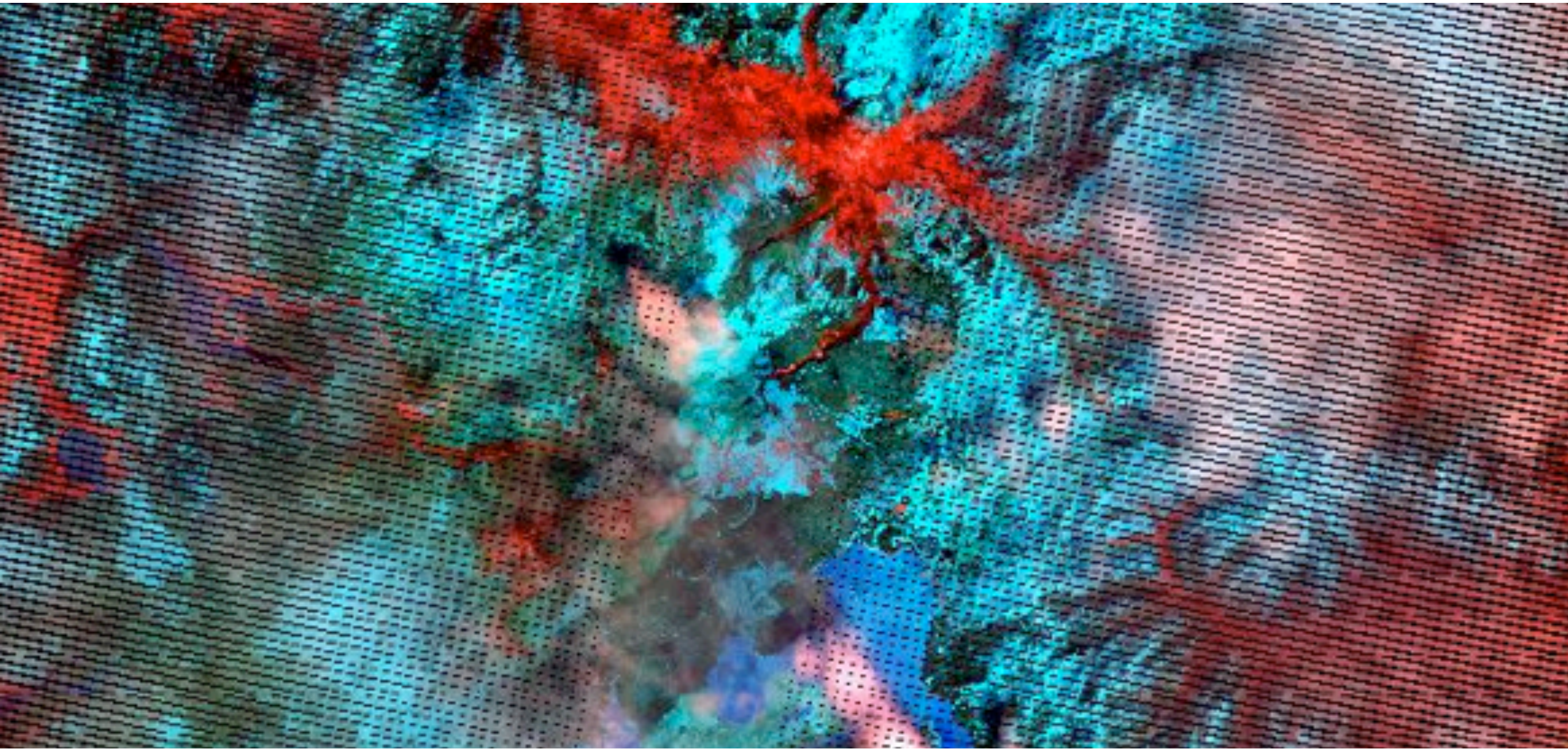


# Accuracy Standards for Partially Cloudy Landsat Visible/Infrared Snow Maps



Christopher J. Crawford<sup>1&2</sup> and Dorothy K. Hall<sup>2</sup>

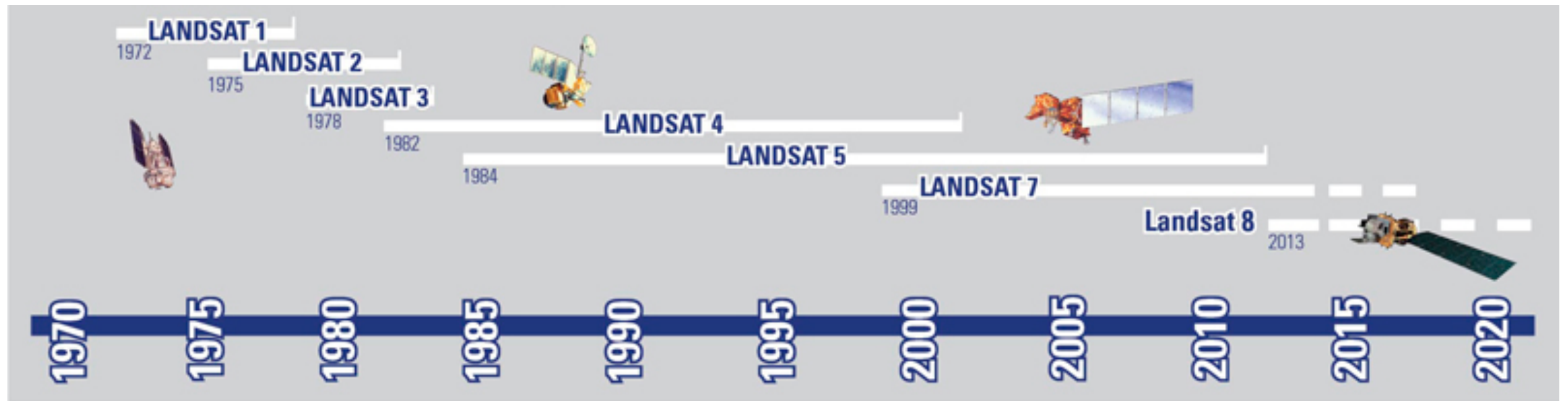
<sup>1</sup>*Oak Ridge Associated Universities*

<sup>2</sup>*Cryospheric Sciences Laboratory (Code 615), NASA/GFSC*

*snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP1), College Park, Maryland*

