SPECTRAL PREPROCESSING TRANSFORM FOR MULTISPECTRAL AND HYPERSPECTRAL IMAGE COMPRESSION

INDEPENDENT COMPRESSOR IMPLEMENTATIONSOF CCSDS-122.0-B-2 AND CCSDS-122.1-B-1

CCSDS MHDC WG

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1 INTRODUCTION

1.1 PURPOSE

This document is a record of two independent implementations of a multispectral and hyperspectral image compressor being developed as a Recommended Standard CCSDS 122.1-B-1 by the CCSDS Multispectral & Hyperspectral Data Compression (MHDC) working group, extending the Recommended Standard CCSDS 122.0-B-2 [1] by the former CCSDS Data Compression working group and by the MHDC working group.

Currently in May 2017, the draft Recommended Standard (Red Book) [2] has undergone agency review, and minor changes have been made by the MHDC working group as a result of this review. These changes are included in the May 2017 revision of the Red Book being used by the working group, and all of the compressor implementations described in this document are based on this revision.

In order to complete the conversion into a CCSDS recommended standard, CCSDS document [3] requires that "At least two independent and interoperable prototypes or implementations must have been developed and demonstrated in an operationally relevant environment, either real or simulated, unless a waiver of the interoperability testing requirement has been approved: the WG Chair is responsible for documenting the specific implementations that qualify the specification for CCSDS Recommended Standard status, along with reports relevant to their testing". This document serves that purpose.

1.2 SCOPE

This document is not part of any CCSDS Recommended Standard.

1.3 ORGANIZATION OF THIS REPORT

This document is divided into four parts. Section 1 (this section) presents the purpose and organization of the report. Section 2 describes several independent implementations of the compressor. Section 3 describes the test data used for cross-verification. Section 4 summarizes the methodology and results of the cross-verification.

1.4 REFERENCE

The following documents are referenced in this document. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS documents.

[1] Image Data Compression. Recommendation for Space Data System Standards, CCSDS 122.0-B-2. Blue Book. Issue 2.

[2] Spectral Preprocessing Transform for Multispectral and Hyperspectral Data Compression. Recommendation for Space Data System Standards, CCSDS 122.1-B-1. Blue Book. Issue 1.

[2] Organization and Processes for the Consultative Committee for Space Data Systems. CCSDS A02.1-Y-4. Yellow Book. Washington, D.C.: CCSDS, April 2014.

2 INDEPENDENT COMPRESSOR IMPLEMENTATIONS

2.1 OVERVIEW

Two software implementations of the compressor have been independently developed. Section 2.2 provides a brief overview of each.

2.2 IMPLEMENTATIONS

2.2.1 CNES/UAB

Ian Blanes leaded the development of a compressor by the Universitat Autònoma de Barcelona (UAB) under contract by CNES. The implementation is written in C++ code.

2.2.2 NASA/GSFC

Mark Wong and Penshu Yeh, engineers at the NASA Goddard Space Flight Center (GSFC), have implemented the compressor in a combination of Matlab and C code.

3 COMPRESSION TEST DATA

3.1 OVERVIEW

Cross-verification testing made use of multispectral and hyperspectral images from airborne and space-borne imagers, summarized in Section 3.2, and small test images described in Section 3.3.

3.2 MHDC WORKING GROUP TEST IMAGES

The follow multispectral and hyperspectral images previously collected by the MHDC working group were used for cross-verification testing.

Table 3-1: Images

Image Name	Size $(z \times y \times x)$	Data type (stored as)	Reference
AIRS	1501x135x90	16-bit unsigned big endian	AIRS airs_gran9
Yellowstone sc0	224x512x512	16-bit signed big endian	AVIRIS f060925t01p00r12_sc00.c.img
Yellowstone sc3	224x512x512	16-bit signed big endian	AVIRIS f060925t01p00r12_sc03.c.img
MODIS	17x2030x1354	16-bit unsigned big endian	MODIS MOD01.A2001222.1200night
Toulouse	3x1024x1024	16-bit unsigned big endian	SPOT5 toulouse_spot5_xs_extract1

3.3 SMALL TEST IMAGES

Five small images were created for the purposes of cross-verification testing.

