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# A LOGARITHMIC ENCODER FOR BINARY WORD COMPRESSION

*by Joseph A. Sciulli*

*Goddard Space Flight Center*
*Greenbelt, Md.*

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1968

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## ABSTRACT

During the past several years efficient information transmission and processing techniques have attracted wide interest and have increased applicability. The present paper describes a logarithmic encoding device which has had particular application in energetic particle detection experiments. The paper provides a generalized encoding error analysis in order to evaluate the performance of the device. Both peak and average error are derived in terms of word size and desired accuracy. The implementation of a flexible logarithmic encoder is also described.

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# A LOGARITHMIC ENCODER FOR BINARY WORD COMPRESSION

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## INTRODUCTION

Growing interest in the development of efficient information transmission techniques is stimulating much theoretical and experimental work. Particular emphasis has been placed on the development of video data compression techniques which exploit the predictability (or redundancy) of the data (Reference 1). Many of these techniques are not specifically designed for the video information source and can, in principle, be applied to any information source. For example, recent experiments have applied a simple predictor/encoder compression technique to energetic particle experiment data. The experimental data were obtained from a multi-channel device flown on the 1963-38C-APL satellite in which each channel was designed to detect particles in a specific energy region. Typically, an experiment of this kind requires a rather large word size because of the wide range of possible sample values. (The experiment considered used 16 bits per sample.) The compression simulations showed that average energy savings of approximately 4 db can be achieved with an allowable peak error of approximately 5 percent.

The main difficulty with such an approach, however, is defining an error criterion which is suitable over the entire range of possible sample values. Logarithmic encoding, however, is extremely useful in experiments of this type which involve wide dynamic range. The function of the encoder is to reduce the number of transmitted bits per sample while maintaining a relatively small error in the word reconstructed at the receiver. This paper describes a logarithmic encoding procedure and develops an expression for the error between the original sample value and the sample value reconstructed at the receiver. In addition, several design considerations are outlined and the operation of the device is discussed briefly. This procedure results in a fixed compression, independent of the *predictability* of the data. Since the bit rate at the output of the encoder is constant, there is no need to consider the yet-unsolved buffer queuing problem.

## ENCODING PROCEDURE

Suppose each sample is originally represented by an n-bit binary word S with components $(\sigma_{n-1}, \sigma_{n-2}, \cdots \sigma_{n-j}, \sigma_{n-j-1} \cdots \sigma_0)$. The most significant bit (MSB) is $\sigma_{n-1}$; $\sigma_0$ is the least significant bit (LSB); and $\sigma_{n-j}$ is the first component (from the left) which is a 1. We now describe an encoder which converts S into two subwords, the characteristic (C) and the mantissa (M). The mantissa is a k-bit word specifying the k MSBs following $\sigma_{n-j}$. The position of $\sigma_{n-j-k+1}$ is specified by C, an r-bit word. The encoder output, therefore, consists of $(r + k)$ bits where $(r + k) \leq n$. The operation is best illustrated by an example:

let $n = 19$, $k = 4$, and $r = 4$ and suppose the input word is $S = 1011001110110010110$.

Here the first 1 appears at the MSB, hence $j = 1$. The 4 bits of M must then consist of the second, third, fourth, and fifth MSBs of S (i.e., $M = 0110$). The position of the LSB of M must then be specified by C. Thus, $C = n - k - j + 1 = 15$ or $C = 1111$. The encoder output is then,

$$\underbrace{1111}_{C} \qquad \underbrace{0110}_{M} .$$

Some additional examples are

| Input | Output |
|---|---|
| 1111111111111111111 | 11111111 |
| 1000000000000000000 | 11110000 |
| 0000000000110000000 | 01011000 |
| 0000000000000010000 | 00010000 |

This example was given by Schaefer (Reference 2).

