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Encoding Approaches for Data Link Transmission of Weather Graphics

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16. Abstract

To provide pilots with necessary information to make informed decisions on the avoidance of hazardous weather and to maintain situational awareness of the weather conditions, the FAA is actively developing the capability to provide real-time graphical weather information to aircraft through the use of bandwidth-limited data links such as Mode S. The information content of weather images and the restricted bandwidth of the transmission channel require that the images be extensively compressed.

This paper provides the results of a study concerning the applicability of various data compression algorithms to the weather image problem. Its conclusion is that the Polygon-Ellipse Algorithm developed at Lincoln Laboratory provides the best combination of compression, computational efficiency, and image quality for the encoding of weather images over the Mode S data link or other similarly bit-limited data links.

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EXECUTIVE SUMMARY

The current TDWR (Terminal Doppler Weather Radar), ASR-9 (Airport Surveillance Radar), and NEXRAD (NEXt generation weather RADar) radars are designed to provide weather information to controllers located at the tower or at an en route center. To provide pilots with necessary information to make informed decisions on the avoidance of hazardous weather, and to supply them with the same information the controllers have, the FAA is actively developing the capability to provide real-time graphical information of weather conditions to aircraft through the use of bandwidth-limited data links such as Mode S.

The information content of weather images and the limited bandwidth of the transmission channel require that the images be compressed. The amount of data that can be transmitted with each weather image is restricted by the bandwidth of the ground-to-air data links. Available and planned aviation data links can provide a typical average throughput of 100-300 bits per second per aircraft. A reasonable goal is to be able to uplink a single weather image to a given aircraft in a few seconds. This equates to compressing each image to the order of 1 to 2 kilobits, or to 1 or 2 ELM's for the Mode S application.

A compression algorithm appropriate for aviation graphical weather images should be able to guarantee a specified level of image compression. The application utilizing the compression algorithm should state the maximum number of bits available for use in encoding the weather image. The compression algorithm should encode the given weather image within the stated bit limitation. The compression algorithm should minimize the amount of distortion introduced in the compression of the weather image, and should permit the control and prioritizing of distortion at each weather level. Finally, the image quality of the expanded image should be as smooth and realistic as possible. The basic shapes and sizes of weather image regions should be maintained at a high level of fidelity. Also, the computational requirements of both the compression and decompression processes need to be considered. Both the compression and decompression processes will be under significant real-time constraints and must run in economically reasonable processing environments.

With no adequate model to analytically describe weather images, the effectiveness of a compression scheme could only be measured by testing on a wide variety of weather images and comparing the results. For our testing purposes, we chose a few dozen actual recorded weather scenarios. The images ranged from 64x64 pixel target-area images with the weather values quantized to the standard six NWS levels, to 256x256 pixel wide-area images with three weather levels (all four NWS storm levels grouped together). Hence, using the above bit-limitation goals, it is possible to determine the compression ratios desired for the transmission of weather images:

Image Type	Bits	Bit Goal	Compression Ratio
64x64, 6 level	12K	1K	12
256X256,3 level	128K	2K	64

This report presents the results of research performed at Lincoln Laboratory concerning possible data compression schemes. Run length coding and variations, Huffman coding, variable-to-block coding, vector quantization, contour coding, shape fitting, fractals, and other new compression techniques were all considered, along with the Weather-Huffman (W-H) and Polygon-Ellipse (P-E) algorithms developed at Lincoln Laboratory. Pre-filtering of weather maps prior to compression was also addressed in each case.

The average compression results were as follows:

Table 1. Average Compression Ratios For Various Algorithms

	64x64	64x64 filtered	256x256	256x256 filtered
GOAL	12.0	12.0	64.0	64.0
runlength	2.0	4.0	4.0	7.5
long/short	2.5	5.0	6.0	10.5
Huffman (with table)	3.0	4.5	6.0	9.0
Lempel-Ziv	3.0	4.5	6.0	8.0
Weather-Huffman (W-H)	4.5	7.5	8.0	12.0
W-H (bit-limited)	12.0	12.0	64.0	64.0
Polygon-Ellipse (P-E)	4.0	5.0	7.0	11.0
P-E (bit-limited)	12.0	12.0	64.0	64.0

It is clear from these results that only the Weather-Huffman and Polygon-Ellipse Algorithms provide the desired degree of compression when a bit limit is imposed. The Polygon-Ellipse Algorithm was identified as the preferred approach because it is able to

1. provide less distortion in general,
2. present a more easily interpreted picture, as it is smoother and less blocky,
3. provide weather level distortion priorities more accurately, and
4. scale to different image dimensions more easily.

In conclusion, the Polygon-Ellipse algorithm has significant potential for the encoding of weather images over the Mode S data link or other similarly bit-limited data links. Further research needs to be done to study the effects of weather image compression on a pilot's situational awareness.

