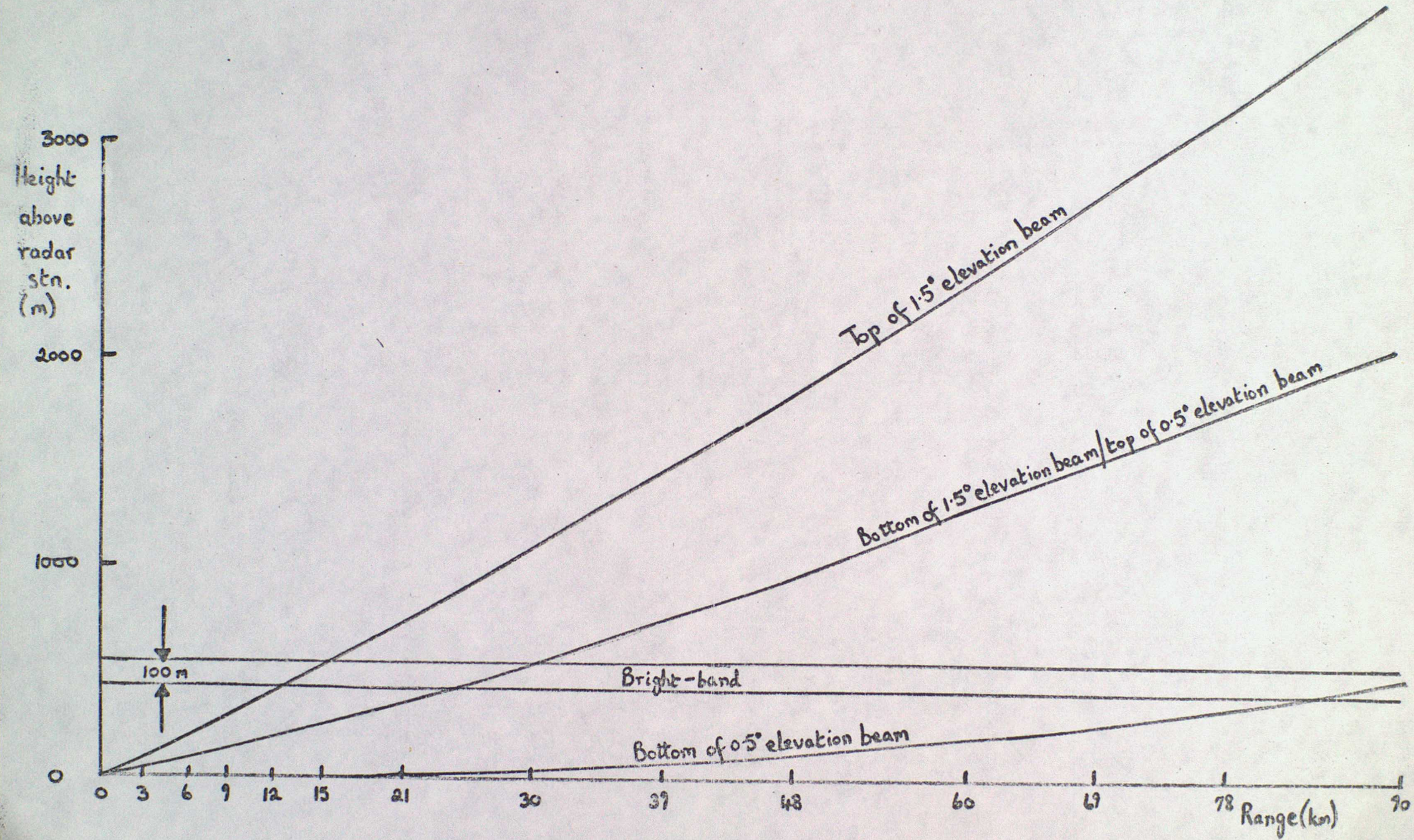
3000
2000
1000
0
Height above radar stn. (m)
Top of 1·5° elevation beam
Bottom of 1·5° elevation beam/top of 0·5° elevation beam
200m
Bright-band
Bottom of 0·5° elevation beam
0
3
6
9
12
15
21
30
39
48
60
69
78
90
Range (km)

