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Lossless compression of hyperspectral images with pre-byte processing and intra-bands correlation

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Abstract

This paper considers an approach to the compression of hyperspectral remote sensing data by an original multistage algorithm to increase the compression ratio using auxiliary data processing with its byte representation as well as with its intra-bands correlation. A set of the experimental results for the proposed approach of effectiveness estimation and its comparison with the well-known universal and specialized compression algorithms is presented.

Keywords: remote sensing; hyperspectral images; lossless compression; intra-bands correlation; byte representation of data.

Lossless compresión de imágenes hiperespectrales con tratamiento pre-byte e intra-bandas de correspondencias

Resumen

Este documento se refiere a la compresión de datos hiperespectrales de teleobservación de la tierra mediante la sugerencia de un algoritmo de múltiples etapas para aumentar la relación de compresión, utilizando una formación de datos auxiliares de gran redundancia en su presentación de bytes y teniendo en cuenta la correlación intra-bandas. Aquí se presentan los resultados de los estudios sobre la eficacia de la compresión de imágenes hiperespectrales espaciales realizadas por el algoritmo de compresión propuesto con software de compresión universal y especializado.

Palabras clave: la teledetección; imágenes hiperespectrales, sin pérdida de compresión; intra-bandas de correlación; representación de bytes de datos.

1. Introduction

Modern centers for space monitoring and systems for remote sensing (RS) continually process, archive and distribute data, which constitute tens or hundreds of gigabytes [1-11]. A key problem in the process is compressing RS data to increase effectiveness of a data transfer via connection channels of limited carrying capacity and archiving in RS storage subsystems of a limited capacity. The necessary classification of this data must be of the highest value. That is why lossless compression which is free of any distortions of statistic brightness characteristics of restored data is more appropriate.

The solution of the compression problem, which is the most accessible for practical implementation presupposes

the usage of universal and widely-known algorithms and means of compression, for instance, in the archival software *WinRar*, *WinZip* or compressor *Lossless JPEG (JPEG-LS)* on the base of *JPEG* [12-17] image compression standard. However, RS data is classified by various characteristics – spectral, radiometric, spatial resolutions and by geometrical size of the scene. The above-mentioned universal means of compression fail to consistently consider the variable differences [18-21]. Thus, there are multispectral and hyperspectral aerospace images (AI), which have essentially different parameters of spectral resolution and are characterized by high dependence (correlation) between data of different bands [22]. If for multispectral aerospace images the coefficient of mutual correlation of bands is $R \in (0.3; 0.8)$, then for hyperspectral AI representing values of

brightness which are received in various spectral bands with the high spectral resolution, the correlation of neighboring bands is $R \approx 1.0$. This shows the high redundancy of data and the pertinence of applying this feature during compression [23,24].

Besides, knowing the correlation value (intra-bands correlation) between bands of hyperspectral AI, it is expedient to operate values of deviations (difference) between it and actual reference values, and that will allow the reduction of the range of data change and hence demand a smaller number of categories for their storage. The effective usage of specialized means of the compression is possible, considering the above-stated features of hyperspectral AI.

The software intended for the analysis of spatial data and processing of AI are *ERDAS Imagine*, *ERDAS ER Mapper*, *ArcView GIS*, *GeoExpress* and others often dispose of specific modules for compression of AI. Thus, the *ERDAS Imagine* package utilizes the compression tool for images in the *MrSID* format (*IMAGINE MrSID Desktop Encoder* and *IMAGINE MrSID Workstation Encoder*), based on wavelets and intended for lossy compression of large RS images. The *ERDAS ER Mapper* system has modules of loss compression on the basis of the standards *JPEG2000* and *ECW* [25]. In the *ArcView GIS* package there is a *MrSID* module which compresses raster image files with loss [26]. The software product *GeoExpress* is intended for compressing raster data with the use of the popular formats *MrSID* and *JPEG2000* [27]. Thus, all commercial systems of RS data processing have the means of loss compression on the basis of well-known standards.

Recent hyperspectral RS images lossless compression research attempts to apply various approaches and methods [28-33]. The separate stages of transforming data while compressing AI and the possibility of decreasing power inputs and algorithmic complexity are discussed. Additionally, there are various attempts at adapting standards, which have proven successful for compressing hyperspectral AI.

