






# Tensor-based Factorization Algorithms for Pixel-wise Classification of Hyperspectral Data Using Deep Convolutional Networks

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**Abstract:** Tensor-based algorithms for data compression have evolved in recent years according to the needs of several research areas. Tucker Decomposition (TKD) is one of the most popular factorization methods based on tensor algebra, but it is clear that it is not the only algorithm which can produce a factorization for a given input data set. Besides, this decomposition does not have singular solutions, i.e., it converges to local minima. Hence, depending on the input data, tensor-based decompositions can achieve better solution to a specific input. The phenomenology of Remote Sensing (RS) Hyperspectral Images (HSI) belongs to the set of natural numbers, i.e., the set of positive integers. Then, a non-negative tensor factorization suggest a more suitable decomposition for positive data by nature. The main purpose of this work is to prove the benefits in processing time, as well as in accuracy, of using a well-posed factorization algorithm. Specifically, this paper performs a quantitative analysis of tensor-based factorization algorithms applied to semantic segmentation of HSI using Deep Convolutional Networks (DCN).

**Keywords:** deep convolutional networks; hyperspectral imagery; tensor decomposition

## 1. Introduction

Reducing the dimensionality of input data for machine learning algorithms has been one of the most active research areas in recent years []. The insertion of tensor-based algorithms for these types of tasks inspired a change in several areas, such as image processing. [].

Most of the researchs in the image processing area require data acquired by multiple sensors. Even in the simplest case, color images, data acquired by three sensors that perceive reflectance of an object are processed. Each sensor receives reflectance in different wavelength ranges, and by merging that data, a color image is produced. Thus, the images can be represented in a form of three-dimensional arrays or third-order tensors. Two dimensions represent the spatial properties and the third dimension denotes the depth, i.e., the spectral bands. Medical analysis [], minorology [], agriculture, [], radar images [] and, above all, remote sensing multi- and hyper-spectral images [] can be represented, by nature, as third-order tensors.

Spectral images make certain image processing tasks much easier []. Recently, the use of this type of data has grown exponentially in various areas such as agriculture [], medical analysis [], biomedical [], natural disaster prediction [], security affairs [], among others. The ability to obtain

information about a target not only by its reflectance in the spatial domain, but also by response at different wavelengths, has driven a growth in accuracy and precision in tasks such as classification and segmentation [1].

Few years ago, several unsupervised classification and segmentation algorithms [2] were developed, taking advantage of the properties that spectral data produce. Subsequently, with the introduction of supervised machine learning algorithms such as Support Vector Machines (SVM) [3], k-Nearest Neighbors (k-NN) [4] and Artificial Neural Networks (ANN) [5], it was found that, under certain conditions, there is a direct relationship between the number of bands used and the performance of these algorithms [6]. However, with the aim of improving results, ANN models evolved into Deep Learning Neural Networks (DLNN) [7]. This caused the computational complexity to rise considerably and spectral image processing was not easily achievable. The foregoing requires having robust computer equipment to achieve competitive results in time.

Several works opted for matrix factorization algorithm to reduce the high-dimensionality of spectral images [8]. More recently, with the development of tensor factorization algorithms [9], it has been found that some algorithms based on tensor algebra produce advantages over those based on matrices [10]. Nevertheless, the data produced by both of them are hard to understand for supervised classification algorithms that need spatial relation between pixels to produce a wise prediction [11].

In this work, the proposal is to find an alternative solution to the problem described previously. We propose a model that reduces the computational load of hyperspectral imagery classification supervised algorithms through tensor decomposition models. This produces a lower dimensional tensor while preserving the structural and numerical nature of the original data.

### 1.1. Previous work

There are several works focused on the development of frameworks that reduce computational complexity of machine learning algorithms for semantic segmentation of hyperspectral datasets [12]. The crucial factor, which is addressed in this work, is to achieve compression of the input data to reduce the high number of computations, but without sacrificing pixel accuracy, overall accuracy, precision and recall in the classification task.

Before the introduction of tensor decomposition algorithms, the way to use hyperspectral images as input for supervised classification algorithms was by band selection [23] and [22]. Later, matrix decomposition algorithms were used, such as PCA in [24], and even non-negative matrix decomposition methods [25]. In 2015 Zhang et al. [26] were pioneers in experimenting with multilinear algebra-based decompositions on hyperspectral images.

On the other hand, there was also the possibility of using multispectral images due to the small number of spectral bands, which still made efficient results in classification without dimensionality reduction achievable, as done in [11], [18], [21] and [27]. However, the need to increase classification performance forces researchers to use data with more features that favor and aid the classification of various classes, which are difficult to differentiate with little spectral data. Thus, more recent researchs have decided to use hyperspectral images with tensor decompositions, which has increased the results in classification accuracy [26], [27], [29], [30] and [31].

Recently, Sayeh [32] published a work close to our research. They proposed a non-negative tensor decomposition of hyperspectral images but, different to the framework proposed in this work, they try to preserve certain spatial-spectral features into the so called abundance maps, i.e. the projection matrices, while this work pursuists to preserve the nature of the image just compressing the main information in the positive core tensor.

Table 1 summarizes some of the most cited related papers, wich deal with the compression-classification issue.

**Table 1.** Related work in spectral imagery semantic segmentation.

| Reference                     | Input          | Decomposition   | Reduction        | Classifier   |
|-------------------------------|----------------|-----------------|------------------|--------------|
| Li, S. et al. [23] (2014)     | HSI            | -               | Band selection   | SVM          |
| Zhang, L. et al. [24] (2015)  | HSI            | TKD             | Spatial-Spectral | -            |
| Wan, Q. et al. [22] (2016)    | HSI            | -               | Band selection   | SVM/kNN/CART |
| Kemker, R. et al. [11] (2017) | MSI            | -               | -                | CNN          |
| Tong L. et al. [] (2017)      | HSI            | NMF             | Unmixing         | -            |
| Hamida, A. et al. [21] (2017) | MSI            | -               | -                | CNN          |
| Chien, J. et al. [] (2017)    | RGB            | TFNN            | Spatial-Spectral | TFNN         |
| Dewa, M. et al. [] (2018)     | HSI            | PCA             | Spectral         | PCA          |
| Xu, Y. et al. [] (2018)       | HSI            | -               | -                | CNN          |
| Li, J. et al. [28] (2019)     | MSI            | NTD-CNN         | Spatial-spectral | -            |
| An, J. et al. [27] (2019)     | HSI            | T-MLRD          | Spatial-spectral | SVM/1NN      |
| An, J. et al. [29] (2019)     | HSI            | TDA             | Spatial-spectral | SVM/1NN      |
| Lopez, J. et al. [] (2019)    | MSI            | TKD             | Spectral         | FCN          |
| Sayeh, M. [] (2019)           | HSI            | NTD             | Spatial-Spectral | 3D-CNN       |
| <b>Our framework</b>          | <b>MSI/HSI</b> | <b>iNTD/NTD</b> | <b>Spectral</b>  | <b>CNN</b>   |

### 1.2. Motivation

Nowadays, RS image processing is applied in several areas related to caring of the planet. Nevertheless, task such as classification becomes more complex due to low spatial resolutions, this is offset by the use of devices with other features such as spectral sensors.

On the other hand, CNNs have been widely used in recent years in the area of RGB image semantic classification and segmentation. Its performance is highly competitive and the development of various improvement strategies have considerably reduced its computational cost []. However, the computational complexity of the algorithm means that the increase in the dimensionality of the input data produces a significant increase in the computational load []. This is why the processing of high-dimensional images such as multi and hyperspectral images becomes unfeasible.

Some data compression strategies have favorably reduced the dimensionality of the data. Decomposition methods based on the matrix and tensor approaches have been applied as pre-processing of input data of neural networks. In tensor decompositions, the processing of the data in its natural format, i.e., as N-th order tensors, improves the decomposition process because it considers the dependence of the data in its different modes. Although a decomposition can compress the data, it is also important to note that the inappropriate selection of some decomposition parameters could lead to information losses, which would penalize the performance of a CNN.

Under these considerations, this work is motivated to develop a low computational complexity and competitive in performance framework that helps various fields of application of remote sensing image processing to solve classification tasks.

### 1.3. Contribution

Unlike previous works, this work seeks to adapt the data in a more efficient way to the input of deep convolutional networks. Convolutional Neural Network models are designed to extract and interpret all the spatial properties of an image by moving the kernels over the input data []. Therefore, producing uncorrelated data in space and spectrum, would make harder the interpretation of the data in the convolutional network [? ]. Thus, the proposed framework maintains the integer and non-negativity tensor nature of the spectral images and the spatial dimensionality to preserve spatial-spectral correlation of the data while reducing the spectral dimensionality, in order to decrease computational load in the pixel-wise classification process. Besides, we approach the problem of setting the compression rank selection hyperparameters by the measurement of divergences, which aids to estimate a lower rank approximation.

The main contributions of this work can be summarized by the following three points:

1. The framework INTD1-CNN proposed in this work, develops an approximation strategy to improve performance of semantic segmentation convolutional neural networks by finding suitable tensor data, preserving spatial correlation and values in the set of the natural numbers while compressing the spectral domain and in turn decreasing computational load.
2. Furthermore, this work proposes a strategy for defining the rank in mode 3 of the compression models based on the Tucker decomposition from the information theory point of view.
3. This work also presents an exhaustive performance analysis measuring and comparing its efficiency with the most popular metrics, i.e., as pixel accuracy (PA), also PA in function of the number of new tensor bands, precision, recall, F1, orthogonality degree of the factor matrices and the core tensor, reconstruction error of the original tensor, and execution time.

The remainder of this work is organized as follows. Section ?? introduces tensor algebra notation and basic concepts to familiarize the reader with the symbology used in this paper. Section ?? presents the problem statement of this work and the mathematical definition. In Section ??, CNN theory is described for classification and semantic segmentation. Section ?? presents the framework proposed for compression and semantic segmentation of spectral images. Experimental results are presented in Section ?. Finally, Sections ?? and 8 present a discussion and conclusions based on the results obtained in the experiments.

## 2. Notation and definitions

Matrix-based factorizations, such as PCA [] and SVD [] have been significant and useful tools for dimensionality reduction and other approaches. Nevertheless, they are limited to data representations in 2-dimensional spaces. Most of current applications have data structures often as higher-order arrays, e.g. dimensions of space, time, and frequency. This 2-way view in matrix factorizations may be inadequate and it is natural to use tensor decomposition approaches [? ].

A tensor can be defined as a multi-way or multidimensional array. The order of a tensor is the number of dimensions, also known as modes, i.e., an  $N$ -order tensor  $\mathcal{X} \in \mathbb{R}^{I_1 \times I_2 \times I_3}$  is an  $N$ -dimensional array, which elements  $x_{i_1, i_2, \dots, i_n}$  are indexed by  $i_n \in 1, 2, \dots, I_n$  for  $1 \leq n \leq N$ .

Throughout this paper, the mathematical notation used by Kolda et al. [17] has been adopted. Table 2 summarize this notation.

It is also necessary to introduce some tensor algebra operations and basic concepts used in later explanations.

