# Impact of Hyperspectral Image Coding on Subpixel Detection

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***Abstract*—Four lossy hyperspectral image data coding schemes are compared with regard to their aptitude for subpixel detection use. The coding standards H.265/HEVC and JPEG2000 are investigated with and without a PCA preprocessing. As evaluation criteria, both the 'Area under Receiver Operation Curve' as well as the 'Peak Signal to Noise Ratio' are calculated. The 'Area under Reiceiver Operation Curve' is based on the 'Spectral Angle Mapper'.**

**Under both criteria, the two coding schemes with PCA preprocessing are the best while the JPEG2000 coding scheme works significantly less efficient. Furthermore, it was shown why the classification is not monotonically improving over increasing data rate.**

**The PCA&HEVC and PCA&JPEG2000 schemes are stable at data rates of 0.1 bit per pixel per band [bpppb] and above while achieving an 'Area under ROC' of at least 0.99. If a data link of 0.3 bpppb is available, even the HEVC coding scheme reaches an 'Area under ROC' of 0.99 or more. Thus, it depends on the available data link, whether the HEVC coding scheme can be applied or if one of the more complex coding schemes with PCA preprocessing is required.**

## I. Introduction

Several earth surface materials can be distinguished by their spectral characteristics of absorption or reflectance [1]. Based on this, hyperspectral image sensing allows to detect and identify surface properties, e.g. for geological mapping, for monitoring agriculture and forest status, for environmental studies, for disaster managment, or for military surveillance.

For each image pixel in a region being viewed, a hyperspectral image sensor provides hundreds of narrow and contiguous spectral bands with a bandwidth of 10-20 nm, ranging from the visible to the short-wave infrared regions of the electromagnetic spectrum.

On one hand, the high spectral resolution leads to the ability to detect objects smaller than one pixel by using the spectral information. This so called subpixel detection is an interesting application of hyperspectral image sensing. On the other, the high spectral resolution leads to an extremly large volume of data.

Efficient transmission of hyperspectral image data from an airborne sensor to a receiving ground station requires a strong onboard data compression with real-time capability. Hence, efficient lossy coding techniques have to be applied. For this, redundancy reduction alone does not achieve a sufficient compression ratio. Therefore, not only redundancy has to be reduced by exploiting the spectral and spatial correlation but also irrelevance by eliminating information not used at the ground station. Automatic feature extraction from hyperspectral images is known to perform reliably well even on strongly compressed data [2]. In other words, when compressing hyperspectral image data, only the important spectral and spatial information has to be preserved.

Among known approaches of hyperspectral image compression, some extend established 2D image coding techniques [3] into 3D, e.g. the wavelet-based techniques 3D Set Partitioning in Hierarchical Trees (3D SPIHT) [4] as an extension of 2D SPIHT [5], 3D Set Partitioning Embedded bloCK (3D SPECK) [6] as an extension of 2D SPECK [7] or 3D JPEG2000 [8] as an extension of JPEG2000 [9].

Other so called separable approaches typically apply a Principal Component Analysis (PCA) across the spectral bands followed by still image coding like JPEG2000 to reduce the spatial correlation [10], [11]. The approach of [11] is used as a reference in this paper since it tends to perform best.

Other approaches for hyperspectral image compression base on the concept of distributed source coding [12], [13].

Recently, video coding standards H.264/MPEG-4 AVC [14] and H.265/HEVC [15] have been applied to hyperspectral and multispectral image data where the spectral bands are interpreted as an image sequence. In other words, the temporal direction of the video codec is assigned to the spectral direction of the hyperspectral image data cube, such that the spectral correlation is exploited by the temporal prediciton of a video coding standard. [16] applies H.264/MPEG-4 AVC to hyperspectral image data, in [17] multispectral image data is coded with H.265/HEVC.

In this paper, we compare four hyperspectral image data coding schemes for subpixel detection use. Because of the low rate data link, the coding must be applied onboard. The coding standards H.265/HEVC and JPEG2000 are investigated with and without a PCA carried out before. All results are evaluated using as criteria both the 'Area under Receiver Operation Curve' (Area under ROC) [18] well known in classification as well as the 'Peak Signal to Noise Ratio' (PSNR) [19] well-known in coding. In this work, we base the 'Area under ROC' on the 'Spectral Angle Mapper' (SAM) [20]. SAM condenses the spectral similarity between image pixel spectra and a given reference spectrum of an object into a single, scalar angle value.

