5.4 Evaluation of Near-Lossless Performance of SAMVQ and HSOCVQ

5.4.1 Evaluation method and test dataset

One of the unique features of SAMVQ and HSOCVQ allows control of the errors introduced during the compression process. For remote sensing applications, compression is considered near lossless provided that the error introduced by the compression is not larger than the intrinsic noise in the original data caused by the instrument noise and other noise sources from preprocessing, such as calibration and atmospheric correction. Because an original datacube is not exempt from intrinsic noise and other noise sources, these errors propagate into the remote sensing products derived from the original data.

In order to evaluate the near-lossless feature of the two compression techniques, the error introduced by the two compression algorithms was analyzed band by band and pixel by pixel. The compression errors were compared with the intrinsic noise of the original data to see if they were consistent with the level of intrinsic noise in the original data.

A low-altitude AVIRIS dataset acquired in the Greater Victoria Watershed District, Canada on August 12, 2002 was used (information on the dataset is available at http://aviris.jpl.nasa.gov/ql/list02.html). The ground sample distance (GSD) of the dataset is 4 m $\times$ 4 m with an AVIRIS nominal SNR of 1000:1 in the visible and near-infrared (VNIR) region. A spectral subset was selected to remove redundant and bad bands, which reduced the data from 224 bands to 204 bands, including the original bands 6–31 (423.04–664.79 nm, VNIR), bands 35–96 (673.64–1258.39 nm), and bands 98–213 (1263.72–2399.48 nm) for the short-wavelength infrared. A 28 m $\times$ 28 m GSD datacube was derived by spatially aggregating the 4 m $\times$ 4 m GSD dataset. The SNR of the aggregated datacube is $1000 \times \sqrt{49} = 7000{:}1$. Figure 5.7(a) shows the aggregated datacube, whose spatial size is 292 lines with 121 pixels per line. The datacube is encoded in 16-bit digital numbers (DNs). This datacube is considered noise-free because the noise is too small to have a significant impact on the evaluation. Figure 5.7(a) is a RGB image with bands 38 (702.2 nm), 20 (557.9 nm), and 2 (432.6 nm) being displayed as red, green, and blue.

Figure 5.7(b) shows a datacube identical to Fig. 5.7(a) except that its SNR is 600:1, generated by adding simulated instrument noise and other possible noise sources to (a). An additive noise (Gaussian model) was used. This noise-added datacube was used as an original datacube for compression and for evaluation of the near-lossless feature of the compression algorithms here; it is considered to be representative of a real satellite hyperspectral dataset because the SNR for such an instrument is likely to be approximate to that level.[2] The noise of the original datacube caused by the instrument noise and other noise