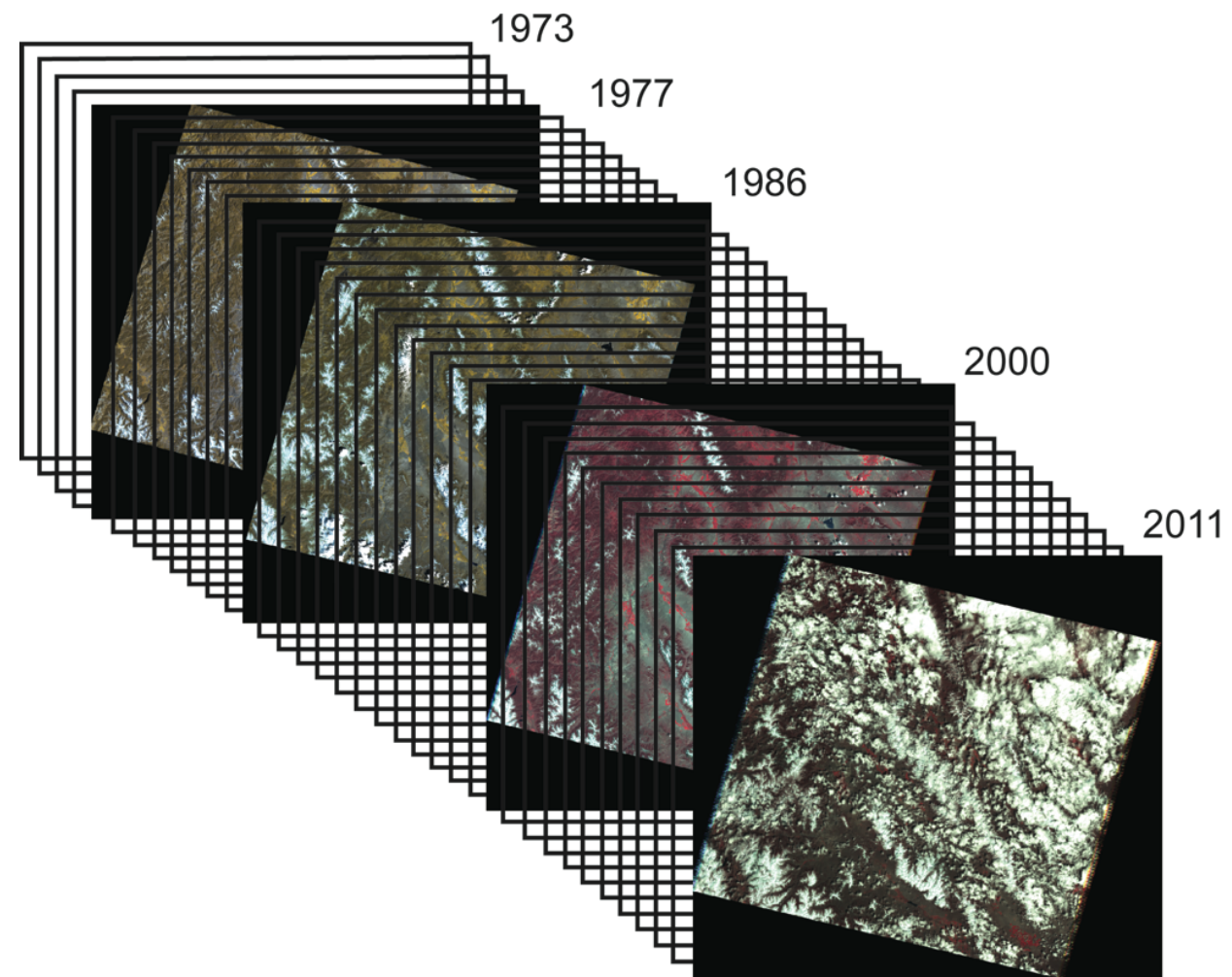