FIGURE 6B



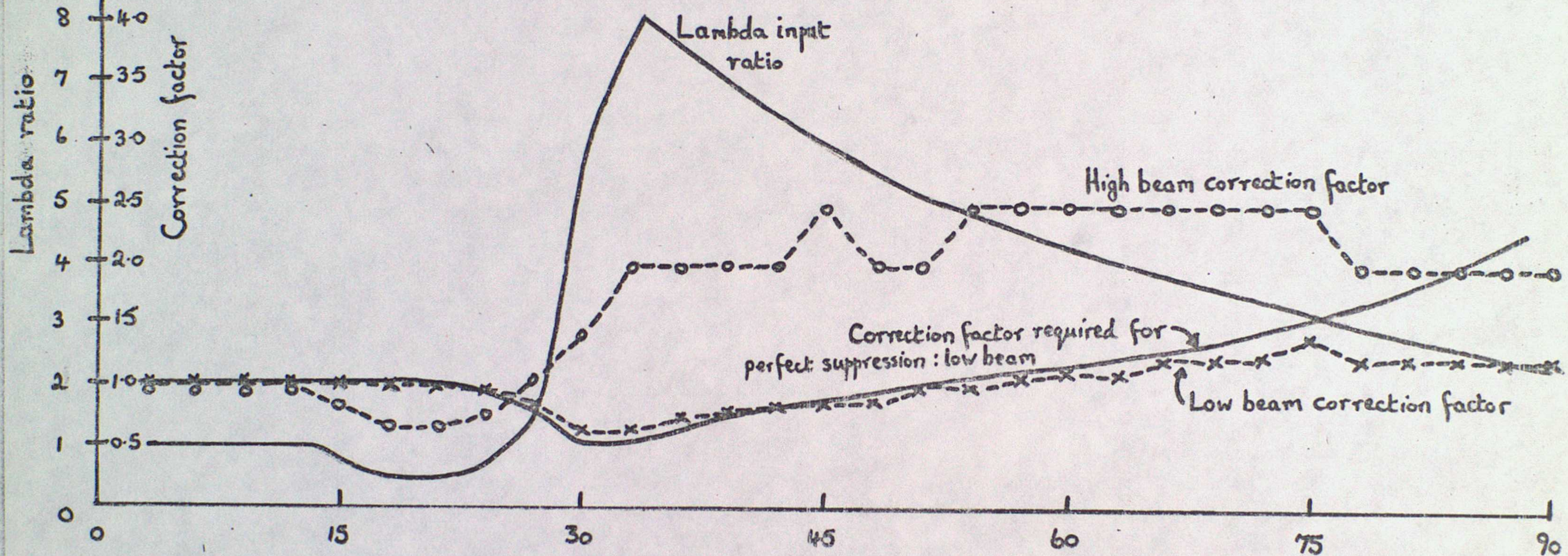
Lambda ratio
Correction factor
12
11
10
9
8
7
6
5
4
3
2
1
0
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Lambda input ratio
High beam correction factor
Low beam correction factor
Correction factor required for perfect suppression : low beam
0
15
30
45
60
75
90
Range (km)

FIGURE 7a



3000
Height above radar stn. (m)
2000
1000
0
100 m
Top of 1·5° elevation beam
Bottom of 1·5° elevation beam/top of 0·5° elevation beam
Bright-band
Bottom of 0·5° elevation beam
0
3
6
9
12
15
21
30
39
48
60
69
78
90
Range (km)

FIGURE 7b



Lambda ratio
Correction factor
8
7
6
5
4
3
2
1
0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
15
30
45
60
75
90
Lambda input ratio
High beam correction factor
Correction factor required for perfect suppression : low beam
Low beam correction factor

Reprinted from Preprint Volume, 16th Radar Meteorology Conf., April 22-24, 1975, Houston, Texas. Published by Amer. Meteor. Soc., Boston, Mass.

MEASUREMENT OF SURFACE RAINFALL USING RADAR WHEN THE BEAM INTERSECTS THE MELTING LAYER

T W Harrold and P G Kitchingman

Meteorological Office, UK

1 INTRODUCTION

In middle and northern latitudes the accuracy of radar derived estimates of surface rainfall is sometimes diminished because of the presence of the melting layer (bright band) within the radar beam. Harrold, English and Nicholass (1974) showed that errors could be reduced significantly by applying a statistically derived correction factor which was a function of the height of the melting layer and the range of the area of interest. However, a disadvantage of their method is that it is not clear to what extent the corrections can be applied in areas other than the hilly terrain in which they were derived. In this paper an objective method of reducing the magnitude of the errors is described and assessed. This method has the advantage over the earlier method that it can be applied in any locality.