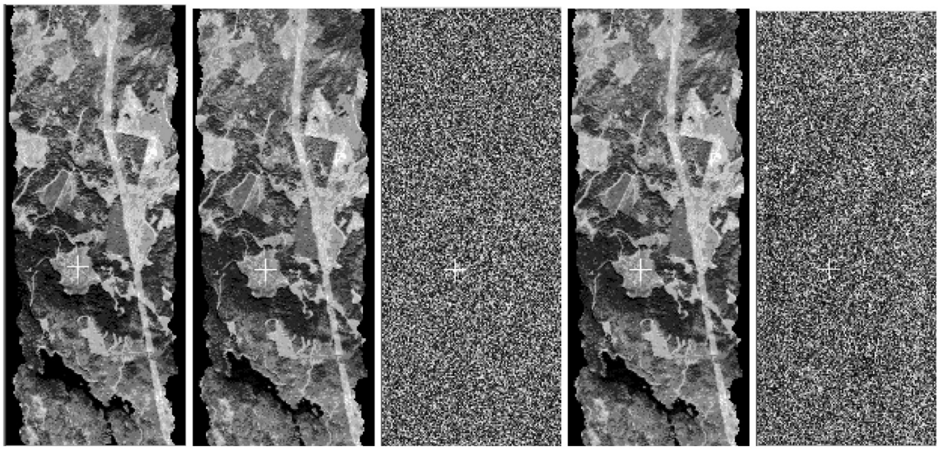


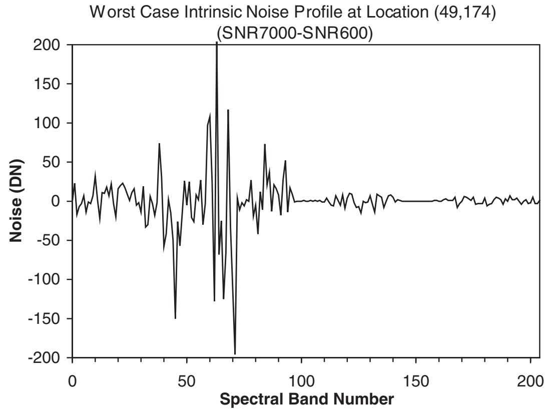
Figure 5.7 AVIRIS Greater Victoria Watershed District datacube: (a) noise-free datacube, (b) noise-added datacube (uncompressed), (c) intrinsic-noise datacube, (d) compressed datacube, and (e) compression-error datacube (reprinted from Ref. 1). For a color version of this figure, see Plate 5 in the color plate section of this book.

sources is referred to as intrinsic noise in this section. Figure 5.7(c) shows an intrinsic noise image at band 38 (702.2 nm) of the noise datacube, which was obtained by subtracting the datacube with a SNR of 600:1 (b) from the noise-free datacube (a). The display scale is stretched to between the minimum (–155 DN) and maximum (149 DN) amplitude of the noise image for better contrast.

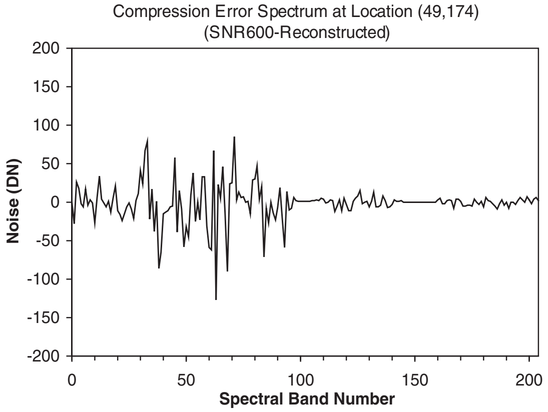
The original datacube was compressed using SAMVQ at a compression ratio 20:1, and then the compressed data was decompressed to obtain the reconstructed datacube, as shown in Fig. 5.7(d), for evaluation. It is difficult to visually distinguish the difference between the original and the reconstructed datacubes. Figure 5.7(e) shows the compression-error image (difference between the original datacube and the reconstructed datacube) at band 38. The display scale is stretched to the same range as Fig. 5.7(c). The pattern of the compression error image looks similar to that of the intrinsic noise image; also, there are no apparent structures.

5.4.2 Evaluation of a single spectrum

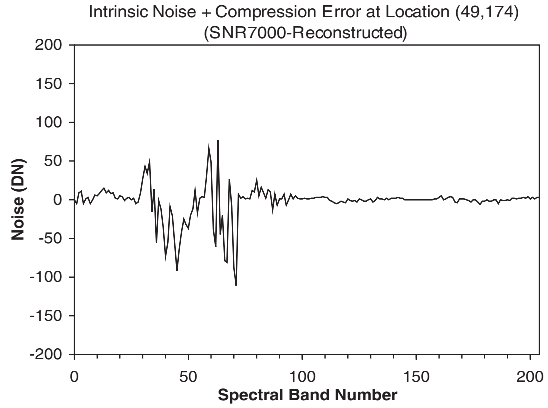
The intrinsic noise of the original datacube has been analyzed; Figure 5.8(a) shows the worst-case noise profile of a ground sample pixel at location (49, 174) of the intrinsic-noise datacube as a function of spectral band number. The noise magnitudes for the VNIR bands and the beginning of the SWIR bands are large. The maximum value of the noise is 204 DN at band 66 (1050.45 nm), and the minimum value of the noise is –196 DN at band