### 2.1. Matricization

The mode- $n$  matricization is the process of reordering the elements of a tensor into a matrix along axis  $n$  and it is denoted as  $\mathbf{A}_{(n)} \in \mathbb{R}^{I_n \times \prod_{m \neq n} I_m}$ .

### 2.2. Inner Product

The inner product of two tensors  $\mathcal{A}, \mathcal{B} \in \mathbb{R}^{I_1 \times \dots \times I_N}$  is the sum of the products of their entries; i.e.,  $\langle \mathcal{A}, \mathcal{B} \rangle = \sum_{i_1=1}^{I_1} \dots \sum_{i_N=1}^{I_N} a_{i_1 \dots i_N} b_{i_1 \dots i_N}$ .

### 2.3. N-Mode Product

It means the multiplication of a tensor  $\mathcal{A} \in \mathbb{R}^{I_1 \times \dots \times I_N}$  by a matrix  $\mathbf{U} \in \mathbb{R}^{J \times I_n}$  or vector  $\mathbf{u} \in \mathbb{R}^{I_n}$  in mode  $n$ ; i.e., along axis  $n$ . It is represented by  $\mathcal{B} = \mathcal{A} \times_n \mathbf{U}$ , where  $\mathcal{B} \in \mathbb{R}^{I_1 \times \dots \times I_{n-1} \times J \times I_{n+1} \times \dots \times I_N}$  [17].

### 2.4. Rank-One Tensor

A tensor  $\mathcal{X} \in \mathbb{R}^{I_1 \times \dots \times I_N}$  is rank one if it can be written as the outer product of  $N$  vectors, i.e.,

$$\mathcal{X} = \mathbf{a}^{(1)} \circ \dots \circ \mathbf{a}^{(N)} \quad (1)$$

where  $\circ$  denotes the outer product and  $\mathbf{a}^{(n)}$  denotes a vector in a sequence of  $N$  vectors. Each element of the tensor is the product of the corresponding vector elements; i.e.,  $x_{i_1 i_2 \dots i_N} = a_{i_1}^{(1)} \dots a_{i_N}^{(N)}$ .

#### 2.4.1. $N$ -Rank

The  $n$ -rank of a tensor  $\mathcal{X} \in \mathbb{R}^{I_1 \times \dots \times I_N}$  denoted  $\text{rank}_n(\mathcal{X})$ , is the column rank of  $\mathbf{X}_{(n)}$ ; i.e., the dimension of the vector space spanned by the mode- $n$  fibers. Hence, if  $R_n \equiv \text{rank}_n(\mathcal{X})$  for  $n = 1, \dots, N$ , then  $\mathcal{X}$  has a rank  $-(R_1, \dots, R_N)$  tensor [17].

**Table 2.** Tensor algebra notation summary

|   |  |
|---|--|
| $\mathcal{A}, \mathbf{A}, \mathbf{a}, a$                                      | Tensor, matrix, vector and scalar respectively   |
| $\mathcal{A} \in \mathbb{R}^{I_1 \times \dots \times I_N}$                    | $N$ -order tensor of size $I_1 \times \dots \times I_N$ .  |
| $a_{i_1 \dots i_N}$   | An element of a tensor   |
| $\mathbf{a}_{:i_2 i_3}, \mathbf{a}_{i_1 : i_3},$ and $\mathbf{a}_{i_1 i_2 :}$ | Column, row and tube fibers of the third order tensor $\mathcal{A}$  |
| $\mathbf{A}_{i_1 ::}, \mathbf{A}_{:i_2 :}, \mathbf{A}_{::i_3}$                | Horizontal, lateral and frontal slices of the third order tensor $\mathcal{A}$   |
| $\mathbf{A}^{(n)}, \mathbf{a}^{(n)}$  | A matrix/vector element from a sequence of matrices/vectors  |
| $\mathbf{A}_{(n)}$  | Mode- $n$ matricization of a tensor. $\mathbf{A}_{(n)} \in \mathbb{R}^{I_n \times \prod_{m \neq n} I_m}$   |
| $\mathbf{a}^{(1)} \circ \dots \circ \mathbf{a}^{(N)}$                         | Outer product of $N$ vectors   |
| $\langle \mathcal{A}, \mathcal{B} \rangle$                                    | Inner product of two tensors.  |
| $\mathcal{B} = \mathcal{A} \times_n \mathbf{U}$                               | $n$ -mode product of tensor $\mathcal{A} \in \mathbb{R}^{I_1 \times \dots \times I_N}$ by a matrix $\mathbf{U} \in \mathbb{R}^{J \times I_n}$ along axis $n$ . |

### 3. Tensor decompositions (TDs)

As an extension of the matrix-based singular value decomposition, two main specific tensor decompositions can be considered; Tucker Decomposition (TKD) [1] and CANDECOMP/PARAFAC (CP) [2]. There are many other tensor decompositions; INDSCAL, PARAFAC2, CANDELINC, DEDICOM, PARATUCK2, among others [17]. Furthermore, there are also nonnegative variants of all of the above. With the aim of preserving particular characteristics of hyperspectral images for pixel-wise classification, this study is limited to use decompositions based on the Tucker model.

#### 3.1. Tucker Decomposition (TKD)

The TKD [17], for the particular case of third-order tensors, can be formally formulated as follows [?]. Given a third-order data tensor  $\mathcal{X} \in \mathbb{R}^{I_1 \times I_2 \times I_3}$  and three positive indices  $J_1, J_2$  and  $J_3$ , find a core tensor  $\mathcal{G} \in \mathbb{R}^{J_1 \times J_2 \times J_3}$  and three component matrices called factor matrices  $\mathbf{U}^1 \in \mathbb{R}^{I_1 \times J_1}$ ,  $\mathbf{U}^2 \in \mathbb{R}^{I_2 \times J_2}$  and  $\mathbf{U}^3 \in \mathbb{R}^{I_3 \times J_3}$  which perform the following approximate decomposition:

$$\mathcal{X} = \mathcal{G} \times_1 \mathbf{U}^{(1)} \times_2 \mathbf{U}^{(2)} \times_3 \mathbf{U}^{(3)} + \mathcal{E} \quad (2)$$

where  $\mathcal{E}$  denotes the approximation error tensor. The core tensor  $\mathcal{G}$  preserves the level of interaction for each factor or projection matrix  $\mathbf{U}^{(n)}$ . The factor matrices are commonly considered orthogonal, but in Tucker models with non-negativity constraints, that is not necessarily imposed [?]. These matrices can be seen as the principal components in each mode [17] (see Figure 1).  $J_n$  represents the number of components in the decomposition; i.e., the rank  $-(R_1, R_2, R_3)$ .

The TKD can also be denoted by the matricization approach and expressed as

$$\mathbf{X}_{(1)} = \mathbf{U}^{(1)} \mathbf{G}_{(1)} (\mathbf{U}^{(3)} \otimes \mathbf{U}^{(2)})^T \quad (3a)$$

$$\mathbf{X}_{(2)} = \mathbf{U}^{(2)} \mathbf{G}_{(2)} (\mathbf{U}^{(3)} \otimes \mathbf{U}^{(1)})^T \quad (3b)$$

$$\mathbf{X}_{(3)} = \mathbf{U}^{(3)} \mathbf{G}_{(3)} (\mathbf{U}^{(2)} \otimes \mathbf{U}^{(1)})^T \quad (3c)$$

where  $\otimes$  denotes the Kronecker product and  $\mathbf{X}_{(n)}$  and  $\mathbf{G}_{(n)}$  are the  $n$ -mode matricized versions of tensor  $\mathbf{X}$  and  $\mathbf{G}$  respectively.

Starting from (2), the reconstruction of an approximated tensor can be given by

$$\hat{\mathbf{X}} = \mathbf{G} \times_1 \mathbf{U}^{(1)} \times_2 \mathbf{U}^{(2)} \times_3 \mathbf{U}^{(3)} \quad (4)$$

where  $\hat{\mathbf{X}}$  is the reconstructed tensor. Then, the core tensor  $\mathbf{G}$  can be acquired by the multilinear projection

$$\mathbf{G} = \mathbf{X} \times_1 \mathbf{U}^{(1)T} \times_2 \mathbf{U}^{(2)T} \times_3 \mathbf{U}^{(3)T} \quad (5)$$

where  $\mathbf{U}^{(n)T}$  denotes the transpose matrix of  $\mathbf{U}^{(n)}$  for  $n = 1, \dots, N$ . The reconstruction error  $\zeta$  can be computed as

$$\zeta(\hat{\mathbf{X}}) = \|\mathbf{X} - \hat{\mathbf{X}}\|_F^2 \quad (6)$$

and  $\|\cdot\|_F$  represents the Frobenius norm. To compute the best rank approximation of a tensor, it can be used an iterative algorithm as ALS, HALS, HOOI after a HOSVD initialization [? ].

HOOI initializes the factors matrices using HOSVD and assumes that orthogonal matrices are known, so that the core tensor is obtained with (5). Then, it maximizes the cost function

$$\max_{\mathbf{U}^{(1)}, \mathbf{U}^{(2)}, \mathbf{U}^{(3)}} \|\mathbf{X} \times_1 \mathbf{U}^{(1)T} \times_2 \mathbf{U}^{(2)T} \times_3 \mathbf{U}^{(3)T}\|_F^2 \quad (7)$$

with  $\mathbf{U}^{(n)}$  unknown. Fixing all factor matrices but one, tensor  $\mathbf{X}$  can be projected onto the  $\{R_1, \dots, R_{n-1}, R_{n+1}, \dots, R_N\}$ -dimensional space as

$$\mathbf{W}^{(-n)} = \mathbf{X} \times_1 \mathbf{U}^{(1)T} \dots \times_{n-1} \mathbf{U}^{(n-1)T} \times_{n+1} \mathbf{U}^{(n+1)T} \dots \times_N \mathbf{U}^{(N)T} \quad (8)$$

and the orthogonal matrices can be estimated as an orthonormal basis for the dominant subspace of the projection by applying the standard matrix SVD for  $n$ -mode unfolded matrix  $\mathbf{W}_{(n)}^{(-n)}$  for  $n = 1, 2, 3$  [? ].

### 3.1.1. Non-negative Tucker Decomposition (NTD)

The NTD is a decomposition based on the Tucker model. It is develops a new tensor factorization method with nonnegativity constraints [1]. For the third-order case, the NTD, as defined by Cichocky [15], can be formulated as follows. Given a third-order tensor  $\mathbf{X} \in \mathbb{R}_+^{I_1 \times I_2 \times I_3}$  find a core tensor  $\mathbf{G} \in \mathbb{R}_+^{J_1 \times J_2 \times J_3}$  and the factor matrices  $\mathbf{U}_1 \in \mathbb{R}_+^{I_1 \times J_1}$ ,  $\mathbf{U}_2 \in \mathbb{R}_+^{I_2 \times J_2}$  and  $\mathbf{U}_3 \in \mathbb{R}_+^{I_3 \times J_3}$  which performs the approximation given in Eq. (2). As well as for the TKD model, the best rank approximation of a nonnegative tensor can be computed by an iterative algorithm as HOOI, maximizing the cost function given in equation 7. Algorithm 1 shows the HOOI algorithm for a NTD.

