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STUDY OF STATISTICAL CODING FOR DIGITAL TV

FINAL REPORT

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SECTION 1.0

SUMMARY

1.0 SUMMARY

1.1 Object of Contract

This final report, prepared for the Telemetry and Communications Systems Division, NASA Manned Spacecraft Center under Contract NAS 9-11749, contains the results of a detailed study to determine a pseudo-optimum statistical code to be installed in the Digital TV Demonstration Test Set, which was built by Radiation Incorporated for NASA MSC, Houston.

Digitally processed and transmitted TV can be a very efficient means of video transmission. However, a method of source encoding other than PCM is required to reach the full potential of the method.

To date, considerable effort has been expended in studies of source encoding using redundancy removal techniques in which the picture is reproduced within a preset tolerance.

Another method of source encoding, which preliminary studies show to be encouraging, is statistical encoding. With this technique, efficiency of transmission is increased by coding the most common element of information with a minimum number of bits while encoding rarer information with a larger number of bits as required. On the average, the number of bits/element (B/E) will be less.

This study was required to further the investigation of statistical encoding to a point of defining a pseudo-optimum code and determining the associated performance of the code.

For the purposes of this study, the TV format was fixed at 525 lines per frame, 30 frames per second, per commercial standards.

1.2 Statement of Work

The study covered four basic phases of effort.

The first phase was to prepare equipment for gathering the statistical data. The TV camera, video processing circuitry, and analog-to-digital converter of the Data Compression/Error Correction Test System developed on Contract NAS 9-10441 were utilized. A description of this system is contained in the final report for that contract. In addition, a special purpose Digital Analyzer was utilized. This unit accepted digitized video samples from the analog-to-digital converter and processed them to obtain statistics of the differences between adjacent sample values.

A block diagram of the Digital Analyzer is shown in Figure 1.2. Data from the analog-to-digital converter is applied to a storage register and one input to the subtractor. The subtractor obtains the difference between the current sample and the prior sample contained in the storage register. The subtractor output is decoded by the Difference Decoder to provide pulses on seven individual lines for differences of zero; plus or minus one, two, three, four or

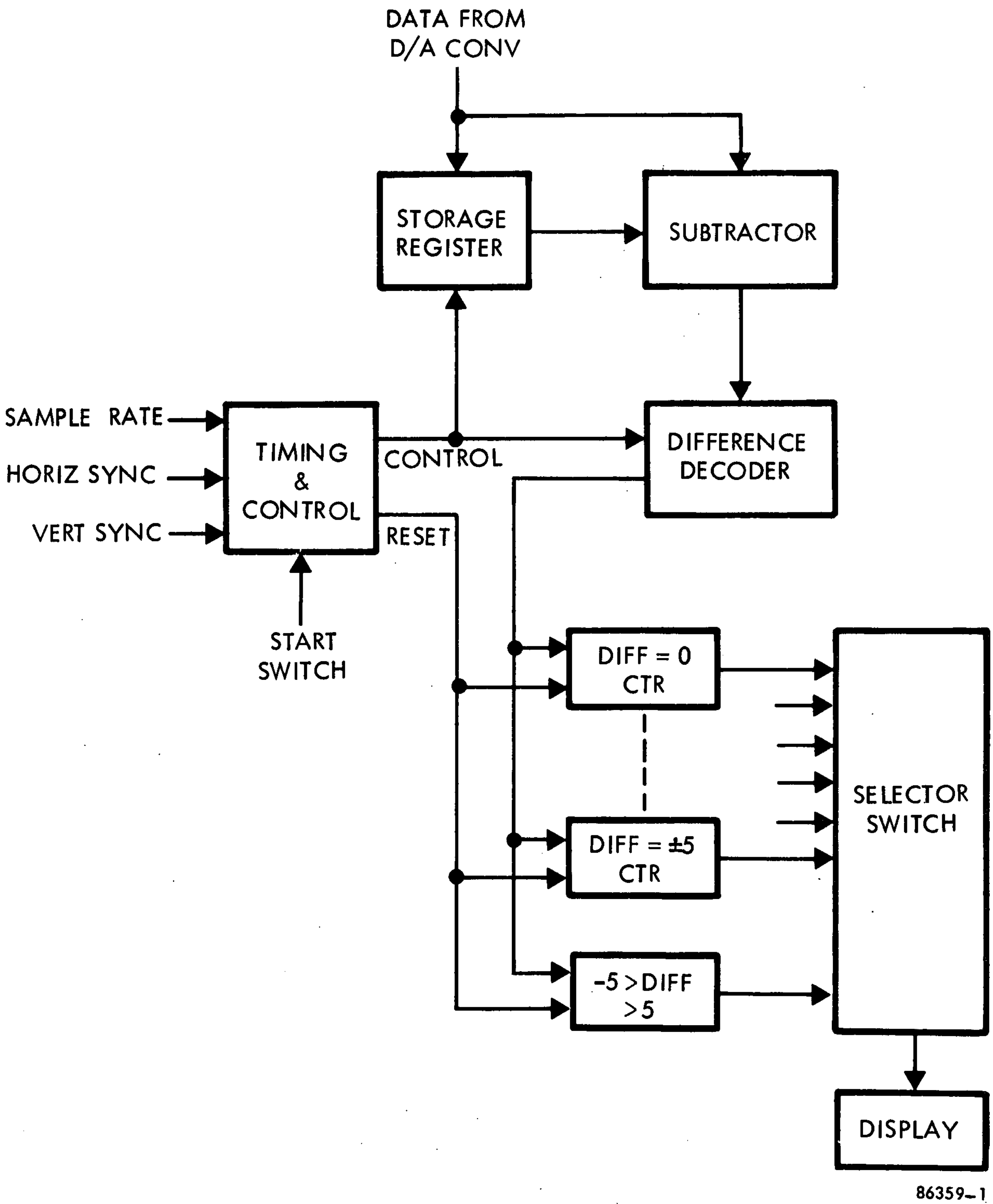


Figure 1.2. Digital Analyzer Block Diagram

five; or greater than an absolute value of five. These pulses are applied to seven counters. The output of one of these counters is selected by a switch for display. The timing and control unit accepts sample rate, horizontal and vertical sync pulses, and a manually generated start signal. Upon receipt of the start signal the counters are reset, and the system is armed for the next vertical sync pulse. This pulse causes the system to accept and process samples, accumulating difference values in the counters. The next vertical sync pulse terminates operations, leaving the accumulated differences in the counters. The contents of the various counters can be displayed by means of the selector switch, and recorded. Horizontal sync pulses cause the unit to discard the differences between the last sample of one line and the first sample of the next line.

The second phase of the program was the selection of scenes which represent the full spectrum of video activity. Much of this process was based on work previously done by Radiation, where many dozen pictures had been scanned and the redundancy measured. Pictures with much redundancy were considered inactive and pictures with little redundancy were considered to have maximum activity. Three pictures were selected representing minimum, average and maximum activity.

The third phase of the study was to measure the statistics of each of the three pictures for various values of presampling video filter cut-off frequency, amplitude shaping, sampling rate and number of bits in the sample.

The fourth phase was the development of optimum and pseudo-optimum codes. A code was developed from the statistics of each of the three scenes, for each combination of parameters listed in phase three. These codes are optimum for each picture since they were developed from their statistics.

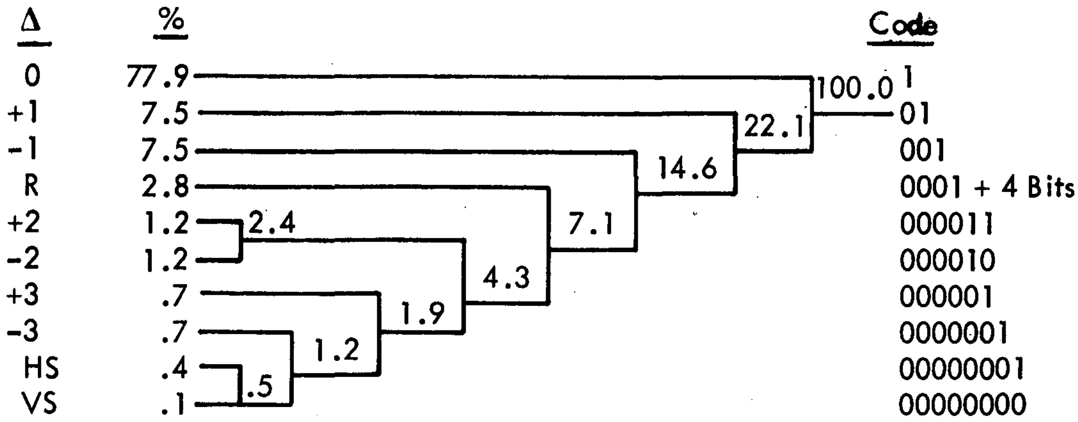
A pseudo-optimum code good for all scenes was developed for each combination of parameters listed in phase three.

A final pseudo-optimum code good for all scenes and parameters was developed.

1.3 Summary of Conclusions

During the course of the study over 90 sets of statistics and monitor photographs were taken, using three different pictures with various combinations of sampling rates, number of bits per sample, amplitude shaping, and presampling filters of various types and cut-off frequencies. Optimum codes were developed for each case, and significant results are presented in the body of the report.

A general purpose code was developed from the averaged statistics of 5-MHz sample rate, 4-bit per sample pictures, and is given in Figure 1.3-1. This code observed the practical constraints imposed by the Test System design, namely: delta is limited to a maximum value of ±3; no code can be longer than 8 bits; two 8-bit codes are reserved for horizontal and vertical synchronization; delta values greater than 3 are represented by a 4-bit code, plus 4 bits of absolute value.



VS is repeated three times plus 6 Bits.

Figure 1.3-1. Final Pseudo-Optimum Statistical Code

For good quality pictures of 5-MHz sampling rate and 5-bit amplitude resolution, this code required the following transmitted bit rates:

Average complexity picture (Admiral):	9.50 Mb/s
High complexity picture (Rack):	11.6 Mb/s

For lower quality pictures of 4-bit resolution at the same sample rate, the required bit rate is reduced by from one to two Mb/s. Over a range of picture complexity and amplitude resolution, the performance of this code is nearly as good as the optimum code for the particular conditions. Some results for 5-MHz sampling rate and a 2.2-MHz Butterworth pre-sampling filter are shown in Table 1.3, and other comparisons are given in Section 4.3.

It can be seen in Table 1.3 that the amplitude shaping provided a consistent improvement in performance. It should be noted that even the "linear" mode involved considerable nonlinearity in the camera, in the direction of an equal perceptibility response, so that the difference would probably have been larger as compared to a truly linear response.

Two characteristics of the equipment used for gathering these statistics warrant discussion.

First, the TV camera used had a measured signal-to-noise ratio of about 25 dB. This does not seriously degrade the visual quality of either an analog or a straight digital picture, but does affect the statistics. The quantization noise for 4-, 5-, and 6-bit quantization is about 24, 30, and 36 dB, respectively. Thus the statistics of the 5-, and particularly the 6-bit pictures are influenced significantly by the noise, and less by the picture characteristics. In tests on other programs, the same rack photo was scanned with a flying spot scanner with a signal-to-noise ratio of about 34 dB. Optimum coding of this data would allow transmission of the 6-bit picture with about a 40 percent lower bit rate than was required for the optimally coded data from the TV camera.

Table 1.3

Admiral Picture
(Average Activity)

	6 Bits		5 Bits		4 Bits	
	Test 6.2 Linear	Test 15.4 Nonlinear	Test B-1.2 Linear	Test 16.4 Nonlinear	Test B-1.3 Linear	Test B-1.6 Nonlinear
Bits/Element	2.75	2.52	2.10	1.90	1.68	1.63
Optimum B/E	2.72	2.30	2.09	1.85	1.69	1.61
Difference	0.03	0.22	0.01	0.05	0.01	0.02
Bit Rate with GP code	13.75×10^6	12.60×10^6	10.5×10^6	9.50×10^6	8.40×10^6	8.15×10^6

Rack Picture
(Maximum Activity)

	6 Bits		5 Bits		4 Bits	
	Test 4.2 Linear	Test 18.4 Nonlinear	Test 8.5 Linear	Test 19.4 Nonlinear	Test 8.6 Linear	Test 20.4 Nonlinear
Bits/Element	4.04	3.36	3.01	2.33	2.13	1.69
Optimum B/E	3.76	2.89	2.89	2.27	2.08	1.61
Difference	0.28	0.47	0.12	0.06	0.05	0.06
Bit Rate with GP code	20.20×10^6	16.80×10^6	15.05×10^6	11.65×10^6	10.65×10^6	8.45×10^6

Although the code was developed from 4-bit statistics, it is near optimum even for 6- and 5-bit statistics, due to the camera noise. Previous measurements of statistics on these pictures indicate that this would not be the case if the signal-to-noise ratio were higher.

This noise further makes the code very insensitive to picture characteristics, since the amount of redundancy is a 4-bit picture and is much less than for a 5- or 6-bit one.

The second equipment peculiarity affecting the statistics was a distortion in the analog-to-digital converter causing a bias toward certain level changes (deltas) at 5- and 6-bit resolution. Favored level changes were 2 and 4 and the magnitude of this bias changed with time, as can be seen in Section 4.1.

When developing an optimum code this bias can be accounted for in the code structure, but the change of bias with time still causes a problem. The difference between the general purpose code and the optimum 6-bit code can be seen in Table 1.3, Tests 4.2 and 18.4. The bias in the 2 and 4 levels causes the difference to be large. If, however, these are reversed with 1 and 3 levels, the difference in both cases is less than 0.1 bit/element.