2 METHOD

The correction procedure utilises data gathered from azimuth scans (PPI mode) at two angles of elevation selected so as to provide information from independent heights at a given range. For the 1° wide beam (to half power points) used in the study reported here the elevations of the beam axis were at 0.5° and 1.5°. Consider the beams divided into horizontal layers defined by the increase in height of the top of the upper beam between range gates, as shown in Fig. 1. In the data presented here the range gates were 1.5 km apart; thus the layers were about 50 m deep.

The input of the correction procedure requires two sets of data, one fixed and the other variable. These are:

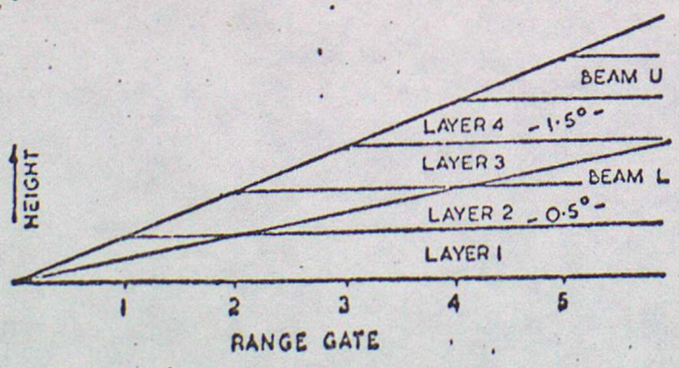


Figure 1 Diagram showing the definition of the layering system described in the text.

i The percentage of the total power transmitted within the beam for each of the layers. These percentages, which are range dependent, have been calculated from measurements of the beam polar diagram. The two height-range arrays of power percentages constitute the fixed input. In the following $P_{y,r,L}$, $P_{y,r,U}$ designate the percentages, at layer y, range r, of the total power transmitted within the lower (0.5°) and upper (1.5°) beams respectively.

ii The ratio of the reflectivity factors (or received power) observed in the two beams as a function of range. This is the variable input, obtained from the radar scans. As an example of the ratio, Fig. 2a shows the form it would take if there were a bright band present at and above layer 4 in Fig. 1.

The variation of the ratio of reflectivity factors with range is used to derive the profile of reflectivity at each range, using the power array, in the manner described below. Once the profile is known, the observed reflectivity with-

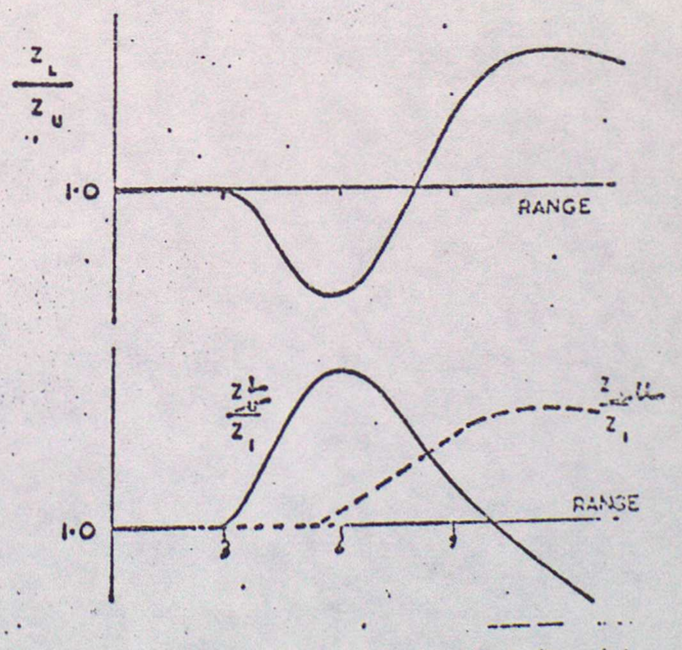


Figure 2 (upper curve) Variation of Z_L/Z_U with range when a melting layer is present.

(lower curves) Correction factors to relate the reflectivity in the lower (solid line) and upper (dashed line) beams to the reflectivity in the lowest layer.

in the lower beam is then related to the reflectivity, and hence rate of rainfall, at the base of the beam, see Fig. 2b.