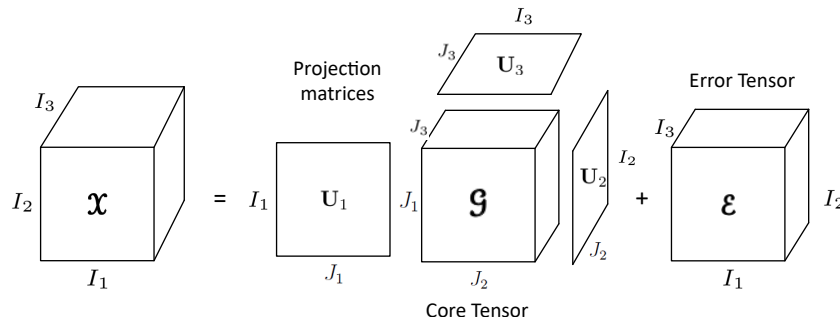


Figure 1. Tucker decomposition for a third-order tensor.

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**Algorithm 1:** HOOI algorithm to compute a rank- $(R_1, \dots, R_N)$  NTD for an  $N$ th-order tensor  $\mathcal{X} \in \mathbb{R}^{I_1 \times \dots \times I_N}$ .

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**Function** HOOI( $\mathcal{X}, J_1, \dots, J_N$ ):

    initialize  $\mathbf{U}^{(n)} \in \mathbb{R}^{I_n \times J_n}$  for  $n = 1, \dots, N$  using HOSVD or random

**repeat**

**for**  $n = 1, \dots, N$  **do**

$\mathcal{W}^{(-n)} \leftarrow \mathcal{X} \times_{-n} \{\mathbf{U}^{(T)}\}$

$[\mathbf{U}^{(n)}, \Sigma^{(n)}, \mathbf{V}^{(n)}] \leftarrow \text{svds}(\mathcal{W}_{(n)}^{(-n)}, J_n, \text{'LM'})$

$\mathbf{U}^{(n)} \leftarrow [\mathbf{U}^{(n)}]_+$

**end**

**until** fit ceases to improve or maximum iterations exhausted;

$\mathcal{G} \leftarrow \mathcal{W}^{(-N)} \times_N \mathbf{U}^{(N)T}$

**Output:**  $\mathbf{U}^{(n)} \in \mathbb{R}_+^{I_n \times J_n}, \mathcal{G} \in \mathbb{R}_+^{J_1 \times J_2 \times \dots \times J_N}$

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## 4. Problem phenomenology

### 4.1. Spectral Imagery

Multi- or Hyper-spectral images are by nature multidimensional integer nonnegative arrays. A spectral image can be sorted and represented as a third-order tensor  $\mathcal{X} \in \mathbb{N}^{I_1 \times I_2 \times I_3}$ , where  $\mathbb{N}$  denotes the space of natural numbers,  $I_1$ ,  $I_2$  and  $I_3$  represent the height, width and spectral bands respectively. In RS image processing, spectral images are frequently used for classification of different material in a scene of interest. However, due to the low spatial resolution produced by the distance between the sensor and the target, spatial features are not sufficient to discern certain classes. That is why spectral resolution plays an important role in this type of task.

The separation into spectral bands allows perception of reflectance at different wavelengths. This helps to better characterize various materials, in order to simplify the process of discernment between classes. The effort to obtain these spectral features generates a greater amount of data, which increases the processing complexity. This is where the spectral decomposition task becomes relevant.

### 4.2. Problem Statement

Let  $\mathcal{X} \in \mathbb{N}^{I_1 \times I_2 \times I_3}$  be a spectral image represented as a third-order tensor, and  $\mathbf{Y} \in \mathbb{N}^{I_1 \times I_2}$  its corresponding ground truth matrix for a specific number of classes  $C$ . Find the best rank- $(R_1, R_2, R_n)$  approximation and its core tensor  $\mathcal{G} \in \mathbb{R}^{I_1 \times I_2 \times J_3}$ , through Non-negative Tensor Decompositions. The rank of the decomposition  $\text{rank}_n(\mathcal{X})$  is set as  $\text{rank}-(I_1, I_2, J_3)$ , where  $J_3 < I_3$ . This built the input space of a pixel-wise classification using CNNs and produce an output matrix  $\hat{\mathbf{Y}}$  of predicted classes, achieving competitive performance metrics for pixel-wise classification while decreasing computational load in the classification process.

### 4.3. Mathematical Definition

the problem statement described above can be mathematically defined as the optimization problem



$$\begin{aligned}
& \min_{\mathbf{g}, \mathbf{U}^{(1)}, \mathbf{U}^{(2)}, \mathbf{U}^{(3)}} \|\mathbf{X} - \mathbf{g} \times_1 \mathbf{U}^{(1)} \times_2 \mathbf{U}^{(2)} \times_3 \mathbf{U}^{(3)}\|_F^2 \\
& \text{subject to} \quad \mathbf{U}^{(n)} \in \mathbb{R}_+^{I_n \times J_n} \quad \text{for } n = 1, 2, 3 \quad \text{and} \quad \mathbf{g} \in \mathbb{R}_+^{J_1 \times J_2 \times J_3} \\
& \quad J_1 = I_1, J_2 = I_2 \quad \text{no compression in the spatial domain,} \\
& \quad J_3 < I_3 \quad \text{reduced spectral domain at the core tensor,} \\
& \quad \xi(\hat{\mathbf{X}}) \leq \xi_s \quad \text{measure of representativity} \\
& \quad D(\mathbf{g}_{j_3}) - D(\mathbf{g}_{j_3+1}) < D_s \quad \text{divergence stop criterion}
\end{aligned} \tag{9}$$

## 5. Methodology

The following subsections describe the methodology of the framework proposed in this work. The big picture is summarized in three steps: the HSI modeling, the tensor decomposition, the classifier and the decision making.

### 5.1. Tensor modeling

Consider an input dataset  $\mathbf{X} \in \mathbb{N}^{I_1 \times I_2 \times I_3}$  with  $I_1 \times I_2 \times I_3$  samples in the space of the natural numbers  $\mathbb{N}$ , where a fiber  $\mathbf{x}_{i_1 i_2}$  represents the spectra or endmember of pixel  $i_1 i_2$  and can be represented by the Linear Mixing Model (LMM) as follows

$$\mathbf{x}_{i_1 i_2} = \sum_{c=1}^C (\alpha_{i_1 i_2 c} \mathbf{m}_c + \boldsymbol{\eta}) \tag{10}$$

where  $\alpha_c$  is the contribution of material  $c$  at pixel  $i_1 i_2$ ,  $\mathbf{m}_c$  denotes the endmember of a specific material  $c$ , and  $\boldsymbol{\eta}$  represents an additive noise vector. The abundance vectors  $\alpha_{i_1 i_2}$  must always satisfy two constraints, i) the non-negativity,  $\alpha_{i_1 i_2 c} \geq 0$  for all  $c = 1, \dots, C$ , and ii) the sum-to-one restriction,  $\sum_{c=1}^C \alpha_{i_1 i_2 c} = 1$ . Figure 2a shows the spectral signatures for the Indian Pines dataset.

### 5.2. Tensor factorization

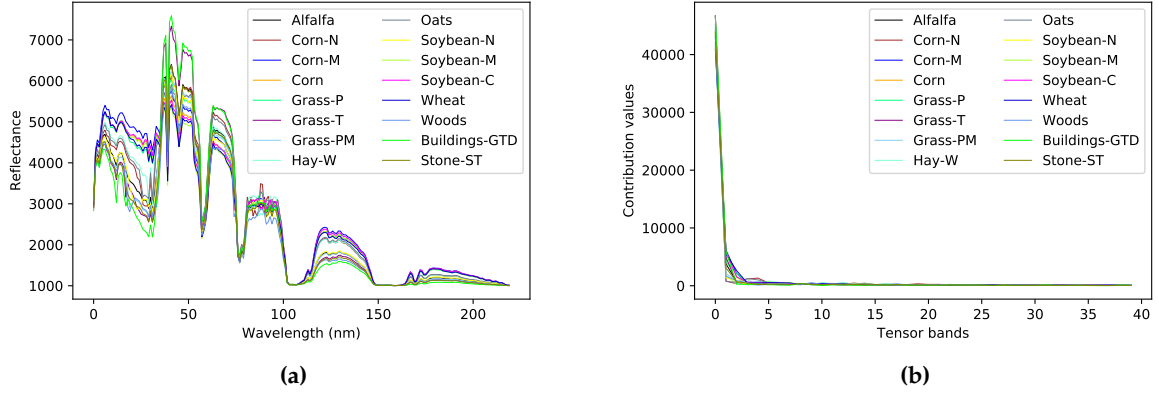
Consider  $\mathbf{Y} \in \mathbb{C}^{I_1 \times I_2}$  as the matrix of actual classes corresponding to our dataset  $\mathbf{X}$ , and  $\hat{\mathbf{Y}} \in \mathbb{C}^{I_1 \times I_2}$  as the prediction matrix, where  $\mathbb{C}$  defines the set of  $C$  different classes. In order to reduce data dimensionality of the input dataset  $\mathbf{X}$  while keeping classifier performance, we propose to use a restricted NTD denoted as  $\mathcal{T}$ , producing a core tensor  $\mathbf{g} \in \mathbb{R}^{I_1 \times I_2 \times J_3}$  and  $n$  factors matrices  $\mathbf{U}^{(n)} \in \mathbb{R}^{I_n \times J_n}$ , expressed as

$$\mathbf{X} \xrightarrow{\mathcal{T}} (\mathbf{g}, \mathbf{U}^{(n)}) \tag{11}$$

where the decomposition is restricted to preserve the spatial domain and to be only in the 3rd-mode by the Tucker-1 model

$$\mathbf{X} = \mathbf{g} \times_1 \mathbf{I} \times_2 \mathbf{I} \times_3 \mathbf{U}^{(3)} \tag{12}$$





**Figure 2.** Behavior of the 16 classes of the Indian Pines dataset, a) in the spectral domain (spectral signatures) and b) in the the tensor bands domain after NTD.

Hence, each fiber  $\mathbf{x}_{i_1 i_2}$  of the core tensor takes a new representation in the tensor bands domain and can be mathematically defined as follows

$$\mathbf{g}_{i_1 i_2} = \sum_{c=1}^C (\beta_{i_1 i_2 c} \mathbf{s}_c + \boldsymbol{\eta}) \quad (13)$$

where  $\beta_c$  is the contribution of material  $c$  at pixel  $i_1 i_2$  and  $\mathbf{s}_c$  denotes the endmember of a specific material  $c$ . Figure 2b shows the new tensor bands values for each class after NTD.

We also propose an approximation based on the NTD, which computes an integer decomposition, the Integer Non-negative Tucker decomposition (INTD). The INTD follows the same Tucker model described in Section 3.1. It considers the additional restriction of decomposing a tensor in the set of the natural numbers.