TABLE OF CONTENTS

Executive Summary iii
List of Illustrations vii
List of Tables vii

1. INTRODUCTION 1

2. THE COMPRESSION PROBLEM 3
    2.1 ONE-DIMENSIONAL IMAGE COMPRESSION 4
        2.1.1 Runlength Coding 9
            2.1.1.1 Runlength Variations 9
            2.1.1.2 Huffman Coding 9
            2.1.1.3 Variable-To-Block Coding 10
        2.1.2 Isolated Pixel Removal 10
    2.2 TWO-DIMENSIONAL IMAGE COMPRESSION 10
        2.2.1 Vector Quantization 11
        2.2.2 Contour Coding 11
        2.2.3 Representation by Simple Shapes 12
            2.2.3.1 The Polygon-Ellipse Compression Scheme 12

3. RESULTS ON SAMPLE WEATHER IMAGES 13

4. MODERN COMPRESSION TECHNIQUES 19

5. CONCLUSION 21

REFERENCES 23

LIST OF ILLUSTRATIONS

Figure No.		Page
1	Typical 64x64 Weather-Detailed Image	5
2	Typical 256x256 Weather-Overview Image	7
3	Polygon-Ellipse Compression of 64x64 Images	15
4	Polygon-Ellipse Compression of 256x256 Images	17

LIST OF TABLES

Table No.		Page
1	Average Compression Ratios for Various Algorithms	13

1. INTRODUCTION

The current TDWR (Terminal Doppler Weather Radar), ASR-9 (Airport Surveillance Radar), and NEXRAD (NEXt generation weather RADar) radars are designed to provide weather information to controllers located at the tower or at an en route center. The Integrated Terminal Weather System (ITWS) and the Aviation Weather Products Generator (AWPG) will provide ground personnel with further weather information – much of it in graphical form. Pilots lacking airborne weather avoidance equipment currently rely on verbal exchanges with controllers or flight service personnel to develop awareness of the weather situation. Onboard weather avoidance equipment has range and weather penetration limitations and may not provide a sufficiently accurate picture of the weather. Access to ground-based, graphical weather information transmitted via data link has the potential to greatly improve a pilot's weather situational awareness.

To provide pilots with this information, the FAA is actively developing the capability to provide real-time graphical information of hazardous weather conditions to aircraft by use of data links such as the Mode S data link. This paper describes a study performed to determine how effectively graphical weather images could be compressed for effective transmission given the bandwidth limitations of ground-to-air aviation data links. Section 2 states the goals of weather image compression. Section 2.1 describes a number of one-dimensional compression techniques, while Section 2.2 describes two-dimensional compression techniques. Section 3 gives the measured compression performance for the tested algorithms. Section 4 discusses some additional compression techniques including fractals. Finally, Section 5 states the conclusions of this report.

2. THE COMPRESSION PROBLEM

The information content of weather images and the limited bandwidth of the transmission channel require that the images be compressed. The amount of data that can be transmitted with each weather image is restricted by the bandwidth of the ground-to-air data links. Available and planned aviation data links can provide a typical average throughput of 100-300 bits per second per aircraft. A reasonable goal is to be able to uplink a single weather image to a given aircraft in a few seconds. This equates to compressing each image to the order of 1 to 2 kilobits, or to 1 or 2 Extended Length Messages (ELMs) for the Mode S application.

The importance and content of information within the images is suited to the spatial and temporal resolution of the data, making compression a difficult task. A compression algorithm appropriate for aviation graphical weather images should be able to guarantee a specified level of image compression. The application utilizing the compression algorithm will state the maximum number of bits available for use in encoding the weather image. The compression algorithm should encode the given weather image within the stated bit limitation. The compression algorithm should minimize the amount of distortion introduced in the compression of the weather image, and should permit the control and prioritizing of distortion at each weather level. Finally, the image quality of the expanded image should be as smooth and realistic as possible. The basic shapes and sizes of weather image regions should be maintained at a high level of fidelity. Also, the computational requirements of both the compression and decompression processes need to be considered. Both the compression and decompression processes will be under significant real-time constraints and must run in economically reasonable processing environments.

With no adequate model to analytically describe weather images, the effectiveness of a compression scheme could only be measured by testing on a wide variety of weather images and comparing the results. For our testing purposes, we chose a few dozen actual recorded weather scenarios. The images ranged from 64x64 pixel target-area images with the weather values quantized to the standard six NWS levels, to 256x256 pixel wide-area images with three weather levels (all four NWS storm levels grouped together). Hence, using the above bit-limitation goals, it is possible to determine the compression ratios desired for the transmission of weather images:

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This report presents the results of research performed at Lincoln Laboratory concerning possible data compression schemes. Runlength coding and variations, Huffman coding, variable-to-block coding, vector quantization, contour coding, shape fitting, fractals, and other new compression techniques were all considered, along with the Weather-Huffman (W-H) and Polygon-Ellipse (P-E) algorithms developed at Lincoln. Pre-filtering of weather maps prior to compression was also addressed in each case. The compression ratios of a number of these algorithms for dealing with graphical weather images will be given in Section 3 of this report.

Typical 64x64 and 256x256 graphical weather images are presented in Figures 1 and 2, respectively. The former image is a detailed look at a severe weather region derived from an ASR-9 radar where each pixel is one kilometer in extent, while the latter image is an overview of a storm system derived from a commercial weather vendor where each pixel is approximately 1.6 kilometers in extent.

2.1 ONE-DIMENSIONAL IMAGE COMPRESSION

The term “one-dimensional compression” refers to those routines that act upon the data as a stream of serial values. This serial stream may be generated simply by raster scanning, or by more complex space filling curves such as a Hilbert Curve.