(a)



(b)



(c)

Figure 5.8 Profiles of (a) the worst-case intrinsic noise of the original data at location (49, 174), (b) compression error introduced by SAMVQ at a compression ratio of 20:1, and (c) overall noise (i.e., intrinsic noise with compression error) at the same location (reprinted from Ref. 1).

71 (1097.72 nm). The noise magnitudes are between –15 DN and 15 DN between bands 100 (1363.50 nm) and 204 (2399.48 nm).

Figure 5.8(b) shows the compression error (or noise) profile of the reconstructed datacube compressed by SAMVQ with a compression ratio of 20:1 at the same location as Fig. 5.8(a). The error introduced due to the compression is not larger than the intrinsic noise of the original datacube across the spectral bands. The maximum value of the compression error is 85 DN at band 71 (1097.72 nm), and the minimum value of the compression error is –127 DN at band 63 (1022.09 nm). The compression-error magnitudes between bands 100 (1363.50 nm) and 204 (2399.48 nm) are in the same range as the intrinsic noise of the original datacube: between –15 DN and 15 DN.

After compression/decompression, the reconstructed data contains both the intrinsic noise of the original datacube and the compression error (or compression noise). This section refers to the combination of intrinsic noise and compression error as overall noise, which is the final noise budget of the datacube if the reconstructed data is sent to a hyperspectral data user for deriving their products. Figure 5.8(c) shows the overall noise profile at the same location (49, 174); it was obtained by subtracting the spectrum of the reconstructed datacube from the spectrum of the noise-free datacube at the same location. Interestingly, the overall noise profile shows that the maximum value of the noise is reduced to 77 DN at band 63 (1022.09 nm), and the minimum value of the noise is increased –111 DN at band 71 (1097.72 nm). The magnitudes of the overall noise between bands 100 (1363.50 nm) and 204 (2399.48 nm) are reduced to between –5 DN and 5 DN rather than between –15 DN and 15 DN, as in the original datacube. The range of the overall noise magnitudes in the VNIR bands is also smaller than for the intrinsic noise of the original datacube, which is probably due to the random error introduced by the compression algorithm that cancelled the intrinsic noise in the original data. These results show that the VQ-based compression algorithm evaluated here can act as a low-pass filter, suppressing high-frequency noise during compression.[8]

Figure 5.9 shows the noise profiles of the intrinsic noise of the original data, compression error introduced by SAMVQ at a compression ratio of 20:1, and overall noise as a function of spectral band number for a randomly selected ground pixel at location (94, 90). The profiles of the compression error and the overall noise show better results than in Fig. 5.8.

5.4.3 Evaluation of an entire datacube

In order to assess the compression error of the entire reconstructed datacube, the standard deviation of each band image of the compression-error datacube was calculated and plotted as a function of spectral band number. These standard deviations were used to estimate the noise level of the compressed data. The standard deviations of each band image of the intrinsic noise and of