### 5.3. Classifier

The tensor decompositions based on the Tucker1 model produce a core tensor, where the first tensor bands provide a signature enough to differentiate the classes of interest of the input dataset. Then, the core tensor  $\mathbf{G} \in \mathbb{N}^{I_1 \times I_2 \times J_3}$ , with  $J_3 < I_3$ , and its corresponding ground truth  $\mathbf{Y}$  form the input tuple of the classifier  $\Theta$ , which produce a predicted label for each element of the input, i.e.,

$$(\mathbf{G}, \mathbf{Y}) \xrightarrow{\Theta} \hat{\mathbf{Y}} \quad (14)$$

The performance of our classification model can be measured by the cross-entropy loss, whose output is a probability value. The cross-entropy loss increases as the predicted probability diverges from the actual label and it is computed as

$$J(\mathbf{W}) = -\mathbb{E}_{\mathbf{y} \sim p} \log p(\mathbf{Y}|\mathbf{G}) \quad (15)$$

where  $J(\mathbf{G})$  represents the loss function. For a multiclass probability distribution, the cross entropy cost function can be written as

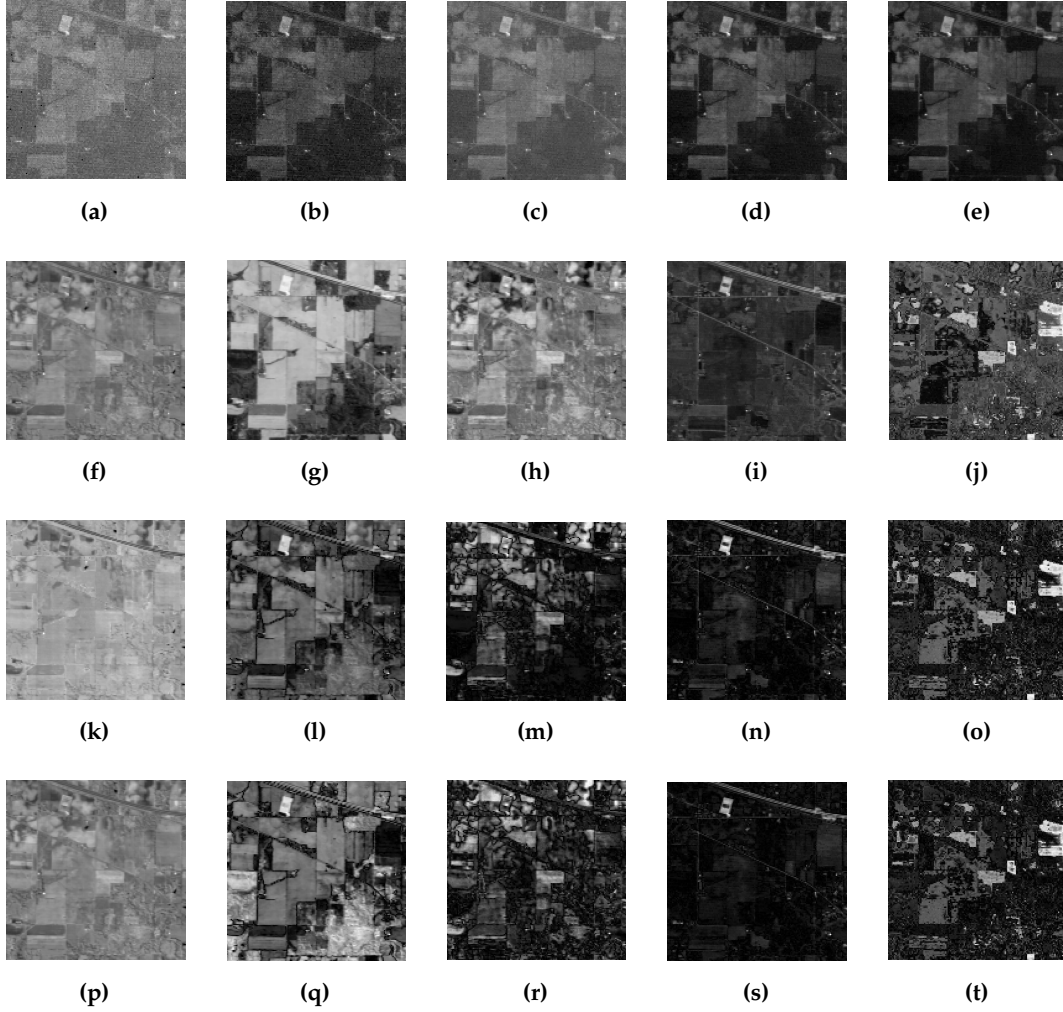
$$H(y, p) = - \sum_{c=1}^C y_c \log(p_c) \quad (16)$$

where  $H(y, p)$  denotes the cross entropy of targets  $y$  with a probability  $p$ .

The softmax function is used as the output of the classifier, to represent the probability distribution over  $C$  different classes. Formally, the softmax function is given by

$$\delta(\mathbf{z})_c = \frac{e^{z_c}}{\sum_{l=1}^L e^{z_l}} \quad (17)$$

where  $\delta(\mathbf{z})_c$  denotes the softmax function of vector  $\mathbf{z}$ , which is each 3rd-mode fiber of the activation maps at the last convolutional layer. Hence, the softmax function produces a normalized probability distribution for every input pixel, which can be seen as the contribution parameter in the LMM (Eq. 10).



**Figure 3.** Visualisation of Indian Pines 1st to 5th 3a to 3e original spectral bands, 3f to 3j tensor bands with TKD, 3k to 3o tensor bands with NTD, and 3p to 3t tensor bands with INTD.

In this paper, we aim to feed supervised classifiers, based on 3D-CNN, with a lower dimensionality tensor than the original dataset. This has three particular motivations: 1) to avoid overfitting the DCNN, 2) to reduce the computational complexity, and 3) keep the classifier performance while reducing the execution time. Figure 4 shows the big picture of the framework proposed.

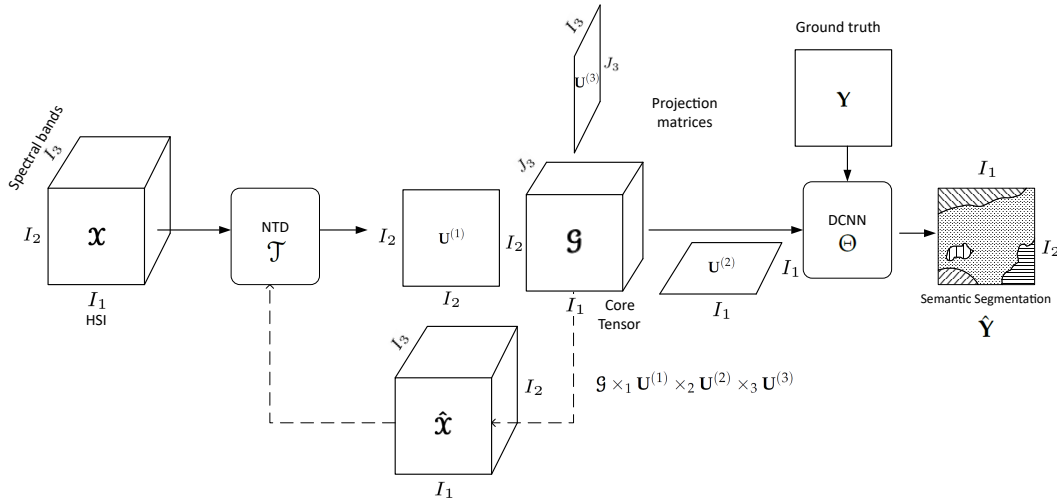


Figure 4. Big picture of the framework proposed.

#### 5.4. Divergence analysis

The framework proposed in this work faces two main challenges. The first is the selection of the decomposition method. We are looking for a better representation of the input dataset for a 3D-CNN, so, we limit the set of methods to those that produce a decomposition tensor with the same structure as the input tensor. TKD, NTD and the INTD proposed generate a core tensor with the desired properties.

The second challenge is the search for the rank  $(J_1, J_2, J_3)$ . As we want to preserve the spatial domain  $J_1 = I_1$  and  $J_2 = I_2$ , but  $J_3$  has to be selected so that the performance of the classifier does not decrease considerably. Both decisions are made under a criterion under the probabilistic point of view.

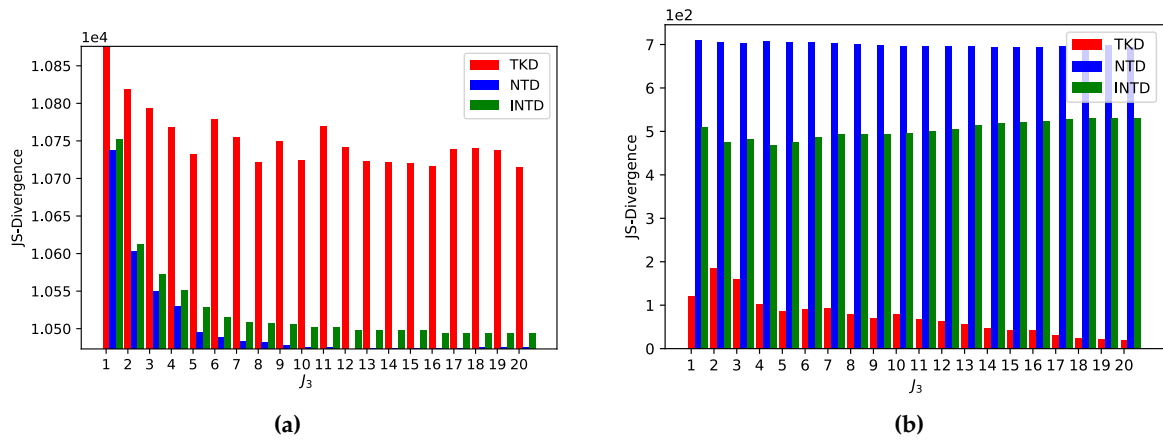
For this work the Jensen-Shanon divergence (JSD) is used as a metric to quantify how different the core tensor of a decomposition is from the input dataset from an information theory point of view. This method measure the similarity between two probability distributions. The JSD can be computed as

$$D_{JS}(X||G) = \frac{1}{2}D_{KL}(X||M) + \frac{1}{2}D_{KL}(G||M) \quad (18)$$

where  $D_{JS}(X||G)$  represents the JS divergence of the probability distributions  $X$  and  $G$ ,  $M = \frac{X+G}{2}$  is the mean of the probability distributions, and  $D_{KL}$  denotes the Kullback-Leibler divergence, which is a asymmetric version of the JSD and it is computed as

