CHAPTER I

INTRODUCTION

1.1 GENERAL

Vision is the most elegant and chief of all our senses [Campbell and Gubisch, 1966]. As a matter of fact, 80% to 90% of all neurons in the human brain are predicted to be devoted to vision signal processing [Roger and Margaret, 2006]. Consequently, it is not amazing that images play the single most important role in human perception [Ambadar et al., 2005]. The image serves as a medium of communication between human beings, irrespective of their language [Manovich, 2001].

1.2 IMAGES

The Lexicon defines that, the image is the optical appearance of an object produced in a mirror or through to a lens [Goldberg and McDermott, 1987]. An image can be created by other means, using radiant energy and devices. But, optical images are most common and most important of all. The quantity of light energy received at a point of a scene by an observer or by an image sensor varies with direction and distance of the point. The image is formed by recording the energy at its corresponding points on a plane. Hence, the luminosity and color recorded in an image can be denoted as the function of several variables. The black and white images are the modest kind of intensity image that can be created [Bjelkhagen et al., 1996].

1.3 DIGITAL IMAGES

A digital image is the numerical representation of a two-dimensional image. Digital images may be acquired from a three-dimensional scene in the real world. Normally digital images consume a finite set of digital values, which are represented by picture element or pixels [Yang et al., 2004]. The pixels are represented by using a static number of columns and rows. Pixels are the tiny unique element in an image, which holds a quantized value to represent the luminance of the specified color at any specific point. Naturally, in computer memory the pixels are stored as a two-dimensional array of integers which are used to transmit the image are stored the image in memory [James and E. Blelloch and, 1989] and [John, 2016].
1.3.1 Capturing Digital Image

Usually, the images captured by the cameras are converted into electrical signals and stored using Charge Coupled Device (CCD) cells. The analog charge stored in the CCD cell should be converted into a digital value. This process is done by applying a flash analog to digital converter. By this process, the image produced are lossless. Digital images can be denoted as M x N matrix, the elements present in the matrix array should represent a pixel. The digital images can be classified into three categories, Black and White, Gray Scale and Color images, depending on the number of colors that each pixel in the image can represent [Nakamura, 2016].

1.3.2 Binary (Black and White) image

Single bit of the pixel is used to represent the Black and White image. These bits can be either in on or off state, in binary image every pixel can represent only one color, the color may be black or white. The incapability to represent the shades of gray color limits the use of black and white imaging to deal with photography.

1.3.3 Gray Scale Image

Pixels are used to form a grayscale image, each pixel in the grayscale image can hold a single value which is equivalent to the gray level of the image at a specified location. The black and white images are transformed into a gray color image by a series of very fine steps. Usually, the gray color has 256 different gray levels [Welsh et al., 2002].

1.3.4 Color Image

Same as binary and grayscale image, color images are also constructed by pixels. Each pixel holds the numbers representing Red, Green and Blue (RGB) levels of the image at a particular location.

The RGB colors are the primary colors used for mixing light. By mixing Red, green, and blue lights in correct proportion any color lights or any color can be created. Each color pixels uses three bytes to storage space in memory. If 256 levels for each primary color is given, we can easily create 16.7 million different colors. In order to store color image, it takes three times more memory space than a gray scale image [Plataniotis and Venetsanopoulos, 2013] and [Adams et al., 1998].
Usually, a logical MxN matrix is used to represent binary image which has a pixel values of true (1) and false (0). Hence, MxN bits are stored. A image with height of M pixels and width of N pixels are represented as a matrix of size MxN. The element values for black and white image is 0 and 255 for grayscale image it is from 0 to 255 respectively. Hence, MxNx8 bits are required to store a grayscale image. RGB images are three dimensional and represented in matrix form as MxNx3. Each pixel in a color image needs to hold three color components red, green and blue along with the three dimensional values ranging from 0 to 255. So, the storage requirement of the color image is MxNx24. As the resolution increases, the storage requirement also increases [Mishra et al., 2015].

The image data needs a sizable transmission bandwidth and storage capacity. The capabilities of available technologies are outstripped, due to the demand in data storage capacity and transmission bandwidth, mass growth in storage density, speed of the processor and the performance of digital communication system are generating a huge volume of image data. The recent growth in multimedia based web applications need an extensive data to be handled every day. So, they need more efficiency to sustain the need to encode the signals and images. compression made such signals to store in central storage system and to transmit when needed. The compression can only be achieved by analyzing the redundancies present in the images [Adrian and Knowles, 1992].

1.4 REDUNDANCY IN IMAGES

The redundancy in images are formed by the correlation between the neighboring pixels this characteristic is most common in all type of images. The primary task is to find less correlated representation of the image. The two basic parameters of compression are irrelevancy reduction and redundancy [Haralick and Shapiro, 1985]. Removing the duplication from the signal source is the aim of redundancy reduction and the irrelevancy reduction works by omitting few signal parts which will not be noticed by the signal receiver, usually the HVS (Human Visual System). Generally, the redundancy that can be identified are divided into three.

- Spatial Redundancy
- Code Redundancy and
- Temporal Redundancy.
1.4.1 Coding Redundancy

A code can be represented as a symbol in a system. The code can be of a letter, numbers, bits, etc. which are used to represent a set of events or information. The sequence of symbols assigned to the information or to the event are referred to the term called code word and the length of the code word is measured by the number of symbols it is holding. The symbols length can be reduced by allotting smaller number of bits to represent more frequent symbols and large number of bits for less frequent symbols. By this reduction of coding redundancy can be achieved [Larsen and Reed, 1972].

1.4.2 Spatial Redundancy

The inter-pixel correlations within an image is directly associated to spatial redundancy. Spatially correlated pixels are mostly available in images obviously, the representation of information is unnecessarily replicated with respect to the correlated pixels. The value of any pixel can be reasonably predicted from the value of its neighbors. The individual pixels carry only a small quantity of information. Most of the visual contribution from a pixel to an image is redundant. It can be predicted on the basis of the value of its neighbors [Larsen and Reed, 1972].

1.4.3 Temporal Redundancy

This type of redundancy is usually found in video data. The video data is represented using a series of image frames. These frames contain spatial and temporal redundancy. The compression method tries to make the code smaller in size or delete it. The encoding can be done only by recording the alteration between frames, or by using the unique feature of human vision system [Larsen and Reed, 1972].