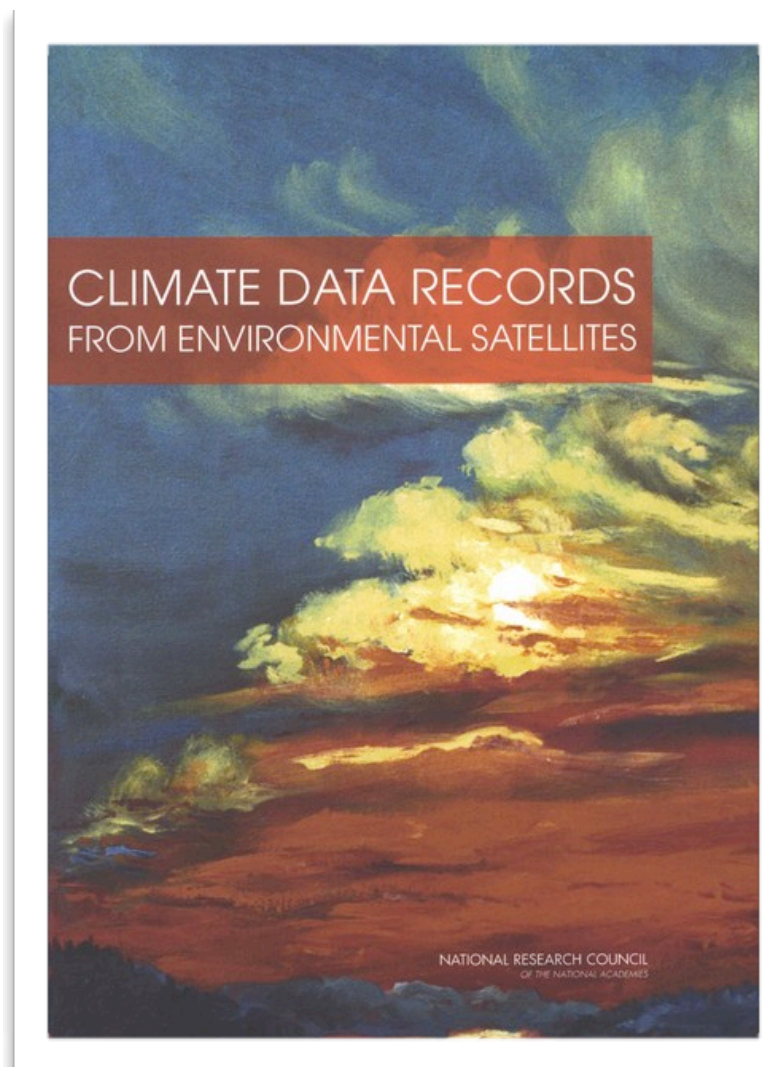


