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ON THE COMPRESSION OF DIGITAL RADAR DATA*)

by

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Abstract

The paper deals with possibilities of compressing the vast amounts of data produced by digitalized weather radar into a more compact form in order to facilitate archiving, transmission or reuse of the data. Some simple methods based on elimination of »zeroes» are described and tested with real data. With the most effective compression method tested the average compression ratio with 3-dimensional data was 23:1, being about 10:1 at low elevation angles, about 20:1 at medium elevation angles and more than 100:1 at high elevation angles. If only those elevation angles were included in the analysis on which at least one echo point existed, the average ratio was about 8.5:1, increasing from about 6:1 at 1° elevation to about 12:1 at 25° elevation.

1. *Introduction*

Weather radar is a source of vast amounts of rapidly flowing data. As stated *e.g.* by SMITH *et al.* [14] flow rates as high as 10^7 bit/s are typical of those obtainable from a raw radar video signal. This high data rate can be reduced to about 10^5 bit/s by averaging the echo signal over a number of independent returns. If we are talking about digitized radar reflectivity we are also dealing with just this reduced rate.

Although there are no big problems in handling digital data rates of 10^5 bit/s locally using modern technology, difficulties are met as soon as the data in its all

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five dimensions (x, y, z, t, Z_e) has to be archieved for later use or transferred to some remote location. For example a 2400 ft reel of magnetic tape will be filled at a writing density of 1600 bpi in about 50 min. Continuous measurements would thus produce about 30 tapes per day. This is much too much for most practical applications, except perhaps some case study of a storm lasting only one or two hours.

Typical bit rates transmissable by normal good quality telephone lines are nowdays 2400 or 4800 bit/s. These values are more than an order of magnitude smaller than the rate of raw digital reflectivity data.

From these considerations it is necessary to try to devise methods by which the data could be compressed into a more compact form without too much affecting the original quality and the information content of the data.

In many of the articles dealing with digital radar data the problem has been mentioned (*e.g.* ECCLES [5], SILVER and GEOTIS [13], SCHROEDER *et al.* [12], RAMSDEN *et al.* [11], BELLON and AUSTIN [2], HOGG [6]). Compression methods used so far are mostly based on elimination of »zeroes» from data records. However, exact descriptions and evaluations of the effectiveness of various compression methods used have not been made as far as is known. In the present paper some simple compression methods used at the University of Helsinki are described and evaluated using real radar data.

2. *General aspects on radar data compression*

Broadly speaking, radar data compression methods can be divided into three categories:

1. Reducing resolution in space, time and intensity but keeping the data otherwise in its original form
2. Coding the data in a new form which takes into account statistical or climatological properties of radar echo patterns
3. Taking into account the needs of the users

In most cases these principles are applied separately. Some methods, however, include features from more than one of the above categories at the same time. Although we mainly concentrate on the second category, some comments on the first and third categories are necessary.

Resolution can be reduced as long as the original radar echo field is still possible to reconstruct, e.g. by interpolating methods, with sufficient accuracy. In order to determine the reduction possible, information is needed on the space autocorrelation function and on the time cross correlation functions of the data as well as on the accuracy of the estimates of the radar reflectivity factor. According to KESSLER and RUSSO [7], ZAWADZKI [15] and AUSTIN and BELLON [1] space autocorrelations as well as time crosscorrelations may vary considerably from case to case depending on the rainfall type and also on the coordinate direction. Thus in principle, for optimum solution, different resolutions are needed with respect to time and each coordinate direction for each individual case, or at least for different rain types.

For practical reasons it may be better to keep horizontal resolution fixed varying only time resolution and perhaps also vertical resolution of the data to be archieved. A general principle for taking into account the optimum resolution in practice might be to calculate both the space autocorrelation and time crosscorrelation functions in real time during measurements and to add new data into storage according to the decrease of each correlation. For example vertical spacing of data may be determined using vertical autocorrelations and a new 3-dimensional record is stored using the so-determined vertical resolution as soon as the maximum value of the time crosscorrelation function falls below a certain preselected value. However, much work has to be done before this kind of technique is operational.

Regarding the maximum resolution attainable, it is restricted by the original accuracy of the estimates of the average power received, by the length of the pulses transmitted, by the properties of the radar beam together with the sampling mode of the system and last by the bandwidth properties of the receiver as well as the stability of every link of the transmitter-receiver-processor chain. For further details of these aspects the reader is referred to MARSHALL and BALLANTYNE [8], NATHANSON and SMITH [9] and DOVIAK and ZRNIC [4].