Table 3-2: Small Images

Image Name	Size $(z \times y \times x)$	Data type
AIRS_64	64x64x64	16-bit unsigned big endian
tiny	7x17x17	16-bit unsigned big endian
sixteenblocks	1x25x25	16-bit unsigned big endian
tall	15x510x19	16-bit signed big endian
repeat	2x18x18	16-bit signed big endian

The first image is a subset of the AIRS hyperspectral image cube. The four remaining images were created from a high entropy random source and fully cover a 16-bits dynamic range. The image “tiny” was created with the purpose of having a very small image where many parameter combinations could be tested efficiently. The image “sixteenblocks” was created with the purpose of testing rare CCSDS-122.1-B-1 and CCSDS-122.0-B-2 header combinations. The image “tall” was created with the purpose of testing more input variations. The image “repeat” was created with the purpose of testing a corner case for one transform.

4 CROSS-VERIFICATION

4.1 PROCEDURE

The compressors operation has been cross-verified by ensuring that they produce identical results under different test conditions.

Cross-verification results are compared at three different stages of the compression process: first, results of the spectral transforms described in CCSDS-122.1-B-1 are compared; then results of individually encoding transformed image bands with CCSDS-122.0-B-2 are compared; and finally the bitstreams produced according to CCSDS-122.1-B-1 are compared.

4.2 SPECTRAL TRANSFORM VERIFICATION

The four transforms defined in Section 5 of CCSDS-122.1-B-1 have been implemented independently and cross-verified by UAB and NASA, namely the Identity Transform (IT), the Integer Wavelet Transform (IWT), the Pairwise Orthogonal Transform (POT), and the Arbitrary Affine Transform (AAT). In addition, the upshift and downshift parameters defined in CCSDS-122.1-B-1 Section 4 are also cross-verified at this stage.

4.2.1 IDENTITY TRANSFORM

The input and output are identical for the IT. For the purpose of the cross-verification, this only tests the most basic operation of the compressor.

4.2.2 INTEGER WAVELET TRANSFORM

The IWT filter implementation only depends on the number of input image bands. No specific parameter is required for this transform.

Results for the five MHDC Working Group test images were verified for this transform. Both forward and inverse transform operation was cross-verified.

4.2.3 PAIRWISE ORTHOGONAL TRANSFORM

The POT implementations were verified with the following parameter combinations: $\Omega \in \{9, \ldots, 16\}$, $F \in \{1, 2, 4, 8, 16, 32\}$, both stable and bypass modes. In addition, side information fields *mean*, *flip*, B and C, were also verified as produced by the POT implementations. Both forward and inverse transform operation was cross-verified.

4.2.4 ARBITRARY AFFINE TRANSFORM

For the AAT, two cases of linear transforms were used. Initially, an identity matrix was selected for the transform matrix Q and the linear transform vector was set to $V = 0$. Scaling parameter was set to $\Psi = 0$. The purpose of this was to verify the AAT encoded structure and the corresponding side information. Afterwards, some sets of KLT transforms were generated with different combinations of Q, V and Ψ by UAB. These parameters were used by NASA Goddard for cross-verification.

Side information produced by the AAT implementations was verified to match.

Inverse operation of the transform was verified for a few simple cases; however, the transform is irreversible (produces rounding errors) and results are not expected to match bit-per-bit from different implementations.

4.3 CCSDS-122.0-B-2 IMAGE DATA COMPRESSION ENCODER

The following tests were carried out in order to verify the correct operation of the combination of CCSDS-122.0-B-2 and CCSDS-122.1-B-1. Particularly, the spectral transform images were preprocessed with 2D-IWT and encoded with Bit-Plane Encoding.

For the cross-verification, all optional CCSDS-122.0-B-2 headers were included for all segments and the OptDCSeclect and OptACselect parameter were set to “Optimal”.