The reflectivity profile is computed stepping out in range from range 3 (4.5 km) in Fig. 1. Ground clutter prevents measurement of reflectivity at shorter ranges, so it is assumed that $Z_1 = Z_2$, where Z_1, Z_2 are the reflectivities in layers 1 and 2 respectively. At range 3 we have

$$\frac{Z_L}{Z_U} = \frac{P_{1,3,L} Z_1 + P_{2,3,L} Z_2}{P_{2,3,U} Z_2 + P_{3,3,U} Z_3} \qquad (1)$$

← Lo beam in Layer 1+2
← Hi beam in Layer 2+3

where Z_L, Z_U are the measured reflectivities in the lower and upper beams respectively. This equation is solved for Z_3 in terms of Z_1, all other quantities being known, viz.

$$Z_3 = f_3 Z_1$$

$$\text{where} \quad f_3 = \frac{1}{P_{3,3,U}} \left[\frac{Z_U}{Z_L} (P_{1,3,L} Z_1 + P_{2,3,L} Z_1) - P_{2,3,U} Z_1 \right] \qquad (2)$$

The final stage of the calculation at range 3 is to relate the observed echo in the two beams to that in layer 1, viz.

$$\left. \begin{array}{l} Z_L = F_L Z_1 \\ Z_U = F_U Z_1 \end{array} \right\} \qquad (3).$$

where F_L, F_U are correction factors to be applied to the observed reflectivity and are the output of the correction procedure.

The calculation then steps to range 4 and so on. At each range it is assumed initially that the values Z_1, Z_2, Z_3 etc from the previous range apply and the reflectivity factor in the uppermost layer (Z_r) is calculated. That is, it is assumed that changes in Z_L/Z_U are a result of the additional echo introduced at the top of the upper beam. So, in the first stage of the calculation at each range

$$\frac{Z_L}{Z_U} = \frac{\sum_L (P_{y,r,L} f_y) Z_1}{\sum_U^{y=r-1} (P_{1,r,L} f_y) Z_1 + P_{r,r,U} Z_r} \qquad (4)$$

which is solved for Z_r in terms of Z_1.

As the calculation steps out in range a stage is reached when the calculated reflectivity increases markedly in the upper layers. This occurs as the upper beam extends in to the higher reflectivity within the melting layer. As the range is further increased the top of the beam extends into the snow of lower reflectivity above the melting layer and the calculated reflectivity of the uppermost layer decreases again. In this way, as the calculations step out in range the reflectivity profile of the bright band is derived. However it is found that the simple procedure above tends to produce increasingly unrealistic reflectivity profiles, and hence correction factors F, as the range is increased. For example the solution to equation 4 may be a negative value of Z_r, which is of course physically impossible. This can arise because the reflectivity in each layer is in fact not constant with range. To improve the correction factors a constraint is placed on the value Z_r that it must not exceed the reflectivity in the layer beneath by more than a factor of two. If at any range this value is exceeded, then Z_r is fixed at the appropriate limit. To compensate for this adjustment the reflectivity in some other layer or layers must be changed in order to satisfy equation 4. It is assumed that fluctuations of reflectivity at layers within the bright band itself are the most significant of the variations of Z with range. On occasions when the reflectivity of the uppermost layer is constrained, the reflectivity in the layer with the largest value of Z is recalculated. The recalculated value is also constrained, this time to be no more than a factor of two different from the values in the layers immediately above and below. If the constraint is applied then layers linked by the constraint of a factor of two ("linked layers") are formed and at times, depending on whether the echo in the layer has to be increased or decreased to satisfy equation 4, these links may have to be retained in the calculation. A further complication arises if the layer or 'linked layers' straddle both beam positions. Any adjustment to the reflectivity then affects both beams and tend to cancel in equation 4. To counteract this, a layer or linked layers which extend into both beams are not altered and, instead, the layer with the next highest reflectivity is found and its reflectivity recalculated. In this manner the reflectivity profile is allowed to change with range.(1) The model is thus rather complex in that all calculations must be checked to ensure that the physical constraints are maintained, but this does produce physically more realistic correction factors than does the simple procedure of assuming reflectivities invariant with range.

---

(1) The 'rule' of changing the highest value of reflectivity once Z_r is constrained is relaxed in one other circumstance. This is when there is a pronounced minimum in the reflectivity profile between the maximum value and the top layer. If $\frac{Z_r}{Z_{MIN}} > Z_{MAX}$ then Z_{MIN} is recalculated instead of Z_{MAX}. The effect of this modification is to produce a slightly smoother reflectivity profile rather than any large change in the correction factor F.