1.4.4 Irrelevant Information

The human visual system normally discard few information contained in an image while viewing it, which are available more than to express the intended use of the image. The main goal of the compression algorithm research is to eliminate the irrelevant information present in image data. This process will decrease the number of bits used to represent the image by which the storage volume of the image will be reduced.
1.5 IMAGE COMPRESSION

Image compression is the process of dropping the volume of data needed to represent the image [Shi and Sun, 1999]. By this it reduces the storage and transmission time. The compression techniques usually, compress the data by finding the redundancies present in the data and eliminating those redundancies or by eliminating irrelevant information. The compressed data or image is the remaining portion of this elimination process.

Ideally, the image compression methods use a reversible transform to de-correlate the image data, this process is done by manipulating the redundant data. Depending up on the compression methods the transform can be applied directly to the whole image are to the small segment of the image. The compression method using transforms for de-correlating the image before compression is known as transform coding [Sayood, 2012]. While using transform coding, the original image will be segmented and transformed to another form, the coefficients representing the transform are known as transform coefficients which are highly de-correlated. The decorrelation filters the important information into a compact form [DeVore et al., 1992].

Then the redundancy available in transform coefficients are removed by the compressor and the remaining data is stored as the compressed file. In order to recover the original file after compression a reverse process of compression is performed in the compressed file or data. The decompressed image may have few errors or distortion while comparing to the original image [Tomar and Jain, 2016]. Figure 1.1 shows the block diagram of encoder and decoder of typical image compression system.

The part of the encoder is transform which may or may not be applied because the transform is not used by all compression methods, the transform in the encoder is not often used in whole image. Since it deals with smaller regions of image blocks [Jayaraman, 2011].

1.5.1 Image Segmentation

Segmentation is the process of splitting the data into various sized and shaped regions. The transform procedure cannot be applied in the whole image data, because the efficiency of the transform will be reduced. Consequently, the regions of the image blocks are shaped in order to increase the effectiveness of the transformation [Zhang, 1996].
1.5.2 Transform

Typically, a pair of functions perform the transforms the first function is forward and second one is inverse transforms. If both the functions are applied without compression, then the transform is either seamlessly rebuilding (lossless), or the image data is quantized and lost after the transform stage (lossy). A lossless transform does not further complicate an image compressor since it makes no conclusions about which portions of the image data are useful. Nevertheless, a lossy transform can often get more compression or allow the transform algorithm to operate faster, both of which may be advantageous [Pensiri, 2011].

A transform can be of the three-type orthogonal, orthonormal or non-orthogonal. Widely image compression algorithms use orthogonal/orthonormal transform; because there efficient in de-correlating the transform coefficients. The ‘Wavelet Transform’ and ‘Discrete Cosine Transform’ (DCT) are examples of orthonormal transforms [Stankovic et al., 2015].

1.5.3 Compression

After image transformation, the necessary step is to compress the decorrelated data, entropy coding and quantization are two methods used to achieve compression.

Quantization remains the method of dropping the precision of the transformed coefficients, maybe some coefficient is completely eliminated. This process is often done before entropy coding in order to expand the compression.

The compression of the image is normally measured by compression ratio and bpp. Compression ratio is calculated by relating the original image with the compressed image by using Equation 1.1.
**Compression Ratio** \( (CR) = \frac{(Compressed\ Size)}{(Original\ Size)} \) \hspace{1cm} (1.1)

Bits Per Pixel (bpp) is the number of bits required to define one pixel of the image, usually an average over the whole image, which can be measured by Equation [1.2]

\[
bp\text{p} = \frac{(Total\ bits\ needed\ to\ represent\ the\ compressed\ image)}{(Total\ number\ of\ pixels\ in\ the\ image)} \hspace{1cm} (1.2)
\]

The relation between compression ratio and bpp for a grayscale image is given in Equation [1.3]

\[
Compression\ Ratio = \frac{8}{bpp} \hspace{1cm} (1.3)
\]

The definitive goal of an image compressor is to provide extreme compression ratio with minimum alteration [Jun and Kun, 1996].

### 1.5.4 Alteration Measures

The alteration or mistake happened in the compressed image after compression procedure, can be measured in numerous ways. The commonly used distortion measures are broadly classified into two groups, subjective and objective.

**Subjective Method**

Spontaneously we can say human himself is the best judge to define a character, so subjective methods are believed to be the most accurate measures of perceptual quality and to date subjective experiments are the only widely known method of judging perceived quality, in this test humans are involved humans are involved who have to vote for the quality of a medium in a controlled test environment. This can be caused by just offering a distorted medium of which the quality has to be appraised by the study. Another path is to additionally supply a reference medium which the field can use to learn the comparative tone of the distorted medium.

The images are provided to the group of assessors, each assessor assigned are asked to grade the compressed image with regard to the original picture. These marks may be splendid, good, fair, poor and unacceptable. The grades allotted by the assessors give an
overall idea about the reconstructed image quality.

This process is a branch of psycho-visual image analysis, with enormous scope, but regrettably just a little forward motion has been built for automated method for calculating psycho-visual distortion measure.

**Objective Methods**

Objective quality metrics are divided into three they are.

**Full-Reference (FR)**

Full-Reference is alternative possible classification of image quality measures can be created according to the accessibility of a reference image. Most of existing approaches are full-reference (FR), which means that complete reference image is available during an evaluation Shnayderman et al. [2006].

**No-Reference (NR)**

In this method reference image is not available at all.

**Reduced-Reference (RR)**

This method measures the image quality with the help of features extracted from a reference image [Soundararajan and Bovik, 2012].

Mean Square Error (MSE), Signal to Noise Ratio (SNR) and Peak Signal to Noise Ratio (PSNR) are the mainly used objective measures. The cumulative square error is known as MSE, if the error is low, MSE values will be less and it will be converted to a higher value of PSNR. The ratio among meaningful information and the unwanted information is known as SNR calculated using Equation (1.6), it is a measure of the signal strength related to background noise [Kusuma and Zepernick, 2003] and [Saffor and Ramli, 2001].

The peak error among the compressed image and original image is determined by PSNR values. For better compression PSNR value must be higher, signal in the original image and noise is the error in the reconstructed image [Turaga et al., 2004].