One-dimensional coding algorithms have a number of features that appear to make them attractive for the encoding of weather images. The most desirable feature is the property that they can be made to be information-lossless; that is, the decoded image will be an exact replica of the original image. Besides being information lossless, they also tend to be simple to implement on both the encoding and decoding end, their performance can be predicted and bounded, and they are readily available and well documented.

Several types of one-dimensional coding schemes for the compression of weather have been considered. Some are variations on runlength coding, while others are forms of variable-to-block codes.

2.1.1 Runlength Coding

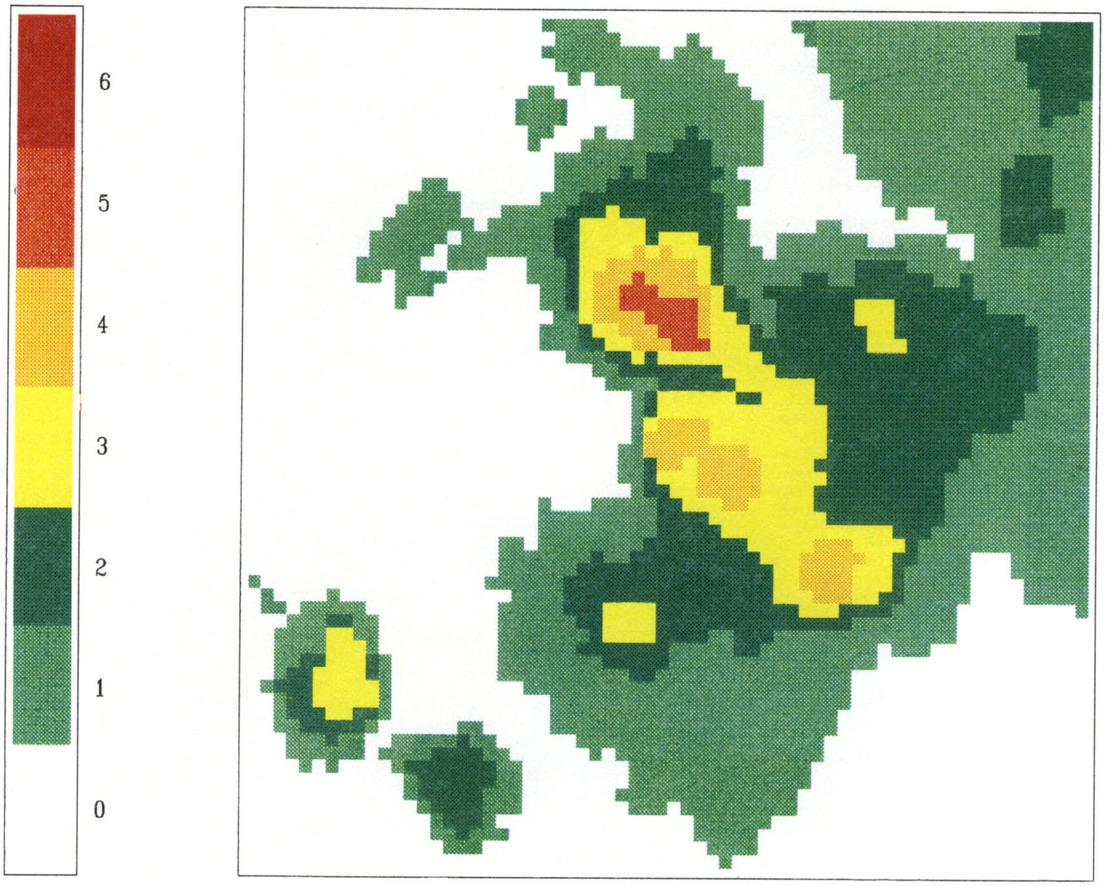
The simplest of the codes studied, and the one serving as a reference for the others, is straight runlength coding. This coding scheme is performed by scanning an image to determine how many successive values occur prior to each transition between levels. The encoded information consists of the value of the new level (or change in level) and the number (runlength) of successive elements with that value. In its most basic implementation, runlength encoding requires that the coded words consist of log(M) bits to represent the weather level plus log(L) bits to represent the runlength count, where:

log() = base-2 logarithm

M = number of quantized weather levels

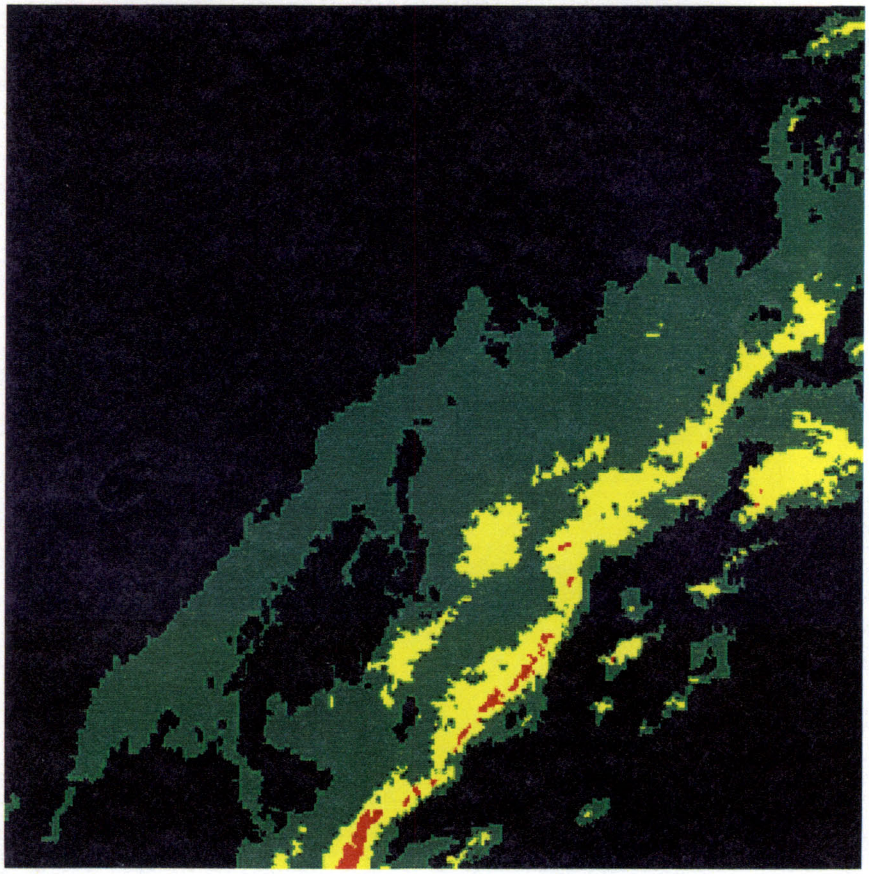
L = longest represented runlength (chosen to be 1 row of the image)

While runlength encoding is efficient for images consisting of long runs, it loses its effectiveness when short runs exist. In fact, in regions of an image that lack large runs of consecutive pixels, runlength coding will actually expand the number of bits required.



ASR-9 Weather Image,
1-Kilometer Resolution
Colors Correspond to NWS Intensity Levels as
Depicted in Bar at Left

Figure 1. Typical 64x64 Weather-Detailed Image.



Commercial Long-Range Weather Image,
1.6-Kilometer Resolution, 400-Kilometer Square

Color Key:

Black: no weather
Green: NWS level 1
Yellow: NWS level 2
Red: NWS levels 3 and above

Figure 2. Typical 256x256 Weather-Overview Image.

2.1.1.1 Runlength Variations

To overcome runlength encoding's drawback when short runs occur, numerous variations have been developed. One commonly used method, *Select*, presents short runs in an unencoded form. An improved method, developed at Lincoln Laboratory, is named *Long/Short*. This approach uses short codewords for short runs and full-length codewords for longer runs. For example, 3-bit words might be used for runs up to 8, and 8-bit words for the remaining runs up to 256; a single bit preceding each word specifies the length. The length of the short codewords is chosen to be optimal for each image, and the selected value is included as the first 3 bits of the transmitted message.

2.1.1.2 Huffman Coding

Theory tells us that if successive runlengths are independent random variables, then the most efficient codes should be entropy codes. Entropy codes are those whose word lengths are based on the frequency of occurrence of a symbol. The most efficient of these codes is the Huffman code. Huffman coding is a variable encoding algorithm where code words are assigned based on runlength probability. This code assignment is optimal in the sense that the average number of bits required to transmit information is minimal subject to the constraint that no code word is the prefix of any other code word, allowing the received sequence to be uniquely decodable. Huffman coding of the runlengths, although optimal, loses some of its attractiveness due to the overhead associated with the transmission of the code table to the decoder.

In addition to the decoding table problem, the Huffman algorithm produces some very long codewords due to the need to assign a unique codeword to every combination of level and length. These problems have been circumvented at Lincoln by modifying the Huffman coding procedure to create the Weather-Huffman Algorithm [1]. This algorithm re-uses codewords; in fact each short codeword can be used once for each image level. In addition, the decoding table is itself compressed by numerous special techniques. The result has been that the Weather-Huffman Algorithm, with its table, requires far fewer bits than the normal Huffman approach without its table.

The Weather-Huffman Algorithm includes mechanisms to reduce the bit transmission requirement to meet any pre-specified limit. This is useful when it is desired to constrain the entire weather image to a preset number of bits.

2.1.1.3 Variable-To-Block Coding

Adaptive variable-to-block codes constrain each output codeword to be a fixed length. Depending on the parameters of the particular code and the statistics of the source, variable numbers of the source pixels will be encoded in the fixed output block code. Much like runlength coding, the length of source code represented by each codeword is dependent on the redundancy of the source, yet unlike runlength coding the redundancy is not restricted to consecutive identical pixels.

The two specific codes of this type that have been studied are Lempel-Ziv and Welch (which is a variation on the Lempel-Ziv scheme). The Lempel-Ziv code describes a segment of source symbols by relating it to what it has in common with symbols that have already been encoded. The more the pre- and post-encoded blocks have in common, the more symbols that can be contained in each encoded block. A variation on the basic Lempel-Ziv code is Welch's code. With Welch, code words are created and placed in a table as new patterns manifest themselves in the code.