Storing or transmitting of complete 3-dimensional reflectivity data is normally necessary only if the final use of the data is not known exactly (*e.g.* the data is stored for possible future research). In most practical applications some special form of data presentation may be more useful than the complete 3-dimensional presentation. For example, the aviation weather service probably needs information on the locations and the movement of rain areas as well as on the heights of the tops and on the strength of possible turbulence within clouds rather than on the whole original 3-dimensional data. Expressing the data in this way in a specially analysed form of one type or another for practical users is compression of type 3. Averaging the fluctuating echo signal may also be classified as category 3 of compression. Taking into account the requirements of the user may also allow a further reduction in resolution.

In the present paper we concentrate on the second category of compression and simply assume that the resolution and the quality of the data to be compressed are suitable and that the final use of the data is not known.

Most of the data compression methods of this type are based on the fact that typically only a small fraction of the total radar observing area is covered by echoes. Thus it is possible to code the locations of the echo-points using fewer numbers than is needed to present numerically each non-echo-point. In following chapters just these types of simple compression methods are evaluated.

More complicated methods of type 2 can be devised by expressing the data in the form of some suitable mathematical series and by taking only part of the terms into account, corresponding to the resolution requirements (BLACKMER and DUDA [3]). Possible series include Fourier expansions and series based on what is called the Empirical Orthogonal Functions (principal components). Although mathematically elegant, these types of methods may be too complicated for practical use.

3. *Description of the methods tested*

Perhaps the simplest technique of compression is to drop all radials containing no echo-points from a B-scan type of data block. With a cartesian type of data this compression can be made by eliminating each echoless row. In any case, numbering or addressing of radials or rows is then needed. This method, which is referred to in the following as »*Non-echo Row Elimination*» (NRE) is profitable if the number of bits used for addressing the rows containing echoes is smaller than the number of bits needed for storing the data of the echo-less rows.

Let n be the number of columns (number of either range-bins or gridpoints in x-direction) and m the number of rows (number of either azimuth angles or gridpoints in y-direction) in the matrix to be compressed. Let a be the number of bits used for each reflectivity value, b the number of bits used for addressing a row and f the number of rows containing at least one echo-point. The NRE method is compressing if

$$(m - f) > bm/(an - b) \tag{1}$$

Typical values for n, m, a and b are 200,180,8 and 8, respectively. Thus NRE method is profitable if $(m-f) > 0.9$, *i.e.* if there is at least one echoless row.

The next step in compressing the data is to eliminate by some means all non-echo points from the prevailing radials or rows. One way of doing this is to establish a »bit map» consisting of a row of n bits before each data row. In the bit map the i:th bit is »one» if the corresponding i:th point in the row in question is an echo-point. Otherwise it has a zero value. After the bit map, reflectivity values are given only at echo-points (example in Appendix). This method, which is referred to as »*Bit Map Presentation*» (BMP), is better than uncompressed presentation if the number of bits eliminated is greater than the number of bits in the bit map. If e is the number of echo points in a row this condition can be written as

$$(n - e) > n/a \tag{2}$$

With $n = 200$ and $a = 8$ more than 25 non-echo-points per row are needed in order to gain something by the BMP method. Because the amount of data per row depends on the number of echo-points, some kind of variable length record system is needed on magnetic tape. It follows from this that additional record length information is necessary in each row (in our experiments the first 8 bits of the record were used for this purpose).

The BMP method does not actually totally eliminate »zeroes» because one bit is needed for each non-echo-point. The bit map itself is actually a complete presentation of the radial but with only one bit resolution. Typically it consists of alternating queues of »ones» and »zeroes». This kind of bit map is also compressible, for example by addressing the starting points and lengths of each individual queue containing only »ones», *i.e.* instead of a bit map, starting points and lengths of continuous echo-point queues along the radial are given. The effectiveness of this method, which is referred to hereafter as the »*Start-Length Presentation*» (SLP), depends not only on the number of non-echo points but also on the number of continuous echo-queues, N, along the radial to be compressed. If c denotes the number of bits needed to code one starting point or length of echo-queue the SLP method is compressing data if

$$N/(n - e) > a/(2c) \tag{3}$$

With $a = c$ (= 8) this means that the number of non-echo points must be twice as large as the number of unbroken echo-queues. SLP is better than BMP if

$$n > 2cN \tag{4}$$

With $n = 200$ and $c = 8$ this is true if the number of echo-queues is smaller than 12 along each radial.