# The Landsat Mission Timeline



source: [http://landsat.usgs.gov/about\\_mission\\_history.php](http://landsat.usgs.gov/about_mission_history.php)

# Motivation for Landsat Snow Work



Crawford, C.J., S.M. Manson, M.E. Bauer, and D.K. Hall (2013). Multitemporal snow cover mapping in mountainous terrain for Landsat climate data record development. *Remote Sensing of Environment* 135:224-235. DOI:10.1016/j.rse.2013.04.004.

Crawford, C.J. (2014). MODIS Terra Collection 6 fractional snow cover validation in mountainous terrain during spring snowmelt using Landsat TM and ETM+. *Hydrological Processes*. DOI:10.1002/hyp.10134

Crawford, C.J. (2013). Evidence for spring mountain snowpack retreat from a Landsat-derived snow cover climate data record *Cryosphere Discussions* 7:2089-2117. DOI:10.5194/tcd-7-2089-2013.

snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP1)



# Landsat as Reference Data

## Development of Methods for Mapping Global Snow Cover Using Moderate Resolution Imaging Spectroradiometer Data

Dorothy K. Hall,<sup>\*</sup> George A. Riggs,<sup>\*\*</sup> and Vincent V. Salomonson<sup>†</sup>

Hydrological Processes  
*Hydrol. Process.* **12**, 1723–1744 (1998)

### Improving snow cover mapping in forests through the use of a canopy reflectance model

Andrew G. Klein,<sup>1,2,\*</sup> Dorothy K. Hall<sup>2</sup> and George A. Riggs,<sup>2,3</sup>

## Assessment of Snow-Cover Mapping Accuracy in a Variety of Vegetation-Cover Densities in Central Alaska

D. K. Hall,<sup>\*</sup> J. L. Foster,<sup>°</sup> D. L. Verbyla,<sup>†</sup> A. G. Klein,<sup>‡</sup> and C. S. Benson<sup>§</sup>

*Field and aircraft measurements were acquired in April 1995 in central Alaska to map snow cover with MODIS Airborne Simulator (MAS) data, acquired from high-altitude aircraft. The Earth Observing System (EOS) Moderate Resolution Imaging Spectroradiometer (MODIS) is a 36-channel system that will be launched on the EOS-AM-1 platform in 1999. A vegetation-density map derived from integrated reflectances ( $R_i$ ), from MAS data, is compared with an independently-produced vegetation type and density map derived from Thematic Mapper (TM) and ancillary data. The maps agreed to within 13%, thus corroborating the effectiveness of using the reflectance technique for mapping vegetation density. Snow cover was mapped on a 13 April 1995 MAS image, using the original MODIS prototype algorithm and an enhanced MODIS prototype algorithm. Field measurements revealed that the area was completely snow covered. With the original algorithm, snow was mapped in 96% of the pixels having <50% vegetation-cover density according to the  $R_i$  map, while in the areas having vegetation-cover densities  $\geq 50\%$ , snow was mapped in only 71% of the pixels. When the enhanced MODIS snow-mapping algorithm was employed, 99% of the pixels having <50% vegetation-cover density were mapped, and 98% of the pixels with  $\geq 50\%$  vegetation-cover density were mapped as snow covered. These results demonstrate*