The selected code reduced the companded, 5-MHz, 4-bit picture to 8.15 Mb/s or 1.63 bits per element, with the statistics as shown in Figure 1.3-2 and the picture quality as indicated in Figure 1.3-3.

Δ	Samples	Code Length	Total Bits	
0	100,022	1	100,022	
+1	9,675	2	19,350	
-1	9,675	3	29,025	
+2	1,719	6	10,314	
-2	1,719	6	10,314	
+3	876	6	5,256	
-3	876	7	6,032	
R	3,057	8	24,456	
HS	491	8	3,928	
VS	1	30	30	
	128,111		208,727	1.63 B/E

Figure 1.3-2. Operation of Final Code on Companded Admiral Picture

The same picture without companding reduced to 8.40 Megabits/Second or 1.68 bits/element. At 6 bits the improvement is about 1/2 bit/element, however, this decreases as the number of bits is reduced. Also, the quality of the companded picture was always better in that companding improved the overall contrast and sharpness of the picture. As noted earlier, the camera itself was very nonlinear and the analog shaping helps to correct for this. Figure 1.3-4 shows the linear picture.

Figure 1.3-3. Companded Picture Reducible to 8.15 Megabits/Second

Figure 1.3-4. Linear Picture Reducible to 8.40 Megabits/Second

1.4 Summary of Recommendations

The following actions are recommended to improve the performance of the Statistical Encoder in the Test System:

a. Replace the code plug-boards supplied with the system with plug-boards implementing the general purpose code of the preceding section. The picture quality available in a noise-free link will not be significantly affected, but better performance with a noisy link will be obtained because the recommended code re-acquires code sync faster following bit errors.

b. Take steps to improve the signal-to-noise ratio at the analog-to-digital converter input. This may require a new TV camera, or may be possible through readjustment of the existing camera. The camera was adjusted per the instruction book to obtain the "best appearing" analog picture; this may not necessarily yield the best statistically encoded picture. Note also that camera adjustments may also require changes in the amplitude shaping to obtain best performance.

   If the signal-to-noise ratio can be improved to 30 dB or better, the active picture can be reduced from 5 megasamples/second 5 bits to the desired 9 megabits/second, and perhaps even the 6-bit picture could, as indicated from previous studies.

c. Eliminate or reduce the bias toward certain values of change present in the analog-to-digital converter. This may be possible through a careful calibration, or it may require a new A/D Converter.

d. If the above recommendations are implemented, statistics for 5- and 6-bit pictures should be retaken and a new set of codes developed and installed which will improve the quality of the picture. When the noise problem is solved a different code could be used for each of 6, 5 and 4 bits, thus, when the buffer fills and it is necessary to drop to the statistics for a lesser number of bits, a different code would be used. This may, however, present an implementation problem since the test set currently has only one programmable code.

SECTION 2.0

INTRODUCTION

2.0 INTRODUCTION

When analog data is transmitted in digital form, it is necessary to sample and quantize the data. In the process the bandwidth of the original data is increased. Source Encoding provides a means of reducing this bandwidth whereby it can be transmitted over a narrow band channel.

An overall understanding of the sampling process as well as various source encoding methods is imperative in order to perform a comparative study. If the sampling is not done correctly, it will tend to favor one method over the other. Much has been written about imagery transmission but few, if any, consider the starting point, that is, the original analog data produced as a result of the scanning process. The signal-to-noise ratio of this source is an extremely important point and is the limiting factor as to just how much reduction can be obtained.

Most imagery study starts with a square picture with an equal number of picture elements in each direction. This is only true if the scanning spot and its optics have been chosen correctly, such that the optical overlap of the scanning line and the sampling overlap are the same, thus producing equal vertical and horizontal resolution.

The correct sampling rate for pictures is not a straightforward process as it is in telemetry, where a waveform is to be reproduced to a given accuracy. The correct sampling rate for a picture is more a function of what is to be done with the picture and the process as to how the eye works. This is particularly true for TV where many frames a second are used. A great deal can be done to an individual frame without the eye being able to see it. It is a subjective thing at best. However, over the years accepted rules have been generated through empirical testing. These rules generally relate to the scanning process used in television. However, since scanning is a sampling process, in the vertical direction, the sampling in the horizontal direction should be handled in the same manner.

The Kell Factor (determined empirically by Kell in 1934) is the ratio of the number of resolvable black and white lines to the number of scan lines. Various researchers have reported optimum values between 0.64 and 0.75, with the general accepted value being $1\sqrt{2}$ or 0.707. As can be seen, this factor is related to the amount of overlap from one line to the next and is, therefore, a type of optical interpolation. Interpolation in the horizontal direction must be done by an electrical filter and the samples chosen such that the vertical resolution is the same as the horizontal resolution produced by scanning.

Due to this overlap of both lines and samples, the resolution in both the vertical and horizontal directions will be less than the number of lines or samples. This is referred to as resolution elements (resels), and using a Kell Factor of 0.707 on the TV frame, there will be 491 active scan lines which can resolve 347 horizontal lines of the face of the monitor.

With an aspect ratio of 4/3, each line will have 491 x 4/3 = 655 picture elements, if equal horizontal and vertical resolution is maintained. Seventeen percent of each line is inactive, therefore, each line will have 789 samples. There is a total of 525 lines per frame (some of which are used for vertical sync) which means there would be 414,225 samples/frame x 30 frames per second or 12.43 megasamples/second.

These calculations are based on no restriction of resolution due to the video bandwidth. Even with a 4 megahertz bandwidth there is some restriction in the resolution. The TV Standards state that each megahertz of video bandwidth is capable of resolving 80 lines. If 2.2 megahertz of video bandwidth is used there would be 176 resolvable lines per frame or 249 scan lines. Again, maintaining equal horizontal and vertical resolution there would be 249 x 4/3 = 332 active samples, or 400 samples per line x 525 lines = 210,000 samples/frame x 30 = 6.3 megasamples/second. For the 3.0 megahertz video bandwidth used, the correct sampling rate would be 8.6 megasamples/second, the 1.9 filter would require 5.45 megasamples/second.

This sampling rate is required only in areas of the picture with high complexity, and in these areas the eye is more tolerant of errors. Therefore, a lower sampling can be used without significant visual degradation.

In order to bracket the above rates, tests were run at 9, 7, 5 and 3 megasamples/second. Filter cutoffs of 3 to 0.47 megahertz were used.

Pictures of the analog monitor, using a 2.2-megahertz video filter, for the three scenes used in the study are shown as Figures 2.0-1, -2 and -3. Figure 2.0-1 is a simple or inactive scene of a cloverleaf antenna used in the Radiation TSC-54 Satellite Communication Terminal. Under ideal conditions at 6 bits, it has an entropy of about 1.4 bits/element (B/E).

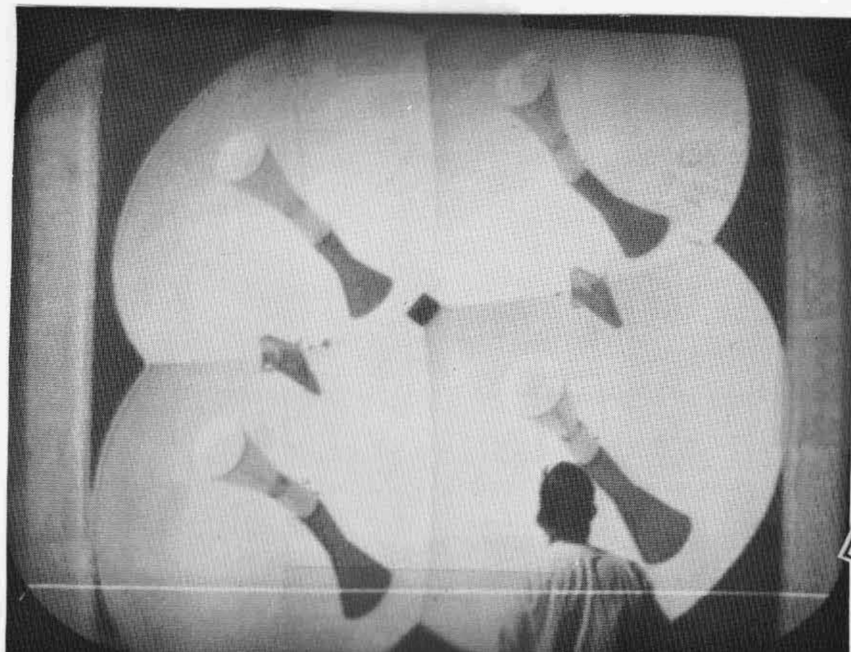


Figure 2.0-1

Figure 2.0-2 is for an average activity scene of an admiral and three other people standing in front of the TSC-54 antenna. Under ideal conditions at 6 bits, it has an entropy of about 1.6 bits/element.

Figure 2.0-2

Figure 2.0-3 is for an active scene of a technician in front of two racks of electronic equipment. Under ideal conditions at 6 bits, it has an entropy of about 2.2 bits/element.

Figure 2.0-3

SECTION 3.0

DESCRIPTION OF STATISTICAL ENCODING

3.0 DESCRIPTION OF STATISTICAL ENCODING

Statistical encoding is a type of source encoding that preserves the entropy of the data by generating an exact code which reproduces the picture exactly as six bits would, yet the average will be less than six bits. This coding scheme is akin to delta modulation in that it encodes the difference from one sample to the next, rather than the absolute value. The difference is that the code exactly represents the value of the difference.

If the amplitude differential statistics of a given set of data are studied, the percentage of changes from one sample to the next can be determined. The level change that occurs the most often is assigned a short code and level change which occurs seldom are assigned longer codes. The overall average bit rate over a relatively long period (one picture) will be less than for straight digital for almost any real picture.

If for example for a given set of data; 50 percent of the time there is no change from one sample to the next, 30 percent of the time the change is plus or minus one level, 10 percent of the time the change is plus or minus two levels, and 4 percent of the time the change is plus or minus three levels. The remaining 6 percent are changes of four levels or greater.

If these percentages are arranged in decreasing order, and the two smaller values added together, followed by the next two smaller values a tree will be formed as shown below:

(VARIABLE LENGTH CODING)

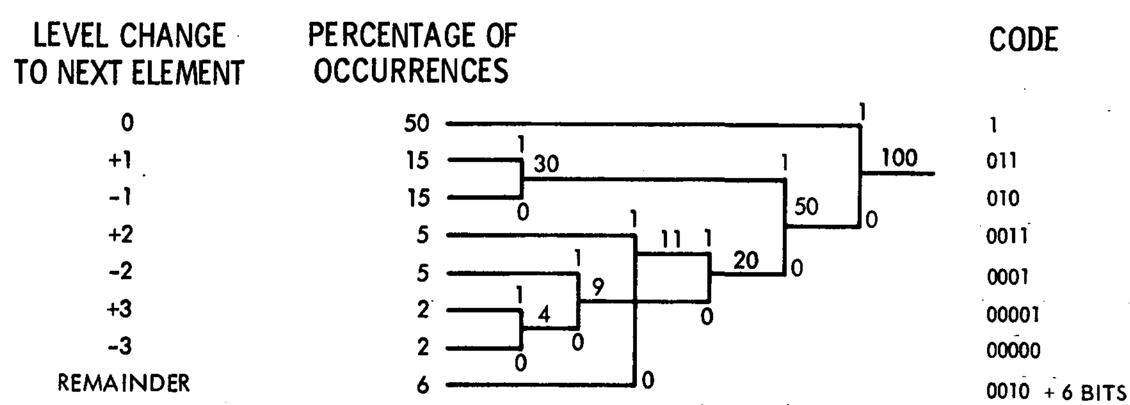


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Figure 3.0-1. Statistical Differential Encoding

The two smaller numbers are added together until all numbers have been used and total 100 percent. Each upper branch of the tree is assigned a one and each lower branch a zero. Beginning at the 100 percent branch and reading to the left a code is generated for each level change. Thus, the zero level change is represented by a code of 1. Each branch adds a one or a zero to the code, thus, the code for +1 level change is 011.

A set of codes generated by this method is completely unique, and any shorter code will not be the leader for the longer codes. For instance, there is no code other than +1 level change that begins with 011. This means that in a given bit stream there is one and only one way to pick out code words.

When the level change is ±4 or larger a unique code of 0010 is used, followed by the absolute value of the sample to the number of bits to which data is being quantized (six bits in the example).

The code is instantaneously decodable, in that there is no delay in determining a code word in a bit stream, since it is not necessary to examine succeeding bits.

SECTION 4.0

ORGANIZATION OF RESULTS

4.0 ORGANIZATION OF RESULTS

This section is broken into four parts, the first being a tabulation of statistics taken along with a few plots of these statistics.

The second part covers the development of the optimum codes for a given condition. Included in this portion will be a tabulation of resulting reductions along with curves to show effects of filtering, companding and sampling rate.

The third portion will be the development of a pseudo-optimum code for each combination of parameters which will provide good results on a scene. These codes will use all five orders of statistics taken but will not include horizontal and vertical synchronization.

The fourth portion will be the development of a final pseudo-optimum code good for all scenes and all parameters. This code will be truncated at the third order statistics and will include horizontal and vertical synchronization.

4.1 Tabulation of Statistics

The following figures tabulate the differential statistics for the three scenes for 81 different combinations of sampling rate, filter cutoff, number of bits, and analog shipping.

The tests were run at three different times, therefore, the bias is different for each of the three; Figures 4.1-1, -2, -3, -4, and -5 were all at one time and are for linear shaping. The bias favors both the ±2 and ±4 levels of differences. This fact becomes more noticeable at the lower sampling rates, such as 5 megasamples/second in Figure 4.1-1. The four bit statistics does not show this bias as seen in Figure 4.1-5. This, again, shows that the A/D converter is only reliable to four bits. This can be seen graphically in Figure 4.1-6 which is a plot of one-half the 6-, 5-, and 4-bit statistics for the Admiral picture with a 5 megasample/second rate and a 2.2 megahertz filter cutoff.