2.1.2 Isolated Pixel Removal

When the Hilbert scan is used on a weather image (rather than the usual raster scan), the most common runlength tends to be one. By removing single isolated pixels between two runs of the same level, i.e., by converting 00010000 to 00000000, significantly greater compression can be attained by all runlength techniques. The resulting image distortion is generally negligible.

2.2 TWO-DIMENSIONAL IMAGE COMPRESSION

Weather images have a two-dimensional structure to their content, and higher compression ratios can be obtained by fully exploiting this structure. By removing the process of converting the image from a two to a one-dimensional source, and instead operating directly on the two-dimensional image, algorithms have been developed that greatly increase compression. Besides operating in two dimensions, the requirement that no information be lost in encoding has also been removed in a further attempt to improve compression results. Of course, this action will require that compression be weighted against distortion when judging the results.

The two-dimensional coding algorithms rely on using descriptors of the images in the plane in order to effect compression. If the image to be described is a very complex one, very little compression can be effected unless image "simplification" is first applied. Simplification, in this context, refers to the removal of isolated non-connected cells, the merging together of closely spaced cells to create large connected regions, and the smoothing of region boundaries. Once the images have been filtered to a set of representative connected regions, compression can be realized by efficiently encoding the contours of the different weather regions, or by fitting shapes to the regions.

A further advantage of these codes (most especially the contour and shape fitting codes) is that the number of bits produced in the encoding need not be specifically tied to the information content of the weather image. That is, provisions in the algorithms can be stipulated that would reduce each image to a predetermined bit level.

2.2.1 Vector Quantization

Vector quantization is the mapping of a block of image samples into one of a finite set of representative vectors, followed by the transmission of a codeword that identifies the vector. To increase compression and keep the processing simple, not all possible sample blocks are assigned unique code words; instead code-words are assigned to a subset of possible blocks and a minimum mean-squared error (MSE) criteria is used for the assignment of codewords to the remaining blocks. It is easy to see the direct tradeoff that can be made between compression and distortion.

This approach was found to be unacceptable for the weather image problem. Even a block as large as 4x4 pixels, represented as a single solid weather level, which would severely distort the weather image, produces over 8000 bits for the 256x256 images.

2.2.2 Contour Coding

Within any single weather display there will exist a number of connected weather regions. The information about these weather regions consists of their intensity level and their location within the image. By converting the separate weather regions into one-dimensional sequences of contour points (each point consisting of an x and y location), and then by processing these sequences, compression may by realized.

The easiest method of encoding the set of x and y contour points is by coding the difference between samples. Due to the nature of a contour, the difference between any two adjacent x or y contour point can be represented by only three bits, used to describe the eight possible directions of movement (North, South, East, West, Northeast, Southeast, Southwest and Northwest).

To add further to the compression, there is the possibility of reducing the number of points in the contour set. One such technique reduces the set by removing the points that lie on a straight line connecting break points; the reduction technique is optimized by picking the end points to be as far apart as possible. Further reduction can be realized by removing points that lie some pre-specified tolerance away from a straight line. The larger the tolerance level, the more points removed, the greater the compression, and the greater the distortion. The contour is reconstructed by returning removed points by linear interpolation.

2.2.3 Representation by Simple Shapes

The final method of compression is shape representation. With this method an area of weather is represented by a simple shape, or a collection of shapes, and then encoded as the set of descriptors of these shapes. Reconstruction is then a simple task of displaying, according to their descriptors, the representative shapes.

The most obvious shape chosen as a means of representing weather is the ellipse. The ellipse not only matches many real weather patterns but also is a shape that is easily extracted from a connected weather region. By altering an ellipse's descriptors — size, center, eccentricity, and orientation — any smooth object within the plane, from lines to circles, can be represented by an ellipse.

2.2.3.1 The Polygon-Ellipse Compression Scheme

The Polygon-Ellipse Algorithm [1] (Patent Pending) developed at Lincoln Laboratory takes the best facets of the contour coding and shape fitting approaches, adds new wrinkles, and produces an all-encompassing approach to compressing weather images within a pre-specified bit limitation. Some of the characteristics of this approach are:

1. the most critical weather levels are most faithfully represented when distortion is required.
2. the parameter change that produces the minimum distortion possible is selected at each bit-reduction step.

3. bit-reduction techniques are used to encode shape parameters so that the most possible parameters can be utilized within the bit limitation.
4. weather "holes," or areas of light weather within a storm contour, are maintained, a drawback of other shape-fitting approaches.

The basic approach of the Polygon-Ellipse Algorithm is to represent elliptical weather regions by ellipses, and other regions by polygons that follow their contour. When bit limitation requires distortion, two processes occur in parallel: more regions are classified as elliptical, and fewer vertices are used to define the contouring polygons.