<sup>\*</sup> Hydrological Sciences Branch, NASA/GSFC, Greenbelt, Maryland  
<sup>†</sup> Forest Sciences Department, University of Alaska, Fairbanks  
<sup>‡</sup> Department of Geography, Texas A&M University, College Station, Texas  
<sup>§</sup> Geophysical Institute, University of Alaska, Fairbanks  
Address correspondence to: D. K. Hall, Hydrological Sciences Branch, Code 974, NASA/GSFC, Greenbelt, MD 20771. E-mail: dhall@glacier.gsfc.nasa.gov  
Received 3 February 1998; revised 6 May 1998.

REMOTE SENS. ENVIRON. 66:129–137 (1998)  
©Elsevier Science Inc., 1998  
655 Avenue of the Americas, New York, NY 10010

0034-4257/98/\$-see front matter  
PII: S0034-4257(98)00051-0

## Estimating fractional snow cover from MODIS using the normalized difference snow index

V.V. Salomonson<sup>a,\*</sup>, I. Appel<sup>b</sup>

Advances in Water Resources 31 (2008) 1515–1526

### Advances in Water Resources

journal homepage: [www.elsevier.com/locate/advwatres](http://www.elsevier.com/locate/advwatres)

## Time-space continuity of daily maps of fractional snow cover and albedo from MODIS

Jeff Dozier<sup>a,\*</sup>, Thomas H. Painter<sup>b</sup>, Karl Rittger<sup>a</sup>, James E. Frew<sup>a</sup>

<sup>a</sup> Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106-5131, United States

<sup>b</sup> D.

A.

Art.

Rec.

Re.

Acc.

Av.

Key.

St.

MC.

Alb.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Re.

Remote Sensing of Environment 113 (2009) 868–879



### Remote Sensing of Environment

journal homepage: [www.elsevier.com/locate/rse](http://www.elsevier.com/locate/rse)

## Retrieval of subpixel snow covered area, grain size, and albedo from MODIS

Thomas H. Painter<sup>a,\*</sup>, Karl Rittger<sup>b</sup>, Ceretha McKenzie<sup>c</sup>, Peter Slaughter<sup>b</sup>, Robert E. Davis<sup>c</sup>, Jeff Dozier<sup>b</sup>

<sup>a</sup> Department of Geography, University of Utah, Salt Lake City, UT 84112, USA

<sup>b</sup> Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA

<sup>c</sup> US Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755, USA

### ARTICLE INFO

Article history:  
Received 10 July 2008  
Received in revised form 30 December 2008  
Accepted 1 January 2009

Keywords:  
Snow  
Grain size  
Albedo  
Spectral mixture analysis  
MODIS

### ABSTRACT

We describe and validate a model that retrieves fractional snow-covered area and the grain size and albedo of that snow from surface reflectance data (product MOD09GA) acquired by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS). The model analyzes the MODIS visible, near infrared, and shortwave infrared bands with multiple endmember spectral mixtures from a library of snow, vegetation, rock, and soil. We derive snow spectral endmembers of varying grain size from a radiative transfer model specific to a scene's illumination geometry; spectra for vegetation, rock, and soil were collected in the field and laboratory. We validate the model with fractional snow cover estimates from Landsat Thematic Mapper data, at 30 m resolution, for the Sierra Nevada, Rocky Mountains, high plains of Colorado, and Himalaya. Grain size measurements are validated with field measurements during the Cold Land Processes Experiment, and albedo retrievals are validated with in situ measurements in the San Juan Mountains of Colorado. The pixel-weighted average RMS error for snow-covered area across 31 scenes is 5%, ranging from 1% to 13%. The mean absolute error for grain size was 51  $\mu\text{m}$  and the mean absolute error for albedo was 4.2%. Fractional snow cover errors are relatively insensitive to solar zenith angle. Because MODSCAG is a physically based algorithm that accounts for the spatial and temporal variation in surface reflectances of snow and other surfaces, it is capable of global snow cover mapping in its more computationally efficient, operational mode.  
© 2009 Elsevier Inc. All rights reserved.