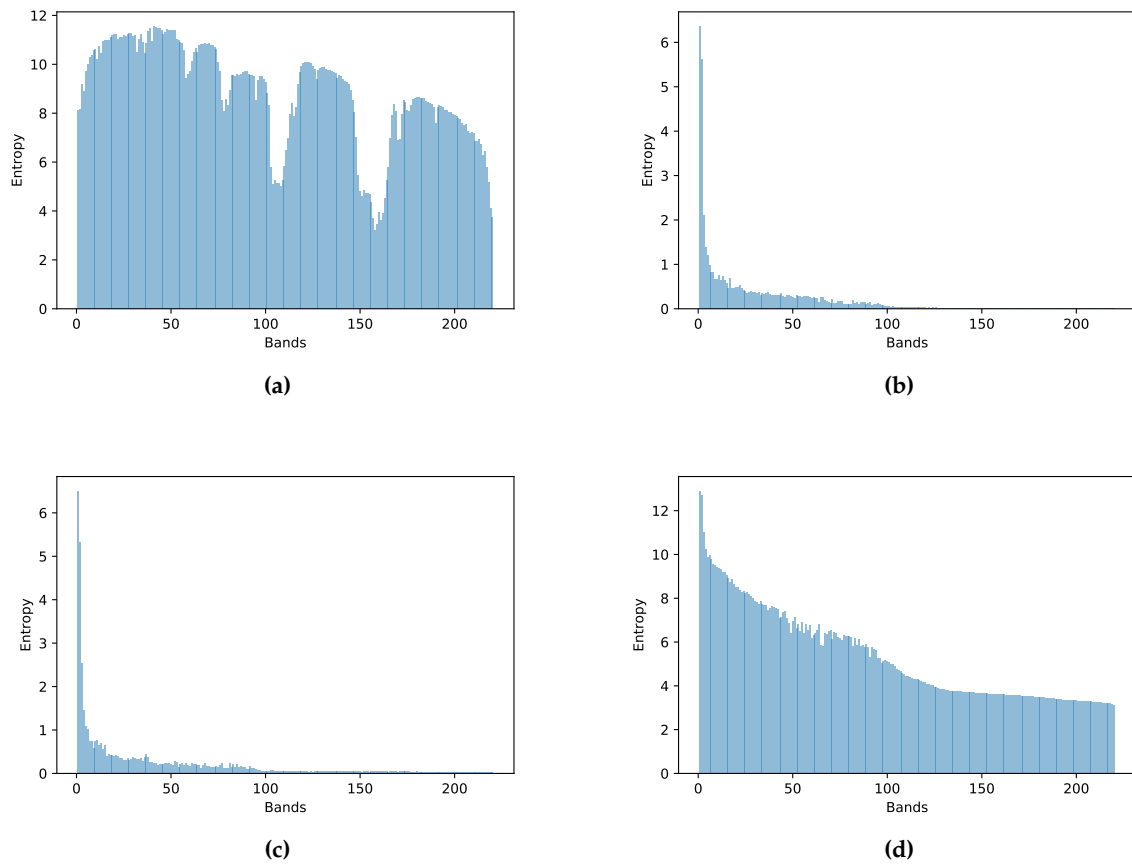
$$D_{KL}(X||G) = \sum_{i=1}^I X_i(x) \log \frac{X(x_i)}{G(x_i)} \quad (19)$$

where  $X(x_i)$  and  $G(x_i)$  represent the probability of the  $i$ -th element at distributions  $X$  and  $G$  respectively. Figure 5 shows the JS divergence between the core tensor of the TKD, NTD and INTD versus the original MSI (Figure 5a), as well as the divergence between the MSI and the recontruion of each decomposition (Figure 5b). In Figure 5a it can be seen that, as expected, decompositions with non-negativity constraints generate core tensors with lower divergence with respect to the input dataset. In turn, this figure shows how the INTD stabilizes its divergence in a lower value of  $J_3$  in comparisson with TKD and NTD. On the other hand, Figure 5b shows that, in reconstruction, the TKD is more precise than the others, which can be attributed to the freedom in the decomposition.



**Figure 5.** JSD between a) TKD / NTD / INTD core tensor vs input dataset, and b) TKD / NTD / INTD reconstruction vs input dataset.

292 The divergence study is reinforced by an entropy analysis to quantify the information contribution  
 293 of each band from the original spectral image and from the core tensor of each decomposition. Figure  
 294 6 presents the entropy of each band at the Indian Pines dataset.



**Figure 6.** Indian Pines entropy a) original dataset, b) TKD, c) NTD, d) INTD

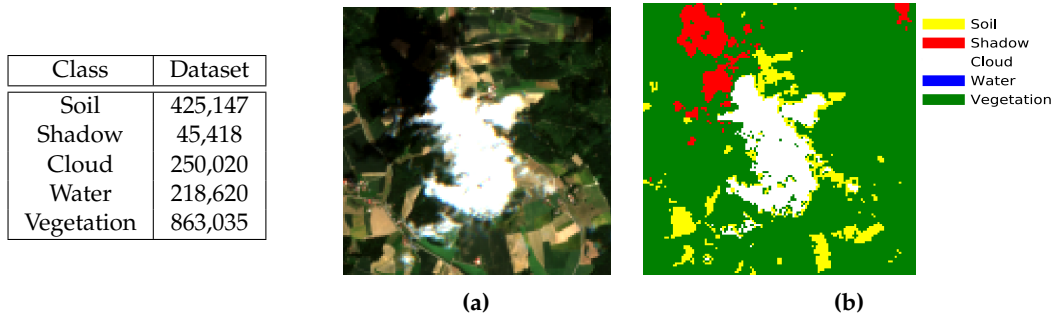
## 6. Experimental Results

### 6.1. Input Data

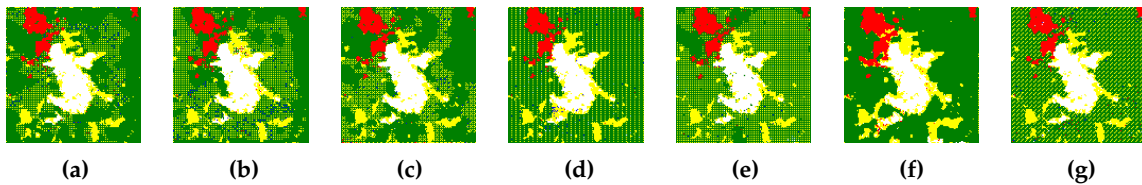
For this work, one multispectral dataset and three popular hyperspectral dataset were selected. For a fair comparison with methodologies cited in Section 1.1, the dataset was processed with the original information from the European Space Agency Sentinel-2 database and from the [Hyperspectral Remote Sensing Scenes](#) web page.

#### 6.1.1. Sentinel-2

This dataset proposed by Lopez et al. [?] is composed of 110 RS Sentinel-2 scenarios from central Europe. It has 100 scenarios as the training space and 10 scenarios for testing, all of them with  $128 \times 128$  pixels with spatial resolution of  $20m^2$  and 9 spectral bands in the range  $490 - 2190nm$ . The labels are semi-manually assigned for five classes of interest: vegetation, soil, water, clouds and shadows. Data are available in the link [Sentinel-2 Dataset](#).



**Figure 8 & Table 2.** Sentinel dataset, Table) Samples per class, a) True color image and b) Ground truth.

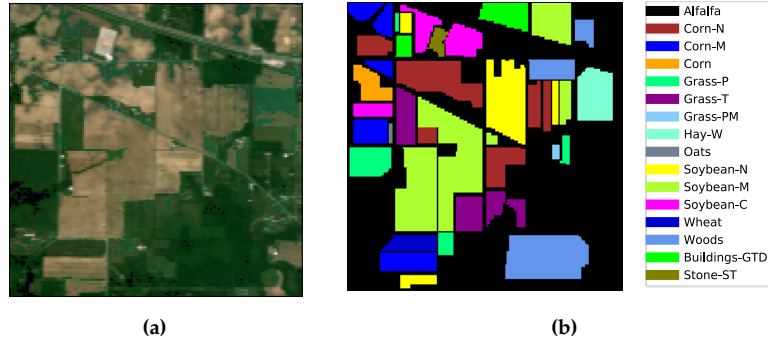


**Figure 9.** Qualitative results. Visualization of the predicted matrix of a testing scene with abundant vegetation and clouds, and presence of shadows and soil. Prediction after 100 epochs in the CNN used for this work a) with the original dataset without data compression, b) with TKD compressing to  $J_3 = 5$ , c) with NTD and no compression,  $J_3 = 9$ , d) with NTD to  $J_3 = 5$ , e) with NTD and no compression,  $J_3 = 9$ , f) with INTD compressing to  $J_3 = 5$  and g) with INTD and no compression,  $J_3 = 9$ .

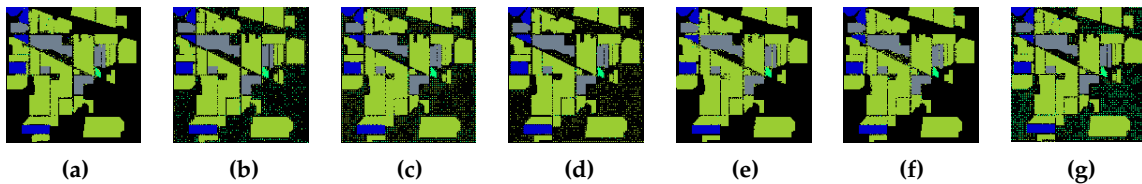
#### 6.1.2. Indian Pines

This dataset is a scene produced by AVIRIS in North-western Indiana and consists of  $145 \times 145$  pixels and 224 spectral bands in the wavelength range  $0.4 - 2.5\mu m$ . The Indian Pines scene contains two-thirds agriculture, and one-third forest or other natural perennial vegetation. There are two major dual lane highways, a rail line, as well as some low density housing, other built structures, and smaller roads. Since the scene is taken in June some of the crops present, corn, soybeans, are in early stages of growth with less than 5% coverage. The ground truth available is designated into sixteen classes and is not all mutually exclusive. Indian Pines data are available at [Indian Pines dataset](#). Figure ?? shows the true color image of Salinas dataset, as well as the ground truth with each of its corresponding classes and Table ?? the number of samples for each class.

| Class        | Samples |
|--------------|---------|
| Alfalfa      | 46      |
| Corn-N       | 1428    |
| Corn-M       | 830     |
| Corn         | 237     |
| Grass-P      | 483     |
| Grass-T      | 730     |
| Grass-PM     | 28      |
| Hay-W        | 478     |
| Oats         | 20      |
| Soybean-N    | 972     |
| Soybean-M    | 2455    |
| Soybean-C    | 593     |
| Wheat        | 205     |
| Woods        | 1265    |
| Building-GTD | 386     |
| Stone-ST     | 93      |



**Figure 10 & Table 3.** Indian Pines dataset, Table) Samples per class, a) True color image and b) Ground truth.

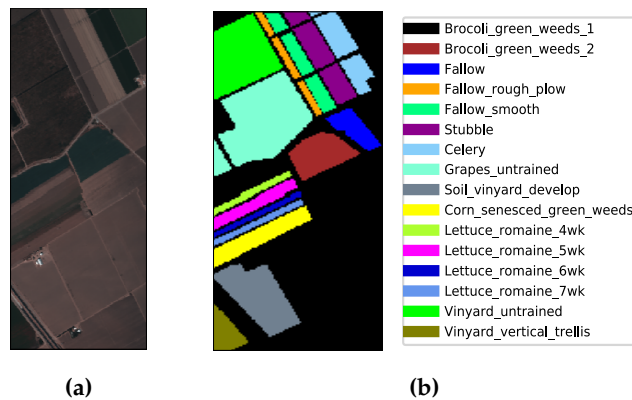


**Figure 11.** Qualitative results. Visualization of the predicted matrix of the Indian Pines dataset. Prediction after 100 epochs in the CNN used for this work a) with the original dataset without data compression, b) with TKD compressing to  $J_3 = 5$ , c) with NTD and no compression,  $J_3 = 9$ , d) with NTD to  $J_3 = 5$ , e) with NTD and no compression,  $J_3 = 9$ , f) with INTD compressing to  $J_3 = 5$  and g) with INTD and no compression,  $J_3 = 9$ .