The general design problem consists of choosing k and r for some specified n. Since k determines how closely the encoded word approximates the input word (n-bits), k should be chosen to satisfy the error specification. After k is fixed, r can be chosen to minimize the number of bits in the output word. The bit compression ratio $n/(r + k)$ then provides a useful system performance measure. In the next section error expressions assuming transmission in a noiseless channel are developed.

## ENCODING ERROR

In practice, an experimenter might specify an upper limit on either the average error, the maximum error, or both. Here both the average error and the maximum error for the special case of equally likely samples are calculated.

The input word S for some value of j is, by definition,

$$S = \sum_{i=0}^{n-j} \sigma_i \; 2^i \; . \tag{1}$$

According to the encoding rule, the word reconstructed at the receiver must be

$$\tilde{S} = \sum_{i=n-j-k}^{n-j} \sigma_i \; 2^i \; , \tag{2}$$

and the error for a given $j$

$$E_j = S - \tilde{S} = \sum_{i=0}^{n-j-k-1} \sigma_i \; 2^i \; . \tag{3}$$

We may now calculate the expected error for a given $j$ according to

$$\overline{E}_j = E\{E_j\} = \sum_{i=0}^{n-j-k-1} E(\sigma_i) \; 2^i \; . \tag{4}$$

If all input words are equally likely, $E(\sigma_i) = 1/2$ . Therefore,

$$\overline{E}_j = \frac{1}{2} \sum_{i=0}^{n-j-k-1} 2^i = \frac{1}{2}\left[2^{n-j-k} - 1\right] \; . \tag{5}$$

To determine the average error we must average $\overline{E}_j$ over all values of $j$ for which an error can occur. That is,

$$\overline{E} = \sum_j \overline{E}_j \; p(j) \; ; \qquad p(j) = \begin{cases} \dfrac{1}{2^j} & \text{for } j = 1, 2, \cdots (n-k-1) \\[2ex] \dfrac{1}{2^{n-k-1}} & \text{for } j = (n-k) \end{cases}$$

where $\overline{E}_j = 0$ for $j = (n-k)$. Therefore,

$$\overline{E} = \sum_{j=1}^{n-k-1} \frac{1}{2}\left[2^{n-j-k} - 1\right] \frac{1}{2^j}$$

$$= 2^{n-k-1}\left\{\sum_{j=1}^{n-k-1} 2^{-2j}\right\} - \frac{1}{2}\left\{\sum_{j=1}^{n-k-1} 2^{-j}\right\} . \tag{6}$$

Since each term in braces is a geometric series,

$$\overline{E} = 2^{n-k-1}\left\{\frac{1}{3}\left(1 - 2^{-2(n-k-1)}\right)\right\} - \frac{1}{2}\left\{1 - 2^{-(n-k-1)}\right\} , \tag{7}$$

and, collecting terms,

$$\overline{E} = \frac{1}{3}\left[2^{n-k-1} + 2^{-(n-k)} - \frac{3}{2}\right]. \tag{8}$$

We can also calculate the maximum error. Returning to Equation 3, the error for a given $j$ is

$$E_j = \sum_{i=0}^{n-j-k-1} \sigma_i \, 2^i .$$

Now the maximum error must obviously occur for $j = 1$ and $\sigma_i = 1$ for all $i$. Therefore,

$$E_{max} = \max_j E_j = \sum_{i=0}^{n-k-2} 2^i = \left[2^{n-k-1} - 1\right] . \tag{9}$$

The average error as a fraction of full scale is

$$\overline{E}_F = \frac{\left[2^{n-k-1} + 2^{-(n-k)} - \frac{3}{2}\right]}{3\left(2^n - 1\right)} , \tag{10}$$

and, for $(n - k) >> 1$ ,

$$\overline{E}_F \doteq \frac{2^{n-k-1}}{3\left(2^n\right)} = \frac{1}{3} \cdot \frac{1}{2^{k+1}} . \tag{11}$$