2. Description of the algorithm

Not all details of the original algorithms of compression are clear. Their numbers exceed the possibilities of most widespread means of compression when application to hyperspectral AI with various characteristics is uncertain.

It is our purpose to promote further search for approaches to lossless compression of hyperspectral RS images, substantially free from the disadvantages of existing universal and specialized facilities of compression.

Considering the features of hyperspectral AI and some details of existing analogues, the most expedient solution of the problem of compressing hyperspectral AI is by multi-stage transformations: first the advantages of universal traditional approaches for data compression, and secondly to consider the specificity of hyperspectral data. The algorithm embodying this approach and some of its results are discussed below [31].

Considering the specificity of compressing hyperspectral AI, the proposed algorithm has the following stages:

1. To consider the functional dependence of values of brightness (albedo) between various bands of images, by calculating the correlation and of deviations (differences) of initial data and the values of those found for functional dependence.
 2. Creation of auxiliary structure of data on the basis of the initial hyperspectral AI, storing the unique pair groups of values of elements in a byte representation, and addressing references on these unique pair groups as well.
 3. Compression of received data transformations with standard entropy algorithm by processing the generated auxiliary structures of the data.
- Let us consider the details of the above-mentioned stages.

In the first stage, the value of deviations of the linear dependence on the matrix of values $\mathbf{I}[m,n,k]$.

For step-by-step description of the first stage consisting in searching correlation and deviations, it is necessary to take into account the following objects:

- an initial image – the matrix of values of the image $\mathbf{I}[m,n,k]$, where m,n,k – are indices of the lines, columns and bands of the initial image, $m = 1,2,\dots,M$, $n = 1,2,\dots,N$, $k = 1,2,\dots,K$;
 - $\mathbf{R}[k]$ – a file for "level-by-level" preservation values of correlation R between the neighboring bands (layers);
 - $\mathbf{Q}[k]$ – a file for placing values of the mathematical expectation for each band $\mathbf{I}[m,n,k]$;
 - $\mathbf{L}[k]$ – a file for preserving the linear dependence;
 - $\mathbf{I}'[m,n,k]$ – a file for placing values of differences (deviations) between $\mathbf{L}[k]$ and $\mathbf{I}[m,n,k]$.
- Step 1. To calculate a mathematical expectation m_k of each band of the initial image $\mathbf{I}[m,n,k]$ and to place values to the file $\mathbf{Q}[k]$, as in (eq.1):

$$\mathbf{Q}[k] = \sum_{n=1}^k \mathbf{I}[m,n,k] \times \rho_1^k \quad (1)$$

where ρ_1^k – relative frequency of occurrence of values of the image \mathbf{I} , $k=1,2,\dots,K$.

Step 2. To calculate (on the base of $\mathbf{Q}[k]$ and $\mathbf{I}[m,n,k]$) correlation R for each pair of all available K bands of the initial image $\mathbf{I}[m,n,k]$, as in (eq.2):

$$\mathbf{R}[k] = \frac{\sum_{m,n} \mathbf{I}[m,n,k] - \mathbf{Q}[k]}{\sqrt{\sum_{m,n} \mathbf{I}[m,n,k] - \mathbf{Q}[k]^2}} \quad (2)$$

To place the result to $\mathbf{R}[k]$, $k=1,2,\dots,K-1$.

Step 3. To calculate (on the base of $\mathbf{Q}[k]$ and $\mathbf{R}[k]$) a linear dependence of the kind $L = m_k \times R$ for each pair of the available K bands of the initial image $\mathbf{I}[m,n,k]$. Result should be placed to $\mathbf{L}[k]$, $\mathbf{L}[k] = \mathbf{Q}[k] \times \mathbf{R}[k]$, $k=1,2,\dots,K-1$.