The data in Figures 4.1-7 and -8 were taken at different times, and the bias has not changed seriously, however, the ±2 level change is more pronounced as can be seen in Figure 4.1-9.

The data in Figure 4.1-10 was taken at a considerable later date and shows a much heavier bias toward the ±2 level, as seen in Figure 4.1-11.

The statistics of these same pictures has been previously taken using a flying spot scanner and in all cases the statistics decay in a logarithmic manner, as does the four bits statistics for this case.

In order to check this bias in the A/D converter, a ramp voltage of a known slope and amplitude was placed directly into the converter and allowed to run for one frame.

Sampling Rate	9 Megasamples/Second			7 Megasamples/Second			5 Megasamples/Second			3 Megasamples/Second	
Filter Cutoff	3 MHz	2.2 MHz	1.9 MHz	3 MHz	2.2 MHz	1.48 MHz	3 MHz	2.2 MHz	1.06 MHz	3 MHz	2.2 MHz
Order of Statistics											
0	44.2	59.6	64.4	44.9	57.5	64.0	45.2	52.7	61.1	44.4	48.1
1	26.1	20.6	18.2	32.8	25.8	20.6	29.2	25.2	18.2	26.8	25.2
2	13.0	7.4	6.0	11.8	6.8	4.8	12.4	8.8	5.8	10.4	8.8
3	6.2	4.2	3.6	3.0	2.2	2.6	3.0	2.6	2.2	3.4	2.8
4	6.2	4.6	4.4	2.8	2.6	3.2	3.6	4.0	6.0	4.6	4.4
5	0.6	0.4	0.4	0.6	0.8	0.6	1.0	0.6	0.4	1.2	1.0
R	3.2	3.2	3.2	4.1	4.3	4.2	5.6	6.1	6.3	9.2	9.7

Figure 4.1-1. Antenna 6-Bit Statistics Linear Shaping

Sampling Rate	9 Megasamples/Second			7 Megasamples/Second			5 Megasamples/Second			3 Megasamples/Second		
Filter Cutoff	3 MHz	2.2 MHz	1.9 MHz	3 MHz	2.2 MHz	1.48 MHz	3 MHz	2.2 MHz	1.06 MHz	3 MHz	2.2 MHz	0.635
Order of Statistics												
0	48.1	59.8	64.0	46.9	57.0	62.7	43.1	52.1	60.4	41.9	43.8	47.2
1	23.6	19.0	17.4	31.4	25.8	21.2	30.6	25.6	18.4	28.4	28.2	21.2
2	12.8	8.4	6.6	11.0	7.0	5.8	12.8	9.0	6.8	10.6	9.6	8.0
3	5.0	3.8	3.4	2.6	2.0	2.0	3.0	2.8	2.4	3.8	4.0	4.0
4	5.8	4.6	4.4	2.4	2.6	3.2	3.4	3.6	5.2	3.8	4.0	8.6
5	0.6	0.6	0.6	1.0	1.0	0.6	1.0	0.8	0.6	1.4	1.4	0.8
R	4.1	3.8	3.6	4.7	4.6	4.5	6.1	6.1	6.2	9.1	9.0	10.2

Figure 4.1-2. Admiral 6-Bit Statistics Linear Shaping

Sampling Rate	9 Megasamples/Second			7 Megasamples/Second			5 Megasamples/Second			3 Megasamples/Second		
Filter Cutoff	3 MHz	2.2 MHz	1.9 MHz	3 MHz	2.2 MHz	1.4 MHz	3 MHz	2.2 MHz	1.06 MHz	3 MHz	2.2 MHz	0.635 MHz
Order of Statistics												
0	34.1	42.9	45.8	30.4	37.6	43.0	26.9	31.2	39.5	25.4	25.2	27.3
1	20.8	19.4	18.8	29.0	27.4	24.8	27.4	25.4	22.0	25.4	27.0	23.8
2	15.2	13.2	11.6	14.6	12.4	12.2	15.4	14.2	12.6	13.0	12.4	12.6
3	7.8	6.4	6.4	6.6	5.6	5.0	7.4	7.0	5.4	7.2	7.0	6.6
4	11.0	10.6	10.8	6.4	7.0	7.6	7.4	8.4	12.4	8.8	8.6	16.4
5	2.2	1.6	1.4	4.2	2.0	1.4	3.8	2.6	1.0	4.4	4.0	1.0
R	8.9	6.2	5.2	8.8	7.6	6.0	11.7	11.0	7.1	15.8	15.8	12.3

Figure 4.1-3. Rack 6-Bit Statistics Linear Shaping

Sampling Rate	7 Megasamples/Second				5 Megasamples/Second			
	5 Bits		4 Bits		5 Bits		4 Bits	
Filter Cutoff	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz
Order of Statistics								
0	66.9	70.6	78.6	80.1	60.9	64.8	73.5	75.1
1	22.0	18.2	15.8	14.2	24.2	19.6	19.0	17.6
2	5.4	5.2	2.4	2.4	7.0	7.6	3.0	2.8
3	1.0	1.0	1.2	1.2	1.0	0.8	1.4	1.4
4	1.6	1.8	0.6	0.8	2.4	2.6	1.0	1.0
5	0.4	0.4	0.6	0.6	0.4	0.4	0.6	0.6
R	2.2	2.8	0.8	0.7	4.1	4.2	1.5	1.5

Figure 4.1-4. Admiral 5- and 4-Bit Statistics Linear Shaping

Sampling Rate	7 Megasamples/Second				5 Megasamples/Second			
Number of Bits	5 Bits		4 Bits		5 Bits		4 Bits	
Filter Cutoff	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz
Order of Statistics								
0	54.2	56.6	68.4	69.7	46.5	49.0	62.4	69.7
1	28.6	26.2	24.6	23.6	30.2	27.6	27.4	23.6
2	10.0	10.4	4.4	4.4	12.4	13.0	5.8	4.4
3	1.8	1.6	1.4	1.2	2.4	1.8	2.2	1.2
4	3.0	3.2	0.6	0.6	4.2	4.6	1.0	0.6
5	0.4	0.2	0.2	0.2	0.8	0.6	0.6	0.2
R	2.0	1.8	0.4	0.3	3.5	3.4	0.6	0.3

Figure 4.1-5. Rack 5- and 4-Bit Statistics Linear Shaping

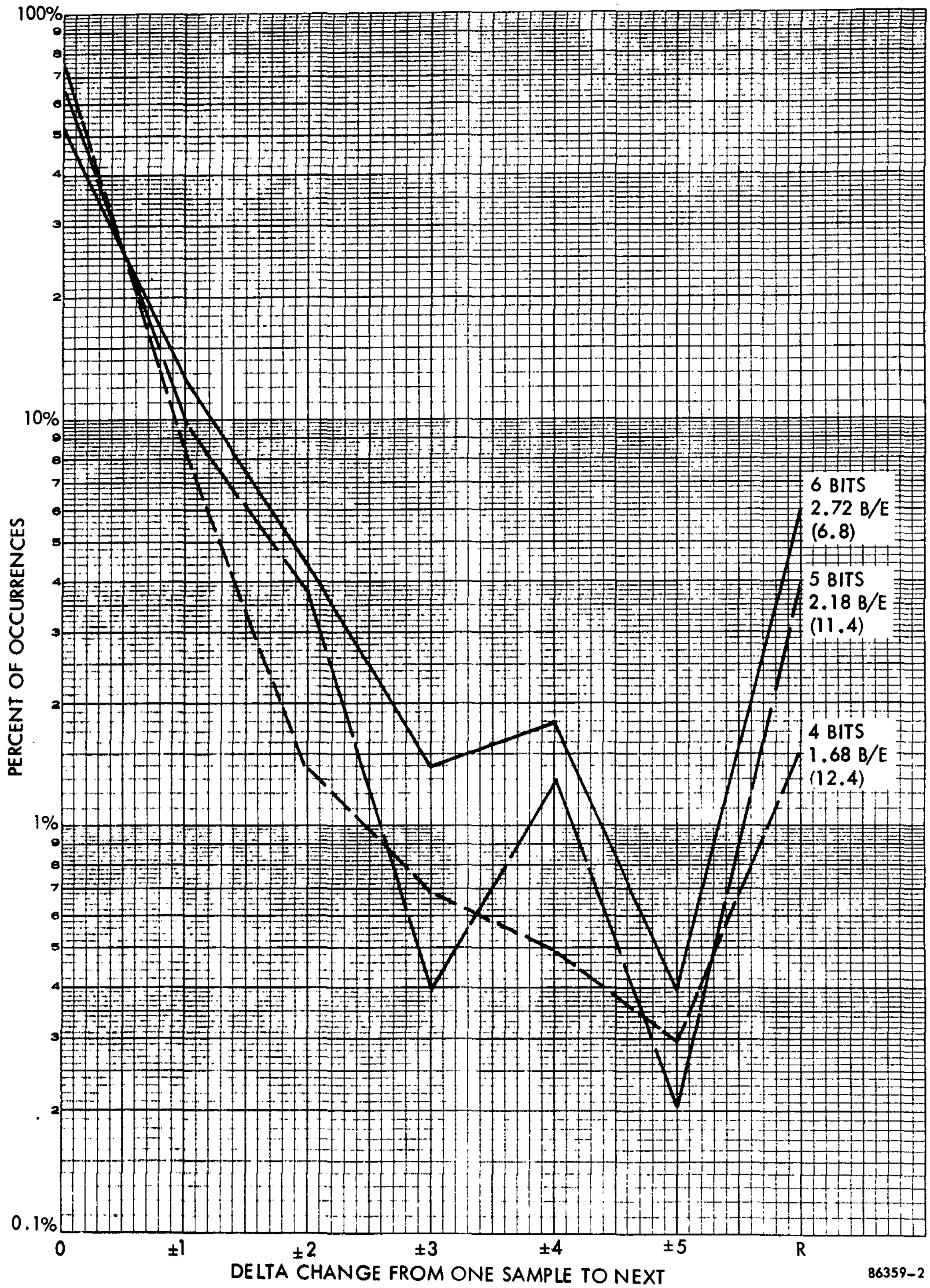


Figure 4.1-6. Differential Statistics on Admiral Picture 5 Megasamples -2.2 Megacycle Filter Linear Shaping

Sampling Rate	7 Megasamples/Second						5 Megasamples/Second					
Number of Bits	6 Bits		5 Bits		4 Bits		6 Bits		5 Bits		4 Bits	
Filter Cutoff	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz
Order of Statistics												
0	71.4	73.0	77.4	78.1	85.3	84.9	66.5	67.2	72.4	72.9	81.6	81.5
1	9.8	8.0	15.4	14.0	11.2	11.4	10.6	10.2	17.2	16.4	13.4	13.8
2	11.0	10.2	3.8	4.2	2.0	2.0	11.6	11.2	5.4	5.8	2.2	2.2
3	1.2	1.2	0.6	0.6	0.8	0.8	2.0	2.0	0.4	0.4	1.2	1.2
4	2.6	2.8	1.6	1.6	0.2	0.4	3.8	3.8	2.0	1.8	0.6	0.6
5	0.8	0.8	0.2	0.2	0.2	0.2	0.8	0.8	0.2	0.2	0.4	0.2
R	3.2	3.2	1.2	1.3	0.3	0.3	4.7	4.8	2.4	2.5	0.5	0.5

Figure 4.1-7. Admiral 6–, 5–, and 4–Bit Statistics Nonlinear Shaping (X2, X0.8)

Sampling Rate	7 Megasamples/Second						5 Megasamples/Second					
Number of Bits	6 Bits		5 Bits		4 Bits		6 Bits		5 Bits		4 Bits	
Filter Cutoff	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz	3 MHz	2.2 MHz
Order of Statistics												
0	56.8	58.4	62.5	64.6	75.6	76.4	48.5	50.3	55.4	57.0	69.5	70.2
1	12.4	11.4	25.8	23.2	20.8	20.0	13.6	12.6	27.2	25.6	24.0	24.2
2	18.2	17.4	8.0	8.4	2.4	2.6	19.0	18.2	10.8	11.8	4.0	3.4
3	2.8	2.6	0.8	1.0	0.6	0.4	4.2	4.2	1.4	1.0	1.2	1.0
4	5.6	6.0	1.6	1.8	0.2	0.2	7.6	8.0	2.8	2.8	0.4	0.4
5	1.0	1.0	0.2	0.2	0.2	0.0	1.6	1.6	0.4	0.1	0.4	0.2
R	3.2	3.0	1.1	0.8	0.2	0.4	5.5	5.1	2.0	1.6	.5	0.6

Figure 4.1-8. Rack 6-, 5-, and 4-Bit Statistics Nonlinear Shaping (X2, X0.8)