### 1. Introduction

Snow cover and its melt dominate regional climate and hydrology in many of the world's mountainous regions. One-sixth of Earth's population depends on snow- or glacier-melt for water resources, and people in these areas generate one-fourth of the global domestic product (Barnett et al., 2005). Recent analyses of long-term surface observations show a declining snowpack in the lower elevations in the western U.S. (Barnett et al., 2008; Howat & Tulaczyk, 2005; Mote et al., 2005), and investigations in the San Juan Mountains of Colorado show a positive feedback between dust from the Colorado Plateau and early snowmelt (Painter et al., 2007a). Dust deposited in the snowpack causes it to melt out three to five weeks earlier than it did before agricultural disturbance of the western U.S. in the second half of the 19th century, as revealed by lake sediment analysis (Neff et al., 2008). Operationally, seasonal forecasts of snowmelt-generated streamflow are leveraged through empirical relations based on past snowmelt periods. These historical data show that climate is changing, but the changes reduce the reliability of the empirical relations (Milly

<sup>\*</sup> Corresponding author.  
E-mail addresses: painter@geog.utah.edu (T.H. Painter), krittger@bren.ucsb.edu (K. Rittger), ceretha1@mac.com (C. McKenzie), peter@bren.ucsb.edu (P. Slaughter), Robert.E.Davis@erdc.crane.army.mil (R.E. Davis), dozier@bren.ucsb.edu (J. Dozier).

0034-4257/\$ - see front matter © 2009 Elsevier Inc. All rights reserved.  
doi:10.1016/j.rse.2009.01.001

Advances in Water Resources xxx (2012) xxx–xxx



Contents lists available at SciVerse ScienceDirect

### Advances in Water Resources

journal homepage: [www.elsevier.com/locate/advwatres](http://www.elsevier.com/locate/advwatres)



## Assessment of methods for mapping snow cover from MODIS

Karl Rittger<sup>a</sup>, Thomas H. Painter<sup>b</sup>, Jeff Dozier<sup>a,\*</sup>

<sup>a</sup> Bren School of Environmental Science & Management, University of California, Santa Barbara, CA 93106-5131, United States

<sup>b</sup> Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, United States

### ARTICLE INFO

Article history:  
Available online xxx

Keywords:  
Snow  
Remote sensing  
Mountain hydrology  
MODIS

### ABSTRACT

Characterization of snow is critical for understanding Earth's water and energy cycles. Maps of snow from MODIS have seen growing use in investigations of climate, hydrology, and glaciology, but the lack of rigorous validation of different snow mapping methods compromises these studies. We examine three widely used MODIS snow products: the “binary” (i.e., snow yes/no) global snow maps that were among the initial MODIS standard products; a more recent standard MODIS fractional snow product; and another fractional snow product, MODSCAG, based on spectral mixture analysis. We compare them to maps of snow obtained from Landsat ETM+ data, whose 30 m spatial resolution provides nearly 300 samples within a 500 m MODIS nadir pixel. The assessment uses 172 images spanning a range of snow and vegetation conditions, including the Colorado Rocky Mountains, the Inner Rio Grande, California's Sierra

HYDROLOGICAL PROCESSES  
*Hydrol. Process.* (2014)  
Published online in Wiley Online Library  
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10134

## MODIS Terra Collection 6 fractional snow cover validation in mountainous terrain during spring snowmelt using Landsat TM and ETM+

Christopher J. Crawford<sup>\*</sup>

Cryospheric Sciences Laboratory (Code 615), NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