Step 4. To calculate (on the base of $\mathbf{R}[k]$ and $\mathbf{L}[k]$) the difference between elements $\mathbf{L}[k]$ and corresponding values of the initial image $\mathbf{I}[m,n,k]$ in each of K bands, as in (eq.3):

$$\mathbf{I}'[m,n,k] = \begin{cases} \mathbf{R}[k] > 0, \mathbf{I}[m,n,k] - \mathbf{L}[k-1] \\ \mathbf{R}[k] \leq 0, \mathbf{I}[m,n,k] \end{cases} \quad (3)$$

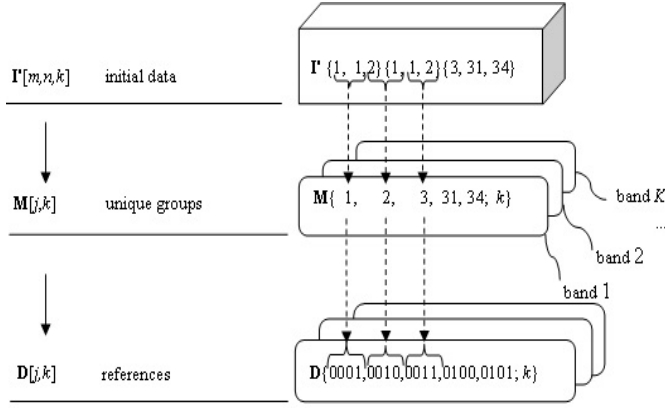


Figure 1. Procedure of forming auxiliary structure of data.
Source: Authors' own elaboration.

for $m = 1..M$, $n = 1..N$. The result is placed to $I'[m,n,k]$.

Step 5. To transform the negative values $I'[m,n,k]$ to positive ones in the byte representation as numbers with a sign demand more bytes than those without a sign (4):

$$I'[m,n,k] = \begin{cases} \text{at } I[m,n,k] \geq 0, & 2 \times I[m,n,k] \\ \text{at } I[m,n,k] < 0, & -2 \times I[m,n,k] - 1 \end{cases} \quad (4)$$

The result is the file $I'[m,n,k]$ considering values of intra-bands correlation $R[k]$.

The essence of the second stage consists of forming a file of unique pair groups of values that represent the initial image in the byte representation. Then, the file is formed containing references to the same pair group of values.

The algorithm proceeds with two additional objects:

- $M[j,k]$ – a file of unique pair groups of values of the initial image in the byte representation;
- $D[j,k]$ – a file for entering references (to unique pair groups of values).

The step-by-step elaboration for the second stage of transformation is shown in Fig.1:

Step 1. To form (on the base of $I'[m,n,k]$) a file $M[j,k]$ for each band K adding unique pair groups of values in the byte representation from the file $I'[m,n,k]$. To place the result to $M[j,k]$, $j = 1, 2, \dots, J$. If repeated pair groups of values are absent, then $J = (M \times N \times K) / 2$, $k = 1, 2, \dots, K$.

Step 2. To form (on the base of $M[j,k]$) a file $D[j,k]$, putting down references to unique pair groups of values from the file $M[j,k]$ to $D[j,k]$. To place the result to $D[j,k]$, $j < J$ as $j = M \times N \times K$, $k = 1, 2, \dots, K$.

At the end of the second stage, context modeling was used with the known arithmetic coding for compressing data of the file $D[j,k]$ to the archival software $D'[j,k]$.

In order to form an initial hyperspectral AI $I[m,n,k]$ from $D'[j,k]$ it is necessary to make a number of transformations opposed to the above-mentioned:

- to make arithmetic decoding of the file $D'[j,k]$ restoring the file $D[j,k]$;
- to find in the file $D[j,k]$ the corresponding references to unique pair groups from the formed structure of the data $M[j,k]$;
- to restore the file $I'[m,n,k]$ containing a file of

dependencies $L[k]$ having counted the absolute values of the file $I'[m,n,k]$ and having restored the initial image $I[m,n,k]$.

3. Experimental study

In order to access the effectiveness of the proposed algorithm in what concerns both the point compression ratio as the limits of its application, a number of experiments were performed using hyperspectral AI of the system RS *AVIRIS* (table 1) in data format of raster geoinformation system *Idrisi Kilimanjaro*. The *AVIRIS* (*Airborne Visible/Infrared Imaging Spectrometer*) system provides 224 spectral images with the wavelength of the band from 400 nanometers to 2500 nanometers. Also, the proposed algorithm was compared with the results of experiments received for universal archivers compression algorithms *WinRar*, *WinZip* and *Lossless JPEG* which applies the resolution of compression standard *JPEG* widely used in commercial compression systems.