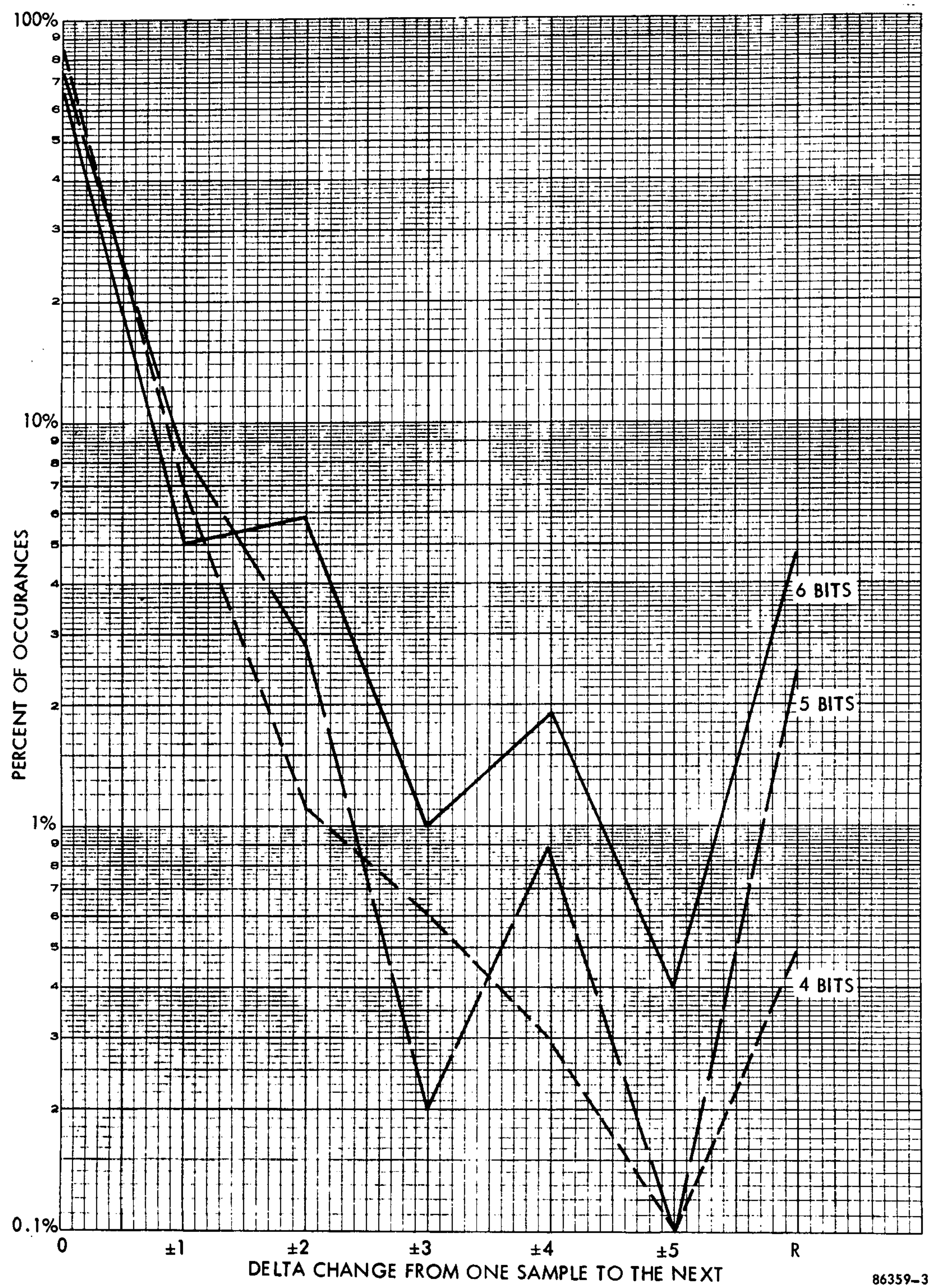


Figure 4.1-9. Differential Statistics on Admiral Picture 5 Megasamples/ Second 2.2 MHz Nonlinear Shaping

	Linear			Nonlinear		
Number of Bits	6	5	4	6	5	4
Order of Cutoff						
0	61.5	67.8	77.9	65.3	68.2	78.3
1	5.0	18.6	15.0	4.2	19.6	15.2
2	18.0	6.2	2.6	16.8	5.8	2.6
3	2.6	1.0	1.4	2.2	1.0	1.4
4	4.4	1.8	1.0	4.0	2.0	0.8
5	1.2	0.4	0.6	1.0	0.2	0.6
R	7.3	9.1	1.7	6.5	3.2	1.1

Figure 4.1-10. Admiral 6-, 5- and 4-Bit Statistics Linear and Nonlinear 5 Megasamples/Second 2.2 Megahertz Presampling Filter

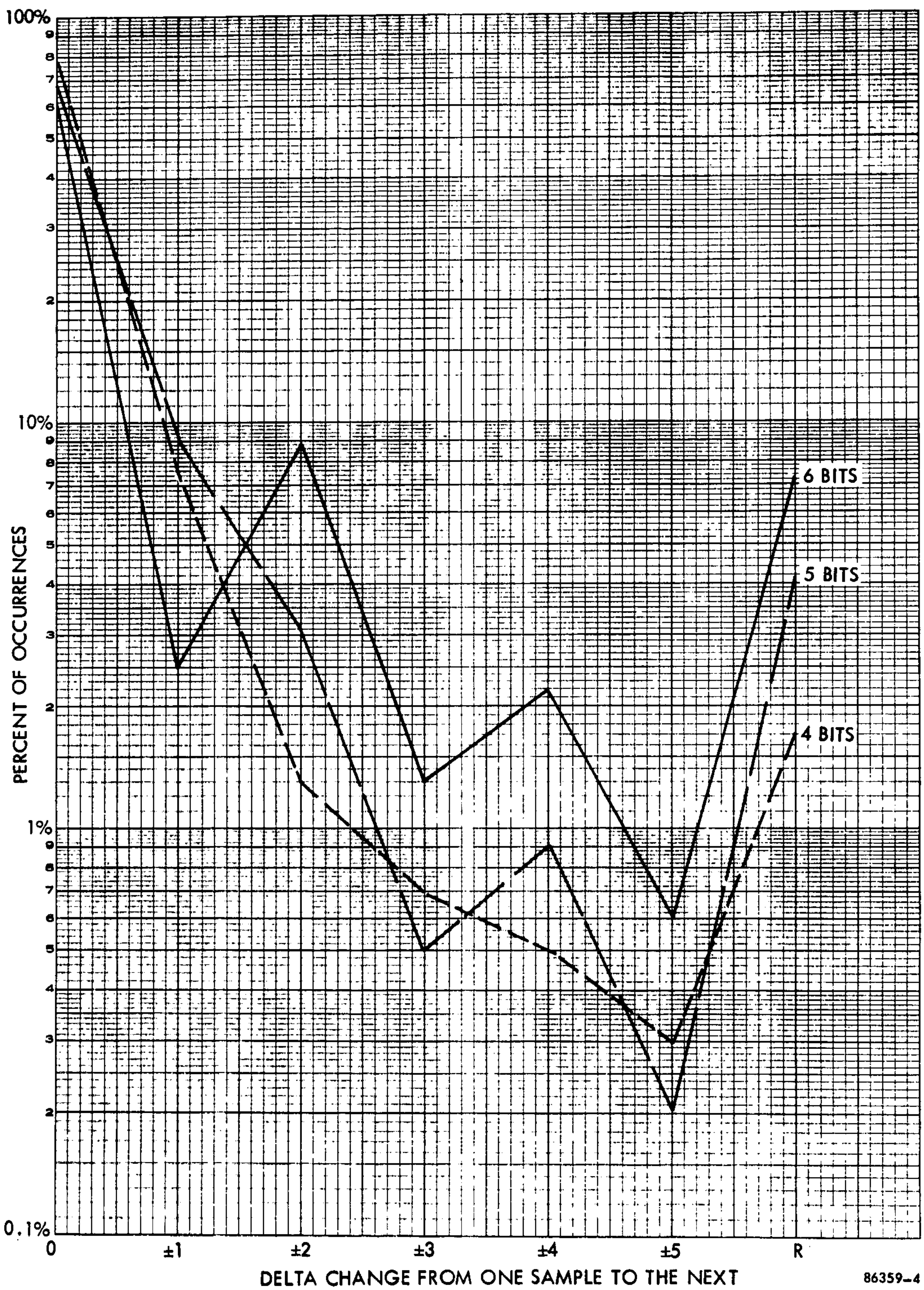


Figure 4.1-11. Differential Statistics on Admiral Picture 5 Megasamples/ Second 2.2 Megacycles Linear Shaping

The count of the number of level changes was made for 1-, 2-, 3- and 4-quantum level change per sample.

The results of these tests can be seen in Figure 4.1-12. As can be seen in the calibration ramp with one level per sample, there is a bias toward 0 and ±2 levels, away ±1. As the input level per sample approaches 4 bits, the situation improves with the 4-level test being close to the actual percentage.

4.2 Development of Optimum Codes

Codes were developed for each set of statistics tabulated in Paragraph 4.1. For the six-bit statistics, the codes were very similar for a given scene with different variables. In fact, the codes for the antenna and admiral at 5 megasamples with a 2.2 MHz filter were identical in code lengths, the only difference being within the structure of the code. The two codes are listed for comparison.

Δ	Antenna Code	Admiral Code
0	1	1
+1	001	011
-1	011	010
+2	0101	0011
-2	0100	0010
+3	000001	000010
-3	0000001	0000001
+4	000011	000001
-4	000010	000011
+5	00000001	00000001
-5	00000000	00000000
R	0001 +6 bits	0001 +6 bits

	PERCENT MEASURED	PERCENT ACTUAL
	1 Quantum Level Per Sample	
0	79.2	51.4
±1	8.8	48.6
±2	11.8	0
±3	0.0	0
±4	0.0	0
R	0.2	0
	2 Quantum Levels Per Sample	
0	53.5	75.8
±1	22.8	0
±2	21.6	24.2
±3	0.0	0
±4	1.6	0
R	0.5	0
	3 Quantum Levels Per Sample	
0	87.3	83.8
±1	0.6	0
±2	3.0	0
±3	0.5	16.2
±4	4.3	0
R	4.3	0
	4 Quantum Levels Per Sample	
0	91.1	87.9
±1	0.2	0
±2	2.2	0
±3	0.2	0
±4	5.4	12.1
R	0.9	0

Figure 4.1-12. Statistics of Calibration Ramp Fed Directly Into 6 Bit A/D Converter

Notice that a shorter code is assigned to ±4 levels than ±3 levels due to the bias in the A/D converter.

These codes reduced the antenna picture from 6 bits/element to 2.70 bits/element and the admiral picture to 2.72 bits/element.

All six-bit codes for the two pictures had the 1, 3, 3, 4 structure with the remainder of the code having some differences. However, any one of them would provide almost identical results, showing that noise and not the scene was the controlling factor.

For the rack picture, there was more variation in the code for different parameter settings, however, the difference was not great enough to produce much variations in total reduction.

The six-bit code for 5 megasamples/second and a 2.2 MHz filter on the rack picture is as follows:

Δ	Rack Code
0	11
+1	101
-1	011
+2	1001
-2	1000
+3	0010
-3	00001
+4	0001
-4	0011
+5	000001
-5	000000
R	010 +6 bits

This code reduced the rack picture to 3.76 bits/element.

This is a poor code due to the similarity of code lengths, which cause code reacquisition after link errors to be slower than for more "triangular" codes.

The 5-bit code for the admiral case did not change appreciably with the 1, 3, 3, 4 structure remaining. The results improved, however, with the reduction being 2.18 bits/element.

The 5-bit code for the rack changed a great deal, with its structure changing to 1, 3, 3, 4. It is very similar to the 6-bit admiral case. Results also improved greatly with the 6-bit case of 3.76 B/E being reduced to 2.61 B/E.

Dropping to 4-bits on the admiral produced a code very similar to the final code reported in Paragraph 1.3. The structure was 1, 2, 3, 5 and the reduction was 1.68 B/E.

The 4-bit rack statistics produced a code through ±3 levels very similar to that of the admiral, the main difference being the remainder code. The reduction was 1.88 B/E. The codes are listed below:

Δ	Admiral 4-Bit Code	Rack 4-Bit Code
0	1	1
+1	01	01
-1	001	001
+2	00010	00011
-2	000001	00010
+3	000011	000011
-3	0000001	000010
+4	0000101	0000010
-4	0000100	0000001
+5	00000001	00000001
-5	00000000	00000000
R	00011 +6 bits	0000011 +6 bits

The companding or analog shaping of the video produced very desirable results, in that the percentage of level changes above ±5 was greatly reduced. As can be seen below, the first three codes are identical. The admiral case was reduced to 1.46 B/E and the rack to 1.61 B/E. Both of these results are somewhat misleading, however, since the setup used had a different field of view, allowing redundant area around the picture.

Δ	Admiral 4-Bit Nonlinear Code	Rack 4-Bit Nonlinear Code
0	1	1
+1	01	01
-1	001	001
+2	00001	0001
-2	00011	0010
+3	000001	000011
-3	000101	000010
+4	0000001	0000001
-4	00000001	00000001
+5	000000001	000000001
-5	000000000	000000000
R	000100 +6 bits	0000001 +6 bits

The results obtained using the optimum code with each set of statistics is tabulated in Figures 4.2-1 and -2. These are tabulated in three different groups which coincide with the three different times that the data was taken.

The same data is also plotted in the form of the resulting bit rate versus the sampling rate for the admiral (Figure 4.2-3) and the rack (Figure 4.2-4). The effect of the video filter and the reduction in number of bits can be readily seen.

RACK

Sampling Rate	9 MS	7 MS	5 MS	3 MS
3 MHz Filter	3.63	3.74	3.81	4.19
2.2 MHz Filter	3.23	3.40	3.76	4.09
1.9 MHz Filter	2.90	--	--	--
1.48 MHz Filter	--	3.13	--	--
1.06 MHz Filter	--	--	3.35	--
0.635 MHz Filter	--	--	--	3.88

ADMIRAL

3 MHz Filter	2.81	2.71	2.95	3.13
2.2 MHz	2.44	2.45	2.72	3.19
1.9 MHz Filter	2.30	--	--	--
1.48 MHz	--	2.31	--	--
1.06 MHz	--	--	2.55	--
0.635 MHz	--	--	--	3.23.

