OPTICAL SATELLITE

Data Compression and Implementation

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OPTICAL SATELLITE
Data Compression and Implementation

Shen-En Qian

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Contents

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Preface

Satellite data compression has been an important subject since the beginning of satellites in orbit, and it has become an even more active research topic. Following technological advancements, the trend of new satellites has led to an increase in spatial, spectral, and radiometric resolution, an extension in wavelength range, and a widening of ground swath to better serve the needs of the user community and decision makers. Data compression is often used as a sound solution to overcome the challenges of handling a tremendous amount of data. I have been working in this area since I was pursing my Ph. D. thesis almost 30 years ago.

Over the last two decades, I—as a senior research scientist and technical authority with the Canadian Space Agency—have led and carried out research and development of innovative data compression technology for optical satellites in collaboration with my colleagues at the agency, other government departments, my postdoctoral visiting fellows, internship students, and engineers at Canadian space industry. I invented and patented two series of near-lossless satellite data compression techniques and led the Canadian industry teams who implemented the techniques and built the onboard near-lossless compressors. I also led a multidisciplinary user team to assess the impact of the near-lossless compression techniques on ultimate satellite data applications. As the representative of Canada, I am an active member of the CCSDS working group for developing international data-compression standards for satellite data systems. Three international satellite data compression standards have been developed by the working group and published by the International Organization for Standardization (ISO). In collaborating with experts in this area in the world, I have co-chaired an SPIE conference on satellite data compression, communication, and signal processing since 2005. I have published over sixty papers and currently hold six U. S. patents, two European patents, and several pending patents in the subjects of satellite data compression and implementation. I feel that I have acquired sufficient knowledge and accumulated plenty experience in this area, and it is worth the effort to systematically organize them and put them into a book.

This book is my attempt to provide an end-to-end treatment of optical satellite data compression and implementation based on 30 years of firsthand

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experience and research outcomes. (It is a companion text to my book *Optical Satellite Signal Processing and Enhancement*, published by SPIE Press.) The contents of the book consist of nine chapters that cover a wide range of topics in this field. It serves as an introduction for readers who are willing to learn the basics and the evolution of data compression, and a guide for those working on onboard and ground satellite data compression, data handling and manipulation, and deployment of data-compression subsystems. The material is written to provide clear definitions and precise descriptions for advanced researchers and expert practitioners as well as for beginners. Chapters open with a brief introduction of the subject matter, followed by a review of previous approaches and their shortcomings, a presentation of recent techniques with improved performance, and finally a report on experimental results in order to assess their effectiveness and to provide conclusions.

Chapter 1 is the introduction to the book that describes the rationale and needs for satellite data compression and introduces a set of image quality metrics for assessing compressed satellite images. Chapter 2 presents a review of satellite lossless-data-compression techniques, considering both prediction-based and transform-based methods. Chapter 3 summarizes three international satellite-data-compression standards developed by CCSDS from the perspective of applying the standards. Chapter 4 describes vector quantization (VQ) based data-compression techniques that I have developed for compressing hyperspectral data. The focus of the research was to significantly reduce the computational complexity of conventional VQ algorithms in order for them to effectively compress hyperspectral datacubes. Many innovative yet practical solutions have been developed, including two of my granted patents: Successive Approximation Multi-stage Vector Quantization (SAMVQ) and Hierarchical Self-Organizing Cluster Vector Quantization (HSOCVQ). Chapter 5 describes how both of these techniques solve the blocking effect when applied to compressing continuous data flow generated aboard satellites and how they restrict the compression error to a level lower than that of the intrinsic noise of the original data to achieve so-called near-lossless compression. Chapter 6 addresses the optimization and implementation aspects of onboard data compression; aspects include the effect of anomalies of input data on compression performance, the location in the onboard data-processing chain where the compressor should be deployed, and the techniques to enhance error resilience in the data downlink transmission channel. Chapter 7 describes the hardware implementation of compression engines and onboard compressors that are based on SAMVQ and HSOCVQ. Chapter 8 reports a multidisciplinary user-acceptance study that assessed the impact of the compression techniques on various hyperspectral data applications to address the users' concern about possible information loss due to the lossy compression nature of SAMVQ and HSOCVQ. Chapter 9

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describes the Hyperspectral Image Browser (HIBR) system, which is capable of remotely displaying large hyperspectral datacubes via the Internet and of quickly processing the datacubes directly on the compressed form for users to identify the interested data, whose richness comes mostly from the spectral information.

