Cloud Implementation of a Full Hyperspectral Unmixing Chain Within the NASA Web Coverage Processing Service for EO-1

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***Abstract*—The launch of the NASA Earth Observing 1 (EO-1) platform in November 2000 marked the establishment of spaceborne hyperspectral technology for land imaging. The Hyperion sensor onboard EO-1 operates in the 0.4–2.5 micrometer spectral range, with 10 nanometer spectral resolution and 30-meter spatial resolution. Spectral unmixing has been one of the most successful approaches to analyze Hyperion data since its launch. It estimates the abundance of spectrally pure constituents (endmembers) in each observation collected by the sensor. Due to the high spectral dimensionality of Hyperion data, unmixing is a very time-consuming operation. In this paper, we develop a cloud implementation of a full hyperspectral unmixing chain made up of the following steps: 1) dimensionality reduction; 2) automatic endmember identification; and 3) fully constrained abundance estimation. The unmixing chain will be available online within the Web Coverage Processing Service (WCPS), an image processing framework that can run on the cloud, as part of the NASA SensorWeb suite of web services. The proposed implementation has been demonstrated using the EO-1 Hyperion imagery. Our experimental results with a hyperspectral scene collected over the Okavango Basin in Botswana suggest the (present and future) potential of spectral unmixing for improved exploitation of spaceborne hyperspectral data. The integration of the unmixing chain in the WCPS framework as part of the NASA SensorWeb suite of web services is just the start of an international collaboration in which many more processing algorithms will be made available to the community through this service. This paper is not so much focused on the theory and results of unmixing (widely demonstrated in other contributions) but about the process and added value of the proposed contribution for ground processing on the cloud and onboard migration of those algorithms to support the generation of low-latency products for new airborne/spaceborne missions.**

***Index Terms*—Earth Observing One (EO-1), hyperion, hyperspectral imaging, NASA SensorWeb, spectral unmixing, Web Coverage Processing Service (WCPS).**

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I. Introduction

THE Web Coverage Processing Service (WCPS) is an image processing framework that can run on the cloud [1]. It will allow dynamic upload of processing algorithms and data collected from airborne and/or spaceborne platforms. It is the result of a three-year grant by the Earth Science Technology Office[1], Advanced Information Systems Technology (AIST)[2], with the goal of providing imagery products of increased value to the end-user at a lower cost. The core-scripting engine of the WCPS is based on Lua[3], a powerful and embeddable scripting language. The size of the raw data from remotely sensed hyperspectral sensors such as NASA's Earth Observing One (EO-1) [2], the Airborne Visible Infra-Red Imaging Spectrometer (AVIRIS) [3], or the Enhanced MODIS Airborne Simulator (eMAS) [4] is rapidly increasing to data sets reaching almost one Terabyte per scene. This is a major distribution problem for low-bandwidth users as well as storage for users interested in time-series spanning many years. On the cloud, the WCPS can leverage scalable computing capabilities of virtual machines, quickly process large amounts of data where it is stored and deliver finished product to the end-user at an extremely low cost.

In other words, WCPS allows scientists to develop their own custom algorithms and execute them directly against existing data sets on the cloud, a feature that could have a dramatic impact to the new decadal missions for Earth observation such as the hyperspectral infrared imager (HyspIRI) [5]. Similar efforts such as ESA's BEAM project[4] exist, but the WCPS discriminator is in its future capability of being embedded as part of an airborne or spaceborne mission. This opens up the capability for the development of products on the Cloud and their dynamic upload to the flight target such as eMAS on an ER-2, AVIRIS/MASTER on a GlobalHawk, or HyspIRI. The WCPS is the latest Open Geospatial Consortium (OGC) Web Service of the NASA SensorWeb. A standard RESTful and secure API is available for automation. That API is used to integrate the WCPS with the internal workflow engine and can also be used to integrate with customer-specific services. Automated processing capabilities are key to providing advanced products in real-time directly to end-users around the world. From a satellite perspective, downlinking the raw data is time-consuming.

[1]http://esto.nasa.gov

[2]http://esto.nasa.gov/info_technologies_aist.html

[3]http://www.lua.org

[4]http://www.brockmann-consult.de/cms/web/beam

In a life-threatening situation, a simple flood extent map of 3 Megabytes may be computed onboard and downlinked right to the end-user as an ad-hoc low-latency product with high social benefit [2]. These ad-hoc algorithms would have been tested on the cloud and uplinked on-demand dynamically to the satellite.

Following the aforementioned ideas, this paper describes the unmixing chain algorithm that will be available online with the WCPS as part of the NASA SensorWeb suite of web services. Despite the fact that the satellite hyperspectral instruments provide hundreds of spectral channels using narrow spectral bands, the spatial resolution of these instruments is still in the range of 30 to 60 meters per pixel. As a result, most of the pixels collected by EO-1 and the new generation imaging spectrometers such as HyspIRI will be likely mixed in nature [7]. Such an unmixing chain algorithm is therefore critical for proper identification of Earth components. This paper will present an approach to execute this computer-intensive algorithm on the cloud running on multiple virtual machines.