The paper is organized as follows: Section 2 presents the experimental setup with its four coding schemes investigated. Coding results are presented and discussed in Section 3 and Section 4 concludes the paper.

## II. Experimental Setup

The experimental setup of the four coding schemes is shown in Fig. 1.

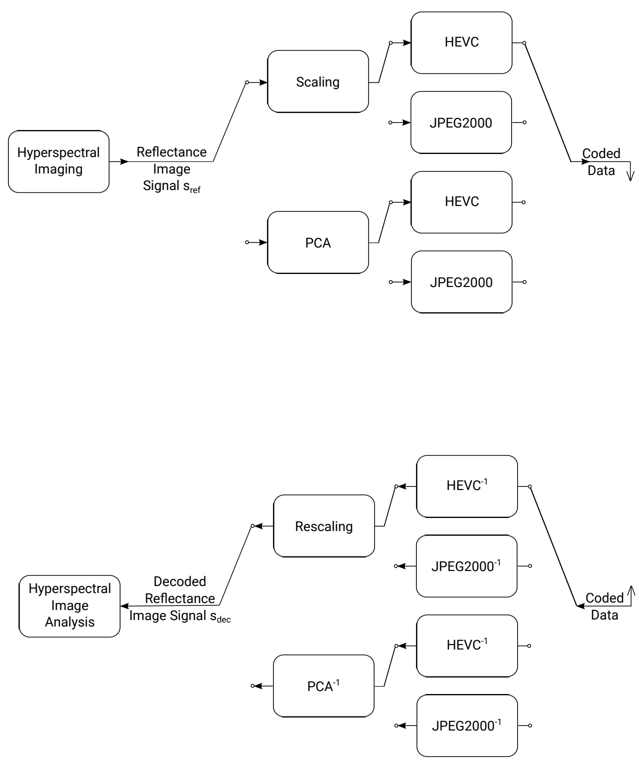


Figure 1. Experimental Setup

The block Hyperspectral Imaging is meant to comprise hyperspectral image sensing followed by a calibration and athmospheric correction providing a reflectance image signal $s_{ref}$. Used as the input signal of the coding schemes, it comprises all spectral bands since the object is expected to be unkown and spectral bands cannot be eliminated before coding. As preprocessing, the signal $s_{ref}$ is scaled to 16 bit with a uniform bit shift operation in such a way that at least one pixel in at least one band uses the most significant bit, or the signal $s_{ref}$ is subjected to the well known PCA across the spectral bands for decorrelating the data. The output of PCA is truncated to 16 bit. The preprocessed signal is the input signal of a coding standard: either the video coding standard HEVC or the still image coding standard JPEG2000.

The coded data is decoded followed by the inverse preprocessing, either the rescaling or by the inverse PCA resulting in the decoded reflectance image signal $s_{dec}$. This signal is analysed for evaluating the influence of the coding errors on subpixel detection.

The video coding standard investigated here is HEVC Monochrome 16 profile. The software applied is the HM 16.6 of [21]. Thus, range extension is used which means that the input and output pixels of the codec have an amplitude range of 16 bit. The temporal direction of the video codec is assigned to the spectral direction of the hyperspectral image data. The prediction of a spectral band from decoded spectral bands in the spectral neighbourhood is calculated depending on the chosen type of intra coded (I), predicitive-coded (P) and bidirectionally predictive-coded (B) images. For HEVC coding the scaled signal, the encoder uses in this experiment a PBBB-frame structure, starting mandatorily with an I-frame. For HEVC coding the PCA output, the encoder uses in this experiment an intraframe structure, which turned out to be best due to the fact that a PCA linearly decorrelates the spectral bands. The prediction error is transformed by an Integer Transform [22], using block sizes of 4x4, 8x8, 16x16 or 32x32. The resulting transform coefficients are quantized and afterwards entropy coded with Context Adaptive Binary Arithmetic Coding (CABAC) [23]. For HEVC coding the scaled signal, the quantizer step size is set to a fixed value. For HEVC coding the PCA output, the initial quantizer step size used for the first component inreases with decreasing eigenvalues of the PCA due to the fact that the spectral bands after passing the PCA suggest such a control.

