The Art of Compression: JPEG and JPEG-2000 on Multispectral Satellite Imaging

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Background

What is Image Compression?

- A process that makes image files smaller for efficient transmission and storage

There are two main methods of Image Compression:

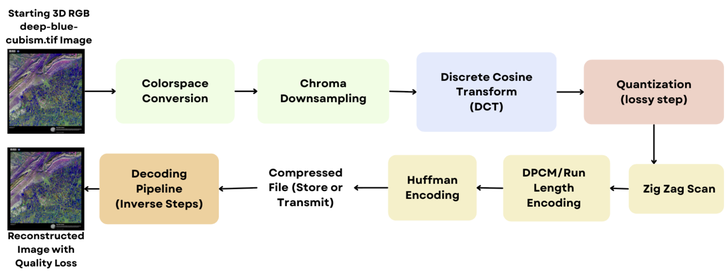
- **Lossy Compression**: Higher compression, lose image quality
- **Lossless Compression**: Less compression, preserve full image quality

Two widely used image compression standards are **JPEG (lossy)** and **JPEG 2000 (lossy or lossless)**

Objectives

- Explore the underlying implementation of different compression pipelines in the context of large satellite tiff images that require large processing power.
- Are there certain optimizations or ideal parameters/methods that better balance the tradeoffs between computational complexity, compression efficiency, and perceptual quality?

JPEG Implementation Pipeline

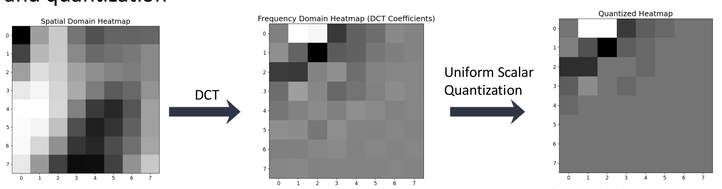


DCT and Quantization

DCT is the main transformation in the pipeline, transforming spatial pixel data into frequency data which is more easily manipulated for compression. Quantization is the subsequent lossy step.

$$\mathrm{DCT}(i,j) = \frac{1}{\sqrt{2N}} C(i)C(j) \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} \mathrm{pixel}(x,y) \cos\left[\frac{(2x+1)i\pi}{2N}\right] \cos\left[\frac{(2y+1)j\pi}{2N}\right]$$

Example 8x8 block transformation from deep-blue-cubism.tif and quantization



Original 8x8 Pixel Block

52.0	139.0	162.0	116.0	97.0	107.0	107.0	108.0
89.0	153.0	163.0	127.0	110.0	114.0	118.0	127.0
139.0	173.0	165.0	142.0	130.0	124.0	120.0	127.0
179.0	187.0	169.0	145.0	120.0	102.0	109.0	133.0
191.0	192.0	170.0	123.0	84.0	74.0	99.0	140.0
190.0	186.0	157.0	95.0	69.0	81.0	105.0	139.0
189.0	170.0	131.0	82.0	73.0	94.0	113.0	143.0
179.0	136.0	88.0	59.0	60.0	88.0	132.0	161.0

DCT Coefficients

-5.8	132.6	123.7	-83.2	-38.8	-26.3	3.4	-1.5
10.4	-36.2	-144.4	-45.6	-38.6	-15.5	-6.4	-2.6
-79.5	-82.8	-1.4	10.5	-25.3	-1.0	0.7	0.8
-26.4	27.0	2.7	-32.0	-19.8	-3.9	7.3	1.5
-16.2	-2.8	6.1	-5.5	10.2	5.3	-3.6	0.5
11.3	9.0	-15.6	9.7	-1.8	-3.5	1.4	-1.0
-5.0	-5.0	0.7	4.5	-3.6	1.1	-0.6	0.7
1.0	3.6	-2.9	-0.5	-0.5	-1.1	0.4	-0.7

Quantized DCT Coefficients

0	12	12	-5	-2	-1	0	0
1	-3	-10	-2	-1	0	0	0
-6	-6	0	0	-1	0	0	0
-2	2	0	-1	0	0	0	0
-1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Metrics & Dataset

Dataset: USGS Earth As Art 6

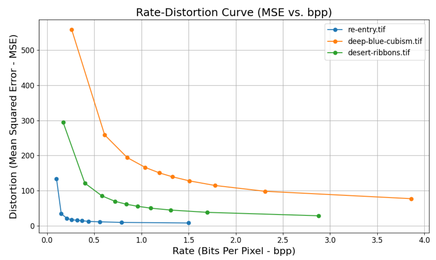
- Contains high-resolution multispectral satellite images, capturing different color combinations the human eye cannot see
- Images act as a gateway for public interest in the Earth that we live on and into better understanding it.
- Files come in raw tiff format (~50MB)