Spectral unmixing aims at estimating the abundance of pure spectral components (called *endmembers*) in each mixed pixel [8], [9]. During the past years, many algorithms and models have been developed for endmember identification and abundance estimation in remotely sensed hyperspectral images [10], [11], thus making spectral unmixing a hot topic in the hyperspectral imaging literature. However, the extremely high dimensionality and complexity of hyperspectral images makes the unmixing process a very time-consuming approach [12]. This is particularly the case for instruments such as EO-1 Hyperion, which provide a significant coverage of the Earth with multi-temporal capabilities. In these scenarios, high performance computing now available on the cloud, becomes highly desirable in order to accelerate hyperspectral-related calculations [13]. This is because the cloud can provide a highly dynamic and adaptive environment for distributed execution of processing algorithms while, at the same time, obtaining most of the advantages of cloud implementations with the advantage of flexibility and high availability. These aspects are of crucial importance for remotely sensed hyperspectral data exploitation.

To illustrate these benefits, we present a virtual machine implementation of a full hyperspectral unmixing chain within the NASA WCPS for EO-1 on a commercial cloud at Joyent. The WCPS has full-access to the data to be processed as well as the spectral unmixing algorithm (among many others). This enables the dynamic processing of the data on the cloud without having to download it. Future systems will automatically store the newly collected data sets into the cloud as soon as they are acquired, so that they can be made widely available to the scientific community together with the processing algorithms with no need to download huge data sets. This is a truly cloud-oriented environment, with the advantage of increased availability of the data and flexibility in the processing.

The considered unmixing chain consists of the following processing modules:

1) *Dimensionality reduction*. For this purpose, we use principal component analysis (PCA) [11] to reduce the input hyperspectral data set to a proper subspace.
2) *Endmember extraction*. This is accomplished by using the N-FINDR approach [14], one of the most widely used and successfully applied methods for automatically determining endmembers in hyperspectral image data without using *a priori* information. The algorithm attempts to automatically find the simplex of maximum volume that can be inscribed within the hyperspectral data set.
3) *Abundance estimation*. Once a set of endmembers has been automatically extracted from the input hyperspectral data using N-FINDR, their abundance in each pixel of the scene is estimated by assuming that the fractional abundances of endmembers in a given pixel must add up to one and cannot be negative [15].

The proposed implementation has been demonstrated using the NASA Earth Observing One (EO-1)[5] Hyperion imager, which operates in the 0.4–2.5 micrometer spectral range, with 10 nanometer spectral resolution and 30-meter spatial resolution. Our experimental results suggest the (present and future) potential of spectral unmixing for improved exploitation of spaceborne hyperspectral data. The remainder of the paper is structured as follows. Section II describes the NASA SensorWeb suite of web services. Section III describes the WCPS framework and some of its internal aspects. Section IV describes in detail the full hyperspectral unmixing chain considered in this work. Section V provides WPCS scripting examples including those related with the aforementioned unmixing chain. Section VI describes the experimental results obtained for a hyperspectral scene collected by EO-1's Hyperion over the Okavango Basin in Botswana. Section VII concludes with some remarks and hints at plausible future research.

II. The NASA SensorWeb Initiative

The NASA SensorWeb was born using EO-1 as a pathfinder for standards to facilitate interoperability between heterogeneous sets of sensors. This effort was a significant success for the mission. The second phase of the NASA SensorWeb focused on ease of access to sensor data for non-scientific end users and social benefits that could be derived from data acquired by many NASA or commercial assets, including spaceborne instruments such as EO-1, AVIRIS or the Moderate Resolution Imaging Spectrometer (MODIS) [16].

The capture of expert knowledge into processing algorithms is essential. As science is migrating towards application science, the support and services of end-users are becoming an important portion of the NASA SensorWeb value chain. This value chain concept is illustrated in Fig. 1. Visualizing this concept is important as it demonstrates the science value providing eventual social benefits to end users as a result of SensorWeb enablement. The NASA SensorWeb value chain is itself part of a much larger system (see Fig. 2). It now encompasses suppliers such as Canadian Space Agency, the European Space Agency, commercial data providers, value-added distributers such as CATHALAC in Panama, the Regional Center of Mapping and Resource Development (RCMRD) in Nairobi, the Pacific Disaster Center (PDC) in Maui, the Caribbean Disaster Emergency Management Agency (CDEMA) and Response Agency (CDERA), the International Federation of the Red Cross and Red Crescent,

[5]http://eo1.gsfc.nasa.gov

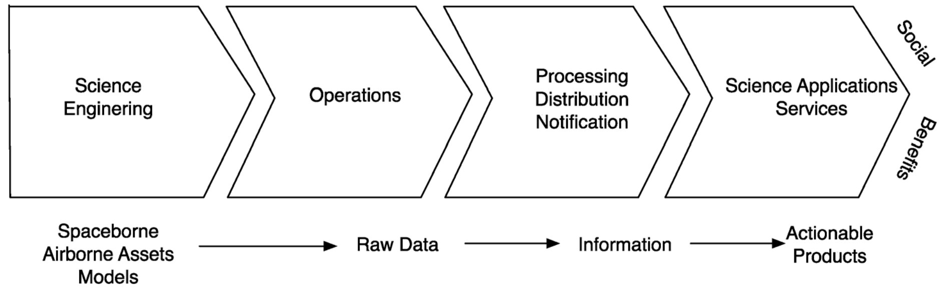

Fig. 1. NASA SensorWeb value chain (borrowed from Michael Porter).