Figure 4.2-1. Bits/Element Resulting from Optimum Code on 6-Bit Linear Statistics

Bits per Element Resulting
from
Optimum Code on 6, 5 and 4 Bit Linear Statistics

RACK PICTURE

Sampling Rate	7 Megasamples/Second			5 Megasamples/Second		
Bits	6 Bits	5 Bits	4 Bits	6 Bits	5 Bits	4 Bits
3 MHz Filter	3.75	2.35	1.71	3.81	2.65	1.92
2.2 MHz Filter	3.40	2.31	1.68	3.76	2.61	1.88

ADMIRAL PICTURE

3 MHz Filter	2.71	2.01	1.56	2.95	2.26	1.75
2.2 MHz Filter	2.45	1.94	1.53	2.72	2.18	1.68

Bits per Element Resulting
from
Optimum Code on 6, 5 and 4 Bit Nonlinear Statistics

RACK PICTURE

3 MHz Filter	2.50	1.97	1.50	2.99	2.28	1.73
2.2 MHz Filter	2.45	1.92	1.48	2.89	2.27	1.61

ADMIRAL PICTURE

3 MHz Filter	2.05	1.66	1.35	2.32	1.86	1.47
2.2 MHz Filter	2.01	1.64	1.35	2.30	1.85	1.46

Figure 4.2-2

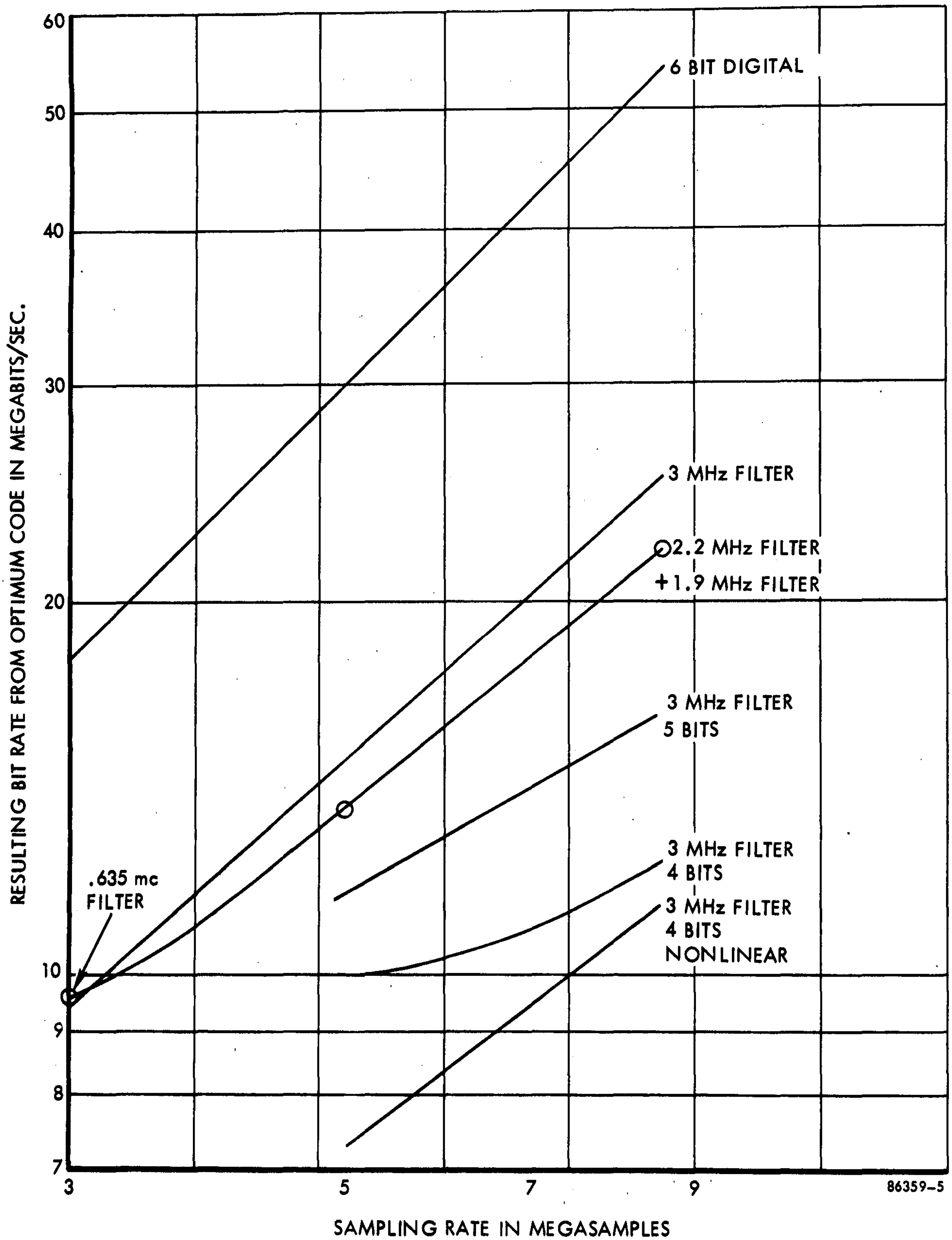


Figure 4.2-3. Admiral Picture

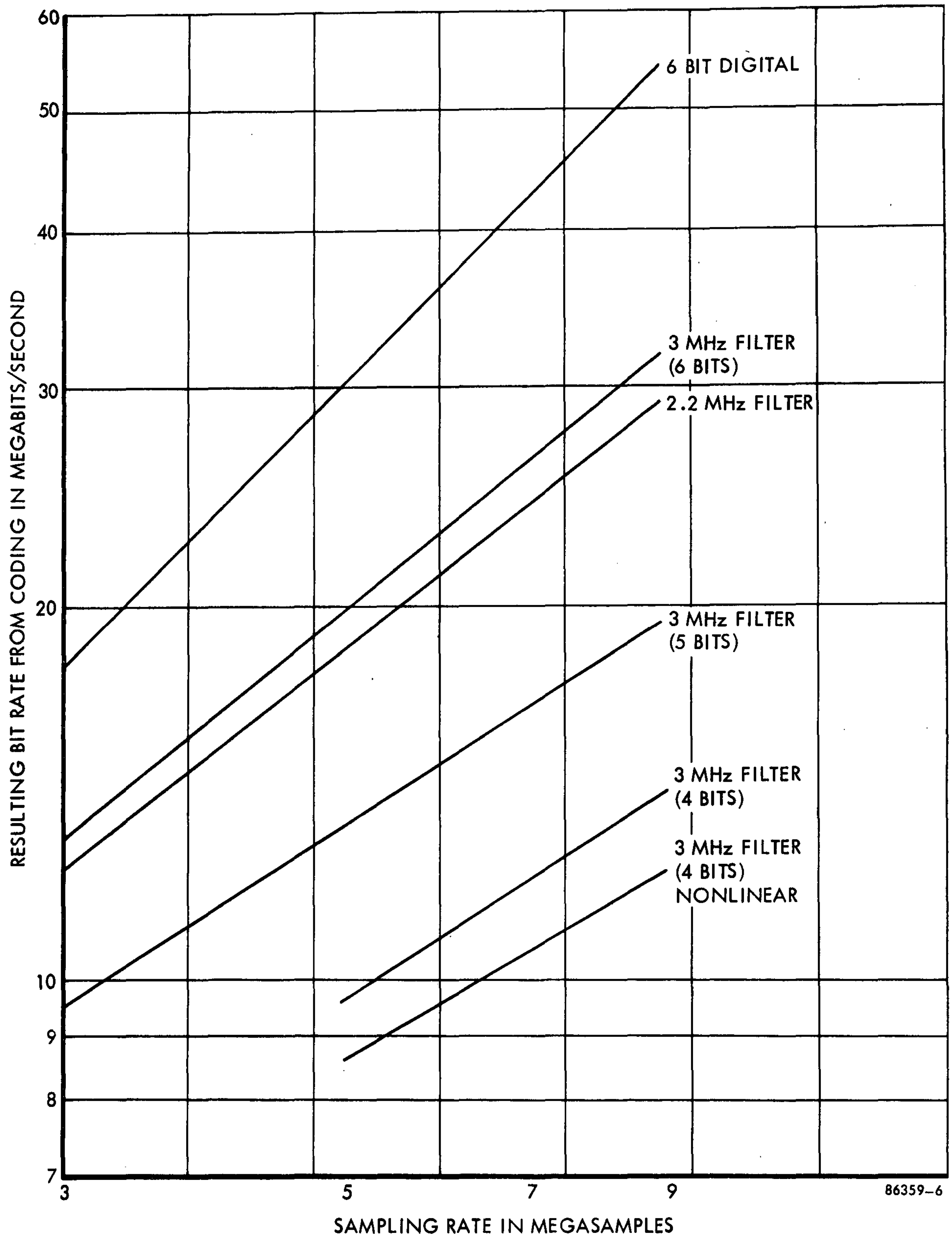


Figure 4.2-4. Rack Picture

4.3 <u>Development of Pseudo-Optimum Codes</u>

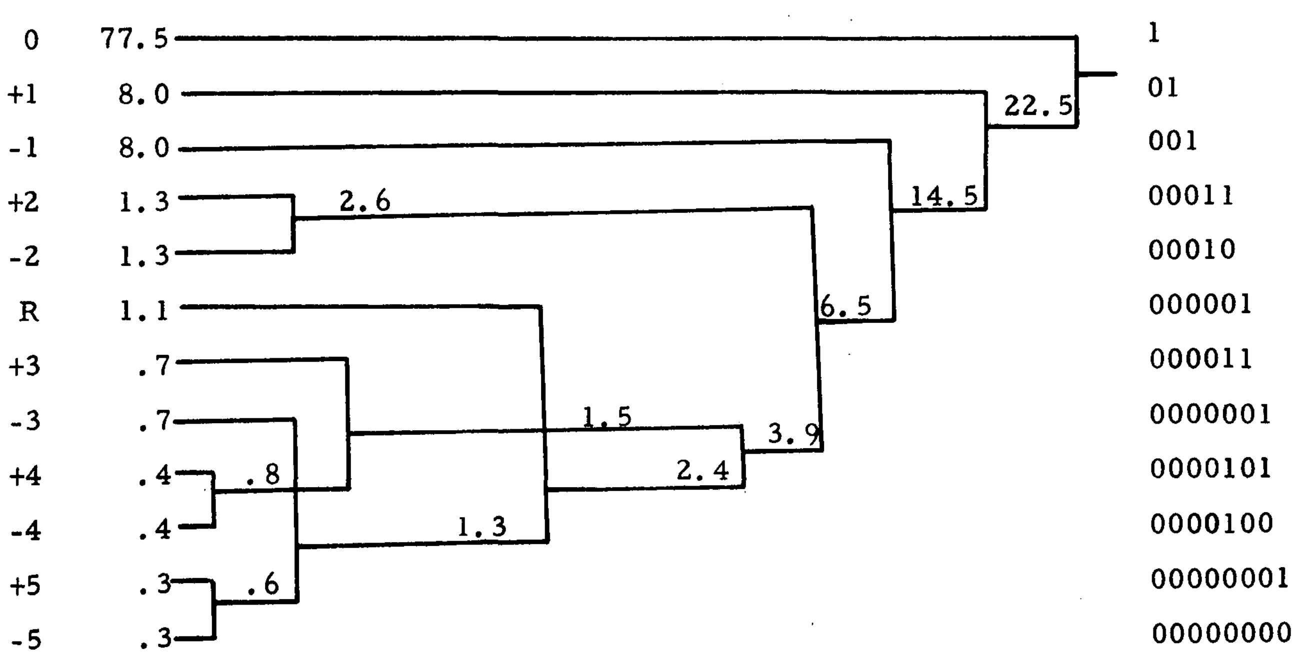
Although 6 bit pseudo-optimum codes were developed for all scenes with the same cutoff frequency and all sampling rates, they are not reported here because of their similarity. This is because of the noise level, which makes one code about as good as the next.

Also, as the number of the bits are reduced, the sensitivity of the code becomes less. The zero order statistics become greater as the number of bits decrease, and the number of changes exceeding 5th order becomes less.

The 4-bit statistics for the admiral picture are averaged for 7 and 5 megasamples/second with each having a filter cutoff of 3 and 2.2 MHz. The following code is obtained:

△ Average Percentage

AVERAGED 4 BIT ADMIRAL CODE



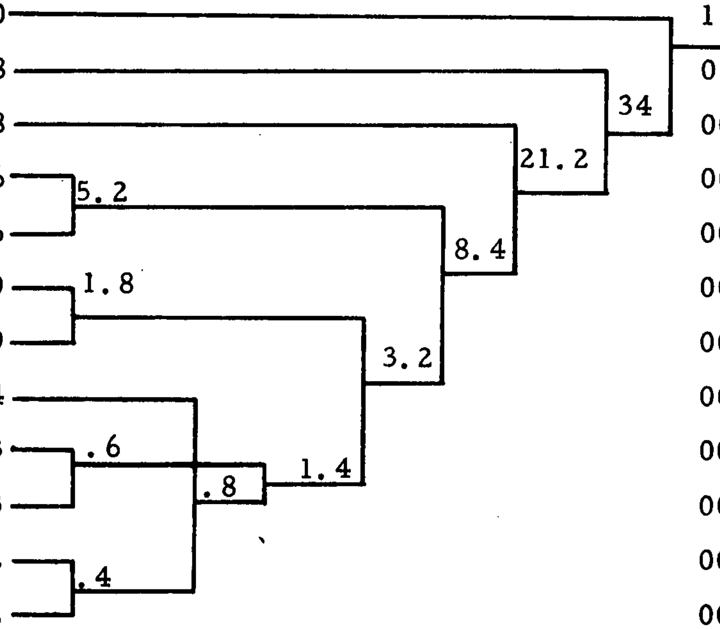
The results of using this code on the 5 megasamples/second, 2.2 MHz statistics provide a reduction to 1.69 B/E, which is within one-tenth of a bit of the optimum code. The same thing holds for the other three combinations of sampling rates and filter cutoffs.