3 A TYPICAL EXAMPLE

In this section an example of a calculation is summarised in order to illustrate the procedure. The input to the correction procedure is shown in Table 1.

Table 1 Z_L/Z_U for each range gate.

range gate	1	2	3	4	5	6	7	8
Z_L/Z_U	1.0	1.0	0.80	0.84	0.71	0.67	0.64	1.06

Equation 4 can be applied at each range interval in turn up to and including range 7. At range 7 the reflectivity profile which is derived is

Layer No y	1	2	3	4	5
Z_y/Z_1	1.00	1.00	1.48	1.35	2.70

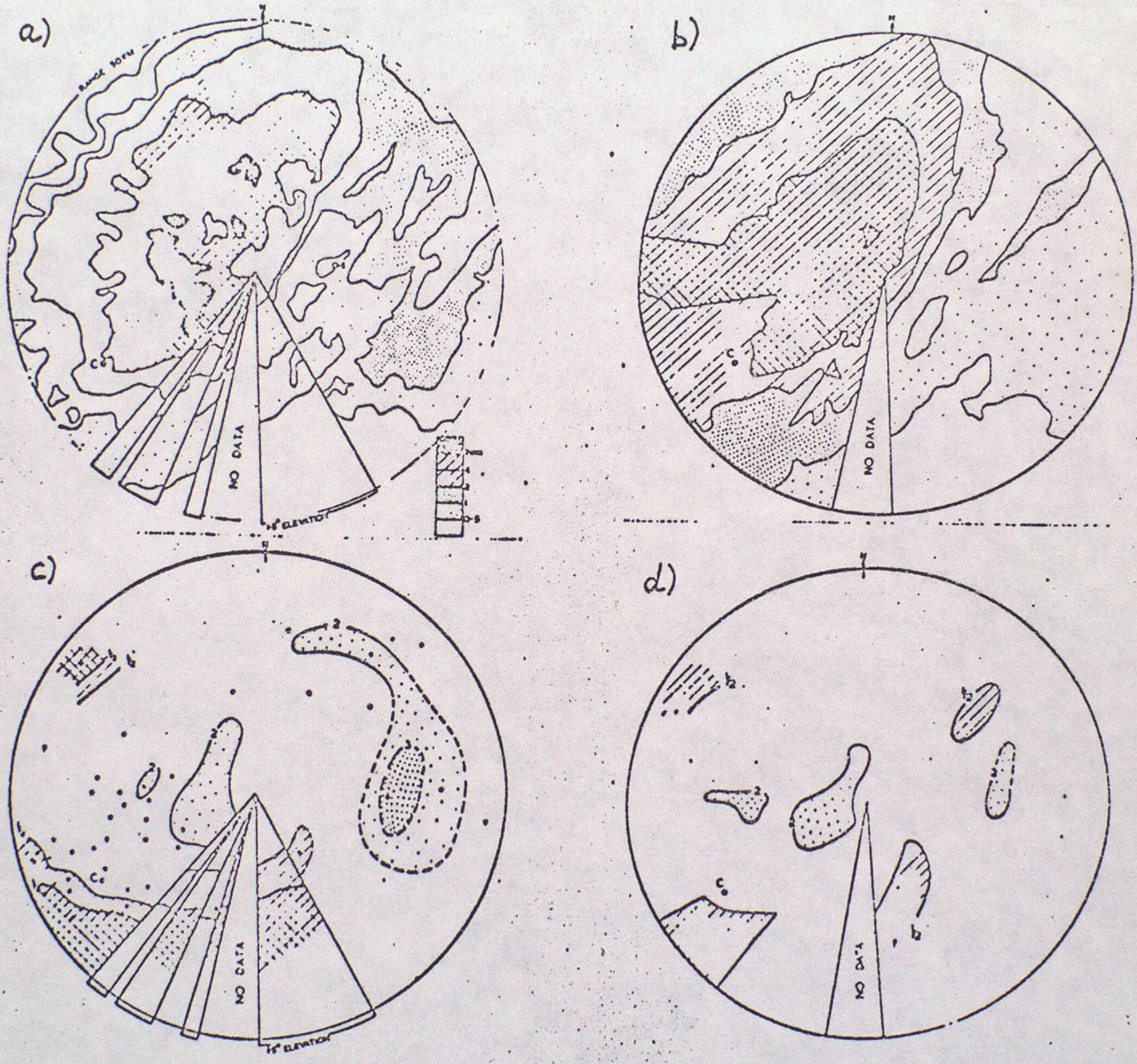


Figure 3 a) An example of radar-derived hourly rainfall amounts when a bright band was within the beam. The data were obtained using a beam elevation of 0.5° over most of the diagram, but 1.5° at some azimuths to the south, (as indicated) where nearby hills screen the lower elevation. The entire field was calibrated above location C.
b) Same as (a) except with the correction procedure included.
c) and d) Errors in rainfall estimates for (a) and (b) respectively. Dots show the locations of the raingauges available for the comparison.