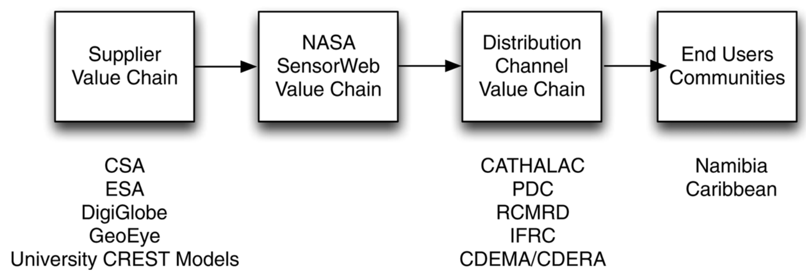

Fig. 2. An illustration of NASA SensorWeb larger value system.

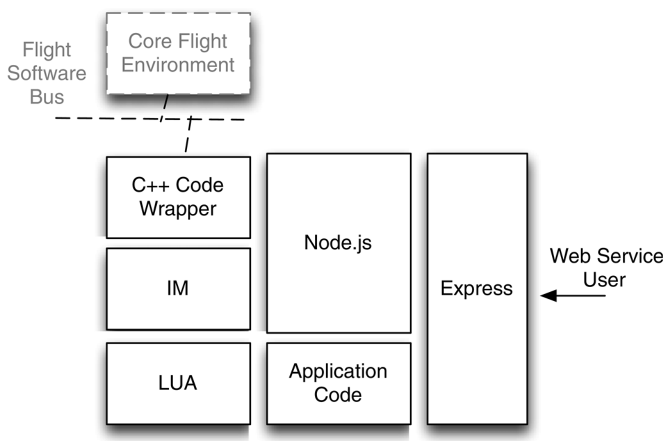

Fig. 3. The web coverage processing system (WPCS) flight/ground component architecture.

and eventually reaches users all the way to Namibia or in the Caribbean. The diagram (Fig. 2) puts in perspective the current scope of the program and its importance as NASA participation to the international Group on Earth Observation.

III. The Web Coverage Processing Service (WCPS) Framework

Data Processing on the cloud is the first focus for the WCPS. The core components of the WCPS are comprised of:

1) LUA, an embeddable scripting Engine[6] developed by a team at PUC-RIO, used for online games and adopted as a new template engine for Wikipedia.
2) The IM Imaging Library, also developed and managed by PUC-RIO.
3) A C++ Interface Wrapper developed by Vightel Corporation[7], MD, USA.
4) The Flight Interface to the NASA Core Flight Executive (cFE)[8].
5) Node.js, a Javascript Platform built on the Google chrome engine and Express, a Node.js web application framework.

The WCPS is also used as a prototype for RESTful/secure standards developed by NASA in coordination with the Open Geospatial Consortium (OGC). It seamlessly integrates with the EO-1 Sensor Planning Service (SPS), the Campaign Manager or Workflow Chaining Service (WfCS), the Notification Service and GeoTorrent distribution services. Users from all over the world are required to pass a two-factor authentication using OpenID/OAuth hybrid protocol in order to start any image-processing request. This is provided by a validation and protection service from Symantec (previously Verisign).

The cloud implementation of WPCS is described in Fig. 4. To leverage the availability of virtual machines that can be instantiated on the fly, the WCPS is broken down into workers waiting on a software bus for imaging tasks generated by end-users. The front-end web service is clustered behind a load balancer (called HAProxy) and high performance HTTP Server and reverse proxy (called NGINX). A single REDIS key-value store is used to manage user profiles and other miscellaneous resources. MONIT[9] is used to manage and monitor the various processes and recover from errors or crashes.

In parallel, NASA's Goddard Space Flight Center (GSFC) in Maryland has several on-going research efforts to ensure that the software will actually perform well in a flight environment. Specifically, we are using a commercial TileraPro64 processor board with 64 cores as a stand-in for the DOD-developed rad-