It is interesting to note that the resulting reduction is almost a linear relation to the zero order statistics, therefore, with very little effort results can be predicted.

The statistics for the 7 and 5 megasamples/second rack picture along with cutoff frequencies of 3.0 and 2.2 MHz for each was averaged and produced the following code.

Averaged 4 Bit Rack Linear Code

Δ	Average Percentage	Code
0	66.0	1
+1	12.8	01
-1	12.8	001
+2	2.6	00011
-2	2.6	00010
+3	0.9	000011
-3	0.9	000010
R	0.4	0000001
+4	0.3	0000011
-4	0.3	0000010
+5	0.2	00000001
-5	0.2	00000000



This code produces exactly the same results as does the four optimum codes. The internal structure of the code is somewhat different but the length is the same for all cases. The same thing holds for the 4-bit nonlinear statistics of the rack picture. This code can be used on those statistics and will never be more than 0.1 bit/element from the optimum code.

4.4 Development of a Final Pseudo-Optimum Code

A summary of the results produced from a code that is good for all scenes and all parameters was presented in Section 1.3, Summary of Conclusions. Additional details are presented in this section in order to show the final results.

For continuity, the percentages and the code are again reproduced.

Δ	%	Code	Code Length
0	77.9	1	1
+1	7.5	01	2
-1	7.5	001	3
R	2.8	0001 +4 bits	8
+2	1.2	000011	6
-2	1.2	000010	6
+3	0.7	000001	6
-3	0.7	0000001	7
HS	0.4	00000001	8
VS	0.1	00000000	8

To show that the code is near optimum even for 6-bit pictures, a tabulation of the results on 12 pictures is included. They include 4 each at six, five and four bits, and each of the 4 include two linear and two companded.

Figure 4.4-1 shows the results using 6-bit statistics with the final code.

Note that the maximum difference between using an optimum code, based on its own statistics, to the final code is only 0.47 bit/element, which represents 2.35×10^6 bits per second increase. This, of course, is a rather large increase, however, it is not real in that the statistics on Test B-1.1 were heavily biased, due apparently to the calibration of the A/D converter at the time the statistics were taken. The 2-level changes exceeded the 1-level change by 12,000 samples while the 4-level changes exceed the 3-level changes by 3,000 samples.

Level Change	Code Length	Test 6.2 Linear Shaping	Test B-1.1 Linear Shaping	Test 15.4 X2, X0.8 Shaping	Test B-1.4 X2, X0.8 Shaping	Code
0	1	66341	78638	89953	83357	1
+1	2	32734	6064	13000	5286	01
-1	3	49101	9096	19500	7929	001
+2	6	34518	69120	42192	64428	000011
-2	6	34518	69120	42192	64428	000010
+3	6	10518	9714	7956	8460	000001
-3	7	12271	11333	9282	9870	0000001
R	8	107416	131800	95288	117808	0001+4 Bits
HS	8	3928	3928	3928	3928	00000001
VS	8	30	30	30	30	00000000
Total Bits In Frame		351375	388843	323321	365524	
Bits/Element(B/E)		2.75	3.03	2.52	2.85	
Optimum B/E		2.72	2.56	2.30	2.40	
Difference		.03	.47	.22	.45	
Final Bit Rate		13.75×10^6	15.15×10^6	12.60×10^6	14.25×10^6	

Figure 4.4-1. Results When Using Final 4-Bit, 3 Level Code on 6-Bit Admiral Picture Statistics 5 Megasamples/Second - 30 Megabits/Second - 2.2 Megahertz Filter

Had these statistics been reversed as they should have been, there would only be 0.02 bit/element 0.1 x 10^6 bits/second over the optimum code.

These results further show that the six bits statistics of the admiral will not reduce the 30 megabits to the desired 9 megabits. The lowest rate obtained was 12.6 x 10^6 bits/second.

Figure 4.4-2 shows the improvement in results when dropping to the 5-bit statistics. Here the maximum difference over optimum was on 0.05 bit/element or 0.25 x 10^6 bits/second. The desired results have still not been reached, however. This is because the amplitude of the noise coming from the camera exceeds 1 part in 32 and must be transmitted in order to reconstruct the time waveform at the decoder.

Figure 4.4-3 shows the results of using the final code on 4-bit statistics of the admiral picture. All pictures have been reduced to less than 9 x 10^6 bits/second. The only difference between these results and the optimum is that the final code has been truncated at ±3 levels, and includes line and frame sync. Test B-1.6 is representative of the final results, although Test 17.4 shows 0.13 bit/element better results. These later results are not accurate since the camera was not arranged properly and a different field of view is included around the picture which naturally increases the amount of redundancy in the frame.

Using the final 4-bit code on the rack picture statistics shows that an active picture requires 3 to 5 megabits/second more bandwidth from an incactive one, like the admiral picture. Figure 4.4-4 shows these results for the 5 and 6-bits statistics. Test 4.2 6-bit linear shaping shows graphically the results of noise. The zero order statistics on this picture was scanned with a flying spot scanner, with a signal-to-noise of about 34 dB, the zero order statistics were 41.0 percent. The companding in Test 18.4 increased this number to 50.3 percent, however, with the flying spot scanner, it was increased to 64.0 percent.

These two tests again show the importance of signal-to-noise ratios of the source and linearizing of the video signal. Even with linearizing, this picture was reduced from 30 megabits/second to 16.8 megabits/second. The flying spot scanner picture was reduced to approximately 10 megabits/second.

Dropping to the 5-bit statistics (Test 8.5) reduced the picture to 15 megabits/second for linear shaping and to 12 megabits/second with companding (Test 19.4).

Figure 4.4-5 shows the results of using the 4 bits statistics from the rack picture. Dropping to 4-bits (Test 8.6) for the linear shaping dropped the bit rate to 10.7 megabits/second with the zero order statistics rising to 59.5 percent. Linearizing the video reduced the rate to 8.5 megabits/second (Test 20.4). This test, however, is again somewhat misleading due to the different field of view. Had this not been the case, the result would have been about 9.5 megabits/second.

Level Change	Code Length	Test 11.4 Linear Shaping	Test B-1.2 Linear Shaping	Test 16.4 X2, X0.8 Shaping	Test B-1.5 X2, X0.8 Shaping
0	1	83136	86477	93327	86408
+1	2	25042	23734	20800	24754
-1	3	37563	34305	31200	37131
+2	6	28560	23358	22044	22164
-2	6	28560	23358	22044	22164
+3	6	3342	4038	1542	3450
-3	7	3899	4038	1799	4025
R	8	71320	64880	46408	55616
HS	8	3928	3928	3928	3928
VS	8	30	30	30	30
Total Bits In Frame		285380	268146	243122	259670
Bits /Element (B/E)		2.23	2.10	1.90	2.04
Optimum B/E		2.18	2.09	1.85	2.03
Difference		.05	.01	.05	.01
Final Bit Rate		11.15×10^6	10.50×10^6	9.50×10^6	10.20×10^6

Figure 4.4-2. Results When Using Final 4-Bit, 3 Level Code on 5 Bit Admiral Picture Statistics 5 Megasamples/Second - 30 Megabits/Second - 2.2 Megahertz Filter

Level Change	Code Length	Test 12.4 Linear Shaping	Test B-1.3 Linear Shaping	Test 17.4 X2, X0.8 Shaping	Test B-1.6 X2, X0.8 Shaping	Code
0	1	95990	99286	103872	100022	1
+1	2	22252	19112	17594	19350	01
-1	3	33381	28668	26391	29025	001
+2	6	9840	9576	8382	10314	000011
-2	6	9840	9576	8382	10314	000010
+3	6	5316	5364	4794	5256	000001
-3	7	6202	6258	5593	6132	0000001
R	8	29584	32600	13184	24776	0001 + 4 Bits
HS	8	3928	3928	3928	3928	00000001
VS	8	30	30	30	30	00000000
Total Bits In One Frame		216363	214398	192150	209147	
Bits/Element (B/E)		1.69	1.68	1.50	1.63	
Optimum B/E		1.68	1.69	1.46	1.61	
Difference		.01	.01	.04	.02	
Final Bit Rate		8.45×10^6	8.40×10^6	7.50×10^6	8.15×10^6	

Figure 4.4-3. Results When Using Final 4-Bit, 3 Level Code on 4-Bit Admiral Picture Statistics 5 Megasamples - 2.2 Megahertz Presampling Filter

Level Change	Code Length	5 BITS: Test 13.4 Linear Shaping	5 BITS: Test 8.5 Linear Shaping	5 BITS: Test 19.4 X2, X0.8 Shaping	6 BITS: Test 4.2 Linear Shaping	6 BITS: Test 18.4 X2, X0.8 Shaping
1	1	62674	55370	73012	39757	64426
+1	2	35294	38964	32706	32382	16198
-1	3	52941	58446	46059	48573	24297
+2	6	49716	49320	44676	55116	69630
-2	6	49716	49320	44676	55116	69630
+3	6	6906	12066	3540	27072	16224
-3	7	8057	14077	4130	31584	18928
R	8	87040	105160	46136	223792	148032
HS	8	3928	3928	3928	3928	3928
VS	8	30	30	30	30	30
Total Bits In Frame		356302	386681	298893	517320	431323
Bits/Element (B/E)		2.78	3.01	2.33	4.04	3.36
Optimum B/E		2.61	2.89	2.27	3.76	2.89
Difference		.17	.12	.06	.28	.47
Final Bit Rate		13.90×10^6	15.05×10^6	11.65×10^6	20.20×10^6	16.80×10^6

Figure 4.4-4. Results When Using Final 4-Bit, 3 Level Code on 5- and 6-Bit Rack Picture Statistics 5 Megasamples/Second - 30 Megabits/Second - 2.2 Megahertz Filter

Level Change	Code Length	Test 14.4 Linear Shaping	Test 8.6 Linear Shaping	Test 20.4 X2, X0.8 Shaping
0	1	81065	76102	89934
+1	2	33746	36022	30966
-1	3	50619	54033	46449
+2	6	22704	25716	13206
-2	6	22704	25716	13206
+3	6	8886	11100	3528
-3	7	10567	12960	4116
R	8	16952	28424	11288
HS	8	3928	3928	3928
VS	8	30	30	30
Total Bits In Frame		251201	274001	216651
Bits/Element(B/E)		1.96	2.13	1.69
Optimum B/E		1.88	2.08	1.61
Difference		.08	.05	.06
Final Bit Rate		9.80×10^6	10.65×10^6	8.45×10^6

Figure 4.4-5. Results When Using Final 4-Bit, 3 Level Code on 4-Bit Rack Picture Statistics 5 Megasamples/Second - 30 Megabits/Second - 2.2 Megahertz Filter

The final results are then that an active picture cannot be reduced from 30 megabits to 9 megabits/second with the present camera and analog-to-digital converter. This fact was borne out when a statistical code was implemented in the Test Set. In order to keep the buffer from overflowing when looking at this picture, the sampling rate had to drop below 5 megasamples/second.

SECTION 5.0

DISCUSSION

5.0 DISCUSSION

5.1 Signal-to-Noise Measurement

In order to determine the signal-to-noise ratio of the camera a video analyzer was used to look at one line of a TV frame. That line was then adjusted to scan the equal perceptibility step tables on the IEEE Facsimile Test Chart. The steps range from a density of 1.78 on Step 1 to 0.02 on Step 15. The line was then stored in the analyzer and played back at a slower speed where it could be recorded on a pen recorder.

The results of that scan is shown in Figure 5.1-1. As can be seen the amplitude variation during minimum signal black, (Step 1) is much less than that for white, (Step 15). This is because of the multiplication nature of the combination of reflection and illumination.

To understand this noise and its effect on coding better, a description of signal-to-noise (S/N) and dynamic range (DR) is needed. The interpretations of these terms often differ with different kinds of users. In general, the noise in any scanner or photographic process varies with the signal, whereas in an "ordinary" electronic amplifier the noise is generally constant. As darker objects are scanned, the signal current decreases to a point when it will be masked by a constant background noise somewhere in the rest of the equipment. A noise that varies with the amplitude of the signal is called multiplicative noise; and noise independent of the signal amplitude is called additive. Additive noise is sometimes called ordinary noise, and multiplicative noise, extraordinary noise.

The following description of S/N and DR is generally accepted when referring to the performance of scanning systems.

Because of the multiplicative nature of noise in a scanning system, the definition of S/N is made more difficult than it would be in common electronic usage where it is simply defined as the ratio of the rms signal to the rms noise. For the purposes of this report, S/N is defined (Figure 5.1-2) in the same manner as it is in television: the maximum

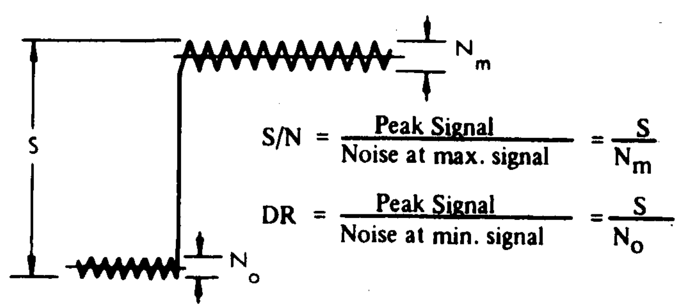


Figure 5.1-2. Definitions of S/N and DR

signal (S) divided by the rms noise (N_m) in the presence of this maximum signal or S/N = $\frac{S}{N_m}$.