There are many people I would like to thank for their contributions to the works included in this book. I would like to thank the Canadian Space Agency, where I have been working for the last 20 years; my colleagues Allan Hollinger, Martin Bergeron, Michael Maszkiewicz, Ian Cunningham, and Davinder Manak for their participation in data compression projects; my postdoctoral visiting fellows Pirouz Zarrinkhat and Charles Serele; and over forty intern students who have each left their mark. I would like to thank Robert Neville (retired), Karl Staenz (now at the University of Lethbridge), and Lixin Sun at the Canada Centre for Remote Sensing for collaborating on the Canadian hyperspectral program; Josée Lévesque and Jean-Pierre Ardouin at the Defence Research and Development Canada for their collaboration on assessing the impact of data compression. I thank David Goodenough at the Pacific Forestry Centre; John Miller and Baoxin Hu at York University for providing datasets and for actively collaborating on the data-compression user acceptability study; and Bormin Huang of the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison for his discussion on satellite data compression.

I would also like to thank the participants in the user acceptability study: Andrew Dyk at the Pacific Forestry Centre; Jing Chen at the University of Toronto; Harold Zwick, Dan Williams, Chris Nadeau, and Gordon Jolly at MacDonald Dettwiler Associates; and Benoit Rivard and Jilu Feng at the University of Alberta. I thank Luc Gagnon, William Harvey, Bob Barrette, and Colin Black at MacDonald Dettwiler Associates (former EMS Technologies) for the development and fabrication of onboard compressor prototypes; and Melanie Dutkiewicz and Herbal Tsang for the development of a hyperspectral browser. I thank Valec Szwarc and Mario Caron at the Communication Research Centre (Canada) for discussions on enhancing resilience to bit errors of compressed data in the downlink channel; and Peter Oswald and Ron Buckingham for their discussion on onboard data compression. I would also like to thank Penshu Yeh at the NASA Goddard Space Flight Center, Aaron Kiely at the Jet Propulsion Laboratory, Carole Thiebaut and Gilles Moury at the French Space Agency (CNES), and Raffaele Vitulli at the European Space Agency for the collaboration within the CCSDS in developing international spacecraft-data standards and for their contributions to the CCSDS work included in this book.

I would also like to thank the three anonymous manuscript reviewers for their tireless work and strong endorsement of this book, their careful and meticulous chapter-by-chapter review on behalf of SPIE Press, and their

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detailed comments leading to the improvement and final results of the book in its current form. Many thanks as well to Tim Lamkins, Scott McNeill, and Dara Burrows at SPIE Press for turning my manuscript into this book.

Finally, I would like to thank my wife Nancy and daughter Cynthia for their help and support. They provided great encouragement and assistance during the period I wrote this book. The credit of this book should go to them.

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List of Terms and Acronyms

%E	Percentage error
%SE	Percentage standard error
3D CB-EZW	Three-dimensional context-based embedded zerotrees of wavelet transform
3D-SPECK	Three-dimensional set-partitioned embedded block
AAC	Adaptive arithmetic coding
AC	Arithmetic coding
ACE-FTS	Atmospheric Chemistry Experiment-Fourier Transform Spectrometer
AIRS	Atmospheric infrared sounder
ALADIN	Atmospheric Laser Doppler Lidar Instrument
ALI	Advanced Land Imager
ALOS	Advanced Land-Observing Satellite
AMEE	Automated morphological end-member extraction
AOS	Advanced orbital system
AOTF	Acousto-optical tunable filter
APD	Avalanche photodiode
APRAD	Average percent relative absolute difference
APSICL	Adjacent pixel spectra in a cross-track line
A-RMSE	Absolute root mean square error
ARSIS	Amélioration de la résolution spatial par injection de structures
ARTEMIS	Advanced Responsive Tactically Effective Military Imaging Spectrometer
ASIC	Application-specific integrated circuit
ATGP	Automatic target generation process
AVIRIS	Airborne visible/infrared imaging spectrometer
AVNIR	Advanced visible and near-infrared radiometer
AWGN	Additive white Gaussian noise
BCM	Band correlation minimization
BDM	Band dependence minimization
BER	Bit-error rate
BIP	Band interleaved by pixel