[6]http://www.lua.org/

[7]http://www.manta.com/c/mm3zwwc/vightel-corporation

[8]http://code.nasa.gov/project/core-flight-executive-cfe

[9]http://mmonit.com

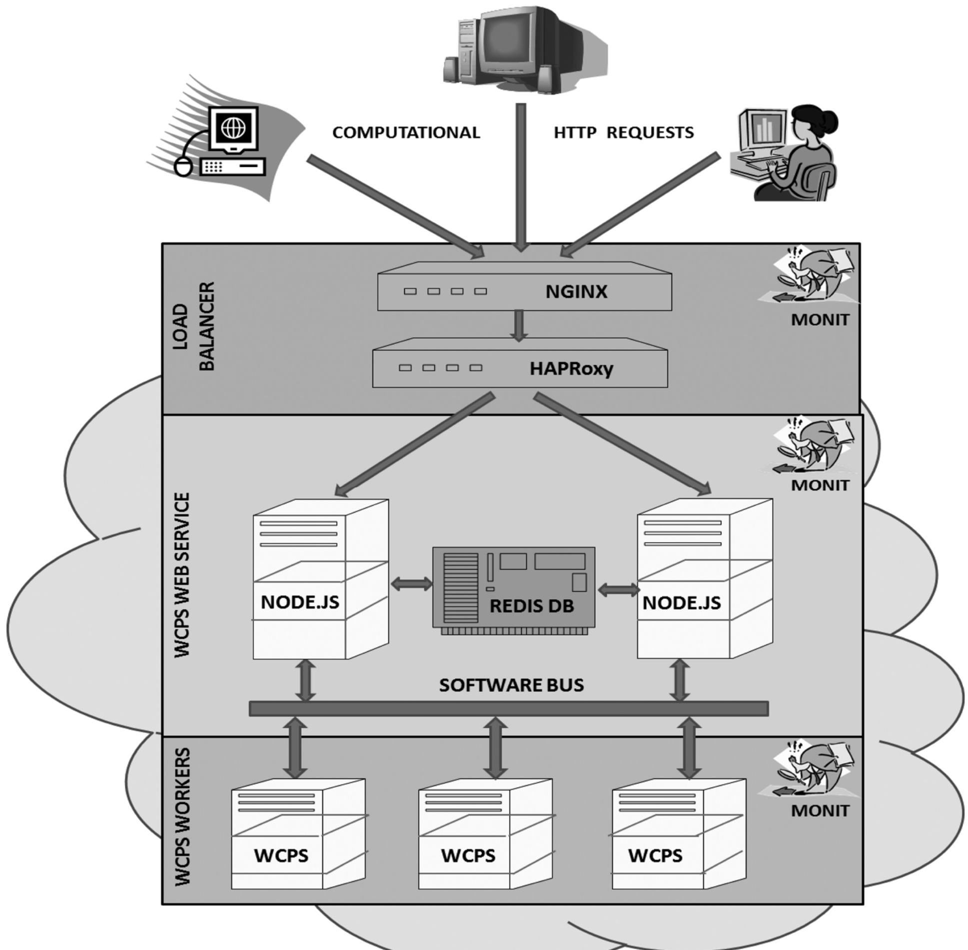

Fig. 4. Cloud implementation of the web coverage processing system (WPCS).

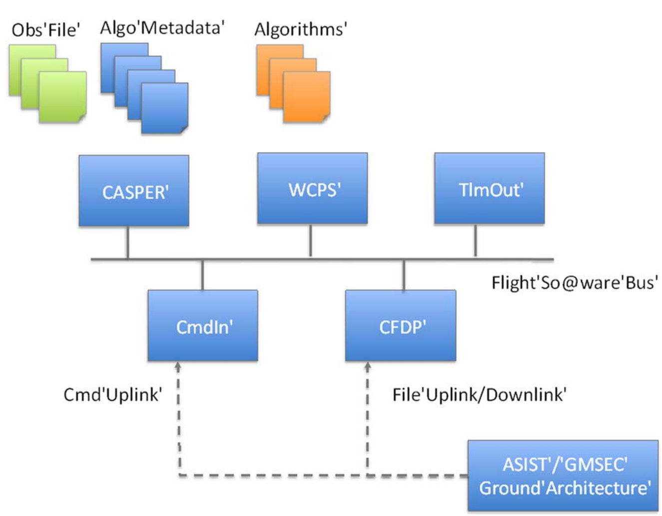

Fig. 5. Current EO-1 flight architecture.

hard MAESTRO that is more likely to be used for space missions. The NASA cFE has been ported to that environment. The WCPS is simply another application sitting on the flight software bus in a very similar configuration to the ground configuration. The current testbed also includes the NASA Jet Propulsion Laboratory's CASPER[10] application for automated planning and scheduling. This application is actually part of the current EO-1 flight software architecture, described in Fig. 5.

IV. Full Spectral Unmixing Chain

In this section, we describe in detail the full spectral unmixing chain implemented in this work in WCPS. It consists of the following steps: dimensionality reduction, endmember extraction and abundance estimation. The chain is graphically illustrated in Fig. 6, and the different steps of the chain are explained in more details below.

A. Dimensional Reduction

In this work, the dimensional reduction step is performed using principal component analysis (PCA), a popular tool for feature extraction in different areas including remote sensing. The implementation of PCA adopted in this work is the one described in [17]. This technique is an approximation to PCA from which principal components can be derived in sequential fashion.

[10]http://casper.jpl.nasa.gov

```
-- ==================================================================
-- title:        ndvi
-- description:  Normalized Difference Vegetation Index (Deering, 1978)
-- author:       Jim Tucker
-- openid:
-- date:         2010-07-09
-- version:      1.0
-- tags:         hyperion_l1r_ac, ndvi, 45, 32
-- duration:     10s
-- ==================================================================

local b45       = band(45)
local b32       = band(32)
local rgba      = normalized_difference_ratio( b45, b32, 'ndvi' )

-- Flip image and write it
local flip = im.ProcessFlipNew(rgba)

-- Load color lookup table as an image
local legend = LoadColorPaletteImage('ndvi')

-- Double its size
local legend2x = im.ImageCreateBased(legend, legend:Width()*2, legend:Height()*2,
legend:ColorSpace(), 0)

im.ProcessResize(legend, legend2x, 0)

-- Insert it
im.ProcessInsert(legend2x, flip, flip, 19, 511 )

-- Write the file
write_file(flip)
```

Algorithm 1. Example of a WCPS script intended to compute the normalized NDVI as described in [16].

B. Endmember Selection

For the endmember identification part, we rely on the well-known N-FINDR algorithm [14], which is a standard for the hyperspectral imaging community. This algorithm looks for the set of pixels with the largest possible volume by *inflating* a simplex inside the data. The procedure begins with a random initial selection of pixels [see Fig. 7(a)]. Every pixel in the image must be evaluated in order to refine the estimate of endmembers, looking for the set of pixels that maximizes the volume of the simplex defined by selected endmembers. The corresponding volume is calculated for every pixel in each endmember position by replacing that endmember and finding the resulting volume. If the replacement results in an increase of volume, the pixel replaces the endmember. This procedure is repeated until there are no more endmember replacements [see Fig. 7(b)].