Matrix a is denoted elements $a_{ij}$, with $i \in \{1..M\}$, $j \in \{1..N\}$, as the input of compression system. where M denotes the number of image elements in vertical path and N denotes the number of image elements in horizontal path. The total number of image element is denoted as MxN. $a'$ with elements $a'_{ij}$ is the resultant matrix formed by the compression system. The error or the loss of image quality is measured by the distance between the elements of matrices $a$ and $a'$. Typically, the error will be superior if the compression ratio is high. The compression ratio can be defined by the user, which directly impact in the data size of the
The total reconstruction error is defined by Equation 1.4:

\[ E = \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \| a_{ij} - a'_{ij} \|^2 \] (1.4)

The distance between matrices \( a \) and \( a' \) is frequently calculated using the MSE (Equation 1.5):

\[ MSE = \frac{E_{MN}}{MN} = \frac{1}{MN} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \| a_{ij} - a'_{ij} \|^2 \] (1.5)

\[ SNR = 20 \cdot \log_{10} \left( \frac{P_{signal}}{P_{noise}} \right) \] (1.6)

The \( M \times N \) is the total number of pixels in an image, and the sum will be applied to all image elements. The range \([0, 2^{n}-1]\) is the amplitude of image elements, \( n \) is the number of bits needed for binary representation of amplitude of each element in the original image. The difference between amplitudes are only considered by MSE, but PSNR is introduced to reflect amplitudes of image elements.

\[ PSNR = 10 \cdot \log_{10} \left( \frac{MAX^2}{MSE} \right) = 20 \cdot \log_{10} \left( \frac{MAX_I}{\sqrt{MSE}} \right) \] (1.7)

The maximum amplitude value of an image pixel is depicted by the variable \( MAX_I \). When the amplitude of the image pixel is represented by \( B \) bits, \( MAX_I = 2^B \). We can define \( n = 8 \) bits/image element by

\[ PSNR = 10 \cdot \log_{10} \left( \frac{255^2}{MSE} \right) \] (1.8)

The SNR and PSNR values are calculated using the Equation 1.6, 1.7 and 1.8 respectively.

PSNR values for classic “lossy” compression images will be between 30 to 50 dB [Jaksic et al., 2015].

### 1.6 HISTORY OF DATA COMPRESSION

Giambattista della Porta, a Renaissance scientist, was the author of a book named *Magia Naturalis* (Natural Magic) written in 1558 is a book in which he discusses many subjects,
including demonology, magnetism, and the camera obscura. The book says about an imaginary device that has later known as the “sympathetic telegraph”. This device was to have entailed of two circular boxes, similar to compasses, each with a magnetic needle. Each box was to be labeled with the 26 letters, instead of the usual directions, and the main point was that the two needles were supposed be magnetized by the same lodestone. Porta assumed that this would somehow coordinate the needles such that when a letter was dialed in one box, the needle in the other box would swing to point to the same letter [Porta, 1957]. Needles to say, such a device does not work (this, after all, was about 300 years before Samuel Morse), but in 1711 a worried wife wrote to the Spectator, a London periodical, asking for advice on how to bear the long absences of her beloved husband. The adviser, Joseph Addison, offered some practical ideas, then mentioned Porta’s device, adding that a pair of such boxes might enable her and her husband to communicate with each other even when they “were guarded by spies and watches, or separated by castles and adventures”. Mr. Addison then added that in addition to the 26 letters, the sympathetic telegraph dials should contain, when used by lovers, “several entire words which always have a place in passionate epistles”. The message “I Love You”, for example, would, in such a case, require sending just three symbols instead of ten. This advice is an early example of text compression achieved by using short codes for common messages and longer codes for other messages. Even more importantly, this shows how the concept of data compression comes naturally to people who are interested in communications [Salomon, 2004].

1.7 ADVANTAGES AND DISADVANTAGES OF COMPRESSION

1.7.1 Advantages

- Storage requirements of the data is condensed
- Audio visual data representation can be done with high quality. The viewers can realize the rich-quality of the signals
- Data security can also be greatly enhanced by encrypting the decoding parameters and transmitting them separately from the compressed database files to restrict access of proprietary information
- The rate of input-output operations in a computing device can be greatly increased due to shorter representation of data
• Data Compression obviously reduces the cost of backup and recovery of data in computer systems by storing the backup of large database files in compressed form [Fisher, 2012]

1.7.2 Disadvantages

• The encoding and decoding process needs an extra overhead, it is one of the most serious downsides of data compression, which dejects its use in some areas

• Data compression commonly decreases the reliability of the records

• Transmission of very sensitive compressed data through a noisy communication channel is risky because the burst errors introduced by the noisy channel can destroy the transmitted data

• Disruption of data properties of a compressed data, will result in compressed data different from the original data

• In many hardware and systems applications, the extra complexity added by data compression can increase the system’s cost and reduce the system’s efficiency, especially in the areas of applications that require very low-power VLSI implementation [Bassiouni, 1985]

1.8 CLASSIFICATION OF IMAGE COMPRESSION TECHNIQUES

The lossless and lossy are the two major categories of image compression techniques. These categories of compression define that is it possible or not all original data can be regenerated during decompression process.

1.8.1 Lossless vs. Lossy Compression

Lossless image compression remains the single bit data of the original image data after the decompressed of the image by restoring the original information of the image. These lossy compression methods are widely used in medical image processing because of the reduction in the original image data.

Moreover, lossy compression methods may negate the inappropriate information while compression. At the same time only the part of the original information of the image will regain after decompressed the image and thus this methods was followed in the field were redction in the few image information which not leads to serious issue [Maniccam and Bourbakis, 2001].
On of the best example for Lossy compression method is JPEG image which used in the photograph and other still image upload in the web. The lossy compression techniques generally permit a trade-off between compression ratio and picture quality [Amir and William, 1996].

The restored image is numerically identical to the original image in lossless compression systems. However, lossless compression can only attain a small quantity of condensation. An image reconstructed following lossy compression contains degradation compared to the original due to the removal of irrelevant data. However, lossy schemes are capable of reaching much higher compression. But with no visible loss is perceived (visually lossless) under normal viewing conditions.

1.8.2 Lossless Compression Techniques

Lossless compression systems yield lower compression ratios than lossy compression system, but they are intended to guard all the pixel in the original picture. Here, the main process used to reduce the size of the image is by excluding the code redundancy. Coding redundancy is exclusion based on the idea that in an image some colors are used frequently and others are occasionally used. By using short codes to the frequently used colors and longer codes to the uncommon ones the repeated color redundancy can be eradicated. The lossless compression methods are widely used methods, in many of today’s graphics file formats, example GIF, PCX, and BMP. The graphical images have most redundancies based on the adjacent pixels of identical values [Yang and Bourbakis, 2005].