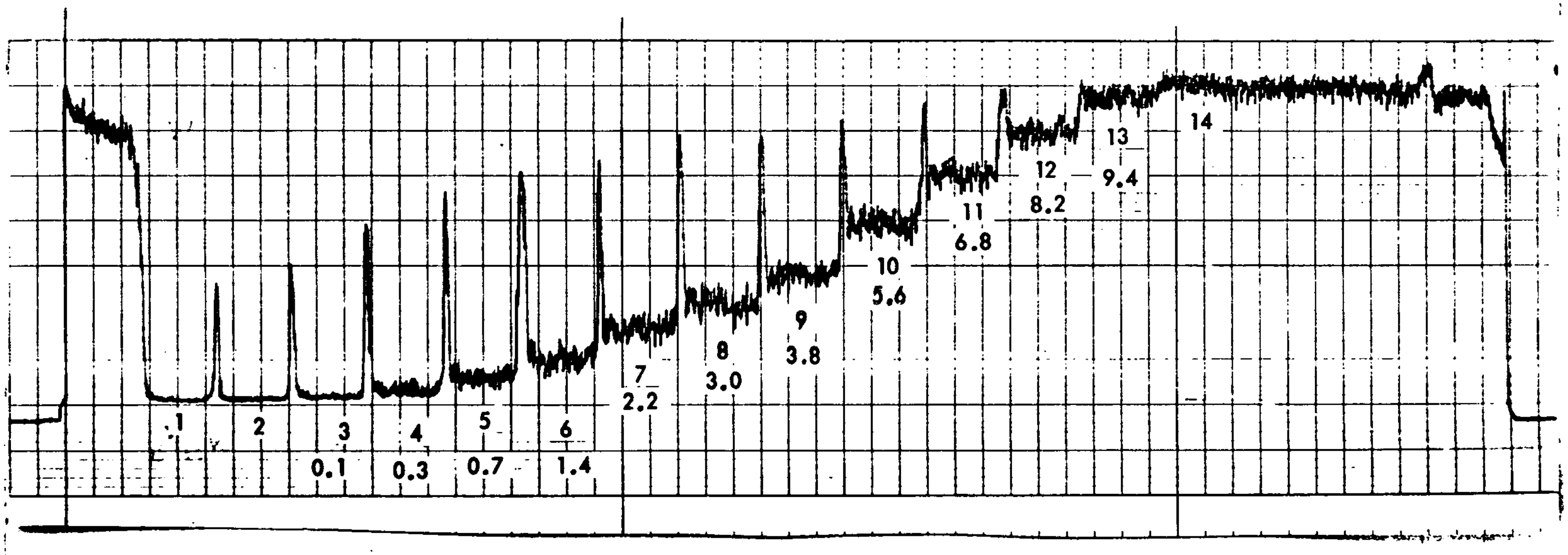


Figure 5.1-1. Oscillogram of Equal Perceptibility Scale (Linear Shaping)

The DR is defined as the maximum signal (S) divided by the noise (N_o) when no other signal is present or:

$$DR = \frac{S}{N_o}$$

These definitions for S/N and DR are selected because they show:

1. The smallest signal increment that can be detected in the presence of the maximum signal; and

2. The smallest signal increment that can be detected in the presence of minimum signal.

Using the definitions above in a system with purely additive noise, DR will equal S/N, while in a system with multiplicative noise, as in the electron beam system, DR ideally with equal 2 S/N measured in dB. In practice, DR will be less because of the presence of the additive noise in the rest of the equipment.

The multiplicative noise on Step 15 in Figure 5.1-1 is much worse than the additive noise on Step 1. The S/N ratio of the TV camera is:

$$20 \log \frac{9}{0.5} = 25 \text{ dB}$$

This is a very poor signal-to-noise ratio and represents the quantization noise of a 4-bit digital system.

This S/N can be improved by nonlinear amplification of the video. That is, the blacks can be amplified while the whites are compressed. This also reduces the noise amplitude on the white but increases the noise amplitude on the black. The S/N is decreased at the expense of the DR.

This can be seen in Figure 5.1-3. The S/N has been increased to about 29 dB.

The S/N can be further improved through the use of a presampling video filter. Of course, this filter also removes some of the data and thus reduces the resolution of the system.

The results of a 2.2 MHz Butterworth type fourth order filter is shown in Figure 5.1-4.

This effect can be graphically demonstrated by scanning a line in a picture that has both black and white. Figure 5.1-5 shows the resulting oscillogram and the picture scanned. The white line in the picture is the one that was scanned. The first pulse on the left is the white area between the man on the left and the admiral. The next two pulses is the admiral's white shirt. The next pulse is the white area to his left, and the last pulse is the badge on the man second from right.

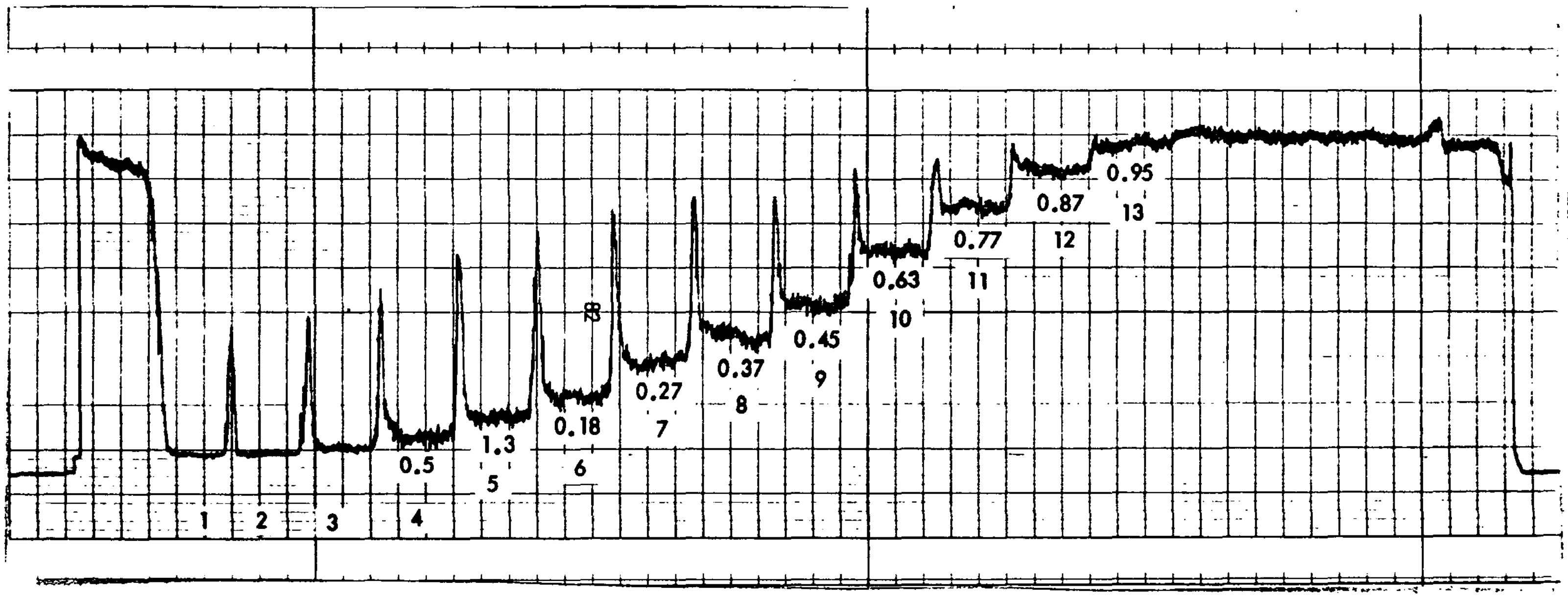


Figure 5.1-3. Oscillogram of Equal Perceptibility Scale (Nonlinear Shaping x 10)

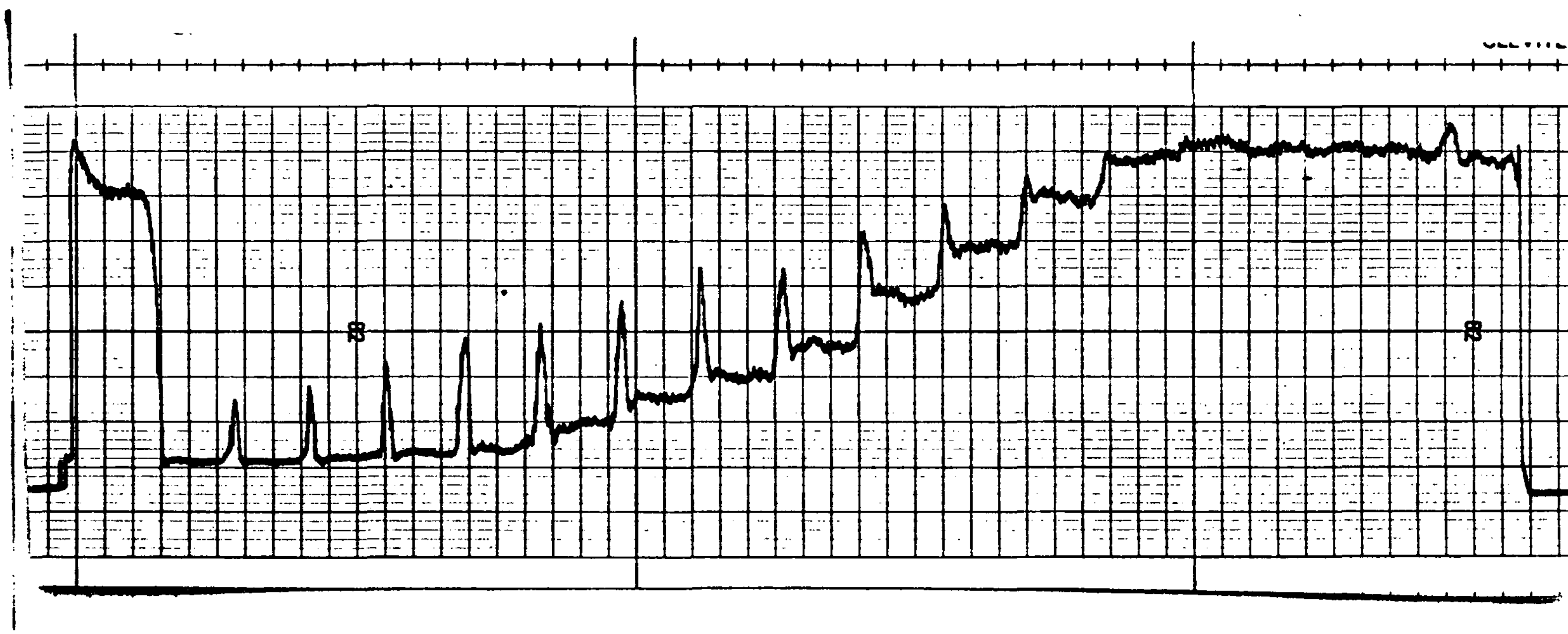


Figure 5.1-4. Oscilloglram of Equal Perceptibility Scale
(Nonlinear Shaping and 2.2 MHz Presampling Filter)

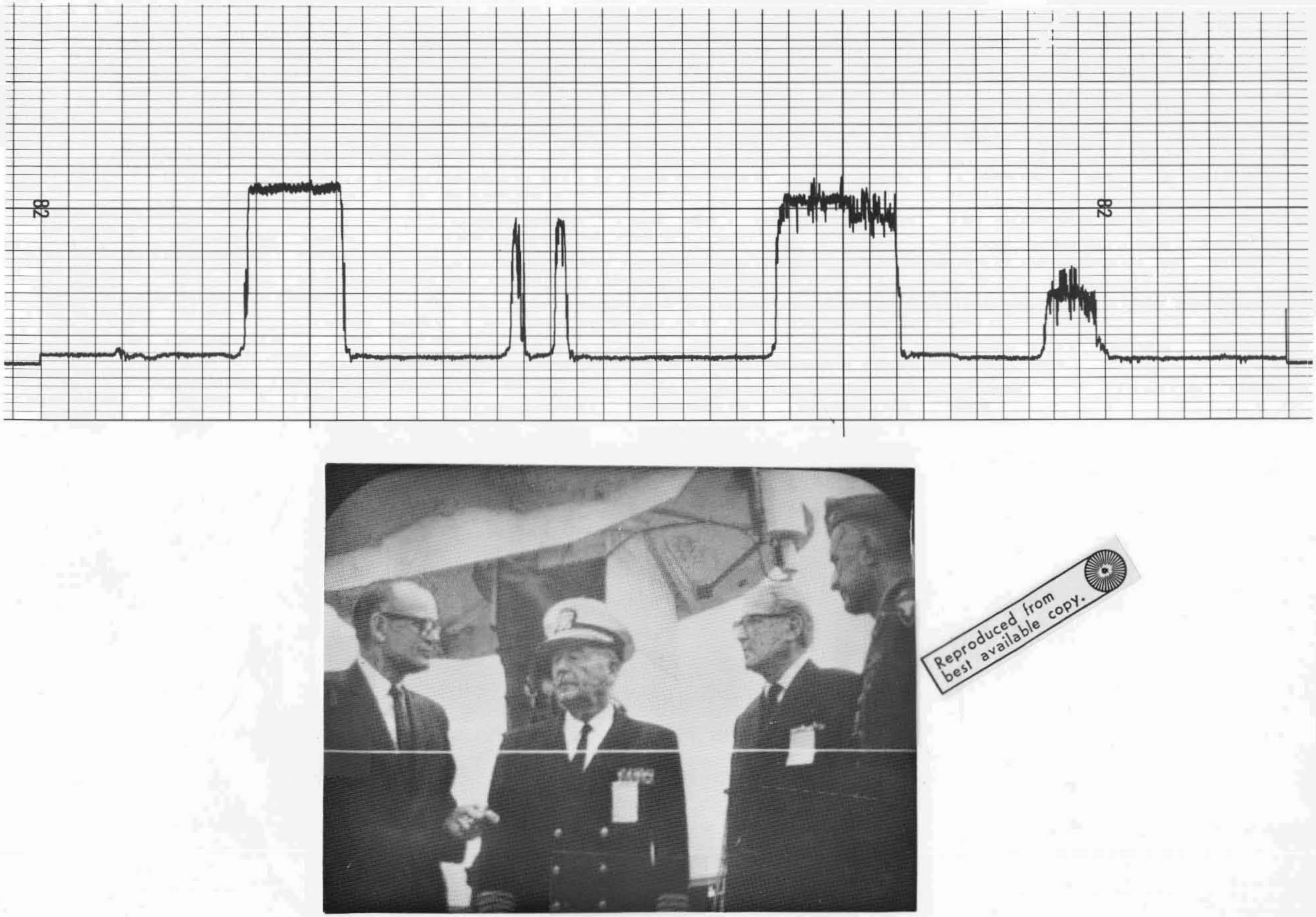


Figure 5.1-5. Oscillogram of a Line Within a Picture

The picture was filtered with a 2.2 MHz filter, sampled at a 7 megasample rate and digitized to 6-bits.