The experiments were undertaken using a computer with the *Intel Core i5* processor, 2,5 GigaHerz and RAM 4 Gigabit under operating system *Windows 7* (updating package 3).

To estimate the robustness of the proposed algorithm another hyperspectral remote sensing (RS) data system *HYPERION* was also used (table 2). *Hyperion* hyperspectral sensor apparatus Earth Observing-1 is able to record 220 spectral images from 0.4 to 2.5 microns, with a spectral resolution of 0.1 to 0.11 micron.

A sequence of stages was then performed to find the most effective:

Sequence I – Consideration of correlation (1) → forming auxiliary data with unique pair groups and references to them (2) → arithmetic coding (3).

Sequence II – Forming auxiliary data with unique pair groups and references to them (1) → arithmetic coding (2).

Sequence III – Consideration of correlation (1) → arithmetic coding (2).

Table 1.
Examples of characteristics of test data (RS system AVIRIS)

Name of hyperspectral AI	K	$M \times N$, pixels	File size, bytes
f970619t01p02_r07_sc01	224	100 × 100	6140096
f970619t01p02_r07_sc02	224	200 × 200	36199296
f970619t01p02_r07_sc03	224	300 × 300	81178496
f970619t01p02_r07_sc04	224	400 × 400	144077196
f970619t01p02_r07_sc05	224	500 × 500	210746396
f970619t01p02_r07_sc06	224	624 × 512	281673728

Source: Authors' own elaboration..

Table 2.
Examples of characteristics of test data (RS system HYPERION)

Name of hyperspectral AI	K	$M \times N$, pixels	File size, bytes
EO1H0750222014K5	224	600 × 600	43502310
EO1H0750222014KA	224	700 × 700	58914561
EO1H0750222014K3	224	800 × 800	77556164
EO1H0750222014K7	224	900 × 900	97807349
EO1H0750222014K1	224	1000 × 1000	112478451

Source: Authors' own elaboration.

Sequence IV – Forming auxiliary data with unique pair groups and references to them (1) → consideration the correlation (2) → arithmetic coding (3).

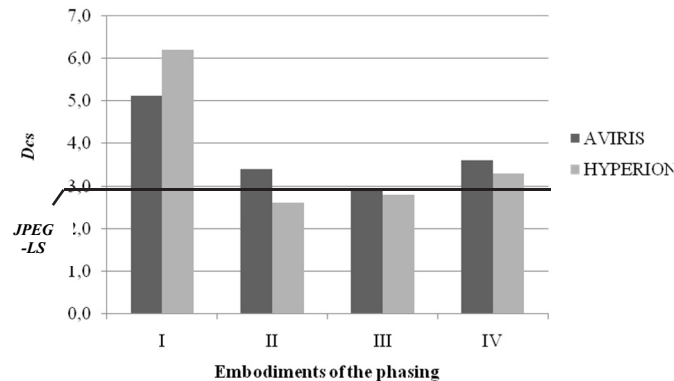
In order to evaluate the most productive sequence considering the contribution of each of these stages, a number of experiments with the different variants was conducted (Figure 2).

A fragment of the results of this experiment is displayed in Figure 2. This shows that various stages of the algorithm have different levels of importance while forming a result. In the 1st, 2nd and 4th variants of the stage sequences, the results surpass *Lossless JPEG* indifferent degrees (from 25% to 46%).

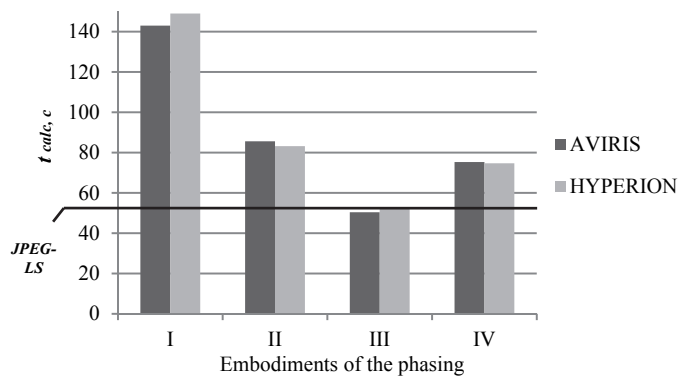
The best result is achieved by sequence I with the highest compression ratio. The results of undertaking sequence II show that the absence of the stage of intra-bands correlation leads to an insignificant exponent of compression in comparison with *Lossless JPEG*.