C. Abundance Estimation

Finally, abundance estimation is carried out using fully constrained least squares spectral unmixing (FCLSU). Once a set of p endmembers has been extracted with the N-FINDR algorithm, their correspondent abundance fractions in a specific pixel vector of the scene can be estimated (in least squares sense) by a simple unconstrained expression [15]. However, it should be noted that the fractional abundance estimations obtained this way do not satisfy the abundance sum-to-one and abundance non-negativity constraints expected for the linear model to work properly. As indicated in [15], a non-negative constrained least squares algorithm can be used to obtain a solution to the problem with non-negativity constraint in abundance estimation, while a fully constrained estimate can also be obtained from the previous estimate in order to obtain the fully constrained estimate.

V. WCPS Scripting Examples

Before describing the experimental results obtained after porting our full spectral unmixing chain to WCPS, we provide in this section some scripting examples indicating how end-users can interact with this framework to run the considered algorithms. It is important to emphasize that WCPS supports many multispectral and hyperspectral instruments such as the Advanced Land Imager (ALI) and Hyperion flying on the EO-1 spacecraft [2]. Basic band manipulations, ratios, and thresholding operations are supported. Other processing techniques include calculations related with Normalized Differential Vegetation (NDVI), Normalized Difference Snow Index (NDSI), Photochemical Reflectance index (PRI), Landsat band ratios, tassel cap transformations, vertical bands destreaking, and so forth [18]. Algorithm 1 shows an example of a WCPS script for computing the normalized NDVI as described in [18].

Atmospheric correction is another feature provided by the WCPS. The EO-1 processing now automatically includes atmospheric correction of ALI and Hyperion L1G data. Users have the capability to re-process the data with different parameters than the ones automatically selected by the operational system. FLAASH [19] and ATREM [20] atmospheric correction packages are currently used for atmospheric correction. A fast, C version of FLAASH with lookup tables is being used. Very recently, pansharpening capabilities have also been added to WCPS. The current algorithm uses a version of the Intensity-Hue-Saturation that allows us to fuse the 10 m ALI Pan

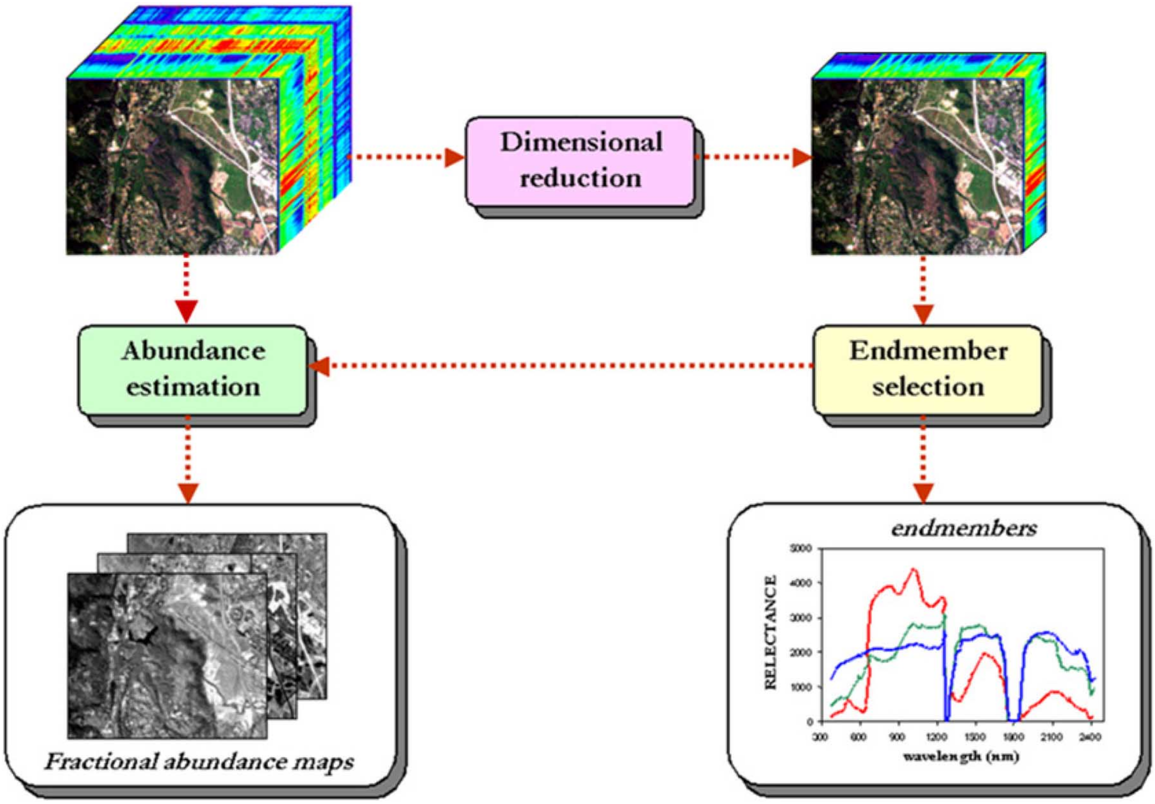

Fig. 6. Spectral unmixing chain implemented in this work in WCPS.