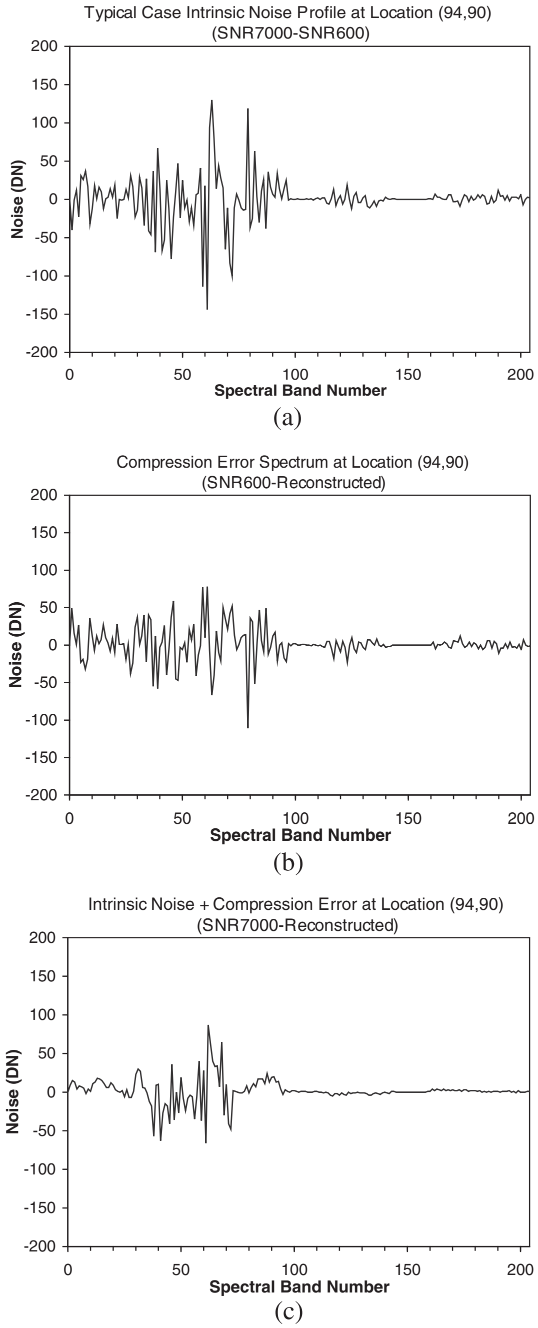


Figure 5.9 Profiles of (a) intrinsic noise of the original data of a randomly selected ground-sample pixel (94, 90), (b) compression error introduced by SAMVQ at a compression ratio of 20:1, and (c) overall noise (i.e., intrinsic noise with compression error) at the same location (reprinted from Ref. 1).

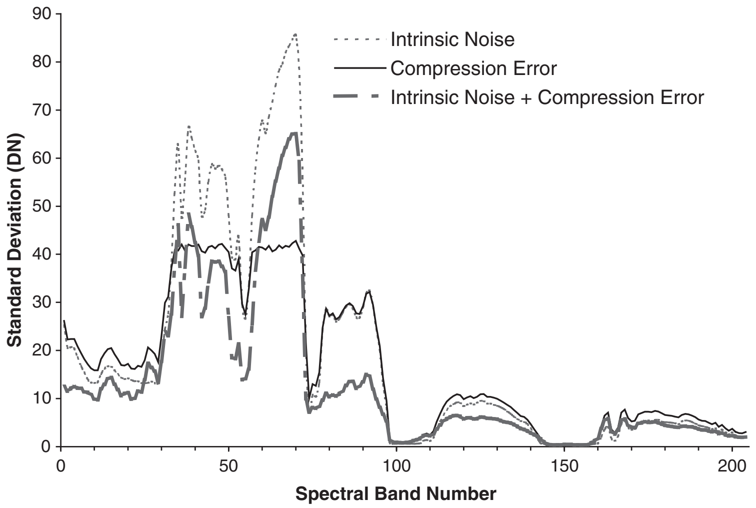


Figure 5.10 Standard deviations of single-band images for intrinsic noise, compression error (using SAMVQ at a compression ratio 20:1), and overall noise (intrinsic noise with compression error). Reprinted from Ref. 1.