Run Length Coding

Run length coding is a very modest method for compression of sequential information. The run length coding takes benefit of the fact that, consecutive single tokens are often identical, in many data streams. While encoding it checks for the stream and enclosures a special token each time a chain of more than two equal input tokens are found. This special input directs the decoder to pullout the next token ‘n’ times into its output stream [Pountain, 1987].

Huffman Coding

The Huffman coding is the widespread method used for rejecting code redundancy. When some individual symbols of an information source are coded, Huffman coding yields the smallest possible number of code symbols per source symbol.

The step one of this method is to create a series of source reductions by setting up the probabilities of the symbols under consideration and combining the lowest probability
symbols into a single symbol that replaces them in the following source reduction.

This procedure is repeated until a reduced source with two symbols is reached. The second step in Huffman’s procedure is to code each reduced source, starting with the smallest source and working back to the original source. The minimal length binary code for a two-symbol source is the symbols 0 and 1 [Pujar and Kadlaskar, 2010].

**Arithmetic Coding**

In arithmetic coding, there is no One-to-one correspondence among code words and source symbols. Instead, a single arithmetic code word is assigned for entire sequence of source symbols (or message). The code word itself defines an interval of real numbers between 0 and 1.

As the number of symbols in the message increases, the interval used to represent it becomes smaller and the number of information units (say, bits) required to represent the interval becomes larger. Each symbol of the message reduces the size of the interval in accordance with its probability of occurrence. It achieves the bound established by the noiseless coding because the technique does not require translating each source symbol into an integral number of code symbols [Langdon and Rissanen, 1981].

**Area Coding**

The improved form of run length coding is known as area coding, which reflects the two-dimensional character of images. Measuring the image as two-dimensional object is a development of area coding among other lossless compression methods. As the images are array of sequences, interpreting it as consecutive streams does not make a wide sense. Therefore, as the two dimensions are independent and of same importance, it is obvious that a two-dimensional coding scheme will be advantageous. The algorithms for area coding try to find rectangular regions with the same characteristics. These regions are coded in a descriptive form as an element with two points and a certain structure. The whole input image has to be described in this form to allow lossless decoding.

The possible performance of this coding method is limited mostly by the very high complexity of the task of finding largest areas with the same characteristics. Practical implementations use recursive algorithms for reducing the whole area to equal sized sub-rectangles until a rectangle does fulfill the criteria defined as having the same characteristic for every pixel. This type of coding can be highly effective but it bears the problem of a non-linear method, which cannot be implemented in hardware. Therefore, the performance in terms of compression time is not competitive, although the compression ratio is competitive.
1.8.3 Lossy Compression Techniques

By surrendering the capability of reproducing the original image the lossy compression method yields a high compression ratio. The widespread compression standard for still image compression is JPEG standard [Rabbani and Joshi, 2002]. It produces high compression ratio than run length coding, implementation is significantly complex than run length coding, but it produces higher compression ratio even if the holds a little amount of redundancy or no redundancy.

While scanning the image each part of it is important and each scan is critical. The principle of JPEG compression is to split the data present in the image by providing certain level of importance, then the data with less importance will be eliminated while storing the image this process will reduce the quality of the stored image. This process is achieved by converting matrix of pixel values into a matrix of amplitude values which are equivalent to particular frequencies in the image. The human eye is not capable of finding all color shifts in an image, so some of the overall data contained in the image can be eliminated without affecting the content of the image.

Typical Lossy Image Coder

Usually, three closely linked mechanisms namely (a) Source Encoder (b) Quantizer, and (c) Entropy Encoder combine to form a lossy compression system. In the image data linear transform to de-correlation were applied to perform the compression, quantize the resulting transform coefficients, and entropy code the quantized values.

Source Encoder

Few variations in linear transform based coding are developed in widespread within a few decades they are, Discrete Fourier Transform (DFT)[Weinstein and Paul, 1971], Discrete Cosine Transform (DCT)[Ramamohan and Ping, 2014], Discrete Wavelet Transform (DWT)[Mark, 1992] which has their own advantages and disadvantages. Depending upon the application any transform can be used, considering its merits and demerits gives increased performance.

Quantizer

A quantizer is a process of many-to-one mapping. It reduces the precision of transformed coefficients by which the number of bits used to store the transform coefficient reduces. Either
a Scalar Quantization (SQ) or Vector Quantization (VQ) can be applied on transform coefficients, because the quantizer is lossy and irreversible method of compression performed in all encoders. Depending upon the problem handled both uniform and non-uniform quantizers can be used.

**Entropy Encoder**

To provide an overall compression entropy encoder additionally perform the lossless compression in the quantized values. In order to confirm that the output stream is smaller than the input stream the entropy precisely determine the probability for each quantized value and produces an appropriate code based on the probability. The arithmetic encoder and Huffman encoder the two widely used entropy encoders. For fast execution simple Run-Length Encoding (RLE) has proven its effectiveness [Agung and Puguh, 2012].

### 1.8.4 Transform Coding

The transform coding function has a procedure of splitting an nxn image into further smaller NxN blocks and then unitary transform will be performed in the divided sub-images. A unitary transform is a reversible linear transform whose kernel describes a set of complete, orthonormal discrete basis functions [DeVore et al., 1992]. The main purpose of transform is to decorrelate the original signal, by this the energy of original signal will be redistributed between a set of transform coefficients. By this process before encoding various coefficients are rejected. Transform coding is implemented in four stages:

- **Image Subdivision.**
- **Sub-Image Transformation.**
- **Coefficient Quantization.**
- **Entropy Encoding.**

Segmentation and transformation are the two-step used to perform the logical modeling of the transform coding process. The subdivision of the image into bi-dimensional vectors, of possible different size. The next step involved is to apply the chosen transform, the transform may be of KLT, DCT, Hadamard. The JPEG and MPEG standards are examples of standards based on transform coding.

**Karhunen-Loeve transform**
The Karhunen - Loeve Transform (KLT), [Ahmed et al., 1976] was initially introduced by Karhunen and Loeve to express a series of expansion for continuous random. The principal component method was studied and introduced by Hotelling, this method is the discrete equivalent of the KL series expansion for random sequences. Since, the KL transform is introduced by Hotelling it also known as Hotelling transform. The vectors for a real MxN image is given by the KL transform are the orthonormalized eigenvectors of its autocorrelation matrix. Where denotes the covariance function of the image array and is a constant for fixed. The set of functions defined by the kernel are the Eigen functions of the covariance function and represents the eigenvalues of the covariance function. It is usually not possible to express the kernel in explicit form.