### 6.1.3. Salinas

This scene was collected by the AVIRIS sensor over Salinas Valley, California. It has  $512 \times 217$  pixels with spatial resolution  $3.7m$ , and 224 spectral bands. It includes vegetables, bare soils, and vineyard fields. Salinas groundtruth contains 16 classes shows in table ?? . Salinas data are available at [Salinas dataset](#). Figure ?? shows the true color image of the Salinas dataset, as well as the ground truth labeled with each of its corresponding classes and Table ?? the number of samples for each class.

| Class         | Samples |
|---------------|---------|
| Brocoli-GW-1  | 2009    |
| Brocoli-GW-2  | 3726    |
| Fallow        | 1976    |
| Fallow-RP     | 1394    |
| Fallow-S      | 2678    |
| Stubble       | 3959    |
| Celery        | 3579    |
| Grapes-U      | 11271   |
| Soil-VD       | 6203    |
| Corn-SGW      | 3278    |
| Lettuce-R-4wk | 1068    |
| Lettuce-R-5wk | 1927    |
| Lettuce-R-6wk | 916     |
| Lettuce-R-7wk | 1070    |
| Vinyard-U     | 7268    |
| Vinyard-VT    | 1807    |

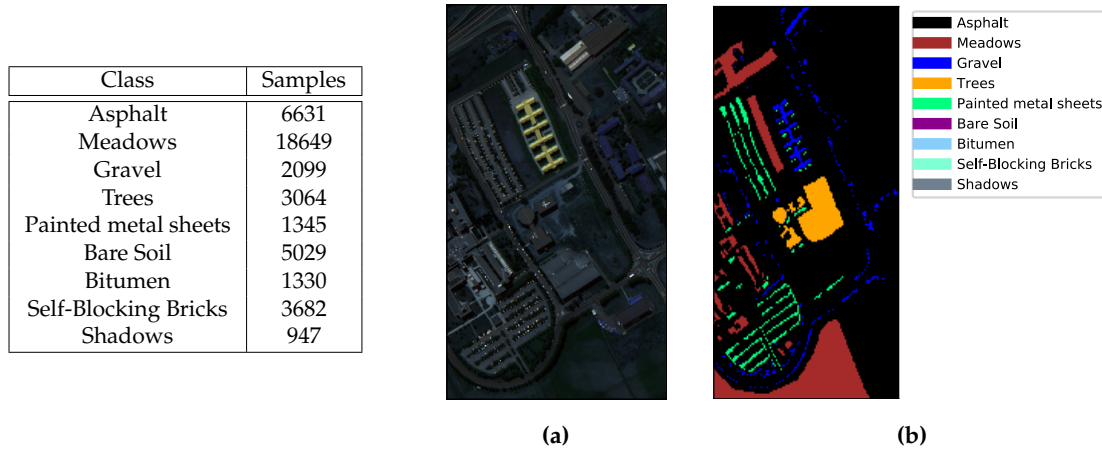


**Figure 12 & Table 4.** Salinas dataset, Table) Samples per class, a) True color image and b) Ground truth.



#### 6.1.4. Pavia University

This scene was collected by the ROSIS sensor over Pavia University, northern Italy. It has  $610 \times 340$  pixels with spatial resolution  $1.3m$ . and 103 spectral bands. Pavia groundtruth contains 9 classes, some of them described in table ?? . Pavia University data are available at [Pavia University dataset](#). Figure ?? shows the true color image of the Pavia dataset, as well as the ground truth labeled with each of its corresponding classes.



**Figure 13 & Table 5.** Pavia dataset, Table) Samples per class, a) True color image and b) Ground truth.

Table 6 summarized the datasets used in this work as well as their spatial and spectral characteristics, the number of classes and their samples.

**Table 6.** Summary of the different dataset used for experiments in this work.

| Dataset           | Spatial dimensions | Bands | Classes | Samples   |
|-------------------|--------------------|-------|---------|-----------|
| Sentinel-2 CNNMSI | $128 \times 128$   | 9     | 5       | 1,802,240 |
| Indian Pines      | $145 \times 145$   | 220   | 16      | 10,249    |
| Salinas           | $512 \times 217$   | 224   | 16      | 53,785    |
| Pavia University  | $610 \times 340$   | 103   | 9       | 40,076    |

#### 6.2. CNN Specifications

The model used to evaluate the framework proposed in this work is Segnet []. Table 7 shows the hyperparameters of the CNN set by cross-validation and the hardware specifications.

**Table 7.** Experiments' software and hardware specifications.

| Hyperparameters   | Software/Hardware   |
|---|---|
| learning rate: $1 \times 10^{-3}$<br>epochs: 100<br>optimizer: Adam []<br>initialization: Xavier []<br>kernel dimensions: $3 \times 3$<br>Activation Function: ReLU / Softmax | Platform: Python 3.7<br>AI Framework: Tensorflow 1.13<br>GPU: NVIDIA GeForce GTX 1050 Ti<br>Processor: Intel core i7<br>RAM: 8GB<br>SSD: 128GB / HDD: 1TB |



| $J_3$ | TKD     | NTD     | INTD    |
|-------|---------|---------|---------|
| 1     | 140.267 | 367.535 | 385.986 |
| 2     | 116.638 | 347.336 | 382.857 |
| 3     | 105.574 | 343.436 | 381.385 |
| 4     | 98.8506 | 343.336 | 381.627 |
| 5     | 92.5201 | 339.647 | 382.37  |
| 6     | 87.4121 | 337.896 | 382.528 |
| 7     | 83.4363 | 335.908 | 382.578 |
| 8     | 79.5316 | 335.914 | 382.685 |
| 9     | 76.1573 | 335.742 | 382.514 |

**Table 8.** RMSE for TKD, NTD and INTD from rank 1 to 9.

### 6.3. Algorithms metrics

#### 6.3.1. Relative Mean Square Error (RMSE)

To compute the reconstruction error of any decomposition, it can be used the relative Mean Square Error, given by

$$\zeta(\hat{\mathbf{x}}) = \frac{1}{Q} \sum_{q=1}^Q \frac{\|\hat{\mathbf{x}}_q - \mathbf{x}_q\|_F^2}{\|\mathbf{x}_q\|_F^2}, \quad (20)$$

where  $\mathbf{x}_q$  represents the  $q$ -th MSI from a dataset with  $Q$  MSIs and  $\hat{\mathbf{x}}_q$  its corresponding reconstruction computed by (4).

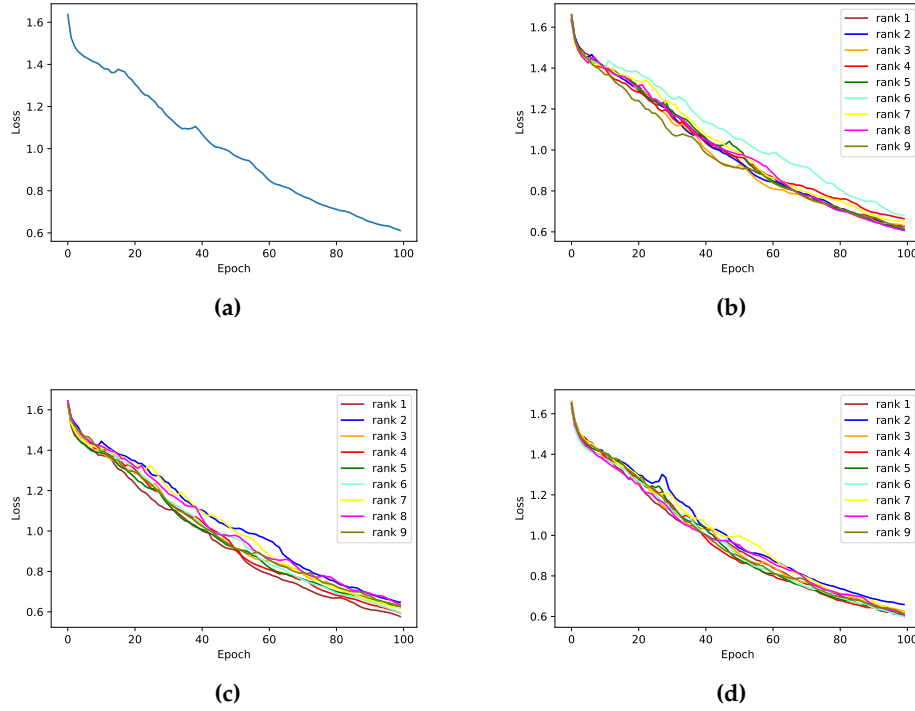
As demonstrated by the results obtained by measuring the divergence between the original dataset and its reconstruction for each decomposition model, Table 8 shows that non-negative decompositions produce a higher reconstruction error than TKD. Furthermore, the fall of the error is very slow as the decomposition rank increases.

#### 6.3.2. Loss

To quantify the convergence of the iterative process in a supervised classification algorithm, it can be used a metric of difference between the labels  $\mathbf{Y}$  and its corresponding prediction  $\hat{\mathbf{Y}}$  as

$$MSE(\hat{\mathbf{Y}}) = \sum \|\hat{\mathbf{Y}} - \mathbf{Y}\|_F^2 \quad (21)$$

Figure 14 shows the behavior of the loss function for each decomposition as well as for the original Sentinel-2 dataset. Figure 14d highlights the stability of the classifier to integer non-negative input data. This can be inferred based on the standard deviation of the INTD loss functions.



**Figure 14.** CNN Loss function with a) Sentinel-2 original dataset, b) TKD, c) NTD, and d) INTD.

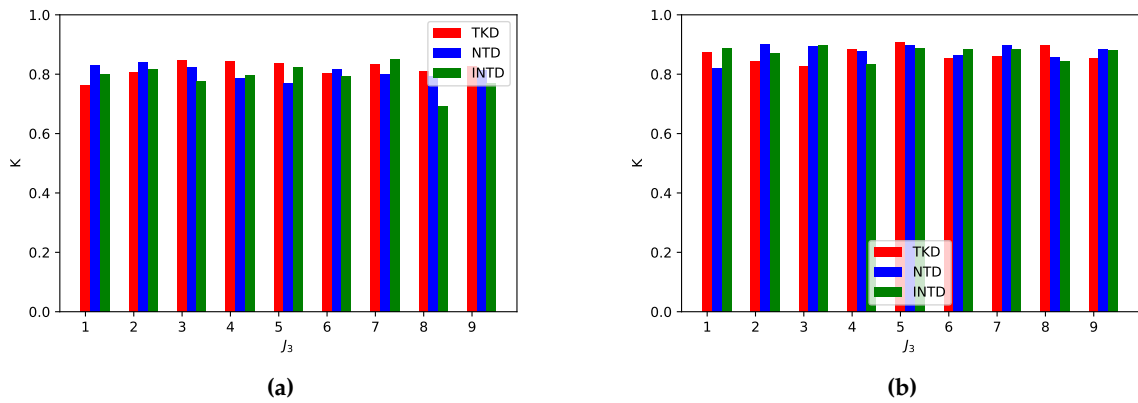
#### 6.4. Evaluation metrics

##### 6.4.1. Cohen's Kappa Coefficient

Cohen's kappa coefficient is a very robust metric used to measure reliability of multi-class and imbalanced class classification algorithms []. It is computed by

$$\kappa = \frac{\rho_o - \rho_e}{1 - \rho_e} \quad (22)$$

where  $\rho_o$  is the observed agreement, and  $\rho_e$  is the expected agreement. This metric will always produce values less than or equal to 1, where 1 means perfect agreement. Negative values indicate no agreement. i.e., futile classification.