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BIPLGC	Binary-input power-limited Gaussian channel
BP	Belief propagation
BPE	Bit-plane encoder
BPOC	Base-bit plus overflow-bit coding
bpppb	Bits per pixel per band
BPSK	Binary phase shift keying
BRDF	Bidirectional reflectance distribution function
BSQ	Band sequential
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CASI	Compact airborne spectrographic imager
CBERS	China-Brazil Earth Resources Satellite
CC	Correlation codevector
CCD	Charge-coupled device
CCSDS	Consultative Committee for Space Data Systems
CDS	Coded dataset
CE	Compression engine
CEM	Constraint energy minimization
CEOS	Committee on Earth Observation Satellites
CFDP	CCSDS File Delivery Protocol
CGT	Codebook generation time
CHRIS	Compact high-resolution imaging spectrometer
CR	Compression ratio
CrIS	Cross-track Infrared Sounder
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CRT	Complex ridgelet transform
CSCI	Component software-configurable item
CT	Coding time
CT	Computation time
CV	Codevector
CVQ	Correlation vector quantizer
CZT	Cadmium-zinc-telluride
DAAC	Distributed active archive center
DC	Digital count
DCT	Discrete cosine transform
DCWG	Data Compression Working Group
DIV	Difference in variance
DLP	Diagonal linear projection
DLS	Diagonal linear shrinker
DMA	Direct memory access
DN	Digital number
DPCM	Differential pulse code modulation
DSP	Digital signal processor
DT	Decoding time

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DTCWT	Dual-tree complex wavelet transform
DWT	Discrete wavelet transform
EDU	Engineering demonstration unit
EM	Endmember
EnMAP	Envrionmental Mapping Analysis
EOS	Earth Observing System
ETF	Electronically tunable filter
ETM	Enhanced thematic mapper
ETM+	Enhanced thematic mapper plus
EUMETSAT	European Organization for the Exploitation of Meterological Satellites
EV	Earth view
EZW	Embedded zerotrees of wavelet transforms
FCLSLU	Fully constrained least-squares linear unmixing
FER	Frame-error rate
FFT	Fast Fourier transform
FIFO	First-in first-out
FIPPI	Fast iterative pixel purity index
FIR	Far-infrared
FOV	Field of view
F-P filter	Fabry-Pérot filter
FPA	Focal plane array
FPGA	Field programmable gate array
FPR	False positive rate
FPVQ	Fast precomputed vector quantization
FR	Full reference
FRIT	Finite ridgelet transform
FTHSI	Fourier Transform Hyperspectral Imager
FTS	Fourier transform spectrometer
FWHM	Full width at half maximum
GIFTS	Geosynchronous Imaging Fourier Transform Spectrometer
GLA	Generalized Lloyd algorithm
GLAS	Geoscience Laser Altimeter System
GPO2	Golomb power-of-two coding
GSD	Ground sample distance
GUI	Graphical user interface
HIBR	Hyperspectral image browser
HIS	Intensity-hue-saturation
HPF	High-pass filter
HRG	High-Resolution Geometrical
HRV	High-Resolution Visible
HRVIR	High-Resolution Visible and Infrared
HS	Histogram-based segmentation

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HSOCVQ	Hierarchical self-organizing cluster vector quantization
HVS	Human visual system
HYDICE	Hyperspectral Digital Image Collection Experiment
IARR	Internal average relative reflectance
IASI	Infrared atmospheric sounding interferometer
IBP	Iterative back-projection
IC	Isoclustering
IC	Integrated circuit
ICESat	Ice, Cloud, and Land Elevation Satellite
IEA	Iterative error analysis
IFOV	Instantaneous field of view
IFTS	Imaging Fourier transform spectrometer
IIR	Imaging Infrared Radiometer
IRMSS	Infrared Multispectral Scanner
ISO	International Organization for Standardization
ISRO	Indian Space Research Organization
IWT	Integer wavelet transform
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
KLT	Karhunen–Loéve transform
LAI	Leaf area index
LAIS	Locally averaged interband scaling
LBG	Linde–Buzo–Gray
LCMV-CBS	Linearly constrained minimum variance constrained band selection
LCTF	Liquid crystal tunable filter
LDC	Lossless data compression
LDCM	Landsat Data Continuity Mission
LDPC	Low-density parity check
LITE	Lidar In-space Technology Experiment
LLE	Locally linear embedding
LOCO	Low-complexity lossless compression
LOLA	Lunar Orbiter Laser Altimeter
LOS	Line of sight
LRO	Lunar Reconnaissance Orbiter
LSU	Linear spectral unmixing
LUT	Lookup table
M3	Moon Mineralogy Mapper
MAD	Maximum absolute difference
MAE	Mean absolute error
MC 3D-EZBC	Motion-controlled three-dimensional embedded zeroblock coding
MCT	Mercury–cadmium–telluride