**Discrete Cosine Transform**

The data points in a sequence of data are denoted as a sum of cosine functions oscillating at different frequencies by Discrete Cosine Transform (DCT). [Chang and Girod, 2007] The several applications in science and engineering seeks DCT as important to, for lossy compression of audio (e.g. MP3) and images (e.g. JPEG), to spectral methods for the numerical solution of partial differential equations. In specific, the DCT is a Fourier-related transform similar to the Discrete Fourier transform (DFT), but using only real numbers. DCTs are equivalent to DFTs of roughly twice the length, operating on real data with even symmetry.

**Discrete Wavelet Transform**

A pyramid can be created with multiresolution images, this pyramid at each level it stores the difference between the image at that level and the pyramid image from the next level [Mohan et al., 1995]. Figure 1.2 shows the different levels of pyramid image.

The residuals can be used to reconstruct the image. Because of the less volume of the residuals it is easy to store the residuals. Figure 1.2 shows the pyramid with different levels of images. The multiresolution images can be easily analyzed and represented using wavelets these can be applied in 1D signals which are useful for image compression.

Wavelets are obtained from a single prototype wavelet called mother wavelet by dilations and shifting. Nowadays the 2D-DWT is recognized as a key operation in image processing. Figure 1.3 depicts the three level decomposition for 2D-DWT.

**JPEG**

The JPEG compression works based on the Discrete Cosine Transform (DCT)[Campbell and Wynne, 2011]. It includes four steps which are depicted in Figure 1.4.
Figure 1.2: The Different Levels of Pyramid Image

Figure 1.3: Three Level Decomposition of 2D-DWT

Figure 1.4: The Steps of JPEG Algorithm in Lossy Sequential Mode
The term Remote sensing was used by Evelyn L Pruitt, a geographer formerly with the office of Naval Research, to replace the limiting term ‘areal’ and ‘photograph’. Remote sensing is the process of sensing earth’s surface from space by making use of the properties of electromagnetic wave emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resource management, land use and the protection of the environment Joseph [2005]. It can also be defined as any process by which information is gathered about an object, area or phenomenon without being in contact with it. An excellent example for remote sensing device is human eye. We are capable of gathering information about our surroundings by determining the amount and nature of the reflectance of visible light energy from some external source, such as the sun or a light source as it reflects off objects in our field of view.

The term remote sensing has come to be associated more specifically with the gauging of interaction between earth surface materials and electromagnetic energy. However, any such attempt at a more specific definition becomes difficult, since it is not always the natural environment that is sensed, the energy type is not always electromagnetic and some procedures gauge natural energy emissions rather than interactions with energy from an independent source.

1.9.1 Remote Sensing: A Historical Perspective

The history of remote sensing began with the discovery of photography. The term “photography” is derived from two Greek words meaning “light” (phos) and “writing” (graphien).

In 1038 AD, Al Hazen an Arabian mathematician described the principle of the camera obscura to observe sun eclipse. The camera obscura incorporates a mirror which directs the image from the lens on to the translucent paper supported on a glass plate. The double interlocking box enables focusing. After a few decades, Leonardo Da Vinci reviewed the concept of camera obscura as dark room in 1490. In order to increase the quality of camera obscura, Cirolama Cardano introduced optic in 1550. Silver salts get darker when exposed to sunlight discovered by Angelo Sala in 1614. While experimenting with prism in 1666, Sir Isaac Newton invent that he could scatter the light into a spectrum of Violet, Indigo, Blue, Green, Yellow, Orange and Red, by using a second prism, he found that he could recombine the colors into white light. Johann Christopher Sturm, in 1676 introduced the relax
lens principle where a mirror is mounted at a 45-degree angle that projects an image, this development leads to the modern single lens reflect camera. The silver chromate darkened by exposure to sunlight could be rinsed off with ammonia, leaving the dark unexposed silver chromate crystals to form a fixed image, invented by Carl Wilhelm Scheele in 1777, a creator to modern photographic film. Thermal infrared electromagnetic radiation was introduced by Sir William Herschel, in 1800 by measuring the temperatures of light scattered using a prism. In 1827, Niepce takes the first picture (Figure 1.5) of nature from a window view of the French countryside using a camera obscura and an emulsion using bitumen of Judea, a resinous substance, and oil of lavender it took eight hours in bright sunlight to produce the image.

Figure 1.5: First Photograph in the World by Niepce

During 1830’s stereoscope was invented by Charles Wheatstone, the pictures used in the stereo views where in the form of "stereographs" which were two pictures of the same scene that were slightly offset and mounted side-by-side. Daguerrotype is an invention of Daguerre in 1839, which consists of a polished silver plate, mercury vapors and sodium thiosulfate (hypo) that was used to fix the image and make it permanent. In the same year, William Henry Fox Talbot, invents a system of imaging on silver nitrate of silver chromate treated paper and using a fixative solution of sodium chloride. In 1855, James Clerk Maxwell defined a theory known as color additive by which he described how to perceive color and how they are created shown in Figure 1.6.

The first aerial photography named “Nadar” (Figure 1.7) was taken by Gasper Felix Tournachon, in 1858 by using a captive balloon from an altitude of 1,200 feet over Paris.
In 1860’s aerial observations and possible photography, for military purposes were acquired from balloons in the Civil War and the same was used for map forest in 1862.

Near infrared sensitive films are discovered by Herman Vogel, in 1873 by soaking silver halide emulsions in numerous dyes, which extends their sensitivity to progressively longer wavelengths. Germans, in 1887 started working on aerial photographs and photogrammetric techniques for measuring features and areas in forests. The first aerial photography using kite is taken in 1889, by Arthur Batut. George Eastman, in 1899 introduced the nitro-cellulose based film that retained the clarity of the glass plates and by which first
Kodak camera was introduced. In 1900, Max Planck’s invented quanta and the mathematical explanation of the black body which places a step stone towards the development of quantum mechanics. The pigeons are used to transmit messages and take aerial photos (Figure 1.8) by the Bavarian Pigeon Corps in 1903.