Layer No 1	6	7
Z_1/Z_1	2.32	3.14

showing the peak intensity of the bright band is at or above layer 7. The correction factors to be applied to the observed echoes in the L and U beams in order to relate the observed echo to Z_1 are

range	1	2	3	4	5	6
F_L	1.0	1.0	1.0	1.04	1.08	1.13
F_U	1.0	1.0	1.25	1.23	1.52	1.68

range	7
F_L	1.16
F_U	1.82

On solving equation (4) at range 8 it is found that $Z_8 < ½ Z_7$. Therefore Z_8 is constrained to be $½ Z_7$, ie $Z_8 = 1.57$ and Z_7, the largest value of Z, is put as the unknown in equation 4 and recalculated. This calculation leads to the result that $Z_7 < ½ Z_6$, so it, too, is constrained, this time to be 1.16, ie $½ Z_6$. The layer now with the highest Z is layer 5. However this layer is within both the lower and upper beams, so it is not changed, and the next largest value, layer 8, is recomputed. Further calculations are made in this stepwise manner until the calculated value does not exceed any constraints. At this stage the reflectivity profile has become

Layer No y	1	2	3	4	5
Z_y/Z_1	1.00	1.00	1.67	1.35	2.70

Layer No y	6	7	8
Z_y/Z_1	1.35	1.16	0.58

and the new correction factor

range	8
F_L	1.27
F_U	1.20

The calculation continues onward in range in this manner, first computing Z_r and then, if necessary, adjusting the bright band profile.

The procedure has been evaluated in two separate ways. The first is a semi-quantitative evaluation over an entire PPI display in order to determine whether the confusing effects of a bright band can be removed sufficiently for the data to be of value in meteorology, for instance as an input to possible future objective forecasting methods utilising radar data. The second evaluation is a quantitative assessment of the accuracy of the corrected radar estimates of surface rainfall over several subcatchments of the River Dee in North Wales, the subcatchments having areas between 20 Km^2 and 100 Km^2 in North Wales.

a) General assessment

Fig.3a shows rainfall totals estimated over a 1 hour period using the C-band radar (wavelength 5.7 cm), in North Wales, which is described by Collier, Harrold and Nicholass (1975). The rainfall estimates were made assuming B = 1.6 in the relationship $Z = AR^B$ (R being the rate of rainfall) and the entire field was calculated by equating the radar estimate with a raingauge measurement at location C, as described by Harrold, English and Nicholass (1974). The figure appears to show heavy rainfall centred about 15 Km west and north west of the radar, with a marked decrease beyond. However, much of this apparent decrease is because the beam extended in to snow at longer ranges. Fig. 3b shows the same occassion with the correction procedure included. Correction factors were computed from hourly values of Z_L and Z_U which were averaged over 10° azimuth sectors. Rainfall isopleths are less concentric than in Fig. 3a, especially in the northwest quadrant, implying a more realistic representation of the actual rainfall. This is confirmed by Figs. 3c and d, which depict the ratio of radar to raingauge measurements of rainfall. On this occasion the figures show that the correction procedure removed all errors greater than a factor of 3 and significantly reduced the extent of errors exceeding a factor of 2. At least some of the errors portrayed in Fig. 3d are probably due to factors other than the melting layer, since similar patterns have been observed on occasions when the melting layer was not within the radar beam. (The estimated errors in Figs. 3c and d are only approximate since the radar has been compared with a generally sparse network of raingauges which might themselves be in error.)

A further advantage of the correction procedure which is apparent in Fig. 3 is that it is possible to obtain much better estimates to the south of the radar, which is blocked by a nearby hill when the radar beam axis is at an elevation of 0.5°. This is because correction factors relating observed echo to that close to the ground are obtained for both the upper and lower beams. Although the use of the 1.5° beam is less satisfactory than using the lower beam, because the precipitation can change and drift appreciably as it falls, it is a considerable improvement on simply using the 1½° data when this is largely within snow.