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MDD	Minimum distance detection
MDP	Minimum distance partition
MDS	Minimal distance selector
MEI	Morphological eccentricity index
MERIS	Medium-Resolution Imaging Spectrometer
MGS	Mars Global Surveyor
MHS	Modified histogram-based segmentation
MIR	Middle-infrared
MISR	Multi-angle imaging spectroradiometer
MLA	Mercury Laser Altimeter
MNF	Minimum noise fraction
M-NVQ	Mean-normalized vector quantization
MODIS	Moderate-resolution imaging spectroradiometer
MOLA	Mars Orbiter Laser Altimeter
MOMS	Modular optoelectronic multispectral scanner
MOS	Modular optoelectronic scanner
MPS	Mean-distance-order partial search
MRO	Mars Reconnaissance Orbiter
MS	Multispectral
MSA	Maximum spectral angle
MSCA	Multiple-subcodebook algorithm
MSE	Mean square error
MSID	Maximum spectral information divergence
MSS	Multispectral Scanner
MSSE	Mean square spectral error
MSX	Midcourse Space Experiment
MT	Multi-thresholding
MTF	Modulation transfer function
NDVI	Normalized difference vegetation index
NEΔT	Noise-equivalent change in temperature
NGST	Next-Generation Space Telescope
NIR	Near-infrared
NIST	National Institute of Standards and Technology
NN	Nearest neighbor
NNP	Nearest-neighbor predictor
NPS	Nearest partition set
NR	No reference
NR	Noisy radiance
NRR	Noise-removed radiance
NWP	Numerical weather prediction
OPD	Optical path difference
OSP	Orthogonal subspace projection
PALSAR	Phased Array-type L-band Synthetic Aperture Radar

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PCA	Principal component analysis
PCB	Print circuit board
PD	Probability of detection
PDS	Partial distance search
PDS	Planetary Data System
PFA	Probability of false alarm
PMAD	Percentage maximum absolute difference
PPI	Pixel purity index
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
PROBA	Project for Onboard Autonomy
PSF	Point spread function
PSNR	Peak signal-to-noise ratio
PT	Processing time
QLUT	Quantized-index lookup table
RBV	Return Beam Vidicon
RDCT	Reversible discrete cosine transform
RE	Ratio enhancement
REP	Red-edge position
ReRMSE	Relative root mean square error
RF	Radio frequency
RGB	Red-green-blue
RMSE	Root mean square error
RMSSE	Root mean square spectral error
ROC	Receiver operating characteristic
ROI	Region of interest
RR	Reduced reference
RTDLT	Reversible time-domain lapped transform
SA	Spectral angle
SAM	Spectral angle mapper
SAMVQ	Successive approximation multistage vector quantization
SAR	Synthetic aperture radar
SC	Spectral correlation
ScaRaB	Scanner for radiation budget
SCPS	Space Communications Protocol Specifications
SDD	Standard deviation difference
SeaWiFS	Sea-viewing wide-field-of-view sensor
SEU	Single-event upset
SFBBC	Spectral-feature-based binary code
SFF	Spectral feature fitting
SFFS	Sequential forward-floating selection
S-FMP	Spectral fuzzy-matching pursuits
SFS	Sequential forward selection

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SFSI	Short-Wave Infrared Full-Spectrum Imager
SGA	Simplex growing algorithm
SID	Sub-identity
SLA	Shuttle Laser Altimeter
SLSQ	Spectrum-oriented least squares
SNR	Signal-to-noise ratio
SOAD/SOSD	Sum of absolute/squared distance
SOFM	Self-organizing feature map
SPIHT	Set partitioning in hierarchical trees
SPIM	Spectrographic imager
SPOT	Système Pour l'Observation de la Terre
SRBC	Solar-radiation-based calibration
SRF	Spectral response function
S-RLP	Spectral relaxation-labeled prediction
SSE	Sum of squared error
SSIM	Structural similarity
SSR	Solid state recorder
SV	Spectral vector
SVM	Support vector machine
SVR	Synthetic variable ratio
SWIR	Short-wavelength infrared
TC	Telecommand
TDLT	Time-domain lapped transform
TDM	Time-division multiplex
TERM	Triangular elementary reversible matrix
TES	Tropospheric Emission Spectrometer
TIE	Triangle inequality elimination
TM	Thematic Mapper
TMC	Thematic Mapper calibrator
TOA	Top of atmosphere
TPR	True positive rate
USES	Universal source encoder for space
UVISI	Ultraviolet and Visible Imagers and Spectrographic Imagers
VA	Vector accumulator
VCA	Vertex component analysis
VD	Virtual dimensionality
VHDL	Very high-speed integrated-circuit hardware description language
VI	Vegetation index
VIF	Visual information fidelity
VLSI	Very large scale integration
VM	Verification model
VNIR	Visible and near-infrared

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VQ	Vector quantization
WER	Word-error rate
WFC	Wide-Field Camera
WGCV	Working Group on Calibration and Validation
WPT	Wavelet-package transform
WT	Wavelet transform
XML	Extensible markup language
ZC	Zero crossing

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