5.2 Linear Phase Versus Maximally Flat Amplitude Video Filters

In normal TV video, when the bandwidth of the video is filtered for transmission over reduced bandwidth, a linear phase (Bessel) filter is used.

This is because of the good phase response of the filter which in turn produces crisp sharp edges. This is much more important than the absolute amplitude of a given frequency which may be reduced by this type filter.

The phase response is good for this filter, however, the final slope of the response curve drops off very slowly. It also starts to cut off at a much lower frequency omitting some of the video data.

When the video is to be sampled the drop off of the final slope is more important than the phase response. If the amplitude response is not down sufficiently, aliasing error or foldover frequencies are produced which are very objectionable. The Butterworth filter is a maximally flat amplitude response with a short cutoff, and helps to solve this frequency foldover problem.

In order to show this effect the admiral's picture was sampled and digitized after having been filtered with both types of filters. Figures 5.2-1 and -2 show the results of this test.

Both figures were sampled at a 5 megasample rate and both used linear shaping and were digitized to 6-bits.

Figure 5.2-1 used a Butterworth presampling filter with a 3 dB point at 2.2 MHz, and it was a fourth order filter.

Figure 5.2-1. 2.2 Megahertz Butterworth Presampling Filter

Figure 5.2-2 used a Bessel type linear phase filter with its cutoff adjusted to 2.5 Megahertz.

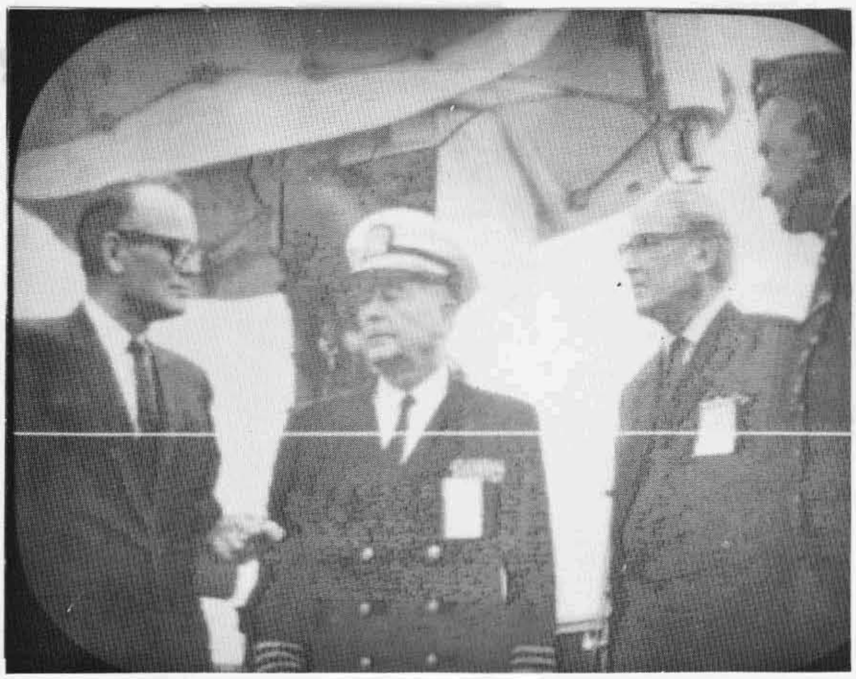


Figure 5.2-2. 2.5 Megahertz Bessel Presampling Filter

Considerable amount of what appears like false contouring can be seen in this picture, particularly in the dark area of the coats. In the previous picture this does not occur. These are interference frequencies produced at the sampling frequency minus the information frequency.

There is some of this type of errors in Figure 5.1-1, particularly in the area around the faces, however, it is not anywhere near as objectionable.

By reducing the cutoff frequency of the filter the amount of foldover frequencies can be improved at the expense of reduced resolution.

This was done for both cases. Figure 5.2-3 shows the results of reducing the Butterworth cutoff to 1.48 megahertz. Notice that the false contouring in the face areas is improved, however, the picture is somewhat fuzzy.

Figure 5.2-3. 1.48 Megahertz Butterworth Presampling Filter

Figure 5.2-4 shows the results of dropping the Bessel filter cutoff to 1.40 megahertz. Note that the false contouring is not appreciably improved, however, the picture is fuzzy.

Figure 5.2-4. 1.4 Megahertz Bessel Presampling Filter

It is therefore concluded that the Butterworth type filter is a better presampling filter to use for digital TV.

5.3 Interpolation Filters

The 5 megasamples/second sampling rate used for most of this study produces an rms interpolation error in excess of 10 percent. This is not a serious error especially considering the 30 frames per second, and the nature of the eye.

This rate produces only about 2.5 samples/cycle of the filter break point. From past experience it has been noted that scanned image data decays at 12 dB/octave or second order.

The interpolation error for second order data is shown in Figure 5.3-1. As can be seen with 10 cycles/cycle the error varies between 10 percent with a first order interpolation filter to about 5.5 percent with an ideal filter.

Also note that the interpolation errors curves are converging and for values above 10 percent the difference would be even less. This means that the type of interpolation filter used is relatively unimportant. In fact, the filtering action of the monitor is probably all that is needed.

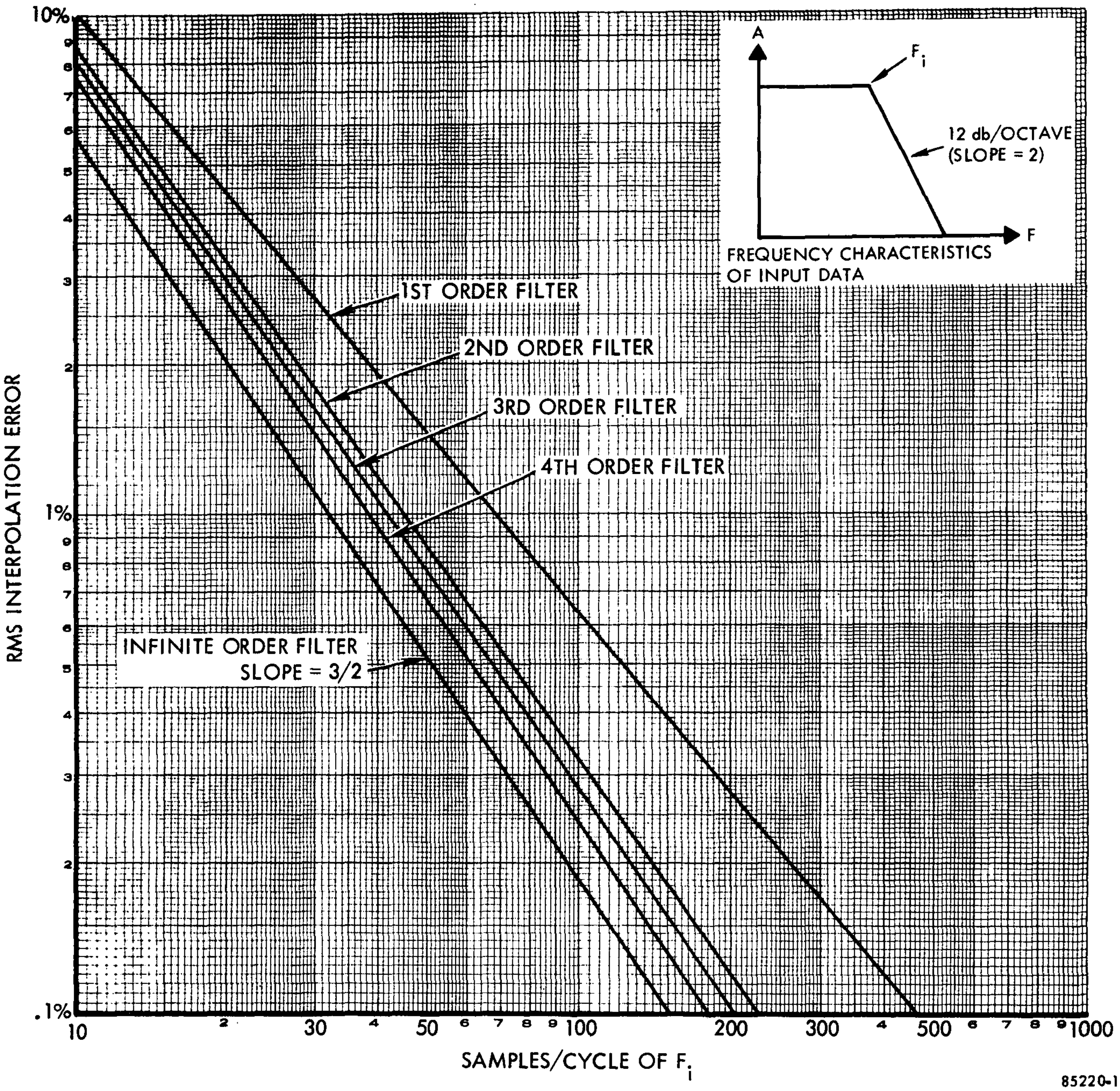


Figure 5.3-1. Interpolation Errors for Second Order Data Using Butterworth Shade Filters and Pulse Stretching

This is verified by photographing the monitor when the maximum activity picture is sampled at a 5-megasample rate as seen in Figure 5.3-2. In this case, no interpolation filter was used. There are foldover frequencies present in the face area, however, in general the picture is of better quality than one that removes these frequencies with an interpolation filter. This can be seen in Figure 5.3-3. There is a considerable amount of reduction in the resolution.

Also part of the false contouring produced in Figure 5.3-2 is due to the 5-bit picture.

It is recommended that a presampling filter not be used unless a lower sampling rate is to be used. In this case, some improvement can be made, as seen in Figures 5.3-4 and -5. The 1 megahertz interpolation filter picture is of better quality than the one with a 2.5 megahertz filter.

Figure 5.3-2. 5 Megasample, 5-Bit Picture without Interpolation Filter

Figure 5.3-3. 5 Megasample, 6-Bit Picture with 1 Megahertz Interpolation Filter

Figure 5.3-4. 3 Megasample 6-Bit Picture with 2.5 Megahertz Interpolation Filter

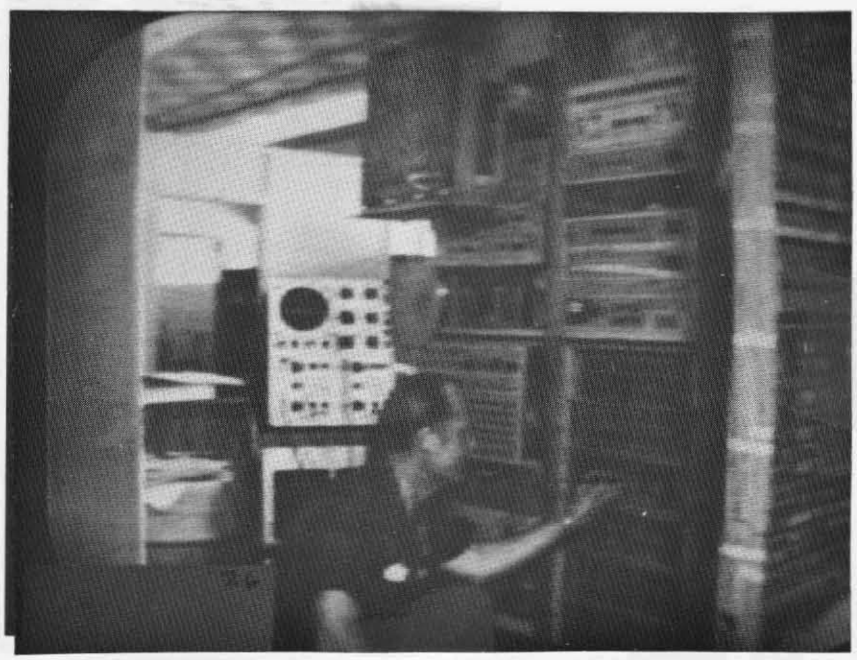


Figure 5.3-5. 3 Megasample 6-Bit Picture with 1 Megahertz Interpolation Filter