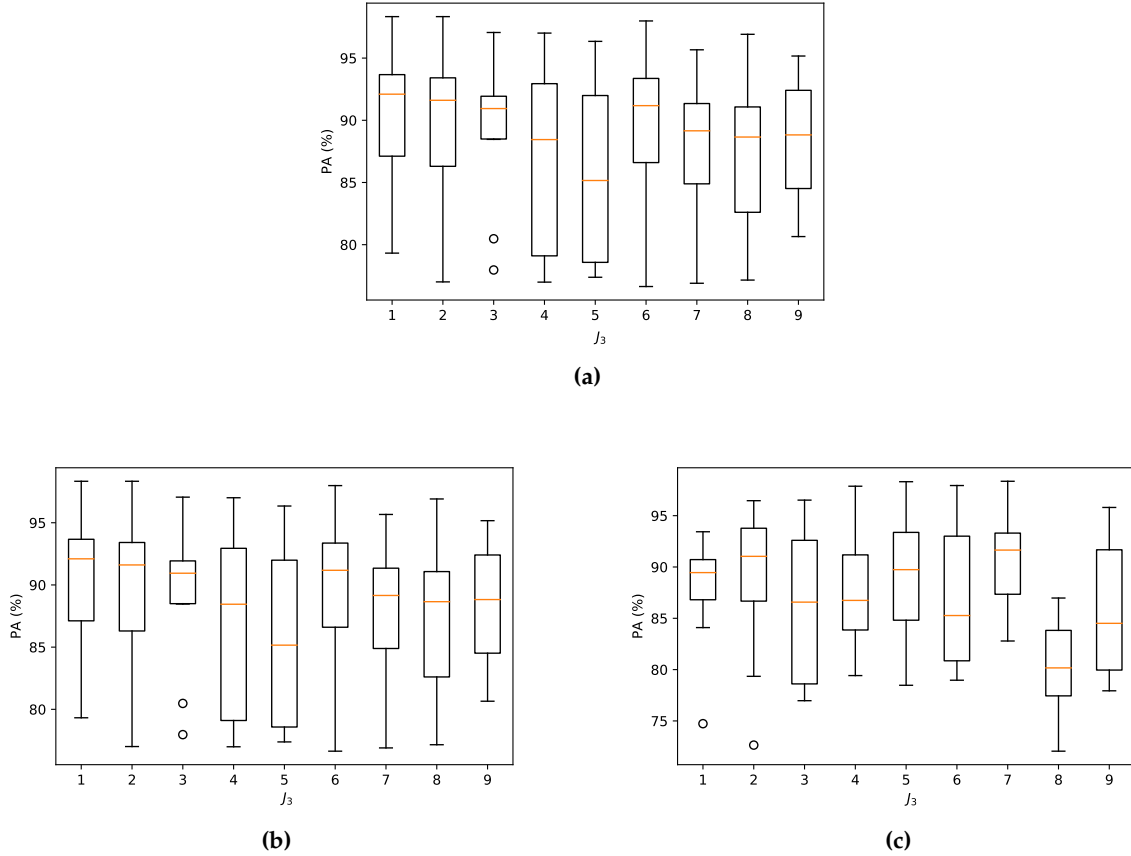
**Figure 15.** Kappa coefficient for TKD, NTD and INTD, a) Sentinel-2 dataset and b) Indian Pines

#### 6.4.2. Pixel Accuracy (PA)

The PA metric is used to compute a ratio between the amount of correctly classified pixels and the total number of pixels as follows. Given a confusion matrix relating the True Positive (TP), True Negatives (TN), False Positives (FP) and False Negatives (FN), the PA is computed by

$$PA = \frac{\sum_{c=1}^C \tau_{cc}}{\sum_{c=1}^C \sum_{d=1}^C \tau_{cd}} = \frac{TP + TN}{TP + TN + FP + FN} \quad (23)$$

where  $c$  is the number of class for  $c = 1, \dots, C$  and  $\tau_{cc}$  is the amount of pixels of class  $c$  correctly assigned to class  $c$  i.e., TP and TN, and  $\tau_{cd}$  is the amount of pixels of class  $c$  inferred to belong to class  $d$ . Despite this metric is wide used, it is not a totally fair metric for imbalanced classes. In this work this metric is used for comparison. However, we also used metrics more in line with multi class classification tasks.



**Figure 16.** Pixel accuracy vs Rank results a) TKD, b) NTD, and c) INTD.

#### 6.4.3. Precision

Another metric used in this work as a performance evaluation metric in multiclass classification is precision. This metric measures the average of pixels from class  $c$  correctly classified. It is computed with the following equation

$$\Psi_c = \frac{\tau_{cc}}{\sum_{d=1}^C \tau_{cd}} = \frac{TP}{TP + FP} \quad (24)$$

where  $\Psi_c$  denotes the precision of class  $c$ .

#### 6.4.4. Recall or Sensitivity

Recall, or also known as sensitivity is a metric that indicates the proportion of pixels classified as class  $c$  that actually belong to class  $c$ . It is computed with the following equation

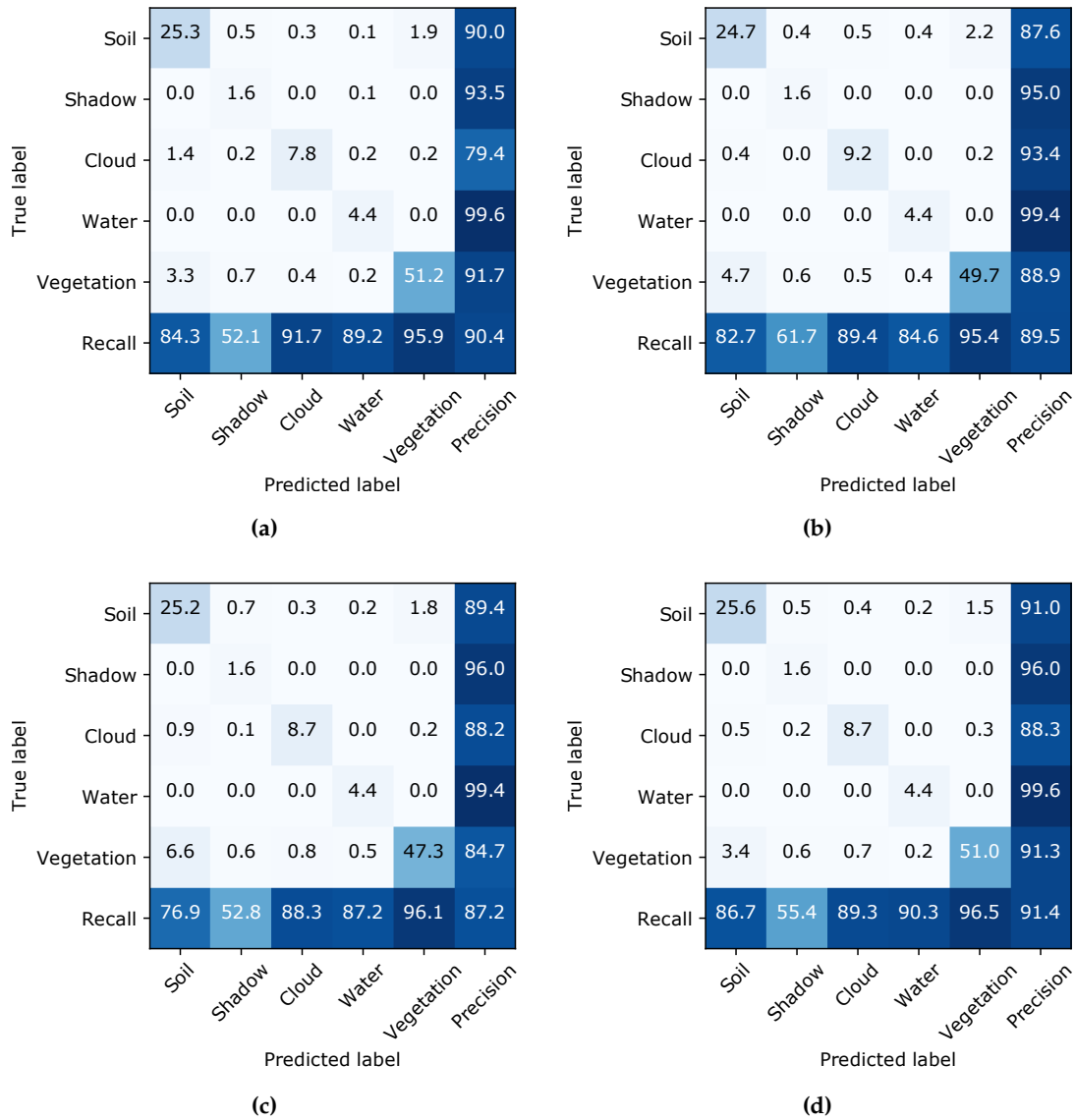
$$v_c = \frac{\tau_{cc}}{\sum_{d=1}^C \tau_{dc}} = \frac{TP}{TP + FN} \quad (25)$$

where  $v_c$  denotes the recall of class  $c$  for  $c = 1, \dots, C$ .