In the SLP method some kind of separator character is needed to separate the queue of »start-length» pairs from the actual echo amplitude values, *i.e.* if the start-length information for the whole row precedes the echo amplitude values as in the BMP method. However, a separator is not needed if the data is grouped so that the echo amplitudes belonging to a particular echo-point queue are given immediately following the corresponding start-length information and each radial or row is coded as a record of variable length (in which case record length information is again needed as in BMP). (Appendix).

In table 1 formulae for calculating the numbers of bits needed for storing a row

Table 1. Formulae for estimating the number of bits needed for various compression methods. Symbols used:

a = number of bits used for each reflectivity value
b = number of bits used for addressing a row
c = number of bits used for one starting point or length
d = number of bits used for additional information per row (*e.g.* record length, time, number of ground-echo-points etc.)
n = number of columns (range bins or points in x-direction)
m = number of rows (azimuths or points in y-direction)
e = number of echo-points in a row
$\bar{e}$ = average of e over all radials in a PPI scan
$\bar{e}'$ = average of e over all radials containing echoes in a PPI scan
f = number of echo-azimuths
N = number of echo-queues
$\bar{N}$ = average of N over all radials in a PPI scan
$\bar{N}'$ = average of N over all radials containing echoes in a PPI scan

Method	Number of bits needed		
	per one row of data		per whole PPI-scan
Uncompressed	$na+d$		$m(na+d)$
NRE	$na+b+d$	1)	$f(na+b+d)$
BMP	$ea+n+d$		$m(\bar{e}a+n+d)$
NRE & BMP	$ea+n+b+d$	1)	$f(\bar{e}'a+n+b+d)$
SLP	$ea+2cN+d$		$m(\bar{e}a+2cN+d)$
NRE & SLP	$ea+2cN+b+d$	1)	$f(\bar{e}'a+2cN+b+d)$

1) zero if $e = 0$

of data or a whole PPI-scan of some elevation cone are given for each method as a function of the size of the original matrix and other relevant parameters. Using these formulae the effectivness, or compression ratio E of each method can be estimated by dividing the number of bits needed in uncompressed form by the corresponding number of bits needed in compressed form.

In addition to the basic methods NRE, BMP and SLP the combined methods NRE & SLP and NRE & BMP also appear in table 1. These methods are better than the basic methods alone if condition (1) is fullfilled, *i.e.* typically if there is at least one echoless row.

One further step in compressing might be to also use a bit map or start-length type of coding to map the rows containing echo-points in these combined methods. By this means addressing of rows individually is no longer necessary. The same could be made also with respect of the elevation angles. However, the probable benefit gained by the last refinements may be questionable. The maximum savings possible in extreme cases are estimated to be roughly of the order of 10 % of the total amount of data compressed by NRE&SLP method. On the other hand, keeping this 10 % may make the data considerably easier to use.

4. *Evaluations with real data*

Data

The data sample used in tests consisted 280 h of 3-dimensional radar data collected in 1977. Measurements were made in a polar co-ordinate system with following recording parameters:

azimuth resolution	2°	(360°)
elevation resolution	1.5°	(1° – 26.5°)
range resolution	750 m	(0 – 150 km)
time resolution	15 min	
amplitude resolution	16 bit	
number of samples per average	32	

(For further details of the measurement system and the original data format see PUHAKKA [10]). The compressed data were not compared to the raw original data but to data in which the reflectivity values were reduced to 8 bit resolution and also in which each record (measurement of reflectivity at 200 ranges) were supplied with only 32 bits of »additional» information (d in table 1) while in the original data d had a much higher value.

For all compression methods tested it is essential to distinguish between »echo-points» and »noise-points». For this reason an estimate of the average background noise level was determined for each 3-dimensional measurement by calculating the average amplitude over all azimuth angles of the signal from the last range bin at the highest elevation angle measured. Thus the estimate is thought to be very accurate (perhaps of the order of 0.1 dB) while the accuracies of the values from individual range bins to be classified as echo points or non-echo points are only of the order of 1 dB (average of 32 independent returns).