Similarly, the maximum error as a fraction of full scale is

$$E_{F[max]} = \frac{2^{n-k-1} - 1}{2^n - 1} , \tag{12}$$

and, again, for $(n - k) >> 1$ ,

$$E_{F[max]} \doteq \frac{1}{2^{k+1}} . \tag{13}$$

The appendix lists both $\overline{E}_F$ and $E_{F[max]}$ for various combinations of $n$ and $k$. Thus, for a given $n$, a $k$ can be chosen, according to Equations 10 and 12, to satisfy given error requirements. After the value of $k$ is established $r$ should be chosen as the smallest integer satisfying

$$(n - k) \le 2^r - 1 ,$$

or

$$r \ge \mathrm{Log}_2 (n - k + 1) . \qquad (14)$$

If equality is obtained in Equation 14, then all possible values of C can occur.

## IMPLEMENTATION

The implementation of this device is quite simple. A generalized system is shown in Figure 1. The n-bit input word is presented serially (MSB first) to a k-bit register. The input word is shifted until a 1 appears in the kth bit of the register. The next clock pulse changes the state of the control flip flop, inhibiting the shift register and starting the r-bit counter. At the nth clock pulse the shift register contains the k bits of M and the counter contains the r bits of C. The contents of the register and counter can then be transferred to an output register. The elements of the encoder are then reset, and the device is prepared to receive the next input word.

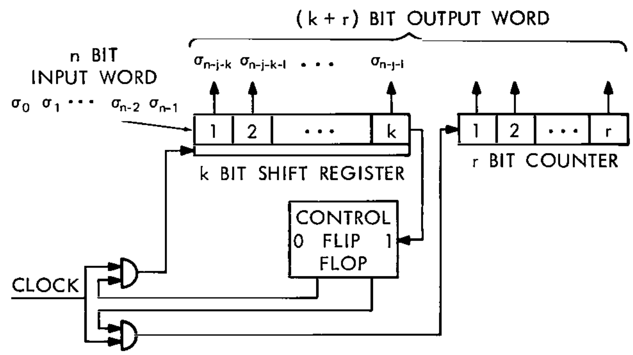


Figure 1—Implementation of the encoder.

## CONCLUSIONS

This encoding procedure provides a useful device which achieves fixed, but modest, bit compression. For example, the 16-bit words of the energetic particle experiment could be encoded to 8 bits ( $k = 4$, $r = 4$ ), resulting in a bit compression ratio of 2:1. This gives an average error of approximately 1 percent and a maximum error of about 3 percent. Moreover, this device could be combined with a zero-order predictor/run-length encoder to achieve further compression. The zero order hold compression might even be applied in the bit planes of C since these should be relatively quiescent from sample to sample.

For a slight increase in complexity, the logarithmic encoder could be made more flexible by varying k and r on command from the ground. Thus, the experimenter would have the capability of selecting the allowable error in the data depending on the activity of his experiment at a given time.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, August 1, 1967
160-44-05-14-51

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2. Schaefer, D. H., "Logarithmic Compression of Binary Numbers," *Proceedings of the IRE* (Correspondence) 49 (7): July 1961.