For lossless compression, the segments per band, code word length and IWT weights parameters were selected with different values.

In terms of lossy compression, segment byte limits were calculated with different rate allocation algorithm described in the next section.

4.4 RATE ALLOCATION

Multiple data sets were used to test the informative description of rate allocation methods provided in an Annex F of CCSDS-122.1-B-1. Weight calculations were independently implemented and verified.

Segment byte limits for the CCSDS-122.0-B-2 corresponding to reverse-waterfill and Lagrange rate allocation algorithms were independently computed by UAB and forwarded to NASA GSFC for further lossy compression verification.

Distortion measures were verified to be consistent with published result in scientific literature by UAB.

5 COMPREHENSIVE TEST SET

As part of the previously described cross-validation efforts, some of the tested cases were bundled in a the following comprehensive test set, which cover a sufficiently large portion of the parameter values. These tests employ the images described in section 3, which are compressed and encoded in either lossy or lossless mode.

Table 5-1: Lossy Tests

Image Name	U	D	S	R	W	2D Wavelet	Wavelet Weights	Trans.	F	Ω or Ψ	POT mode or AAT N_{T_z}	Allocation Method	Target Size (bytes)
repeat	0	0	16	3	1	Integer	Default	Id				Rev. waterfill	512
repeat	0	0	16	3	1	Integer	Default	Id				Rev. waterfill	2048
repeat	0	0	16	3	1	Integer	Default	Id				Rev. waterfill	37777
repeat	0	0	16	3	1	Integer	Default	Id				Rev. waterfill	111512
repeat	0	0	16	3	1	Integer	Default	Id				Rev. waterfill	211111
repeat	0	0	16	3	1	Integer	Default	Id				Lagrange	512
repeat	0	0	16	3	1	Integer	Default	Id				Lagrange	2048
repeat	0	0	16	3	1	Integer	Default	Id				Lagrange	37777
repeat	0	0	16	3	1	Integer	Default	Id				Lagrange	111512
repeat	0	0	16	3	1	Integer	Default	Id				Lagrange	211111
AIRS_64	0	0	16	2	1	Integer	Default	Id				Rev. waterfill	16384
AIRS_64	0	0	16	2	1	Integer	Default	Id				Rev. waterfill	32768
AIRS_64	0	0	16	2	1	Integer	Default	Id				Rev. waterfill	65536
AIRS_64	0	0	16	2	1	Integer	Default	Id				Rev. waterfill	98304
AIRS_64	0	0	16	2	1	Integer	Default	IWT				Rev. waterfill	32768
AIRS_64	0	0	16	2	1	Integer	Default	POT	16	11	Bypass	Rev. waterfill	32768
AIRS	0	0	362880	1	1	Integer	Default	IWT				Lagrange	2279644
AIRS	0	0	362880	1	1	Integer	Default	POT	32	13	Stable	Lagrange	2279644
Yellowstone sc0	0	0	4096	1	1	Integer	Default	POT	16	13	Stable	Lagrange	7340032
Yellowstone sc0	0	0	4096	1	1	Integer	Default	IWT				Lagrange	7340032
Toulouse	0	0	16384	1	1	Integer	Default	POT	32	13	Stable	Lagrange	393216
Toulouse	0	0	16384	1	1	Integer	Default	IWT				Lagrange	393216
Toulouse	1	0	16384	1	1	Integer	Default	AAT	32	31	3	Lagrange	393216
Yellowstone sc0	3	0	4096	1	1	Integer	Default	POT	32	11	Stable	Lagrange	7340032
Yellowstone sc0	8	3	4096	1	1	Integer	Default	AAT	32	13	100	Lagrange	7340032
Toulouse	0	0	16384	1	1	Integer	Default	IWT				Rev. waterfill	393216
Toulouse	0	0	16384	1	1	Integer	Default	POT	8	11	Stable	Rev. waterfill	393216
Yellowstone sc0	0	0	4096	1	1	Integer	Default	IWT				Rev. waterfill	7340032
Yellowstone sc0	0	0	4096	1	1	Integer	Default	POT	8	11	Stable	Rev. waterfill	7340032
Yellowstone sc0	8	3	4096	1	1	Integer	Default	AAT	32	13	100	Rev. waterfill	7340032
Toulouse	0	0	16384	1	1	Float	Default	IWT				Rev. waterfill	393216
Toulouse	0	0	16384	1	1	Float	Default	POT	8	11	Stable	Rev. waterfill	393216
Yellowstone sc0	0	0	4096	1	1	Float	Default	IWT				Rev. waterfill	7340032
Yellowstone sc0	0	0	4096	1	1	Float	Default	POT	8	11	Stable	Rev. waterfill	7340032
Yellowstone sc0	8	3	4096	1	1	Float	Default	AAT	32	13	100	Rev. waterfill	7340032