The still image coding standard investigated here is JPEG2000. It is based on a Discrete Wavelet Transform and allows a flexible scalability of the codestream, e.g. progressive transmission. With the wavelet based JPEG2000-Kakadu V7.4 software [24], a closed-source software is applied which enables a coding of the hyperspectral data cube in one bitstream and a decoding with a JPEG2000 standard decoder.

Thus, four different coding schemes so called HEVC, JPEG2000, PCA&HEVC and PCA&JPEG2000 are investigated in a range of compression ratios appropriate for subpixel detection in this experimental setup. PCA&JPEG2000 as reference to prior work is based on [11].

## III. Experimental Results

The results presented in this paper are obtained using the selftest hyperspectral image data for subpixel detection from the SHARE 2012 Data Campaign [25]. The reflectance image has 360 spectral bands, a spatial resolution of 248x216 pixels and a nominal amplitude resolution of up to 14 bit integer.

In this work, the codecs H.265/HEVC and JPEG2000 work at data rates in the range of 0.01 bit per pel per band (bpppb) to 1.0 bpppb corresponding to data compression factors of between 16 to 1600.

The coding schemes are evaluated by the 'Peak Signal to Noise Ratio' (PSNR) in [dB] well kown in coding as defined in Eq. (1) by

$$PSNR = 10\,log\frac{65535^2}{E[s_{cod\_err}^2]} \quad (1)$$

where we define the coding error $s_{cod\_err}$ as

$$s_{cod\_err} = s_{ref} - s_{dec}. \quad (2)$$

The PSNR relates the square of the 16 bit amplitude range to the expectation of the squared coding error. Assuming that the coding error is noise-like and does not change its principal nature when the data rate is varied, the PSNR is a reasonable quality criterion.

The PSNRs over the data rate in bit per pixel per band [bpppb] are shown in Fig. 2 for the four investigated coding schemes.

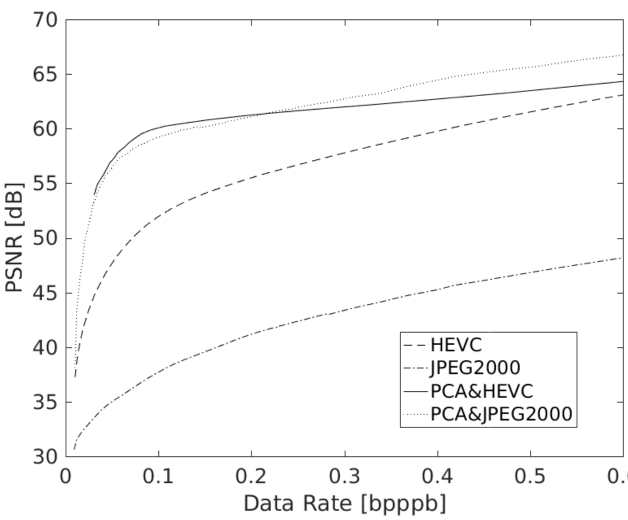


Figure 2. PSNR over data rate of bands 1 to 360

It can be seen that all PSNRs increase with increasing data rate, an indication that the codecs work well. The coding standard JPEG2000 is significantly below the other coding systems which means that this coding system performs less efficient than the others, assumedly because of the missing exploitation of statistical dependencies in spectral dimension. For both codecs, a PCA preprocessing considerably improves the PSNR. The coding scheme with PCA and HEVC improves less with increasing data rate compared to the other coding schemes because the quantizer step size is influenced by the eigenvalue of a band. The PSNR gives a first hint, if and how well a coding scheme works. However, it does not specifically assess the suitability of the coding schemes for subpixel detection.