Appendix

## Listing of $\overline{E}_F$ and $E_{F[max]}$ for Combinations of n and k

| n | k | $\overline{E}_F$ | $E_{F[max]}$ |
|---|---|---|---|
| 2 | 1 | 0. | 0. |
| 3 | 1 | 0.03571428 | 0.14285714 |
| 3 | 2 | 0. | 0. |
| 4 | 1 | 0.05833333 | 0.20000000 |
| 4 | 2 | 0.01666667 | 0.06666666 |
| 4 | 3 | 0. | 0. |
| 5 | 1 | 0.07056452 | 0.22580644 |
| 5 | 2 | 0.02822580 | 0.09677419 |
| 5 | 3 | 0.00806452 | 0.03225806 |
| 5 | 4 | 0. | 0. |
| 6 | 1 | 0.07688492 | 0.23809523 |
| 6 | 2 | 0.03472222 | 0.11111110 |
| 6 | 3 | 0.01388889 | 0.04761904 |
| 6 | 4 | 0.00396825 | 0.01587301 |
| 6 | 5 | 0. | 0. |
| 7 | 1 | 0.08009350 | 0.24409448 |
| 7 | 2 | 0.03813976 | 0.11811023 |
| 7 | 3 | 0.01722441 | 0.05511811 |
| 7 | 4 | 0.00688976 | 0.02362204 |
| 7 | 5 | 0.00196850 | 0.00787401 |
| 7 | 6 | 0. | 0. |
| 8 | 1 | 0.08170956 | 0.24705882 |
| 8 | 2 | 0.03988970 | 0.12156862 |
| 8 | 3 | 0.01999509 | 0.05882353 |
| 8 | 4 | 0.00857843 | 0.02745098 |
| 8 | 5 | 0.00343137 | 0.01176471 |
| 8 | 6 | 0.00098039 | 0.00392157 |
| 8 | 7 | 0. | 0. |
| 9 | 1 | 0.08252048 | 0.24853229 |
| 9 | 2 | 0.04077482 | 0.12328767 |
| 9 | 3 | 0.01990582 | 0.06066536 |
| 9 | 4 | 0.00947896 | 0.02935421 |
| 9 | 5 | 0.00428082 | 0.01369863 |
| 9 | 6 | 0.00171232 | 0.00587084 |
| 9 | 7 | 0.00048923 | 0.00195695 |
| 9 | 8 | 0. | 0. |
| 10 | 1 | 0.08292667 | 0.24926686 |
| 10 | 2 | 0.04121991 | 0.12414467 |
| 10 | 3 | 0.02036748 | 0.06158357 |
| 10 | 4 | 0.00994318 | 0.03030302 |
| 10 | 5 | 0.00473484 | 0.01466275 |
| 10 | 6 | 0.00213832 | 0.00684261 |
| 10 | 7 | 0.00085533 | 0.00293255 |
| 10 | 8 | 0.00024438 | 0.00097752 |
| 10 | 9 | 0. | 0. |
| 11 | 1 | 0.08312994 | 0.24963360 |
| 11 | 2 | 0.04144308 | 0.12457254 |
| 11 | 3 | 0.02059989 | 0.06204201 |
| 11 | 4 | 0.01017877 | 0.03077674 |
| 11 | 5 | 0.00496916 | 0.01514411 |
| 11 | 6 | 0.00236627 | 0.00732780 |
| 11 | 7 | 0.00106864 | 0.00341964 |