Table 5-2: Lossless Tests

Image Name	U	D	S	R	W	2D Wavelet	Wavelet Weights	Trans.	F	Ω or Ψ	POT mode
Test signed pixels exception in subsection 6.3.2.											
tiny	0	0	128	9	1	Integer	0:0:1:0:0:0:0:2:0:0	Id			
Repeat previous test for IWT (shall not trigger exception).											
tiny	0	0	128	9	1	Integer	0:0:1:0:0:0:0:2:0:0	IWT			
Test rare header combination for POT.											
tiny	0	0	128	9	4	Integer	0:1:0:1:0:0:2:0:1:0	POT	32	9	Bypass
Test high dynamic range expansion (triggers stable mode sign change too).											
tiny	6	0	18	1	8	Integer	Default	POT	1	10	Stable
A few tests for Upshift (U) and Downshift (D).											
tiny	6	0	18	1	2	Integer	Default	IWT			
tiny	15	9	21	1	3	Integer	Default	IWT			
tiny	15	15	16	3	4	Integer	Default	Id			
tiny	2	2	24	2	5	Integer	Default	Id			
More value combinations at IWT input.											
tall	0	0	17	3	1	Integer	Default	IWT			
Previous test with destructive downshift, but with enough precision so that it is still lossless.											
tall	4	1	24	2	1	Integer	Default	IWT			
tall	15	9	59049	3	1	Integer	Default	IWT			
More value combinations at POT input.											
tall	0	0	18	4	1	Integer	Default	POT	1	16	Stable
tall	0	0	31	3	2	Integer	Default	POT	8	13	Bypass
Previous test testing also for overflows at region size calculations.											
tall	14	8	1048576	65535	8	Integer	Default	POT	16	15	Bypass
Some AAT tests with high enough precision that for these particular cases it becomes lossless. These tests also overflow region size calculations.											
tall	8	2	1048576	65535	8	Integer	Default	AAT	1	25	
Tests same repeated pattern: this triggers repeat flag in AAT side information and yields one transformed band full of zeros.											
repeat	7	3	16	3	1	Integer	Default	AAT	16	31	
Tests same repeated pattern, but losing one band (still lossless).											
repeat	5	2	16	3	1	Integer	Default	AAT	4	20	
This produces large upshift inside BPE too.											
sixteenblocks	6	0	1048576	65536	6	Integer	3:3:3:3:3:3:3:3:3:3	POT	16	11	Bypass
Tests the §6.3.2 signed pixels exception.											
sixteenblocks	0	0	1048576	1	7	Integer	Default	Id			
Tests Eq. 5.7.											
sixteenblocks	0	0	1048576	3	1	Integer	Default	IWT			
Tests for lossless compression performance on real images											
AIRS	0	0	362880	1	1	Integer	Default	IWT			
AIRS	0	0	362880	1	1	Integer	Default	POT	32	13	Stable
Yellowstone sc0	0	0	4096	1	1	Integer	Default	POT	16	13	Stable
Yellowstone sc0	0	0	4096	1	1	Integer	Default	IWT			
Toulouse	0	0	16384	1	1	Integer	Default	POT	32	13	Stable
Toulouse	0	0	16384	1	1	Integer	Default	IWT			