### Abstract:

Daily swath MODIS Terra Collection 6 fractional snow cover (MOD10\_L2) estimates were validated with two-day Landsat TM/ETM+ snow-covered area estimates across central Idaho and southwestern Montana, USA. Snow cover maps during spring snowmelt for 2000, 2001, 2002, 2003, 2005, 2007, and 2009 were compared between MODIS Terra and Landsat TM/ETM+ using least-squared regression. Strong spatial and temporal map agreement was found between MODIS Terra fractional snow cover and Landsat TM/ETM+ snow-covered area, although map disagreement was observed for two validation dates. High-altitude cirrus cloud contamination during low snow conditions as well as late season transient snowfall resulted in map disagreement. MODIS Terra's spatial resolution limits retrieval of thin-patchy snow cover, especially during partially cloudy conditions. Landsat's image acquisition frequency can introduce difficulty when discriminating between transient and resident mountain snow cover. Furthermore, transient snowfall later in the snowmelt season, which is a stochastic accumulation event that does not usually persist beyond the daily timescale, will skew decadal snow-covered area variability if bi-monthly climate data record development is the objective. As a quality control step, ground-based daily snow telemetry snow-water-equivalent measurements can be used to verify transient snowfall events. Users of daily MODIS Terra fractional snow products should be aware that local solar illumination and sensor viewing geometry might influence fractional snow cover estimation in mountainous terrain. Cross-sensor interoperability has been confirmed between MODIS Terra and Landsat TM/ETM+ when mapping snow from the visible/infrared spectrum. This relationship is strong and supports operational multi-sensor snow cover mapping, specifically climate data record development to expand cryosphere, climate, and hydrological science applications. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS MODIS Terra; Landsat TM; Landsat ETM+; snow cover; validation; mountains

Received 26 November 2012; Accepted 17 December 2013

### INTRODUCTION

Successive snow cover accumulation in mountainous terrain during the hemispheric cool-season forms a resident snowpack that melts as springtime solar irradiance and near-surface air temperature increase and planetary albedo decreases (Barry et al., 1995; Barry, 2002; Barry, 2006). In arid regions like the western United States, mountain snowpack accumulation and melt contribute approximately 50–70% to the total annually available freshwater resource via snow-fed streamflow (Cayan, 1996; Barnett et al., 2005; Bales et al., 2006). Therefore, documenting how basic (i.e. natural variability) snowpack accumulation and melt processes and patterns vary over multiple spatial and temporal measurement scales enables identification of localities where mountain

snowpack has changed, is changing, and will be susceptible to long-term change triggered by climatic warming. Satellite remote sensing is uniquely positioned to address these questions because a spectrally distinct snow cover signal can be optically retrieved over broad regions and remote mountainous terrain with high confidence (Dozier, 1984; Hall and Martinec, 1985; Dozier, 1989; Hall et al., 1995; Rosenthal and Dozier, 1996; Hall et al., 2001; Dozier and Painter, 2004; Hall and Riggs, 2007; Foster et al., 2011; Hall et al., 2012). That said, maximizing the snow cover signal relative to background noise contributed by a mixed land surface response requires quantifying uncertainty and error in snow cover mapping to ensure that remotely sensed snow algorithms and products are robust and continually improved upon using differing techniques (Rosenthal and Dozier, 1996; Hall et al., 1998; Hall et al., 2001; Hall et al., 2002a, b; Metsamäki et al., 2002; Dozier and Painter, 2004; Pepe et al., 2005; Anttila et al., 2006; Dozier et al., 2008; Salminen et al., 2009; Dobrev and Klein, 2011; Hall and

<sup>\*</sup>Correspondence to: Christopher J. Crawford, Cryospheric Sciences Laboratory (Code 615), NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.  
E-mail: christopher.j.crawford@nasa.gov

Copyright © 2013 John Wiley & Sons, Ltd.



# Landsat's Relevance to SnowPEX Objectives

1. Review sensor-specific limitations for optical snow mapping
2. Establish *accuracy* standards for Landsat TM, ETM+, and OLI image pre-processing
3. Reconcile sensor differences in the context of snow map *comparisons and validation*



**Objective #1** Determine the accuracy of cloud/cloud shadow masking for Landsat TM, ETM+, and OLI/TIRS at the pixel scale



# Radiometric Calibration

2074

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 41, NO. 11, NOVEMBER 2003

Revised Landsat-5 TM Radiometric Calibration Procedures and Postcalibration Dynamic Ranges

Gyanesh Chander and Brian Markham

Abstract—The Landsat-5 Thematic Mapper (TM) radiometric calibration procedure has been revised to improve the accuracy of the data. The new procedure will improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10.