| 11 | 8 | 0.00042745 | 0.00146556 |
| 11 | 9 | 0.00012213 | 0.00048852 |
| 11 | 10 | 0. | 0. |
| 12 | 1 | 0.08323162 | 0.24981684 |
| 12 | 2 | 0.04155482 | 0.12478632 |
| 12 | 3 | 0.02071647 | 0.06227106 |
| 12 | 4 | 0.01029743 | 0.03101343 |
| 12 | 5 | 0.00508814 | 0.01538461 |
| 12 | 6 | 0.00248397 | 0.00757021 |
| 12 | 7 | 0.00118284 | 0.00366300 |
| 12 | 8 | 0.00053418 | 0.00170940 |
| 12 | 9 | 0.00021368 | 0.00073260 |
| 12 | 10 | 0.00006105 | 0.00024420 |
| 12 | 11 | 0. | 0. |
| 13 | 1 | 0.08328247 | 0.24990843 |
| 13 | 2 | 0.04161073 | 0.12489317 |
| 13 | 3 | 0.02077487 | 0.06238554 |
| 13 | 4 | 0.01035697 | 0.03113173 |
| 13 | 5 | 0.00514808 | 0.01550482 |
| 13 | 6 | 0.00254375 | 0.00769137 |
| 13 | 7 | 0.00124183 | 0.00378464 |
| 13 | 8 | 0.00059135 | 0.00183128 |
| 13 | 9 | 0.00026706 | 0.00085460 |
| 13 | 10 | 0.00010682 | 0.00036626 |
| 13 | 11 | 0.00003052 | 0.00012209 |
| 13 | 12 | 0. | 0. |
| 14 | 1 | 0.08330790 | 0.24995422 |
| 14 | 2 | 0.04163869 | 0.12494659 |
| 14 | 3 | 0.02080409 | 0.06244277 |
| 14 | 4 | 0.01038680 | 0.03119086 |
| 14 | 5 | 0.00517817 | 0.01556491 |
| 14 | 6 | 0.00257389 | 0.00775193 |
| 14 | 7 | 0.00127180 | 0.00384545 |
| 14 | 8 | 0.00062088 | 0.00189220 |
| 14 | 9 | 0.00029565 | 0.00091558 |
| 14 | 10 | 0.00013352 | 0.00042727 |
| 14 | 11 | 0.00005341 | 0.00018311 |
| 14 | 12 | 0.00001526 | 0.00006104 |
| 14 | 13 | 0. | 0. |
| 15 | 1 | 0.08332061 | 0.24997710 |
| 15 | 2 | 0.04165268 | 0.12497329 |
| 15 | 3 | 0.02081871 | 0.06247138 |
| 15 | 4 | 0.01040173 | 0.03122043 |
| 15 | 5 | 0.00519324 | 0.01559495 |
| 15 | 6 | 0.00258900 | 0.00778221 |
| 15 | 7 | 0.00128690 | 0.00387584 |
| 15 | 8 | 0.00063588 | 0.00192266 |
| 15 | 9 | 0.00031043 | 0.00094607 |
| 15 | 10 | 0.00014782 | 0.00045777 |
| 15 | 11 | 0.00006676 | 0.00021362 |
| 15 | 12 | 0.00002670 | 0.00009155 |
| 15 | 13 | 0.00000763 | 0.00003052 |
| 15 | 14 | 0. | 0. |