In order that as small a number of noise points as possible were classified incorrectly as echo points the average background noise level was increased by an amount $\Delta\bar{A}$ roughly corresponding to 1 dB and the final decision was made using a 3-point weighted running average for each point to be checked. Weighting was carried out as follows: if A_{i-1}, A_i and A_{i+1} are the signal strengths at ranges $i-1$, i and $i+1$ respectively the value at point i is classified as »echo» if

$$(\tfrac{1}{2}A_{i-1} + A_i + \tfrac{1}{2}A_{i+1})/2 > \bar{A}_{200} + \Delta\bar{A}$$

where $\bar{A}_{200}$ is the average noise level. It was estimated that less than 1 % of noise samples are classified incorrectly by this means.

Distributions of echo points and non-echo points

In fig. 1 the percentage of each elevation cone of radials containing at least one echo point (excluding ground echoes) is given as a function of the elevation angle. It can be estimated that elimination of echoless radials (NRE) compresses the data to about 60 % of the original at low elevation angles while at higher elevation angles the method is not very effective.

For BMP and SLP information about the distribution of echo-points along each radial measured is needed. According to table 1, the number of echo-points, e, and the number of continuous echo-point queues, N, are the essential parameters. Fig. 2 presents the frequency distribution of radials containing e echo-points divided into N unbroken queues. A typical radial contains 5–30 echo points (out of 200) divided into 2–3 queues.

Results

Exact values of the compression ratios were calculated by three methods: NRE, NRE & BMP and NRE & SLP. In applying the methods most ground echoes were

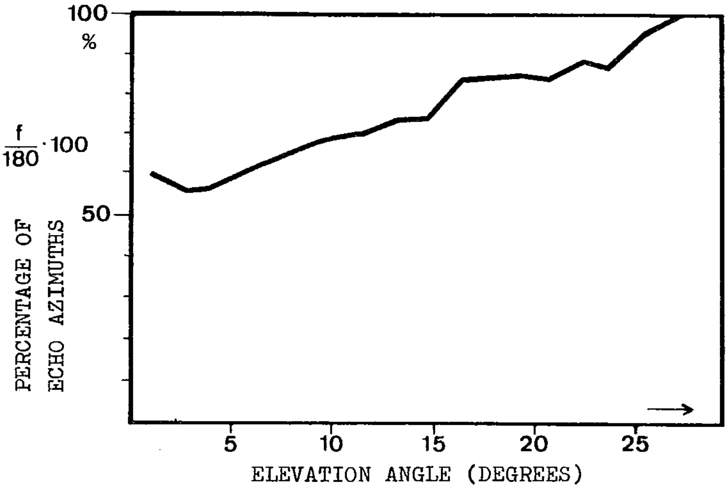

Fig. 1. Percentage of radials containing at least one echo-point as a function of the elevation angle. Totally echoless elevation angles have been excluded.