3. RESULTS ON SAMPLE WEATHER IMAGES

Several of the standard and new compression techniques were tested on a set of sample weather images. Both the actual images, and the isolated-point-removed images were encoded. The Hilbert scan was assumed in each case, as it improves results in all cases over the raster scan. The average compression results were as follows:

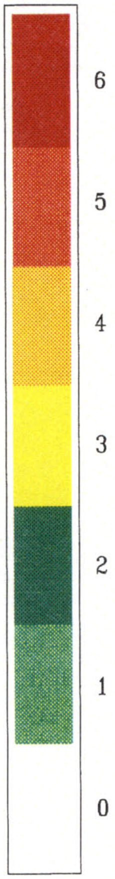
Table 1. Average Compression Ratios For Various Algorithms

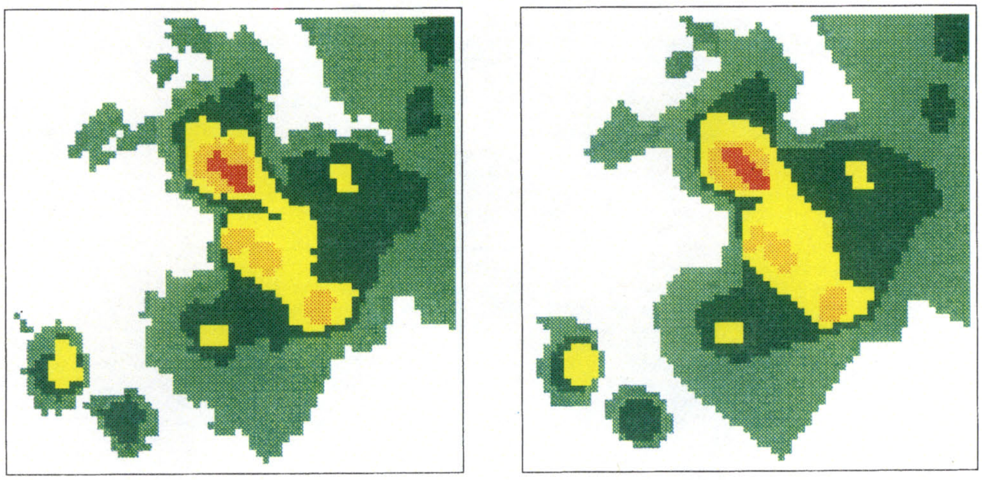
	64x64	64x64 filtered	256x256	256x256 filtered
GOAL	12.0	12.0	64.0	64.0
runlength	2.0	4.0	4.0	7.5
long/short	2.5	5.0	6.0	10.5
Huffman (with table)	3.0	4.5	6.0	9.0
Lempel-Ziv	3.0	4.5	6.0	8.0
Weather-Huffman (W-H)	4.5	7.5	8.0	12.0
W-H (bit-limited)	12.0	12.0	64.0	64.0
Polygon-Ellipse (P-E)	4.0	5.0	7.0	11.0
P-E (bit-limited)	12.0	12.0	64.0	64.0

It is clear from these results that only the Weather-Huffman and Polygon-Ellipse Algorithms provide the desired degree of compression when a bit limit is imposed. It is interesting to note that even without a bit limit, these algorithms provide better compression than any of the other alternatives. The Polygon-Ellipse Algorithm was identified as the preferred approach because it is able to

1. provide less distortion in general,
2. present a more easily interpreted picture, as it is smoother and less blocky ,
3. provide weather level distortion priorities more accurately, and
4. scale to different image dimensions more easily.

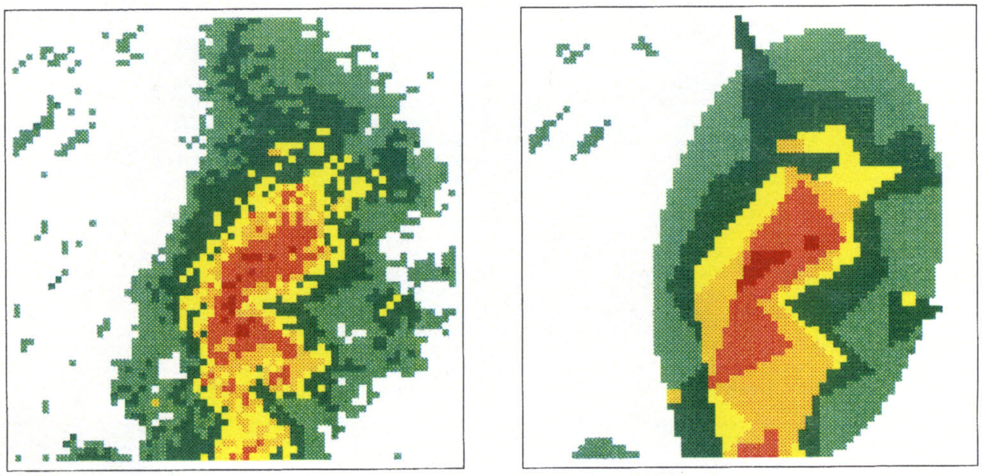
The results of applying the Polygon-Ellipse Algorithm to some sample 64x64 and 256x256 weather images are presented by Figures 3 and 4, respectively. The weather images in the top row of Figure 3 were recorded from an ASR-9 radar and each pixel is one kilometer in extent. The weather images in the bottom row of Figure 3 were recorded from a TDWR radar and each pixel is 0.25 kilometers in extent. The weather images in Figure 4 were recorded from a commercial weather image vendor and each pixel is approximately 1.6 kilometer in extent. These figures illustrate the low levels of distortion that result even when complex images are to be compressed to 1K or 2K bits, respectively. The use of ellipses when appropriate and polygons at other times is clearly shown by these examples.