| n | k | $\overline{E}_F$ | $E_{F[max]}$ |
|---|---|---|---|
| 16 | 1 | 0.08332697 | 0.24998855 |
| 16 | 2 | 0.04165967 | 0.12498664 |
| 16 | 3 | 0.02082602 | 0.06248569 |
| 16 | 4 | 0.01040919 | 0.03123521 |
| 16 | 5 | 0.00520078 | 0.01560997 |
| 16 | 6 | 0.00259658 | 0.00779735 |
| 16 | 7 | 0.00129448 | 0.00389104 |
| 16 | 8 | 0.00064344 | 0.00193789 |
| 16 | 9 | 0.00031793 | 0.00096131 |
| 16 | 10 | 0.00015521 | 0.00047302 |
| 16 | 11 | 0.00007391 | 0.00022888 |
| 16 | 12 | 0.00003338 | 0.00010681 |
| 16 | 13 | 0.00001335 | 0.00004578 |
| 16 | 14 | 0.00000381 | 0.00001526 |
| 16 | 15 | 0. | 0. |
| 17 | 1 | 0.08333015 | 0.24999427 |
| 17 | 2 | 0.04166316 | 0.12499332 |
| 17 | 3 | 0.02082967 | 0.06249284 |
| 17 | 4 | 0.01041293 | 0.03124260 |
| 17 | 5 | 0.00520456 | 0.01561748 |
| 17 | 6 | 0.00260037 | 0.00780492 |
| 17 | 7 | 0.00129828 | 0.00389864 |
| 17 | 8 | 0.00064723 | 0.00194550 |
| 17 | 9 | 0.00032172 | 0.00096893 |
| 17 | 10 | 0.00015897 | 0.00048065 |
| 17 | 11 | 0.00007761 | 0.00023651 |
| 17 | 12 | 0.00003695 | 0.00011444 |
| 17 | 13 | 0.00001669 | 0.00005341 |
| 17 | 14 | 0.00000668 | 0.00002289 |
| 17 | 15 | 0.00000191 | 0.00000763 |
| 17 | 16 | 0. | 0. |
| 18 | 1 | 0.08333174 | 0.24999713 |
| 18 | 2 | 0.04166491 | 0.12499665 |
| 18 | 3 | 0.02083150 | 0.06249642 |
| 18 | 4 | 0.01041479 | 0.03124630 |
| 18 | 5 | 0.00520644 | 0.01562124 |
| 18 | 6 | 0.00260226 | 0.00780871 |
| 18 | 7 | 0.00130018 | 0.00390244 |
| 18 | 8 | 0.00064913 | 0.00194931 |
| 18 | 9 | 0.00032362 | 0.00097275 |
| 18 | 10 | 0.00016086 | 0.00048447 |
| 18 | 11 | 0.00007948 | 0.00024033 |
| 18 | 12 | 0.00003880 | 0.00011826 |
| 18 | 13 | 0.00001848 | 0.00005722 |
| 18 | 14 | 0.00000834 | 0.00002670 |
| 18 | 15 | 0.00000334 | 0.00001144 |
| 18 | 16 | 0.00000095 | 0.00000381 |
| 18 | 17 | 0. | 0. |
| 19 | 1 | 0.08333253 | 0.24999856 |
| 19 | 2 | 0.04166579 | 0.12499832 |
| 19 | 3 | 0.02083241 | 0.06249820 |
| 19 | 4 | 0.01041573 | 0.03124814 |
| 19 | 5 | 0.00520738 | 0.01562312 |
| 19 | 6 | 0.00260322 | 0.00781060 |
| 19 | 7 | 0.00130113 | 0.00390434 |
| 19 | 8 | 0.00065009 | 0.00195122 |
| 19 | 9 | 0.00032456 | 0.00097466 |
| 19 | 10 | 0.00016180 | 0.00048637 |
| 19 | 11 | 0.00008043 | 0.00024223 |
| 19 | 12 | 0.00003974 | 0.00012016 |
| 19 | 13 | 0.00001940 | 0.00005913 |
| 19 | 14 | 0.00000924 | 0.00002361 |
| 19 | 15 | 0.00000417 | 0.00001335 |
| 19 | 16 | 0.00000167 | 0.00000572 |
| 19 | 17 | 0.00000048 | 0.00000191 |
| 19 | 18 | 0. | 0. |
| 20 | 1 | 0.08333293 | 0.24999928 |
| 20 | 2 | 0.04166622 | 0.12499916 |
| 20 | 3 | 0.02083287 | 0.06249910 |
| 20 | 4 | 0.01041619 | 0.03124907 |
| 20 | 5 | 0.00520786 | 0.01562405 |
| 20 | 6 | 0.00260369 | 0.00781155 |
| 20 | 7 | 0.00130160 | 0.00390530 |
| 20 | 8 | 0.00065056 | 0.00195217 |
| 20 | 9 | 0.00032504 | 0.00097561 |
| 20 | 10 | 0.00016228 | 0.00048733 |
| 20 | 11 | 0.00008090 | 0.00024319 |
| 20 | 12 | 0.00004021 | 0.00012112 |
| 20 | 13 | 0.00001987 | 0.00006008 |
| 20 | 14 | 0.00000970 | 0.00002956 |
| 20 | 15 | 0.00000462 | 0.00001431 |
| 20 | 16 | 0.00000209 | 0.00000658 |
| 20 | 17 | 0.00000083 | 0.00000286 |
| 20 | 18 | 0.00000024 | 0.00000095 |
| 20 | 19 | 0. | 0. |



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