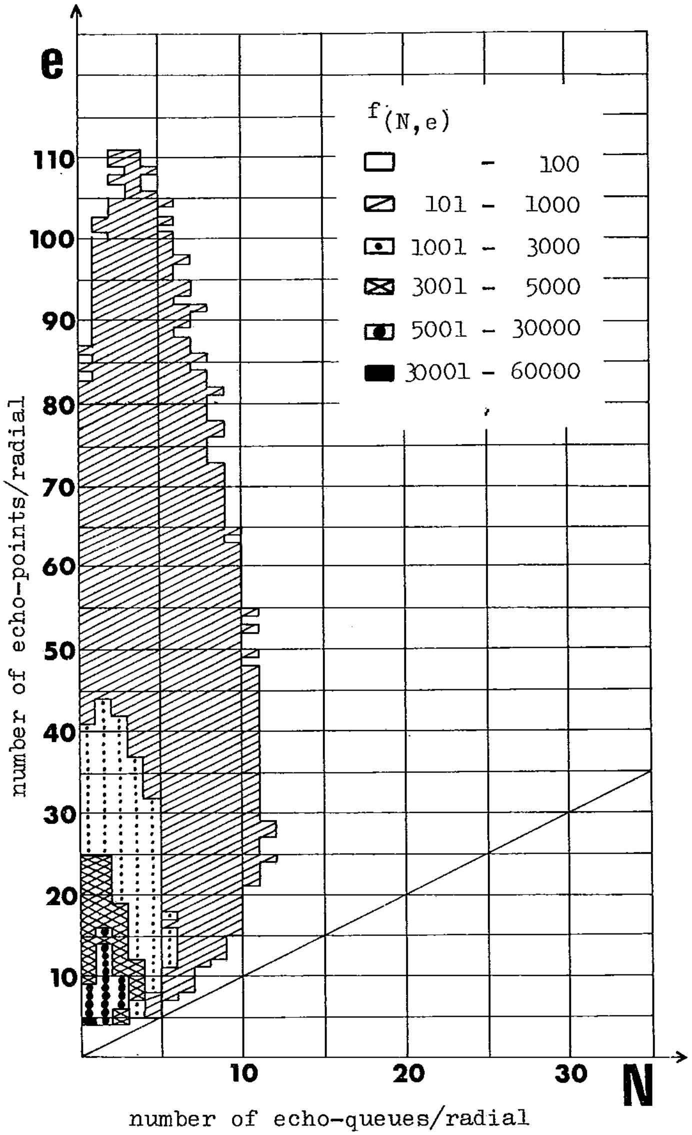

Fig. 2. Frequency distribution $f_{N,e}$ of radials containing e echo-points divided into N uniform echo queues.

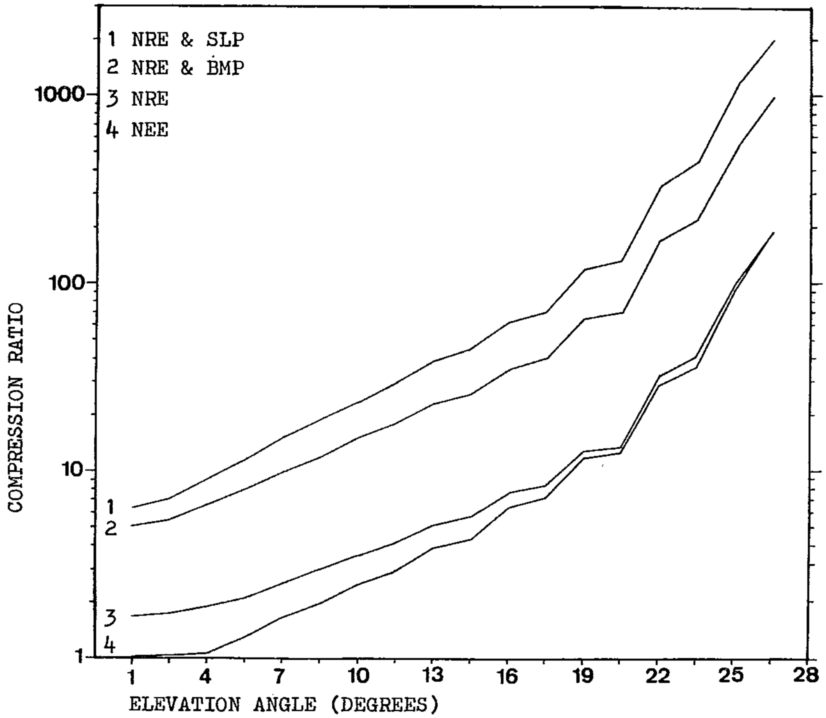

Fig. 3. Average compression ratios of 3-dimensional data as a function of the elevation angle. Methods tested are NRE&SLP, NRE&BMP, NRE and NEE (elimination of echo-less elevations).

first removed by excluding all data within variable radius $r = r$(azimuth, elevation). The number of points removed was 6.4 % of the total number of points measured being about 10 % at the lowest elevation angle and decreasing to 5 % at 10 degrees and above. Compressed values were compared to the original data (including also ground echoes) which were coded to 8-bit resolution and supplied with 32 bits of other than reflectivity information per radial. Coding parameters used were $a = b = c = 8$, $d = 32$, $n = 200$ and $m = 180$.

Figure 3 gives the average compression ratios calculated from the whole material as a function of the elevation angle. All elevation angles were included in the analysis if there were echoes at the lowest elevation angle. This explains the extremely high ratios obtained with high elevation angles. In most cases echoes outside the radius of 20 km did not extent to 26.5° elevation angle. This is also illustrated in the figure by the curve NEE (non-echo elevation) which gives the compression ratios obtained by eliminating echo-less elevation angles alone.