Realization of the stages sequence in accordance with sequence III leads to the most insignificant result as there is no powerful formation of unique pair groups and references to them with creation of corresponding auxiliary structures of data.

In Figure 3, the results of comparative experiments demonstrate the superiority of the proposed algorithm over analogues in exponent of compression D_{cs} at the varied geometrical sizes of RS hyperspectral data of *AVIRIS* (I)



a)



b)

Figure 2. Comparison of indicators of variants of realizing a compression algorithm: a) by exponent of compression D_{cs} ; b) by time of calculation t_{calc} .

Source: Authors' own elaboration.

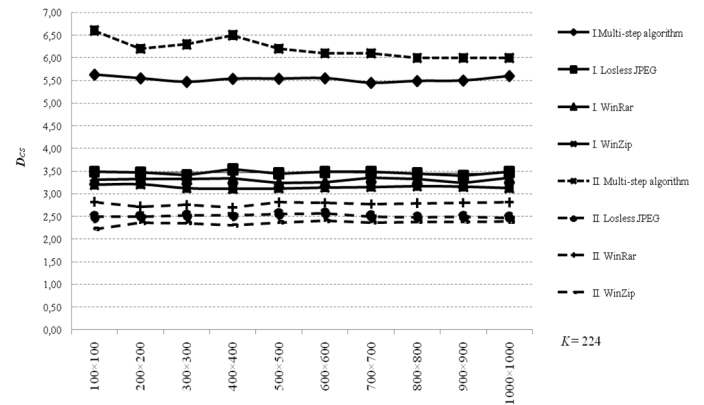


Figure 3. Comparative effectiveness of compression algorithms for different geometrical sizes of scene.

Source: Authors' own elaboration.

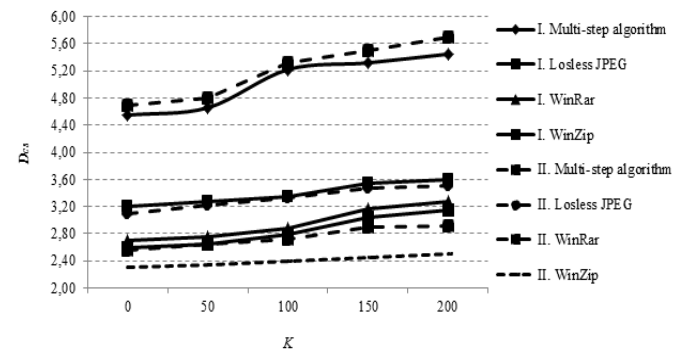


Figure 4. Dependence of compression exponent D_{cs} of algorithms on the number of bands K .

Source: Authors' own elaboration.

and *HYPERION* (II) systems. At increasing the geometrical size of the scenes, all the investigated algorithms show a steady result which exhibits little to no change.

Research was conducted to explore the dependence of compression exponent D_{cs} on the number of bands of AI K (Figure 4). Results show that compression exponent D_{cs} is increasing proportionally to the number of bands K as and that the redundancy of the data of RS hyperspectral data of *AVIRIS* (I) and *HYPERION* (II) systems raises.

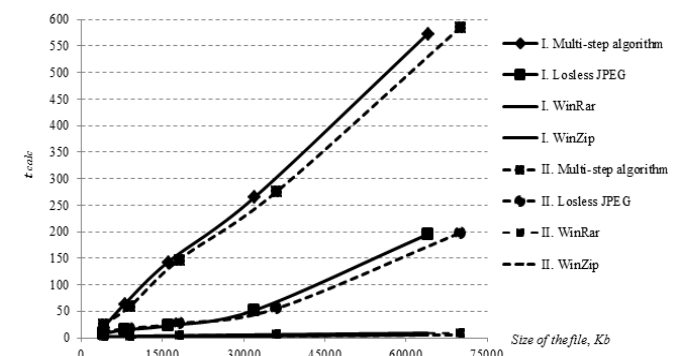


Figure 5. Computational performance of compression algorithms.