ASR-9 64x64 Image,
1-Kilometer Resolution

1 ELM Polygon-Ellipse Compression
of Image on Left

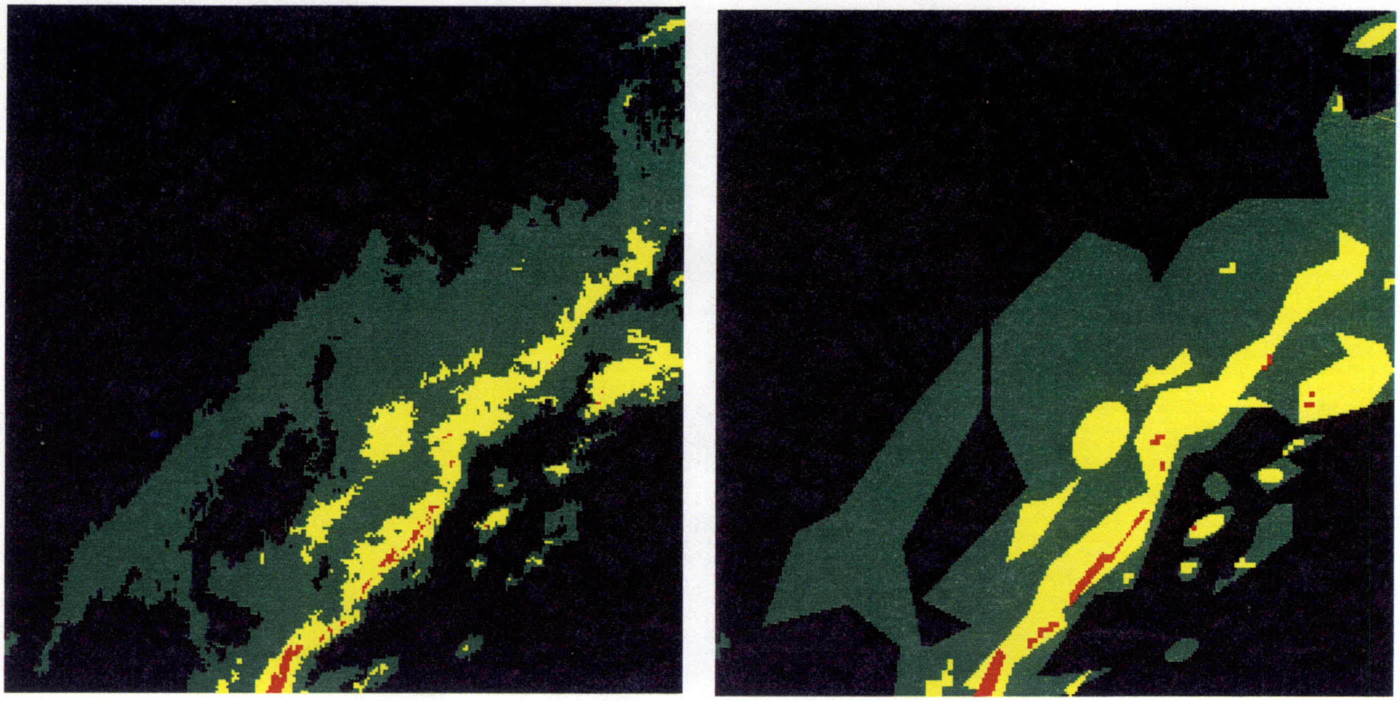


TDWR 64x64 Image,
0.25-Kilometer Resolution

1 ELM Polygon-Ellipse Compression
of Image on Left

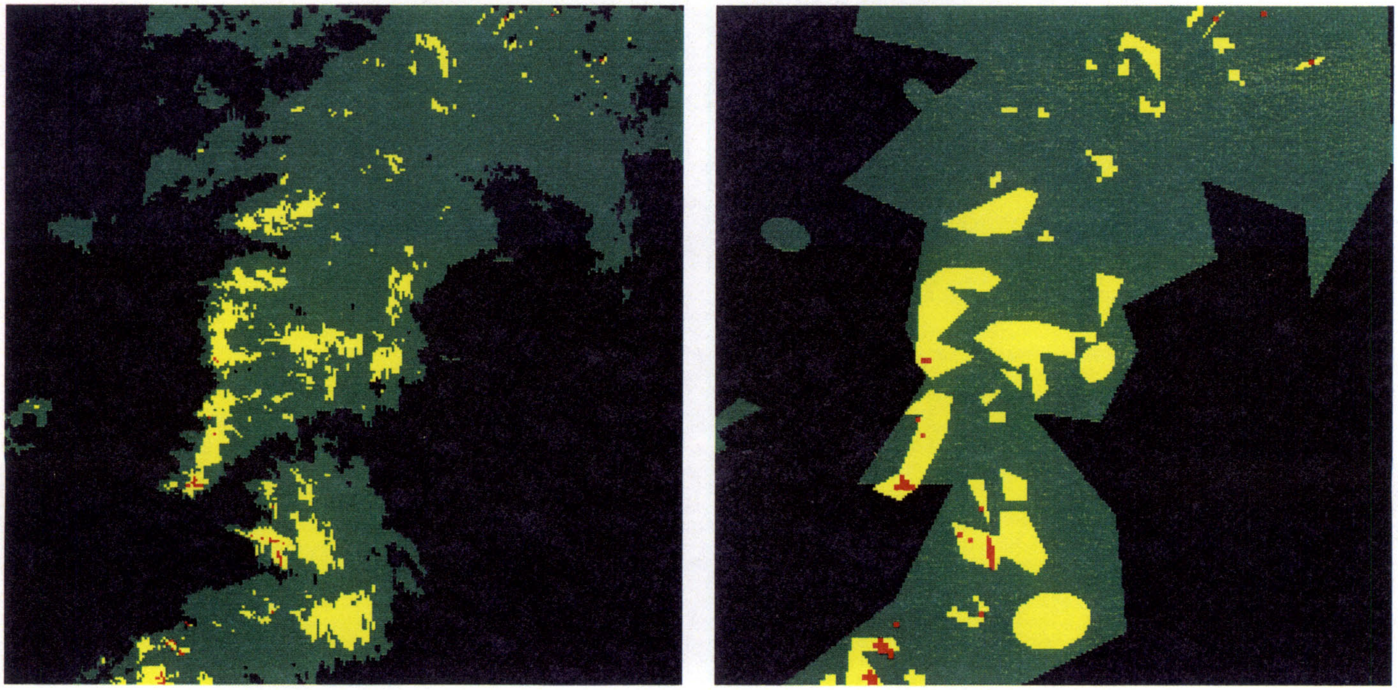
Colors Correspond to NWS Intensity Levels as
Depicted in Bar at Left

Figure 3. Polygon-Ellipse Compression of 64x64 Maps.



Sample Commercial Long-Range 256x256 Image,
1.6-Kilometer Resolution

2 ELM Polygon-Ellipse Compression
of Image on Left



Sample Commercial Long-Range 256x256 Image,
1.6-Kilometer Resolution

2 ELM Polygon-Ellipse Compression
of Image on Left

Color Key: Black: no weather, Green: NWS level 1, Yellow: NWS level 2, Red: NWS levels 3 and above

Figure 4. Polygon-Ellipse Compression of 256x256 Maps.

4. MODERN COMPRESSION TECHNIQUES

In recent years, many new compression techniques have come on the scene with great publicity (for example, see [2]). The best known examples are fractals, wavelets, and cosine transforms. Fractal compression techniques can produce typical compression ratios of over 100-1, with maximum compression ratios approaching 1000-1. Cosine transform and wavelet techniques are typically used at compression ratios of 10-1 up to 25-1, since they can have significant image distortion at higher compression ratios. All of these techniques share two main characteristics: they are computer intensive, and they are meant to compress megabit, highly redundant graphical images such as television pictures. Weather images, unfortunately, do not match the intended audience of these approaches.

Image compression techniques using fractals, wavelets, or the cosine transformation require extensive computational capabilities or special-purpose hardware in order to achieve near real-time performance. For instance, the compression processing of a single image using the fractal technique might take several minutes—compared to the few seconds required for the Polygon-Ellipse or Weather-Huffman compression algorithms. In addition to the ground processing required, the computer onboard an aircraft might require as much as a minute to decode images compressed with some of these techniques – compared to the tens of milliseconds required by the Polygon-Ellipse or Weather-Huffman decompression algorithms. Reference [3] describes an implementation of fractal image compression for complex