Figure 1.8: Aerial Photography by Using Pigeons

From the height of 2,600 feet Albert Maul, in 1906 took an aerial photograph using a rocket propelled by compressed air, after capturing the camera was ejected and parachuted back to the earth. Same year G. R. Lawrence hoisted a camera into the air with the support of balloon kites. Simple color photography system and 35 mm standard were established in 1907 by Auguste and Louis Lumeiere. In 1914 the first airphoto over enemy region has taken by British Flying Service. American Society of Photogrammetry was founded in 1934 and now it was known as The American Society of Photogrammetry and Remote Sensing. In 1936, Albert W. Stevens takes the first photograph of the actual curvature of the earth taken from a balloon at an altitude of 72,000 feet. “The nation with the best photo reconnaissance will win the next war” statement said by a German General Werner von Fritsch in 1938. Sophisticated techniques in air photo interpretation were introduced during World War II in 1940. In 1946, V-2 rockets are used for first space photographs.

In 1957, Russia launched Sputnik -1, this was the revolution in space exploration by the government. First meteorological satellite TIROS-1 was launched in 1960 and United States starts collection of intelligence photography from Earth orbiting satellites. A proto-
type for multispectral camera lens was designed by Zaitor and Tsuprun on 1962. In 1963 D.Gregg, created Videodisk. Nimbus-1 was launched in 1964 for weather satellite program. Between 1972 to 1978 ERTS-1 (Landsat 1), Skylab, Aryabhatta, Bhaskara Sega-I, Landsat 2, GOES, Meteosat-1, Landsat 3 and Seasat were launched. In 1981 to 1989 several updated versions of previously launched satellites are launched Meteosat-2, Landsat-4, SIR-B, Landsat-5, SPOT-1, Meteosat-3 and Ofeq-2. During the period of 1990 to 1998 few modernized satellites were launched but in 1999, MODIS, ASTER, CERES, MISR, MOPITT, IKONOS and IRS-P4 produced a revolution in satellite technologies. In 2005, Google Inc. introduced Google earth, which gives a great increase in public awareness of the use of satellite imagery and other geospatial information. After 2006, several satellite were launched per year by grown and growing countries including India, from Aryabhata in 1975 to Cartosat-2D in 2017, Highest number of satellites launched by a single launch vehicle (104 satellites). Now the era of launching single satellite with a launch vehicle has changed because of the necessity of additional satellites and cost efficacy.

1.9.2 Fundamentals of Remote Sensing

Energy Source

Generally, sensors are classified in to two major groups passive and active. Passive sensors measure ambient levels of existing sources of energy, while active ones provide their own source of energy [Heermann and Khazenie, 1992]. The majority of remote sensing is done with passive sensors, sun is the major energy source for these sensors. For example, in early days the earth features and reflectance of light are measured and recorded using airborne cameras. Arial photography is still a major form of remote sensing, innovative, solid state technologies have prolonged competences for viewing in the visible and near-infrared wavelengths include longer wavelength solar radiation as well. Though, not all passive sensors use energy from the sun. Thermal infrared and passive microwave sensors both measure natural earth energy emissions. Thus, the passive sensors are simply those that do not themselves supply the energy being detected.

Flash photography is a best example of active sensors and while considering environmental and mapping applications, the best example is RADAR, this system emit energy in the microwave region of the electromagnetic spectrum. The reflection of that energy by earth surface materials is then measured to produce an image of the area sensed.

Wavelength
Figure 1.9: The Electromagnetic Spectrum

The electromagnetic energy is mostly used by remote sensing devices. Since electromagnetic spectrum is very extensive not all wavelengths are equally effective for remote sensing purposes. Moreover, not all wavelengths have significant interaction with earth surface. Figure 1.9 represents the electromagnetic spectrum. The atmosphere itself causes significant absorption and or scattering of the very shortest wavelengths. In addition, the glass lenses also cause significant absorption of shorter wavelengths such as the ultraviolet (UV). As a result, the first significant window i.e., a region in which energy can significantly pass through the atmosphere opens up in the visible wavelengths. Even here, the blue wavelengths undergo substantial attenuation by atmosphere scattering, and are thus often left out in remotely sensed images. However, the green, red and near-infrared wavelengths all provide good opportunities for gauging earth surface interactions without significant interference by the atmosphere. In addition, these regions provide important clues to the nature of many earth surface materials. Chlorophyll, is an example for very strong absorber of red visible wavelengths, while the near-infrared wavelengths provide important clues to the structures of plant leaves. As a result, the bulk of remotely sensed images used in GIS related applications are taken in these regions [Gong et al., 2006].

While extending in to thermal infrared and middle regions, a variety of good windows can be found. The longer of the middle infrared wavelengths have proven to be useful in a number of geological applications. The thermal regions have proven to be very useful for monitoring not only the obvious case of the spatial distribution of heat from industrial activity but a broad set of applications ranging from fire monitoring to animal distribution studies to soil moisture conditions. After the thermal IR, the next area of major significant is environmental remote sensing is in the microwave region. Windows existing in this area particularly important for active radar imaging.
Interaction Mechanisms

When electromagnetic energy strikes a material, three types of interaction can follow: reflection, absorption and transmission (Figure 1.10). Our main concern is with the reflected portion since it is usually this which is returned to the sensor system. Exactly how much is reflected will vary and will depend upon the nature of the material and where in the electromagnetic spectrum our measurement is being taken. As a result, if we look at nature of this reflected component over a range of wavelengths, we can characterize the result as a spectral response pattern.

Figure 1.10: Types of Interaction

Spectral Response Patterns

A spectral response pattern is sometimes called a signature. It is a description (Often in the form of a graph) of the degree to which energy is reflected in different regions of the spectrum. Most humans are very familiar with spectral response patterns since they are equivalent to the human concept of color. For example, Figure 1.11 shows idealized spectral response patterns for several familiar colors in the visible portion of the electromagnetic spectrum, as well as for white and dark grey. The bright red reflectance pattern, for example, might be that produced by a piece of paper printed with a red ink. Here, the ink is designed to alter the white light that shines upon it and absorb the blue and green wavelengths.

What is left, then, are the red wavelengths which reflect off the surface of the paper
back to the sensing system (the eye). The high return of red wavelengths indicates a bright red, whereas the low return of green wavelengths in the second example suggests that it will appear quite dark.