Source: Authors' own elaboration.

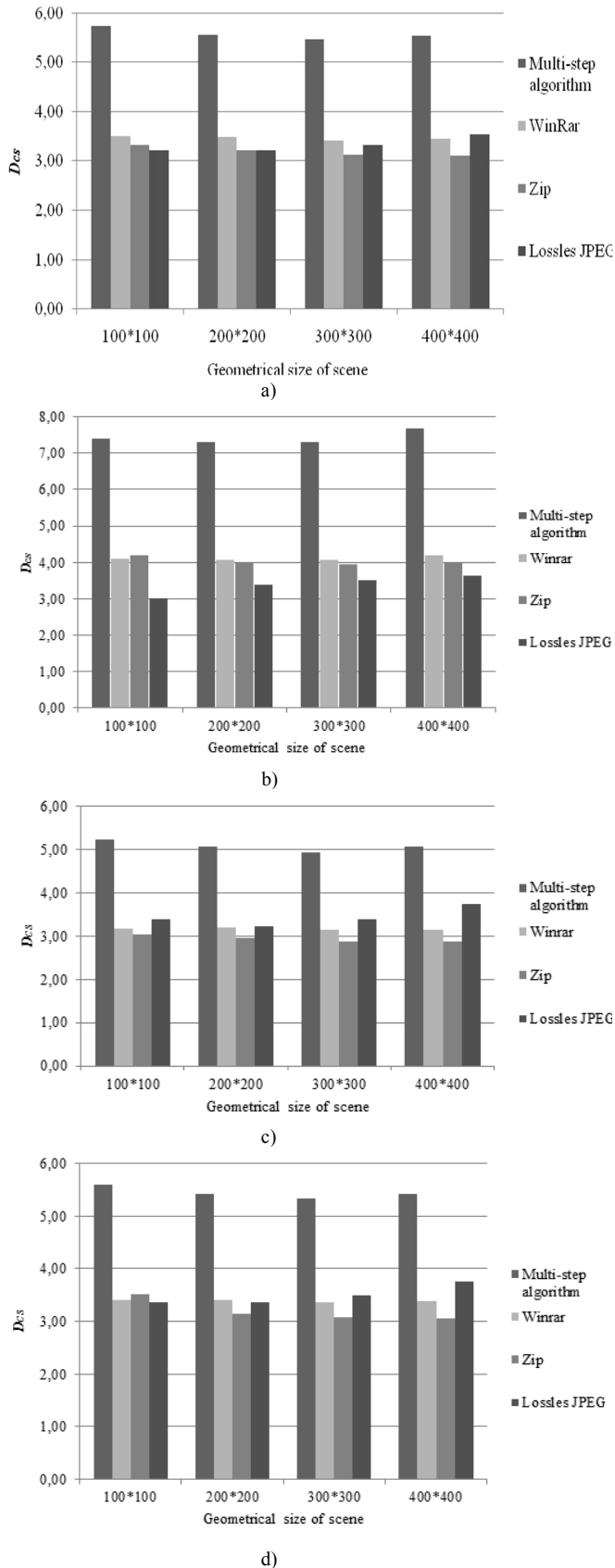


Figure 6. Comparative effectiveness of compression algorithms a) for 224 K; b) for 50 K; c) for 100 K; d) for 10 K.
Source: Authors' own elaboration.

In conducting comparative research of compression exponents it is necessary to pay attention to calculating expenses of compression algorithms for *AVIRIS* (I) and *HYPERION* (II) RS systems (Figure 5).