the overall noise were also calculated for the purpose of comparison (shown in Fig. 5.10). It is observed that the standard deviations of the compression error images (solid line) are much smaller than those of the intrinsic noise images (dotted line) for the bands with high-magnitude noise [between bands 35 (749.96 nm) and 75 (1135.53 nm)]. The rest of the bands are very close. It is also observed that the standard deviations of the overall noise images (thick broken line) that include both the intrinsic noise and the compression error are smaller than those of the intrinsic noise images (dotted line) for almost all of the bands. This observation indicates that the overall noise level of the compressed datacube is even lower than the noise level of the original datacube, which is probably because SAMVQ acts as a low-pass filter, thus suppressing the high-frequency noise. The random errors introduced by the compression algorithm cancelled some of the intrinsic noise in the original data. The test results of standard deviations are consistent with the results of noise profiles shown in Figs. 5.8 and 5.9.

The noise profiles of the compression error and the overall noise of a single ground pixel compressed using HSOCVQ are similar to those compressed using SAMVQ, as shown in Figs. 5.8 and 5.9. Figure 5.11 shows standard deviations of band images for the intrinsic noise (dotted line), the compression error (solid line), and the overall noise (thick broken line) as a function of spectral band number when the datacube was compressed using HSOCVQ at 10:1. The standard deviations of band images of compression error are close to or smaller than those of intrinsic noise for the bands with high-magnitude noise [between bands 35 (749.96 nm) and 75 (1135.53 nm)].

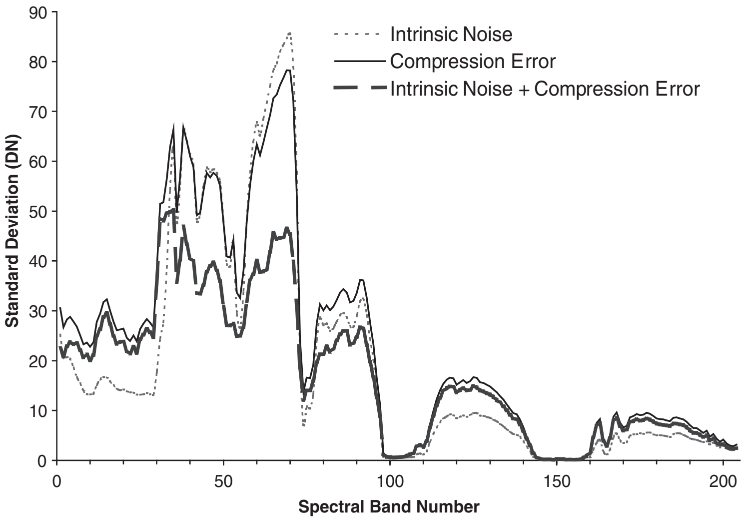


Figure 5.11 Standard deviations of single-band images for intrinsic noise, compression error (using HSOCVQ at a compression ratio 10:1), and overall noise (i.e., intrinsic noise with compression error). Reprinted from Ref. 1.

The standard deviations of the overall noise are smaller than those of the intrinsic noise between bands 35 and 105 (1413.37 nm).

The previous experimental results show that the compression errors introduced by SAMVQ and HSOCVQ are at the same level as the intrinsic noise caused by the instrument noise and other noise sources contained in the original datacube (such as calibration and atmospheric correction). The compression errors are smaller than the intrinsic noise in band images with high-magnitude noise. The experimental results justify the claim that SAMVQ and HSOCVQ are near lossless for remote sensing applications compared to the intrinsic noise of the original datacube. The noise contained in the reconstructed data is the overall noise that includes both the intrinsic noise of the original datacube and the compression error. The overall noise of the reconstructed datacube is even smaller than the intrinsic noise for all of the bands when the data is compressed using SAMVQ and for most of the bands when the data is compressed using HSOCVQ. Statistically, SAMVQ shows better near-lossless performance than HSOCVQ.

5.5 Evaluation of SAMVQ with Regard to the Development of International Standards of Spacecraft Data Compression

The Consultative Committee for Space Data System (CCSDS) is developing new international standards for satellite multispectral and hyperspectral data compression, and the SAMVQ technique has been selected as a candidate.