Other comparisons similar to the

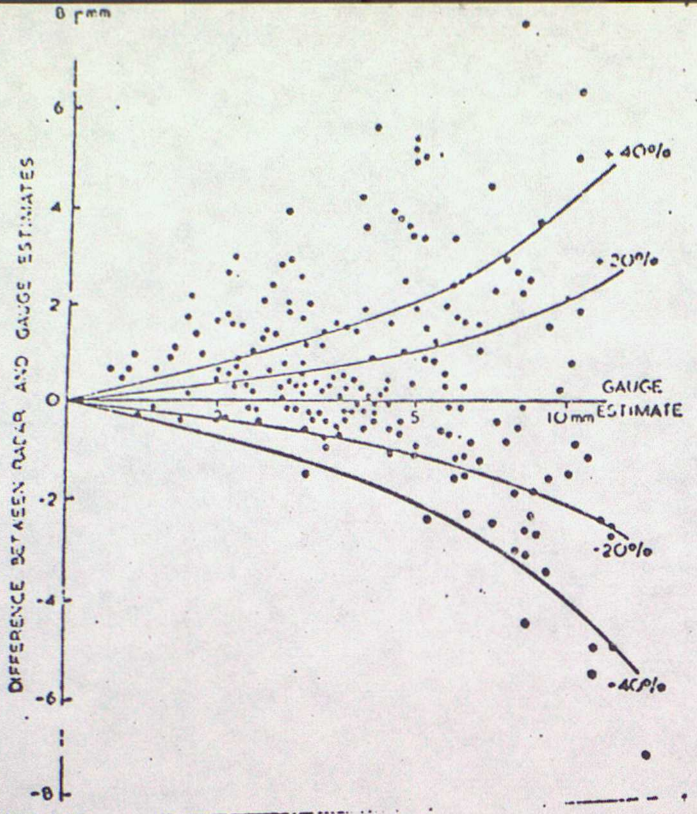


Figure 4 Differences between corrected radar and raingauge estimates of 3(or 2) hour rainfall amounts over river sub-catchments plotted against the gauge estimate on all occasions when a melting layer was present within the beam at an elevation 0.5°.

example shown in Fig. 3 have confirmed that the correction procedure does generally diminish the large errors in estimates of surface rainfall introduced by the presence of the bright band.

b) Accuracy of corrected estimates of rainfall over particular sub-catchments.

In this section both uncorrected and corrected radar measurements of rainfall are compared with estimates based on data from the network of raingauges within about 20 km of the calibration gauge shown in Fig. 3c. 58 hours of measurements, made when the bright band was present in the lower beam within a range of 50 km, are summarised.

Fig. 4 depicts differences between radar and raingauge estimates of rainfall over periods of three hours (or two hours if three hours of data were not available) over sub-catchments which vary in area between 20 km^2 and 100 km^2 - see Collier et alii (1975) for map showing the location of these areas. All the radar measurements were corrected for the bright band effect and calibrated at location C. Of the 193 radar estimates, 42% are within ± 20% of the gauge estimates and 32% differ by more than ± 40%. The average percentage difference, regardless of sign, between the radar and raingauge estimates, ie the average of $100((R_R/R_G)-1)$ % where R_R and R_G are the radar and raingauge estimates respectively, is 34%. The average difference when the bright band correction procedure is excluded is 38%.

One of the causes of the differences between the two methods of measuring rainfall was that the precipitation drifted horizontally in the wind as it fell from the radar beam to the ground. The wind speed at hill top level was typically 15 ms^{-1} during the measurements. On combining the measurements over the subcatchments to produce a single estimate over an area of 700 km^2, the mean difference between the radar and gauge estimates of three (or two) hour rainfall is reduced to 16% with the correction procedure included and 19% with it excluded, partly because the effect of the wind drift is relatively less over the larger area.

It was expected that the differences between radar and gauge estimates when the bright band was intersected would be a function of the height of the bright band. However analysis showed that the day to day variability in the differences at the same bright band height obscured any such relationship.

A further assessment of the corrected radar estimates over the sub-catchments is presented by Collier et alii (1975).

5 DISCUSSION OF RESULTS

The results show that over the area of radar coverage as a whole the errors in estimates of surface rainfall introduced by the bright band are reduced when this correction procedure is applied. However, over individual sub-catchments within a few tens of km of a calibration gauge the reduction in the difference between radar and gauges estimates is only a few percent.