Hence, additionally, the impact of the coding schemes on classification is evaluated, using here the 'Spectral Angle Mapper' (SAM) [20] as a commonly used hyperspectral classifier. SAM condenses the spectral similarity between image pixel spectra and a given reference spectrum of an object into a single, scalar angle value. Each pixel comprising n bands defines a point in n-dimensional space

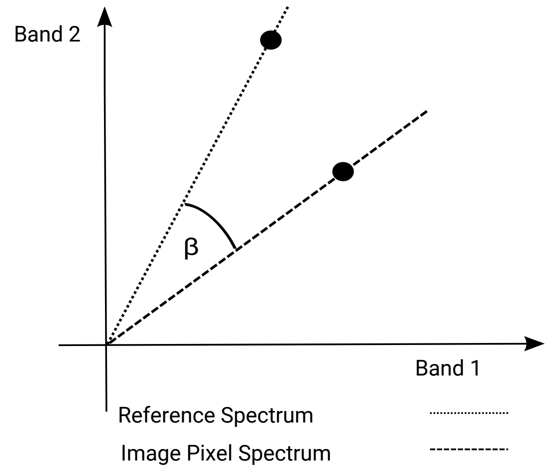


Figure 3. Visualisation of SAM for only two spectral bands

which can be treated as a directional vector that begins at the origin of the coordinate system. SAM determines the similarity between an image pixel spectrum and the reference spectrum by calculating the angle $\beta$ between the two vectors. Fig. 3 illustrates this for only two spectral bands given. A smaller angle indicates greater similarity.

Due to a required dimension reduction [26] for classification, the SAM considers only the spectral bands 10 to 50. A comparison of the PSNR over data rate of all 360 bands and of bands 10 to 50 shows that the coding schemes work well with the spectral bands used for classification purposes.

For a set of data rates, the Receiver Operation Characteristics (ROC) well known in classification are calculated. Measuring the 'Area under each ROC' [18] then yields a single value for each data rate.

Fig. 4 shows the 'Areas under ROC over the data rate in [bpppb] for the four investigated coding schemes. The 'Area under ROC' is smallest with the JPEG2000 coding scheme. Again, as with the PSNR measure, JPEG2000 coding is least effective. Adding PCA preprocessing, the 'Area under ROC' of the two coding schemes increases to nearly identical better values. With PCA preprocessing, the slightly better 'Area under ROC' of PCA&HEVC suggests that subpixel detection will work slightly better that with PCA&JPEG2000.

It is remarkable that the 'Area under ROC' does not increase monotonically with increasing data rate. There are two explanations for this: Firstly, the ROC based on subpixel detection takes into account the true detection result. Together with the fact that only very few pixels in the image are to be classified positive, this leads to the consequence that the ROC - and hence also the 'Area under ROC' derived from it - depends only on the codec performance in very few pixels. For the second explanation, one has to recall that, while PSNR is entirely based on the error between coder input and coder output, the SAM criterion assesses a distance between the spectrum of the coded pixel and a reference spectrum completely unknown to the coder. Loosely said, a worsening coder (in the PSNR sense) can nevertheless be favorable under the SAM criterion, if it happens to bring the pixel spectrum closer to the reference spectrum and thus helps to improve classification.

Fig. 5 illustrates this effect for the symbolic example of two spectral bands. Despite quantization taking place in the transform domain, if we look at the decoded value of a single pixel, the representative values of the coder's quantizer directly translate into sets of representative values in the pixel domain. With quantization taking place independently in both bands, there will be some kind of grid of representative values, as shown by the grey dots. Each image pixel spectrum is quantized to its nearest grey dot. In Fig. 5a) the distance of the grey dots is half of that in Fig. 5b) which means that the quantizer step size is half. As is known, the image quality of a finer quantization is better because the coding error caused by the quanization is smaller. A comparison of the coding error visualized by the arrow from the image pixel spectrum to the decoded pixel spectrum illustrates this.

A comparison of the spectral angle between the reference spectrum and the decoded spectrum in Fig. 5 shows that the angle $\beta$ can be larger with the finer quantization. The reason for that is that the decoded pixel spectrum into which the image pixel spectrum is decoded can be farther away from the reference spectrum although at finer quantization. Thus, the angle $\beta$ and as a consequence of this the 'Area under ROC' can be worse. Thus, the efficiency of the classification is not monotonically increasing with the data rate within limits when only a very few pixels are to be classified positive.

With respect to encoder complexity, applying the PCA in spectral direction requires to buffer all or large groups of bands, whereas HEVC video coding with its temporal prediction needs to buffer no more than two reference images at any time. Thus, the loss in efficiency when not using PCA has to be balanced against the lower complexity.