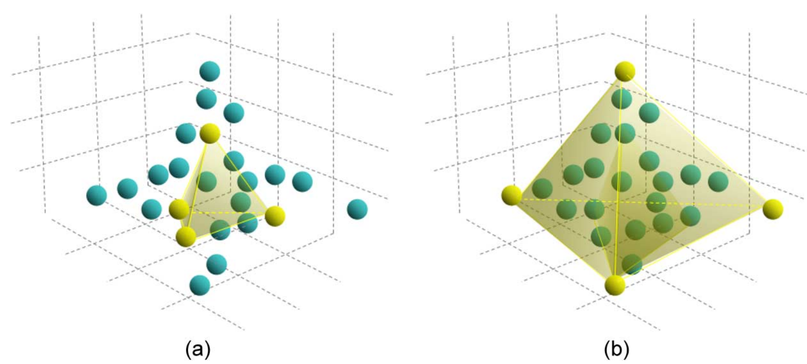

Fig. 7. The N-FINDR algorithm illustrated in a 3-D representation of a hyperspectral data cube in which each point represents a pixel vector in the 3-D spectral space. (a) Initial random initialization of the algorithm. (b) Final result of the algorithm after convergence.

band and three other multi-spectral bands at 30 m-resolution to generate a high-resolution composite visible for example. This has currently been used operationally for a Namibia Flood Pilot. For users in Namibia, Internet bandwidth is an issue. It is extremely difficult to download very large files. For that particular case, the WCPS can actually tile the finished product into keyhole markup language (KML) super-overlays that can be displayed in Google Earth. We are using Python scripts (from MapTiler) controlling the Geospatial Data Abstraction Library (GDAL).

More complex algorithms can also be supported by the WCPS such as the spectral angle mapper [7]. A user-defined signature can get uploaded to the system and detected in a particular scene. Alternatively, the system could detect a full set of p endmembers in a hyperspectral scene using the N-FINDR [14] algorithm, followed by FCLSU for abundance estimation [15]. The unmixing chain has been integrated with the WCPS and will be evaluated in the following section using a 2001 scene acquired by EO-1 in the vicinity of Chief's Island Okavango Basin in Botswana. From a user perspective, the WPCS script that executes the full spectral unmixing chain described in Section IV is illustrated in Algorithm 2.

As shown by Algorithm 2, the WCPS script for running the hyperspectral unmixing chain can be applied to atmospherically corrected data. It first defines the set of bands that will be selected for the processing of the considered hyperspectral scene. Here, we remove noisy bands and water absorption bands, retaining a total of 145 spectral bands for experiments. The endmembers are extracted with N-FINDR, and the maximum numbers to be identified is also specified in the script (in

```
-- ==========================================================
-- title:       unmixing_chain
-- description: Spectral UnMixing Chain
-- author:      Sergio Sanchez, Sergio Bernabe, Antonio Plaza
-- openid:
-- date:        2012-01-16
-- version:     1.0
-- tags:        hyperion_lr_ac, unmixing
--
-- ==========================================================

local selected_bands = {
    0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
    1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
    1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 };

--
-- Model Selection:
-- unconstrained: The abundances are unconstrained and can become any numeric value
-- constrained:   The sum of abundances equals 1.
-- fully_constrained: The sum of abundances equals 1 and abundance values cannot be less
than zero. This is the default unmixing algorithm.

local model         = "fully_constrained"

local iterations    = 400

-- number of requested endmembers
local endmembers    = 7

-- color lookup table to apply to abundance maps
local clut          = "prism"

spectral_unmixing( selected_bands, iterations, model, endmembers, clut )
```

Algorithm 2. Example of a WCPS script intended to compute a fully constrained spectral unmixing chain.

this case, $p = 7$). Three different types of unmixing models are available in the script: unconstrained (meaning that the abundance sum-to-one and non-negativity constraints are not imposed when conducting the abundance estimation step); constrained (meaning that only the sum-to-one is imposed when conducting the abundance estimation); and fully constrained (meaning that both the sum-to-one and non-negativity constraints are imposed when conducting the abundance estimation). The default model used in experiments is the fully constrained. Another parameter that needs to be set in the script is the local number of iterations, which refers to the number of iterations executed by the iterative implementation of the PCA-based dimensionality reduction module that needs to be run prior to the N-FINDR endmember selection. Finally, a color lookup table is applied to improve visualization of the output of the script, which highlights the fully constrained fractional abundance maps estimated for the input hyperspectral scene. As shown by Algorithm 2, the execution of the unmixing chain in WCPS is performed in modular and easy-to-use fashion.

VI. Experimental Results

The WCPS implementation of our considered spectral unmixing chain has been preliminarily tested using a 2001 scene acquired by EO-1 in the vicinity of Chief's Island Okavango Basin in Botswana. These data, along with ground-truth, are available online[11]. The investigations on this scene have been centered on the seasonal flooding of the Okavango Delta. The extreme inaccessibility of the area makes it an ideal candidate for the use of remote sensing to map the annual flooding and land cover in the region. This is the world's largest inland delta. It is fed by the Okavango River, which originates in Angola's western highlands. The catchment area for the Okavango River lies in three countries (Angola, Namibia, and Botswana) and has a total area of approximately 325,000 km^2. The Delta extends 250 km along its radial axis and extends over 22,000 km^2 in area[12].