The JPEG and JPEG 2000 processing pipelines both implemented using Python 3

Metric	Measures	Interpretation
Peak Signal to Noise Ratio (PSNR)	Power of corrupting noise that affects the fidelity of a signal.	High value indicates greater quality
Structural Similarity Index (SSIM)	Similarity between two images. Better mimics human visual perception.	Value of 1 indicates complete similarity between original and decompressed image
Mean Squared Error (MSE)	Measures the average squared difference between original and compressed pixel values.	Smaller value indicates smaller distortion between pixel values
Edge Density	Ratio of edge pixels to total number of pixels	Larger value indicates higher ratio of edges/higher image complexity
Bits Per Pixel (BPP)	Measures the number of bits required to store one pixel.	Smaller value indicates greater compression per pixel

Results and Analysis

Quality Levels (Quantization Scaling) vs Distortion

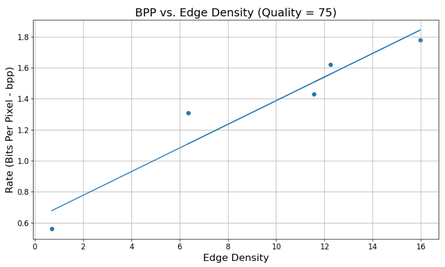


Tested quality levels: 5, 15, 25, 35, 45, 55, 65, 75, 85, 95

Quality = 95

Quality = 5

Image Complexity vs Compression Efficiency



Tested compression efficiency (BPP) on 5 images with varying edge densities.

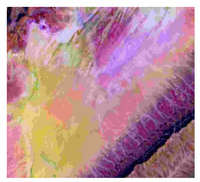
Trend line indicates positive linear relationship between edge density and BPP.

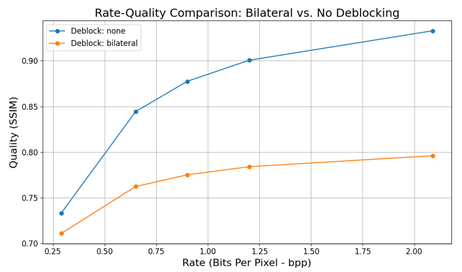
The points are spread near the trend line.

Deblocking and SSIM

No Adjustment
Quality = 5

Bilateral Deblocking
Quality = 5

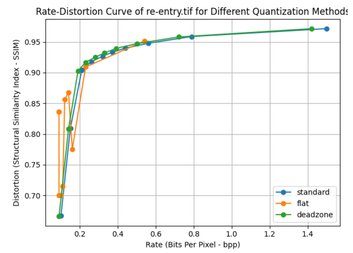


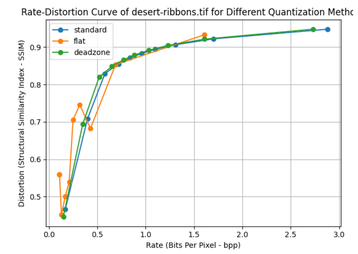


Results and Analysis

Comparison of Compression Efficiency of Quantization Methods

Tested 3 Methods: Standard JPEG Uniform Scalar Quantization (USQ), naïve implementation (flat) with large values of 99, and Uniform Scalar DeadZone Quantization (USDZQ)





For both test images, the flat table fluctuates between high and low SSIM measures relative to the other methods.
Standard and deadzone closely follow similar trends with deadzone method having marginally better SSIM measures than the standard quantization method.

Conclusion and Further Studies

- Increase in scale of quantization (decreasing quality levels) leads to greater distortion of image quality, but simultaneously increases compression efficiency
- Positive linear relationship between the edge density (intrinsic complexity) of an image and the degradation of its compression efficiency.
- Flat quantization is unpredictable, and USDZQ is more computationally intensive than USQ while having slightly better results.
- Bilateral deblocking adjusts visual perception by smoothing out blocking artifacts, however, has lower quality metrics. This indicates that metrics like PSNR and SSIM may have limited ability to represent full aspect of subjective human visual distortion perception.
- Further studies include critical satellite downstream classification analysis using machine learning models (e.g. landslide detection or crop classification) after varying distortion levels from compression.

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