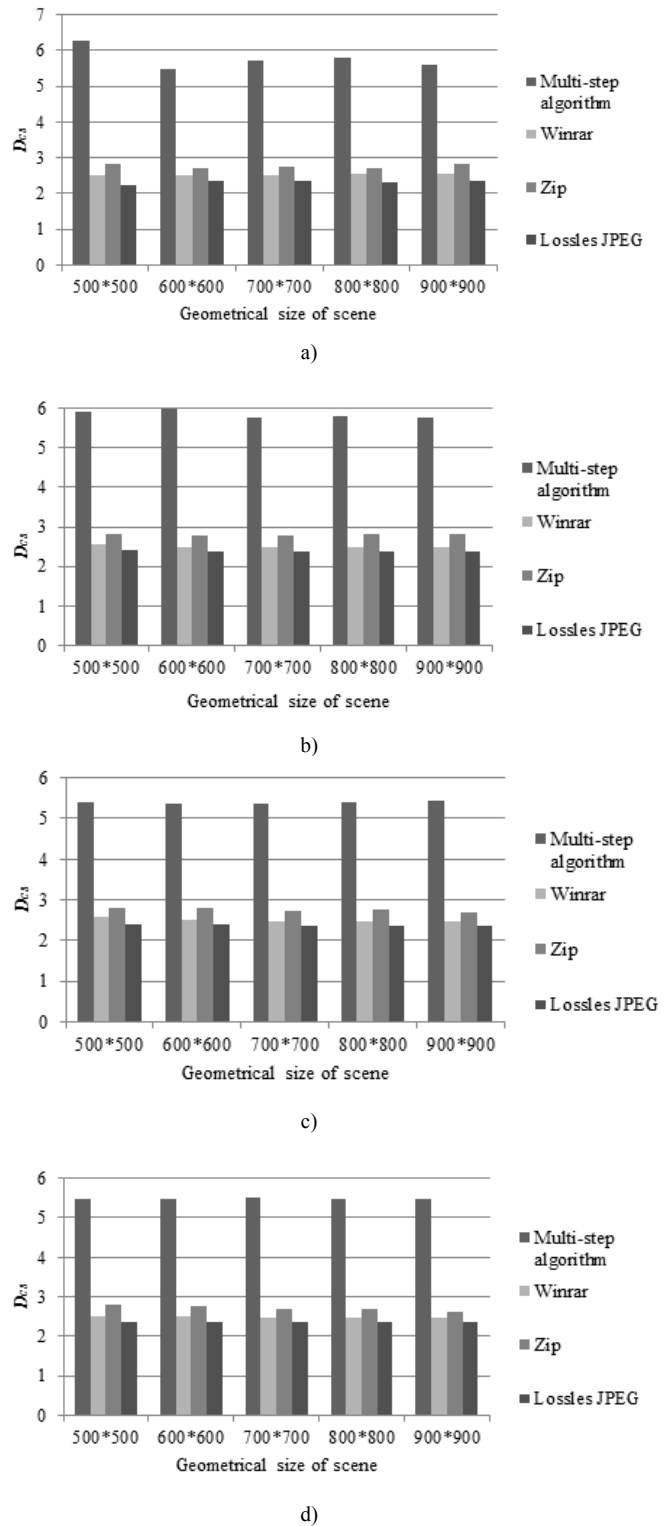


Figure 7. Comparative effectiveness of compression algorithms a) for 224 K; b) for 50 K; c) for 100 K; d) for 10 K.
Source: Authors' own elaboration.

As seen in Figure 5, in the proposed algorithm, the calculated effectiveness in comparison with analogues increased 3 fold. This is explained by an improved multi-stage algorithm which is provided to form auxiliary structures of data on AI considering the correlation and the following arithmetic coding.

Universal archival software does not take into account the specificity of the data being compressed and does not account for such operations.

A large number of studies in different dimensions and number of bands were conducted. The compression ratios results are presented in Figure 6 (*AVIRIS*) and Figure 7 (*HYPERION*).

4. Conclusion

1. A multi-stage algorithm for compressing hyperspectral AI was developed. This algorithm considers intra-bands correlation and the preliminary byte data processing, allowing an increase of up to 46% in data compression systems *AVIRIS* and *HYPERION* (up to 52%) when compared with other algorithms.

2. The analysis of the importance of stages has shown that the stage of preliminary byte processing with formation of auxiliary structures of data allows to improve the result considerably – by up to 45% and 52%. The stage of considering intra-bands correlation is less significant. However, it allows to lower a range of varied values for operating by smaller spacing, allowing to increase the compression ratio considerably – up to 26 %.

3. The analysis of computing efficiency has shown, that in order to achieve significant results of compression in applying a multi-stage algorithm, high computing expenses are required, conceding to the nearest analogue *Lossless JPEG* up to 3 fold.

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