The order of superiority is at all elevation angles the same, NRE & SLP, NRE &

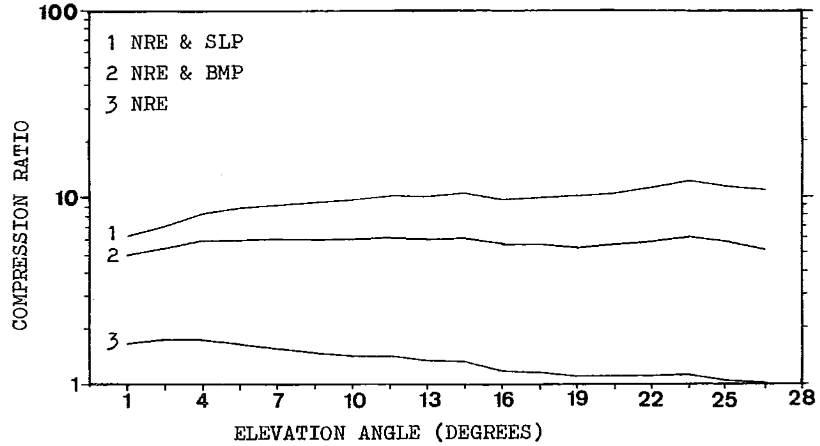

Fig. 4. Average compression ratios of 2-dimensional data as a function of the elevation angle.

BMP, NRE and NEE. With the best method the average value of the compression ratio is about 23:1, being about 6.3:1 at the lowest angles, 20:1 at medium elevations and very large at high elevations. The qualitative changes in the compression ratios of the other methods are similar.

In order to obtain an idea of the possible variations in compression ratio as a function of elevation angle in cases in which echoes were observed at the elevation angle in question compressed data were also compared to data from which all echoless elevations were first removed. The results are in figure 4. The order of superiority remains but the increase of compression ratio with the elevation angle is not as strong as in fig. 3 in the case of methods NRE & SLP and NRE & BMP, and is even reversed in the case of NRE. Average compression ratios obtained by various methods are given in table 2.

Table 2. Average compression ratios obtained by various methods using all elevation angles (3-dimensional) and with echoless elevation angles excluded (2-dimensional).

Method	Average compression ratio	
	3-dimensional	2-dimensional
NRE & SLP	22.8:1	8.3:1
NRE & BMP	15.7:1	5.7:1
NRE	4.2:1	1.5:1
NEE	2.7:1	1:1

5. *Discussion*

NRE is very simple for the user of data. However, it is sensitive to the accuracy of determination of the actual noise level and the variations of the individual measured values around it. If; lets say, 1 percent of all noise points are classified incorrectly as echo-points, one such point very likely exists in each non-echo radial consisting of 200 points. This can be improved by increasing the noise threshold level but at the costs of weak echoes.

SLP and BMP methods are not as sensitive in this respect. A noise point interpreted incorrectly as an echo point causes only a new echo-queue of one point to be established but all other noise points are still eliminated. In general the BMP method seems to be clearly worse than SLP, but as can be seen from eq (4) and table 1 this may only hold for the measurement parameters of this study. With an increasing number of echo queues, N, and decreasing number of range bins, n, the situation may be changed.

On the other hand the BMP method may have certain advantages for data transmission purposes. If, in addition, the order of bits in the presentation of the values at echo points in a record is changed giving first the values of the most significant bits at each echo-point, then the second most significant bits, etc. down to the l.s.b., until all 8 bits are given at each point, the result of the decoding of the bit stream is a radar picture becaming more and more accurate with time. (The bit map represents two-level information, the most significant bits added three levels, etc.). Thus the receiving or transmission of a picture may be truncated at any time in the record and a whole picture is still obtainable with some accuracy. Similar arrangements are, however, also possible with SLP.

Based on the results NRE & SLP seems to be clearly the most effective of the compression methods tested. Some last refinements applicable to this method are discussed. In tests 8 bits was chosen as the basic length of information ($a = b = c = 8$). This is useful because in most computers handling of partial words in multiples of 8 bits is more effective than in other sizes. Also on a 9-track magnetic tape one character position can store 8 bits of information.