**Multispectral Remote Sensing**

While the remote sensed images are visually interpreted, a variety of image features are brought into consideration. Color or tone in the case of panchromatic images, texture, size, shape, pattern, context. In computer-assisted interpretation the spectral response pattern is used. It is for this reason that a strong emphasis is placed on the use of multispectral sensors which are like human eye, look at more than one place in the spectrum and thus are able to gauge spectral response patterns, and the number and specific placement of these spectral bands [Lee et al., 1990].

**Satellite**

A Satellite can also be referred as an ‘Orbiting radio star’ which in general supports ships and aircrafts to navigate very safely in all climatic conditions. In other words, A satellite in general is any natural or artificial body moving around a celestial body such as planets and stars. In the current context, reference is made only to artificial satellites orbiting the planet Earth. These satellites are put into the desired orbit and have payloads depending upon the intended application. A satellite while in the orbit performs its designated role throughout its lifetime.
The major categories of satellites are.

i. Communicational Satellites

ii. Weather Forecasting Satellites

iii. Earth Observation Satellites

iv. Navigational Satellites

v. Military Satellites

vi. Scientific Satellites

A communication satellite is a kind of repeater station that receives signals from ground, processes them and then retransmits them back to Earth. An Earth observation satellite is a photographer that takes pictures of regions of interest during its periodic motion. A weather forecasting satellite takes photographs of clouds and monitors other atmospheric parameters, thus assisting the weatherman in making timely and accurate forecasts. A satellite could effectively do the job of a spy in the case of some military satellites meant for the purpose or of an explorer when suitably equipped and launched for astrophysical applications.

Applications of Satellites

The satellite-based global positioning system (GPS) is used for safe and secure navigation in unknown territories. Earth observation and remote sensing satellites give information about the weather, ocean conditions, volcanic eruptions, earthquakes, pollution and health of agricultural crops and forests. Another class of satellites keeps watch on military activity around the world and helps to some extent in enforcing or policing arms control agreements.

Although mankind is yet to travel beyond the moon, satellites have crossed the solar system to investigate all planets. These satellites for astrophysical applications have giant telescopes on board and have sent data that has led to many new discoveries, throwing new light on the universe.

Satellite Imaging

The satellite images are captured by the satellite cameras known as payloads, which has a specification by which the resolution and the volume of the captured image can be measured. Typically, resolution of satellite imagery can be defined as spatial, spectral, temporal, radiometric and geometric by campbell in 2002.
**Spatial Resolution**

This can be defined as the pixel size of an image representing the size of the surface area being measured on the ground [Lambin and Strahlers, 1994], determined by the sensors instantaneous field of view (IFOV).

**Spectral resolution**

The discrete segment of the Electromagnetic Spectrum and number of intervals that the sensor is measuring [Benz et al., 2004].

**Temporal Resolution**

Amount of time that passes between imagery collection periods for a given surface location [John and Richards, 1999].

**Radiometric Resolution**

Is defined as the ability of an imaging system to record many levels of brightness and to the effective bit-depth of the sensor and is typically expressed as 8bit (0-255), 11bit (0-2047), 12bit (0-4095) or 16bit (0-65535) [John and Richards, 1999].

**Geometric Resolution**

It refers to the ability of satellite sensor to effectively image a portion of the Earth surface in a single pixel and is typically expressed in terms of Ground sample distance (GSD). GSD is a term containing the overall optical and systemic noise sources and is useful for comparing how well one sensor can see an object on the ground within a single pixel [John and Richards, 1999].

The resolution of satellite images varies depending on the instrument used and the altitude of the satellite’s orbit. For example, the Landsat archive offers repeated imagery at 30-meter resolution for the planet, but most of it has not been processed from the raw data. Landsat 7 has an average return period of 16 days. For many smaller areas, images with resolution as high as 41 cm can be available.

Satellite imagery is sometimes supplemented with aerial photography, which has higher resolution, but is more expensive per square meter. Satellite imagery can be combined
with vector or raster data in a GIS provided that the imagery has been spatially rectified so that it will properly align with other data sets.

1.10 NEED FOR SATELLITE IMAGE COMPRESSION SYSTEMS

Usually space missions are intended to leave the Earth’s atmosphere and function in the outer space. The payloads of imaging satellites capture images with high spatial resolution and swath by which the mission needs to handle an extensive volume of image data [Jagadeesh et al., 2014].

Normally the space missions operate a store-and-forward mechanism, the captured images will be stored in onboard memory and transmitted to the ground station later on. In order to represent satellite images, it requires a huge number of bits, if it needs to transmit or stored it is very difficult to do so without reducing the number of bits from the data.

The mechanism of compression is introduced to reduce the unwanted bits present in the image. While considering satellite imaging payloads the compression mechanism can be classified under two major categories, hardware and software.

The hardware compression in satellites can be done by using an onboard chip, for example, ADV212 is a compression chip which used JPEG2000 for image compression or an FPGA can be used to code a compression algorithm in it. Mostly satellites use an onboard compression to reduce the size of the image captured by its payload. The Table 1.1 shows the list of satellites launched using compression system.

1.11 MOTIVATION

Nowadays, the term satellite remains a household name. Irrespective of education and profession it is familiar to everyone. It is no longer the privilege of a few selected nations and not a topic of research and discussion that is restricted to the premises of large academic institutes and research establishments. It is a subject of interest and discussion not only to engineers, scientists and technocrats it attracts hobbyists, electronics enthusiasts and to a wide extent, everyone.

So, in the satellite era, the use of satellite and its technologies are widely spread in all nations and it has achieved a tremendous growth in few decades. The increase in launch of satellites with very high resolution payloads, produces a huge volume of data, which is very difficult to store and transmit to ground from space due to the limited bandwidth and
onboard storage. As a remedy for this limitation compression techniques are used to reduce the volume of the data.

The wide spread of satellite image applications made the frequency of transmission and storage of the satellite images, generally these images cover a wide area and numerous objects. Obviously, the volume of the image increases. Common to this and many other applications are in requirement of huge volume of storage space and communication bandwidth for digital images. Hence digital media is motivated by innovative methods for compression of digital images for efficient utilization of storage space and communication bandwidth.

Although compression techniques reached tremendous growth, innovation is inevitable and the field of remote sensing is in search of new compression methods which is suitable for all types of satellite images and suitable for onboard compression.

As a contribution, in this research work we have developed four novel compression methods exclusively for satellite images.

1.12 ORGANIZATION OF THE THESIS

This thesis is broadly classified into nine chapters and the contents are mentioned below.