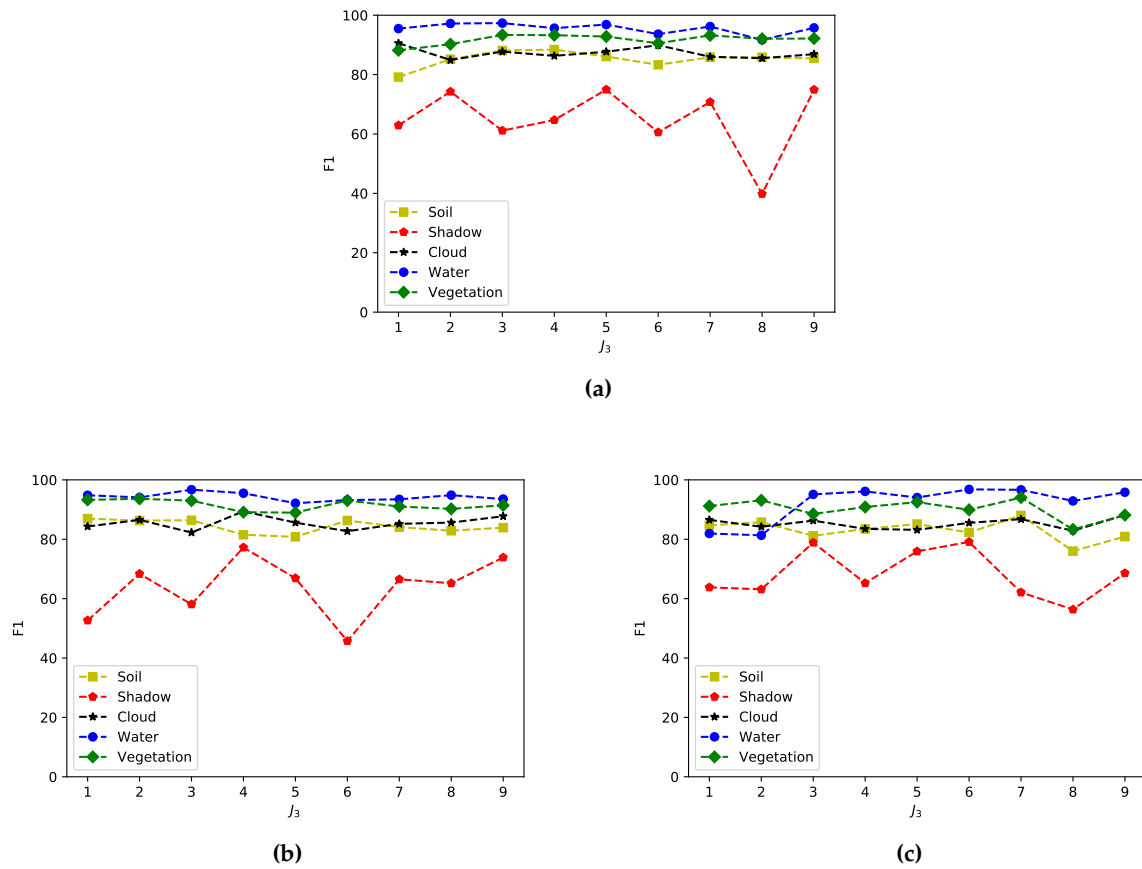
#### 6.4.5. F1 Score

In order to summarize precision and recall in one only metric, the F1 score is used, which is computed by

$$F1 = \frac{2\Psi v}{\Psi + v} \quad (26)$$



**Figure 17.** Confusion matrix for a) Sentiel-2 original dataset, b) TKD<sub>5</sub>, c) NTD<sub>5</sub>, and d) INTD<sub>5</sub>.



**Figure 18.** F1 score for Sentinel-2 dataset with a) TKD, b) NTD, and c) INTD.

**Table 9.** Quantitative results<sup>1</sup> for the Sentinel-2 test dataset running in a NVIDIA GeForce GTX 1050 Ti GPU! (GPU!), Intel core i7 processor, 8 Gb RAM, SSD 128 Gb, and HDD 1 Tb. Decomposition reconstruction error, average processing time per scenario, PA and Kappa's coefficient results for  $J_3 = 1, \dots, 9$ .

| $J_3$ | TKD     |          |              |               | NTD     |          |              |               | INTD    |          |              |               |
|-------|---------|----------|--------------|---------------|---------|----------|--------------|---------------|---------|----------|--------------|---------------|
|       | $\zeta$ | Time (s) | PA (%)       | $\kappa$      | $\zeta$ | Time (s) | PA (%)       | $\kappa$      | $\zeta$ | Time (s) | PA (%)       | $\kappa$      |
| 1     | 398.95  | 9.05     | 90.15        | <b>0.8720</b> | 398.95  | 10.02    | <b>92.21</b> | 0.8350        | 398.95  | 9.52     | 89.82        | 0.8372        |
| 2     | 169.84  | 17.86    | 86.84        | 0.8032        | 329.92  | 19.85    | 87.93        | 0.7462        | 409.54  | 18.32    | 84.19        | 0.7864        |
| 3     | 106.04  | 32.54    | 87.12        | 0.7942        | 310.10  | 35.79    | 87.39        | 0.7870        | 413.29  | 32.96    | 86.83        | 0.7932        |
| 4     | 73.80   | 59.10    | 86.07        | 0.8548        | 309.29  | 60.02    | 91.20        | 0.8310        | 414.55  | 60.05    | 89.75        | 0.7737        |
| 5     | 55.63   | 105.72   | 89.54        | 0.7942        | 304.49  | 105.83   | 88.24        | <b>0.8585</b> | 414.92  | 106.82   | <b>91.47</b> | 0.8292        |
| 6     | 36.85   | 174.19   | 85.39        | 0.8558        | 303.61  | 180.04   | 91.21        | 0.8256        | 415.82  | 179.89   | 89.30        | 0.7645        |
| 7     | 26.65   | 282.97   | 86.02        | 0.8418        | 293.72  | 283.35   | 90.50        | 0.8405        | 416.41  | 284.12   | 90.39        | 0.7743        |
| 8     | 12.24   | 351.40   | <b>91.73</b> | 0.8144        | 280.50  | 350.02   | 88.66        | 0.8335        | 414.42  | 350.74   | 89.89        | <b>0.8627</b> |
| 9     | 9.06    | 415.69   | 89.35        | 0.7837        | 280.38  | 408.21   | 86.87        | 0.8106        | 414.35  | 407.05   | 88.33        | 0.8251        |

<sup>1</sup> For the original MSI: Time = 397.21 s, PA = 90.4%,  $\kappa$  = 0.8415.

**Table 10.** Quantitative results<sup>1</sup> for the Indian Pines dataset running in a NVIDIA GeForce GTX 1050 Ti GPU<sup>1</sup>, Intel core i7 processor, 8 Gb RAM, SSD 128 Gb, and HDD 1 Tb. Decomposition reconstruction error, average processing time per scenario, PA and Kappa's coefficient results for  $J_3 = 1, \dots, 10$ .

| $J_3$ | TKD     |          |        |          | NTD     |          |        |          | INTD    |          |        |          |
|-------|---------|----------|--------|----------|---------|----------|--------|----------|---------|----------|--------|----------|
|       | $\zeta$ | Time (s) | PA (%) | $\kappa$ | $\zeta$ | Time (s) | PA (%) | $\kappa$ | $\zeta$ | Time (s) | PA (%) | $\kappa$ |
| 1     | 375.365 | 15.83    | 82.93  | 0.8207   | 375.36  | 16.21    | 86.41  | 0.8252   | 2965.49 | 15.72    | 86.75  | 0.7799   |
| 2     | 140.6   | 32.83    | 92.51  | 0.9020   | 67.53   | 31.55    | 92.87  | 0.8844   | 2965.49 | 39.63    | 91.82  | 0.8972   |
| 3     | 116.63  | 56.56    | 88.03  | 0.8946   | 343.33  | 57.32    | 92.31  | 0.9074   | 2957.91 | 62.31    | 93.25  | 0.8427   |
| 4     | 105.57  | 92.13    | 91.76  | 0.8766   | 343.43  | 97.10    | 90.83  | 0.8534   | 2951.48 | 98.94    | 88.39  | 0.8855   |
| 5     | 98.85   | 156.21   | 88.53  | 0.8981   | 343.33  | 151.23   | 92.75  | 0.8597   | 2938.82 | 164.32   | 89.91  | 0.8478   |
| 6     | 92.52   | 298.80   | 83.99  | 0.8653   | 339.64  | 301.09   | 89.90  | 0.8990   | 2929.61 | 313.21   | 92.36  | 0.7913   |
| 7     | 87.41   | 520.13   | 89.21  | 0.8973   | 337.89  | 515.63   | 92.74  | 0.8523   | 2895.02 | 535.08   | 88.94  | 0.8540   |
| 8     | 79.53   | 715.69   | 88.33  | 0.8561   | 335.90  | 704.21   | 89.86  | 0.8599   | 2876.32 | 732.12   | 92.15  | 0.8469   |
| 9     | 76.15   | 881.21   | 89.97  | 0.8853   | 335.91  | 876.36   | 92.03  | 0.8891   | 2866.45 | 901.35   | 92.01  | 0.8603   |
| 10    | 72.67   | 934.78   | 88.61  | 0.8871   | 335.74  | 910.84   | 92.93  | 0.8864   | 2854.12 | 978.54   | 91.95  | 0.8462   |

<sup>1</sup> For the original Indian Pines dataset: Time = 878.09 s, PA = 91..22%,  $\kappa$  = 0.9040.

## 7. Discussion and Comparison

In this work, the hyperspectral input dataset is decomposed by a Tucker-based decomposition model to transform them from the spectral bands domain (wavelength) to a new tensor bands domain. The decompositions are restricted to preserve the spatial domain and to compress the spectral domain. Figure 2 it can be seen how the endmembers of the materials of interest behave in a way that, from a salient band point of view, the first new tensor bands are able to provide enough information to a CNN to differentiate diverse materials. On the other hand, From the information theory point of view, the entropy computed for each original and core tensors band reinforce this assertion (See Figure 6).

Unlike previous works, the introduction of information metrics in this work aids to trade off the empirical setting of the multirank TKD parameters. Although the process is still semi-empirical, it is based on metrics that quantify the amount of information and the divergence from the original data. It is worth noting that, in this work, the compression is developed only in the spectral domain, but the basis of the proposal can also be applicable for other kinds of decomposition.

Qualitative results (Figures 9–11) and quantitative results in Figure 16 present the performance evaluation of the CNN, based on PA, comparing the three models based on TKD. Comparing with results shown in previous works [? ], [? ], [? ], the proposed INTD overcomes unsupervised classification algorithms, as well as decomposition without non-negativity and integer restrictions. While it is true that the PA metric is not the best for an unbalanced dataset, it is a good starting point for a general comparison. Nevertheless, the kappa coefficients results, shown in Figure 15, show greater stability in classification for the TKD, but as the value of  $J_3$  increases, the NTD and INTD improve their performance, while the TKD fall. this can be attributed to the phenomenon of overfitting.

Tables ?? and ?? allow us to make a direct comparison among the Tucker-based decompositions. First of all, as expected, the TKD reconstruction error decrease faster than the approximation with non-negativity and integer constraints. On the other hand, the analysis of PA and the Kappa's coefficient, in combination with the entropy, give a measure linked to the diminution of execution time in favor of the NTD and the proposed INTD approximation.

## 8. Conclusions

In this work, we had the purpose of improving the features of a multi- or hyperspectral image, while reducing dimensionality and, in turn, the computational complexity of a classification CNN. From the results presented above and the analysis of each metric, it has been shown that the constraints imposed to a decomposition model, as the NTD and INTD, produce an improvement in classification metrics of CNN. It is worth noting that, depending on the model of the classifier, the TD should be limited to provide characteristics that aids the classifier to improve its performance. From the results shown in Figure 5 we can conclude that the proposed integer non-negative approximation...

## 8.1. Open issues

**Author Contributions:** Conceptualization, J.L.; formal analysis, D.T.; investigation, J.L.; methodology, J.L., D.T., and C.A.; resources, C.A.; software, J.L.; supervision, D.T. and C.A.; validation, D.T. and C.A.; writing—original draft, J.L. and D.T.

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## Abbreviations

The following abbreviations are used in this manuscript:

|       |   |
|-------|---|
| ANN   | Artificial Neural Network                 |
| CNN   | Convolutional neural network              |
| CPD   | Canonical Polyadic Decomposition          |
| DL    | Deep Learning                             |
| FCN   | Fully Convolutional Network               |
| HOOI  | Higher-Order Orthogonal Iteration         |
| HOSVD | Higher-Order Singular Value Decomposition |

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**Sample Availability:** Samples of the compounds ..... are available from the authors.

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