Use of 8 bits on the other hand may cause some restriction because only 256 different numerical values $(0, 1, 2, \ldots, 255)$ are presentable. In our experiment dBZ values are coded from 0.25 to 62.50 using $\frac{1}{4}$dB resolution by multiplying the original value by 4 and rounding to the nearest integer value. If higher values than 62.50 or a better resolution than $\frac{1}{4}$dB are needed, special technique could be used. In the present method (NRE & SLP) higher values than 62.50 dBZ are coded as new echo queues (although these typically are only parts of some wider echo queues) in which the start-length information is preceded by an additional 8-bit character which has a numerical decimal value 255. The echo-points in the corresponding queue are coded in the form 4 x (dBZ – 62.50). This coding is unambiguous because »starts» and »lengths» are always smaller than 251 in our processor. This coding does not much affect the effectivness of the compression because dBZ values greater than 62.50 are very rare. Decimal values 251, 252, 253 and 254 are reserved for special use (*e.g.* coding of missing data-points).

If the number of range bins *n* is greater than 250 the 8-bit coding for starts and lengths can be preserved by dividing each radial into groups of 250 range bins, then numbering bins within each group from 1 to 250 and by adding a special group indicator character (binary 251, 252, 253 or 254) before each start-length pair if these refer to a new group of range bins. No special character is needed for the most common ranges of echoes (bins 1–250), 251 refers to bins 251–500, 252 refers to bins 501–750, 253 refers to bins 751–1000 and 254 refers to bins 1001–1250. It should be noted that the special character has to be used only once for each group of range bins, or not at all if the previous length information automatically extends into a new group of range bins or if there are no echoes in the corresponding group of bins.

In the SLP method compression results can be slightly improved by checking the lengths of the non-echo areas between successive echo-queues and by coding two successive echo-queues as one queue if the number of bits needed for coding one start-length-pair is greater than the number of bits additionally needed to code the non-echo points between the echo-queues with full accuracy. In the present method, where start-length information takes two 8-bit characters, the number of non-echo-points must thus be 3 or more in order that the establishment of two separate echo-queues is profitable.

In all calculations in this study no records other than those containing reflectivity information were included either in uncompressed or compressed data. However, in actual data archiving some kind of identification records preceding each 3-dimensional data block may be very useful. This kind of identification record may contain information such as time of measurement, day, month, values of some basic parameters, etc. Identification records were left out here in order to make the results more general because the amount of data in identification records much depends on each specific application. The effects of the most important identification information can in any case be thought to be included in the results of this study through the 32 bits of »additional data» within each record.

6. *Concluding remarks*

The flow rate of 10^7 bit/s of raw weather radar video signals can be reduced to 10^5 by averaging individual returns over a number of pulses. Estimates of the average power received are thus obtained but at the same time information on the fluctuation of the echo is lost.

Using simple compression methods based on noise-elimination an additional reduction of 23:1 seems to be possible, thus leading to 4×10^3 bit/s. This rate is of the same order of magnitude as the capacities of good quality telephone lines today. If uncompressed data fills one magnetic tape reel in 50 min it is thus possible to record 20 hours of compressed data on one reel.

These estimates are applicable if complete 3-dimensional data is used. With low elevation data the compressed bit rate will be about 10^4 bit/s and a new reel of tape is thus required after each 10 hours of measurements. It should be noted that the simple compression methods do not essentially affect the original accuracy or quality of the data.

In the visualizations above the maximum basic data rate, 10^5 bit/s, was used. If the basic rate is lower the compressed rate will be reduced accordingly. Thus, if 0.15 s averaging is used at 200 range bins (as in our data system) the basic rate is only about 10^4 bit/s and one magnetic tape is filled not earlier than after about 200 hours of measurements during continuous rain if the data is compressed by NRE & SLP method.

These estimates are based on tests made using real radar data collected during rather typical summer rainfalls in Southern Finland within a radius of 150 km. In different climatological regions or with different radius of operation results may be different as well. Compression ratios obtained are also average values for the whole material. If some particular 3-dimensional measurement is examined deviating values may be obtained. Thus in one type of rainfall one reel of magnetic tape may last several days while in another it may be filled in perhaps some 10 hours.

Further reduction in the data rate may be obtained by taking into account the quasistationarity of the pattern and by reducing the resolution accordingly.

In the present paper no methods based on the use of mathematical series expansions are tested. The disadvantage of these kinds of compression methods is the complexity of coding and decoding.

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APPENDIX.

An example of radar data of one pointing direction of the antenna in s.c. A/R form, in raw digitalized form (both in decimal and in binary) and in binary form after compression.