images that achieves 100-1 compression ratios running on a high-performance personal computer. The fractal compression of a single graphical image requires 8 minutes, and the decompression processing requires 7 seconds. [3] also describes a cosine-transform image compression implementation using the Joint Photographic Experts Group (JPEG) algorithm. The JPEG compression of a single image required 41 seconds, with the decompression processing also requiring 41 seconds for a single graphical image. Clearly this load and this delay would be unacceptable for real-time aviation use.

It appears that none of these new image compression techniques is currently appropriate for the task of compressing graphical weather images for real-time data link transmission. Wavelet and cosine transform compression do not typically obtain the necessary compression ratio and image quality for large-scale weather images, and they lack the ability to directly apply a bit-limit or impose distortion priorities to weather levels. Fractal compression can in some cases approach the desired compression ratios and image quality, but is too computationally inefficient for a real-time implementation in contemporary ground systems and avionics.

5. CONCLUSION

This report has illustrated the measured compression performance for a number of algorithms used to compress graphical weather images (see Table 1). Some of these algorithms were standard compression methods, while others were specially developed for the case of graphical weather images. Of these algorithms, only the Polygon-Ellipse and Weather-Huffman achieved the desired compression ratio necessary for effective use of the restricted-bandwidth aviation data links while also being computationally efficient. The Polygon-Ellipse algorithm is preferred over the Weather-Huffman algorithm because it

1. provides less distortion in general,
2. provides a smoother and less blocky image,
3. provides weather level distortion priorities more readily, and
4. scales to different image dimensions more easily.

In conclusion, the Polygon-Ellipse algorithm has significant potential for the encoding of weather images over the Mode S data link or other similarly bit-limited data links. Further research needs to be done to study the effects of weather image compression on a pilot's situational awareness.

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