Chapter 1 - Introduction: In this chapter a brief introduction about images, digital images, history of remote sensing, satellite imaging, image compression methods and their classifications, need for satellite image compression and the chapter ends by discussing the motivation part.

Chapter 2 - Literature Review: A survey of present and past works in natural image compression techniques and satellite image compression techniques are discussed.

Chapter 3 - Quality Analysis of Existing Compression Methods Using Various Satellite Images: In this chapter three types of satellite images namely high resolution satellite images, medium resolution and very high resolution satellite images are discussed, different compression techniques applied for analysis are explained and the analysis results are depicted using graphs and a conclusion is made based on the experimental results obtained.

Chapter 4 - Fusion of DCT and DWT Algorithm for Satellite Image Compression: Introduction about DCT and DWT is given, block diagram of the proposed method is explained and the results obtained are discussed and a conclusion is made based on the results obtained.

Chapter 5 - Color Component Based Lossless Compression for Satellite Images: Representing images in computer, color space, histogram of an image, detailed explanation about
proposed method and results are discussed.

Chapter 6 - Block Similarity Based Compression for Satellite Images: Explains in detail about block based similarity, proposed methods, obtained results are discussed and a conclusion is made.

Chapter 7 - Film Strip Method: Basic principles of H.264 is discussed, protocol of the proposed method is explained, the results obtained are compared with other methods and a conclusion is made.

Chapter 8 - Summary and Future Work: Summary of entire research work is given and few suggestions were provided for future research.
Table 1.1: List of Satellites Launched with Compression System

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Satellites</th>
<th>Compression Algorithms</th>
<th>Theoretical Basis</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SPOT-1 (CNES 1986)</td>
<td>Fixed-rate DPCM</td>
<td>DPCM</td>
<td>EO</td>
</tr>
<tr>
<td>2</td>
<td>Phobos (Soviet Union 1988)</td>
<td>DCT+Scalar quantizer + fixed length coding</td>
<td>DCT</td>
<td>Moon Expl</td>
</tr>
<tr>
<td>3</td>
<td>PoSAT-1 (SSTL-Portugal 1993)</td>
<td>AMPBTC</td>
<td>BTC</td>
<td>EO</td>
</tr>
<tr>
<td>4</td>
<td>Clementine (NASA 1994)</td>
<td>DCT + Quantizer + ZigZag + RLE+Huffman (very close to JPEG)</td>
<td>DCT</td>
<td>Moon Expl</td>
</tr>
<tr>
<td>5</td>
<td>TEAMSAT (ESA 1997)</td>
<td>JPEG-baseline</td>
<td>DCT</td>
<td>Science Demo</td>
</tr>
<tr>
<td>6</td>
<td>TRACE (NASA 1998)</td>
<td>JPEG-baseline</td>
<td>DCT</td>
<td>Science Demo</td>
</tr>
<tr>
<td>7</td>
<td>IKONOS (USGeoEye 1999)</td>
<td>ADPCM Kodak</td>
<td>DPCM</td>
<td>EO</td>
</tr>
<tr>
<td>8</td>
<td>SUNSAT (South Africa 1999)</td>
<td>JPEG-baseline</td>
<td>DCT</td>
<td>EO</td>
</tr>
<tr>
<td>9</td>
<td>Tsinghua-1 (SSTL-THU2000)</td>
<td>AMPBTC</td>
<td>BTC</td>
<td>EO</td>
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<td>10</td>
<td>TiungSAT (SSTL-Malaysia2000)</td>
<td>Improved AMPBTC</td>
<td>BTC</td>
<td>EO</td>
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<tr>
<td>11</td>
<td>MTI (US DOE2000)</td>
<td>CCSDS-LDC</td>
<td>RICE</td>
<td>EO</td>
</tr>
<tr>
<td>12</td>
<td>EO-1 (NASA2000)</td>
<td>CCSDS-LDC</td>
<td>RICE</td>
<td>EO</td>
</tr>
<tr>
<td>13</td>
<td>Mars Odyssey (NASA2001)</td>
<td>CCSDS-LDC fast lossless predictive compressor or slower lossy DCT compressor</td>
<td>RICE DPCM or DCT</td>
<td>Mars Expl</td>
</tr>
<tr>
<td>14</td>
<td>QuickBird (US DigitalGlobe2001)</td>
<td>ADPCM Kodak</td>
<td>DPCM</td>
<td>EO</td>
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<td>15</td>
<td>PROBA-1 (ESA 2001)</td>
<td>JPEG-baseline</td>
<td>DCT</td>
<td>EO</td>
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<tr>
<td>17</td>
<td>SPOT-5 (CNES2002)</td>
<td>DCT (with rate controlled)</td>
<td>DCT</td>
<td>EO</td>
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<tr>
<td>18</td>
<td>Meteisat-8 (ESA 2002)</td>
<td>JPEG-Baseline and Lossless JPEG</td>
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<td>weather</td>
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<td>DCT Lossless JPEG</td>
<td>Science Demo</td>
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<td>DWT</td>
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<td></td>
<td>Satellite/mission</td>
<td>Compression Method</td>
<td>Type</td>
<td>Exploratory Region</td>
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<td>Mars Exploration Rovers (NASA2003)</td>
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<td>DWT and JPEG-LS</td>
<td>Mars Expl</td>
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<td>JPEG-baseline (CR =3.2)</td>
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<td>JPEG-baseline and Lossless JPEG RICE and a lossy wavelet (H-compress)</td>
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<td>EO</td>
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<td>DCT and DPCM</td>
<td>Sun Expl</td>
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<td>Changâ˘ÁŒ-1 (China2007)</td>
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<td>Moon Expl</td>
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<td>IMS-1 (ISRO2008)</td>
<td>JPEG2000</td>
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<td>EO</td>
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<td>RapidEye (SSTL-Germany 2008)</td>
<td>Lossless and Lossy JPEG</td>
<td>DCT</td>
<td>EO</td>
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<td>THEOS (CNES-Thailand 2008)</td>
<td>DCT (CR = 2.8 or 3.7)</td>
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<td>EO</td>
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<td>RASAT (Turkey 2009)</td>
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<td>X-SAT (Singapore2009)</td>
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<td>RICE</td>
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<td>PLEIADES-HR (CNES2010)</td>
<td>DWT + BitPlaneEncoder</td>
<td>DWT</td>
<td>EO</td>
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