A field campaign, conducted in March 2001 by the University of Texas Center for Space Research (CSR) in conjunction with the University of Botswana Harry Oppenheimer Okavango Research Center (HOORC), focused on a portion of the Delta known as Chief's Island. One of the main focus of this study was to characterize the annual flooding by mapping the spatial patterns within the lower Delta as well as to identify small-scale

[11]http://www.csr.utexas.edu/hyperspectral/data/Botswana

[12]http://eo1.gsfc.nasa.gov/new/validationreport/Technology/Documents/Tech.Val.Report/Science_Summary_Crawford.pdf

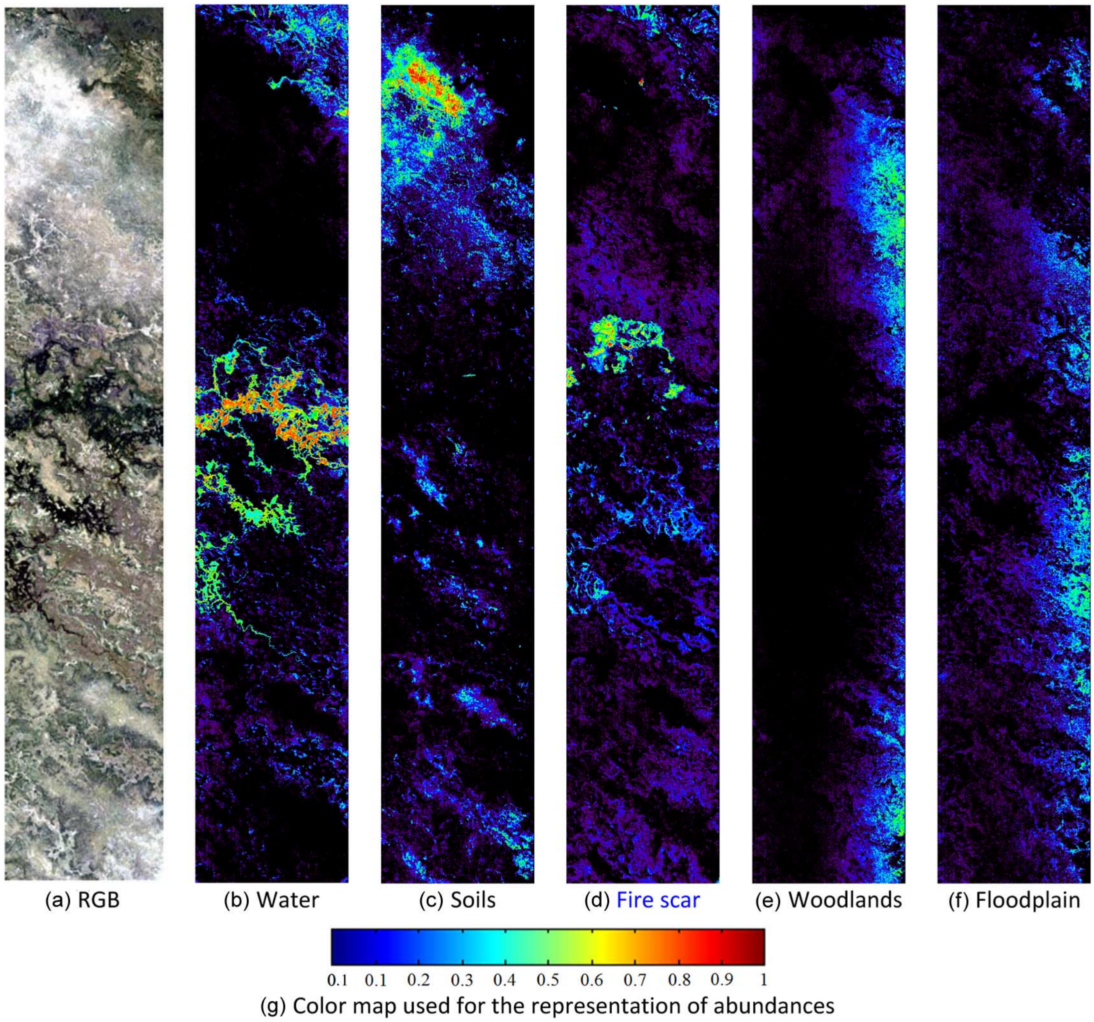

Fig. 8. Example of a WCPS script to compute a fully constrained spectral unmixing chain. (a) Pseudo-RGB color image of the Hyperion Botswana scene. (b–f) Some of the abundance maps estimated by the WCPS implementation of the full spectral unmixing chain represented using the color map in (g). (a) RGB; (b) Water; (c) Soils; (d) Fire scar; (e) Woodlands; (f) Floodplain; (g) Color map used for the representation of abundances.

responses of vegetation. Of particular importance is also the analysis of fire scar areas, meaning the scar or sign left by the fire in some regions after burning. The EO-1 Hyperion data set considered in our experiments consisted of 1476 $\times$ 256 pixels (with 242 spectral bands) and with 14 different land-cover types consisting of seasonal swamps, occasional swamps, and drier woodlands located in the distal portion of the delta. Uncalibrated and noisy bands that cover water absorption features were removed, resulting in 145 features (as indicated in the script shown in Algorithm 2). The land-cover classes in this study were chosen to reflect the impact of flooding on vegetation in the study area.

For illustrative purposes, Fig. 8(a) shows a pseudo-RGB image of the considered scene. Fig. 8(b)–(f) shows some of the abundance maps obtained after processing the scene with the fully constrained unmixing chain using $p = 18$ (the number of endmembers was estimated using the virtual dimensionality concept in [21]. The maps in Fig. 8(b)–(e) are in agreement with the classification results obtained for the same scene in [22]. A distinguishing feature of the results presented in Fig. 8 with regards to those reported in [22] is that the sub-pixel fractions of each of the considered classes can be estimated in the experimental results reported in this paper.