The correction procedure would be useful in improving an uncalibrated radar display in that intensity variations throughout the display could be related to rainfall variations. When a calibration gauge is used, errors well away from the gauge are similarly reduced. This is shown schematically, in Figs. 3 and also by curves b in Fig. 5. The solid line portrays the probability of an error in a rainfall estimate well away from a calibration site, and the dashed line shows the probability at the same location when the correction procedure is included. However within a few tens of km of a calibration gauge

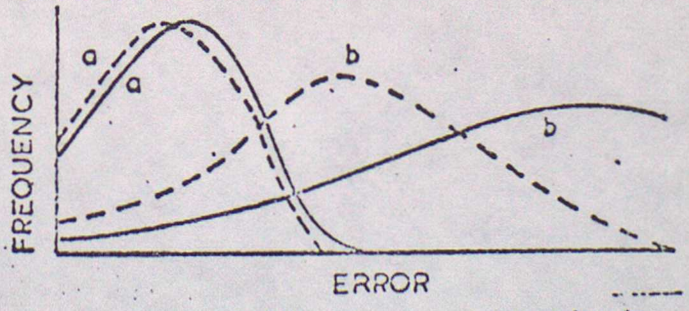


Figure 5 Probability of an error occurring in uncorrected (full lines) and corrected (dashed lines) radar estimates of rainfall for locations close to (curves a) and distant from (curves b) a calibrating site

much of the error introduced by the bright band is accounted for in the calculation procedure itself and further objective correction for the bright band leads to a much smaller improvement. This is illustrated by curves a in Fig. 5.

The form of the Z_L/Z_U input used is important in the performance of the correction procedure. In the preceding analysis hourly averages over bins 10° wide in azimuth and 1½ km in range were used. It is necessary that some averaging should be performed in order to minimise the influence of other factors which affect Z_L/Z_U, for example windshear or movement of echo between the times of the upper and lower beam observations. If ratios over too short a period are used, factors other than the bright band can obliterate the simple profile in Fig. 2, and result in the correction procedure being meaningless.

The correction procedure is now being incorporated in to the real time radar system which is being installed in North Wales (see Taylor 1975). Once this is done the procedure can be assessed further using much more data than it has been possible to analyse in the past.

6 CONCLUSION

A method has been described of objectively reducing the large errors in radar estimates of rainfall which sometimes occur when the bright band is present within the radar beam. The procedure utilises data gathered during azimuth rotations at two angles of elevation. Ratios of the echo at the two elevations are the input to the correction procedure. These data must be averaged over time and space in order to minimise the influence on the ratio of factors other than the bright band. In the data presented here this averaging has been performed over areas 10° in azimuth X 1.5 km in range.

The results to date are encouraging. Once the procedure has been incorporated into the real time system experience should be gained quickly which may lead to modifications of the procedure in order to improve the procedure further.

7 ACKNOWLEDGEMENTS

The data presented in this paper were obtained during the Dee Weather Radar Project. Raingauge data were collected and analysed by staff of the Welsh National Water Development Authority, the Water Data Unit and the Meteorological Office. The radar has been loaned to the Project by Plessey Radar Ltd, and operated by the Meteorological Office Staff. The work of all these people is gratefully acknowledged.

8 REFERENCES

Collier, C G, Harrold, T W, and Nicholass, C A; 1975. A comparison of area rainfall as measured by a raingauge calibrated radar system and raingauge networks of various densities. This conference.

Harrold, T W, English, E J, and Nicholass, C A; 1974. The accuracy of radar-derived rainfall measurements in hilly terrain. QJR Met S 100 331-350.

Taylor B C, 1975; A mini-network of weather radars. This conference.

METEOROLOGICAL OFFICE RADAR RESEARCH LABORATORY - MET.O. RRL.

Research Reports.

No.1. The Short Period Weather Forecasting Pilot Project.
(MRCP 426) K A Browning.

No.2. Observation of Strong Wind Shear using Pulse Compression Radar.
K A Browning. P K James (Met.O. RRL). D M Parkes. C Rowley.
A J Whyman (RSRE).

No.3. Assessment of a Real-Time Method for Reducing the Errors in Radar Rainfall Measurements due to Bright-Band.
J L Clarke, RSRE. C G Collier, Met.O. RRL.

No.4. Meteorological Applications of Radar.
K A Browning