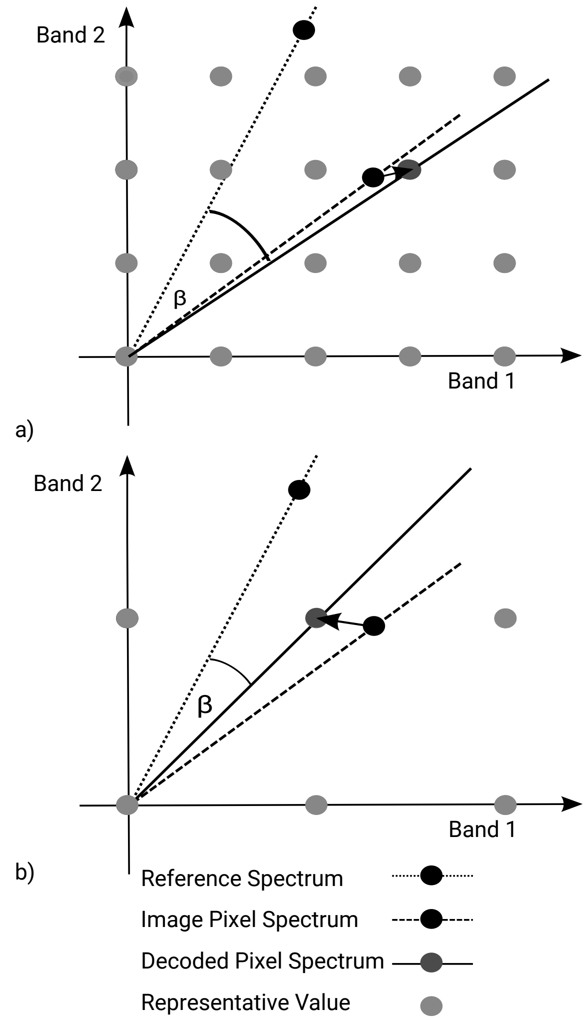


Figure 5. Coarser quantization may decrease angle $\beta$
a) fine quantization
b) coarse quantization

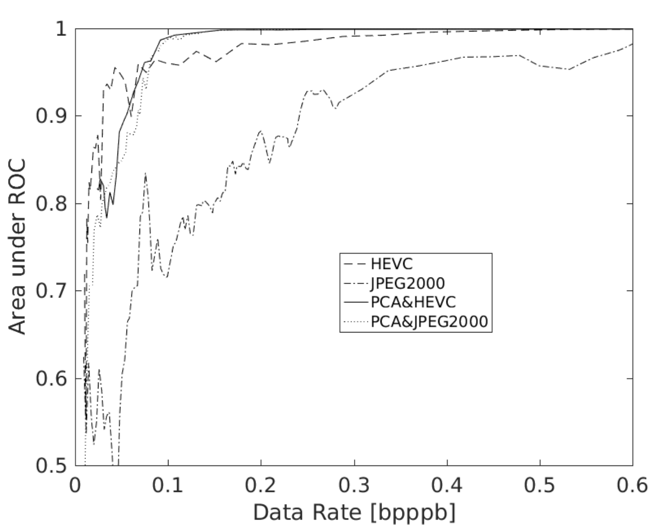


Figure 4. 'Area under ROC' over data rate using SAM classification

## IV. Conclusion

We compared four hyperspectral image data coding schemes for subpixel detection use called HEVC, JPEG2000, PCA&HEVC and PCA&JPEG2000. The evaluation with PSNR showed that all codecs worked well. For subpixel detection all coding schemes were classified by using the SAM. The results illustrated by 'Area under ROC' showed that JPEG2000 is significantly worse. The two coding schemes using PCA are the best. Further, it was shown why the classification is not monotonically improving by increasing the data rate. The PCA&HEVC and PCA&JPEG2000 schemes are stable at data rates of 0.1 bpppb and above while achieving an 'Area under ROC' of at least 0.99. If a data link of 0.3 bpppb is available, even the HEVC coding scheme comes up to an 'Area under ROC' of 0.99 or more. Thus, it depends on the available data link, whether the HEVC coding scheme can be applied or if one of the more complex coding schemes with PCA preprocessing is required.

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