On the other hand, Table I shows the spectral angle scores between some of the endmembers derived by the considered unmixing chain and their corresponding reference spectra, obtained by averaging the pixels belonging to each reference ground class in the online data. The interval in which the spectral values are comprised is [0°, 90°] Hence, the closest the angles in Table I to 0°, the higher the measured spectral similarity. As shown by Table I, the spectral similarity between the extracted endmembers and the average spectra in the reference ground classes identified in the field campaign conducted over the study area is very high, indicating a good agreement between the endmembers extracted from the satellite data and the reference classes identified on the ground.

Despite the encouraging results obtained, further experiments with additional Hyperion scenes are required in order to fully substantiate the contributions introduced by the novel developments presented in this paper. In fact, a major goal in the current research is to show the benefits that can be obtained by transitioning theoretical algorithms (such as the considered hy-

TABLE I
SPECTRAL ANGLE VALUES (IN DEGREES) BETWEEN THE ENDMEMBERS EXTRACTED BY THE CONSIDERED UNMIXING CHAIN FROM THE EO-1 HYPERION BOTSWANA SCENE AND THEIR CORRESPONDING REFERENCE SPECTRA, OBTAINED BY AVERAGING THE PIXELS BELONGING TO EACH GROUND-TRUTH CLASS IN THE REFERENCE DATA AVAILABLE ONLINE FOR THIS SCENE

Water	Soils	Fire scar	Woodlands	Floodplain
8.16º	2.68º	1.58º	1.65º	5.82º

perspectral unmixing chain) to the science applications world using the WCPS framework. Additional benefits will be obtained during flight demonstrations, as the proposed framework is also implemented in the form of a flight test-bed. This is in fact the main societal benefit to the community that we intend to demonstrate in this contribution.

To conclude this section, we emphasize that the integration of the unmixing chain in the WCPS framework as part of the NASA SensorWeb suite of web services is just the start of an international collaboration in which many more processing algorithms will be made available to the community through this service. It is our hope that more scientists and researchers contribute to the NASA WCPS, an open image processing framework that allows dynamic upload of processing algorithms (in addition to the unmixing chain that we addressed in this contribution) and data collected from airborne and/or spaceborne platforms. As a result, this paper is not so much focused on the theory and results of unmixing (which have been widely demonstrated in other contributions) but about the process and the value of the proposed contribution for ground processing on the cloud as well as onboard generation of low-latency products for new airborne and spaceborne missions.

It is our feeling that the results reported in this section are sufficient to demonstrate the expected contributions and added value resulting from having a well-consolidated approach for hyperspectral image analysis from band arithmetic and ratios to spectral unmixing available as a web service from the NASA SensorWeb. This OGC suite of standardized API and services offers the potential to expand its use and consolidate its role as one of the most successful services for processing and distributing actionable products to the end-user community. In effect, it will realize the societal benefit goal of applying Science and Technology to the benefit of the people. Several pilots such as in Namibia and the Caribbean currently demonstrate this value for disaster management. Most importantly, the described technological development is not circumscribed to EO-1 Hyperion but also to future missions such as HyspIRI. In this regard, we would like to emphasize that the tools used in our development are general and consolidated enough to facilitate the integration on global missions or missions with different resolutions and sensor capabilities. However, aspects of standardization and efficient implementation will be of great importance in order to be able to extrapolate the developed cloud implementation to process data collected from other instruments. It is also our feeling that important synergies exist in the data processing chains of EO-1 Hyperion and HyspIRI (the former has been widely used as a demonstrator for the latter [5]) that will greatly facilitate the desired integration.

VII. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we have illustrated how a full hyperspectral unmixing chain made up of the following steps: 1) dimensionality reduction; 2) automatic endmember identification; and 3) fully constrained abundance estimation can be integrated with the Web Coverage Processing Service (WCPS), an image processing framework that can run on the cloud, as part of the NASA SensorWeb suite of web services. The ultimate goal has been to show that, with the support of the proposed cloud implementation, the WCPS can help quickly process large amounts of data and deliver finished products (in this case, obtained through spectral unmixing) to the end-user at an extremely low cost. Our experimental results with a hyperspectral scene collected over the Okavango Basin in Botswana suggest the (present and future) potential of spectral unmixing for improved exploitation of spaceborne hyperspectral data by providing unmixing results which are in agreement with previous classification studies conducted for the same scene.

As a future research line, we will experiment with real-time implementations of the considered unmixing chain on other different kind of hardware devices for on-board processing, such as a commercial TileraPro64 multi-core processor board, which actually performed well in a flight environment. This will be achieved using the adaptive environment for super-compiling with optimized parallelism (AESOP) compiler. Other specialized hardware platforms such as field-programmable gate arrays (FPGAs) [23] or commodity graphics processing units (GPUs) [24] will be also investigated. For instance, the full unmixing chain reported in this work has already been ported onto NVidia GPUs [25], and the N-FINDR algorithm (along with other endmember selection algorithms [26] and abundance estimation [27] algorithms) have been successfully ported to FPGA platforms for real-time exploitation. In the future we are also planning on exploring additional mechanisms to perform the dimensionality reduction step needed by the considered unmixing chain, e.g. using the wavelet transform which has been already successfully been used for this purpose in the literature [28].

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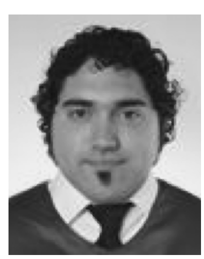

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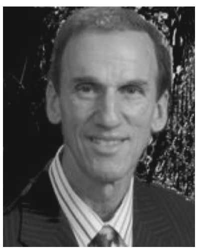

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