Index Terms—Landsat-5 TM, radiometric calibration, dynamic ranges, postcalibration, gain error, offset error, accuracy, data quality.

Abstract

The Landsat-5 Thematic Mapper (TM) radiometric calibration procedure has been revised to improve the accuracy of the data. The new procedure will improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10.

Introduction

The Landsat-5 Thematic Mapper (TM) radiometric calibration procedure has been revised to improve the accuracy of the data. The new procedure will improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10.

PHOTOGRAMMETRY

The Landsat-5 Thematic Mapper (TM) radiometric calibration procedure has been revised to improve the accuracy of the data. The new procedure will improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10.

Landsat-7 Long-Term Acquisition Plan Radiometry - Evolution Over Time

Brian Markham, Samuel Goward, Terry Arvidson, Julia Barsi, and Pat Scaramuzza

Abstract

The Landsat-7 Enhanced Thematic Mapper Plus (ETM+) radiometric calibration procedure has been revised to improve the accuracy of the data. The new procedure will improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10. The new procedure will also improve the accuracy of the data by reducing the gain error by a factor of 10 and the offset error by a factor of 10.

Revised Landsat-5 Thematic Mapper Radiometric Calibration

Gyanesh Chander, Member, IEEE, Brian L. Markham, and Julia A. Barsi

Abstract—Effective April 2, 2007, the radiometric calibration of Landsat-5 (L5) Thematic Mapper (TM) data that are processed and distributed by the U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS) will be updated. The lifetime gain model that was implemented on May 5, 2003, for the reflective bands (1–5, 7) will be replaced by a new lifetime radiometric-calibration curve that is derived from the instrument's response to pseudo-invariant desert sites and from cross calibration with the Landsat-7 (L7) Enhanced TM Plus (ETM+). Although this calibration update applies to all archived and future L5 TM data, the principal improvements in the calibration are for the data acquired during the first eight years of the mission (1984–1991), where the changes in the instrument-gain values are as much as 15%. The radiometric scaling coefficients for bands 1 and 2 for approximately the first eight years of the mission have also been changed. Users will need to apply these new coefficients to convert the calibrated data product digital numbers to radiance. The scaling coefficients for the other bands have not changed.

Index Terms—Bias, calibration, characterization, gain, Landsat-5 (L5), Libya, lookup table (LUT), National Land Archive Production System (NLAPS), offset, radiance, reflectance, relative spectral response (RSR), spectral bands, Thematic Mapper (TM).

I. INTRODUCTION

LANDSAT-5 (L5) was launched on March 1, 1984, with the Thematic Mapper (TM) Earth-imaging sensor onboard. The satellite and sensor continue to operate today, after more than 23 years of service. The TM has seven spectral bands: six 30-m reflective bands and one 120-m thermal band. TM bands have center wavelengths of approximately 0.49, 0.56, 0.66, 0.83, 1.67, 11.5, and 2.24  $\mu\text{m}$ , respectively. The raw and calibrated data products are quantized to eight bits. The TM incorporates an internal calibrator (IC) with lamps for the reflective bands, a blackbody source for the thermal band, and a temperature-monitored shutter for all the bands. The IC is located behind the primary instrument telescope. The

II. RADIOMETRIC CALIBRATION PROCEDURE

Data continuity requires consistency in the interpretation of image data acquired by different sensors. Calculation of radiance is the fundamental step in putting data from multiple sensors and platforms onto a common radiometric scale. The following is a partial list of variables used for radiometric calibration.

$Q$

Raw quantized voltage or response [DN].

$G$

Detector gain or responsivity [DN/(W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$B$

Detector bias or background response [DN].

$L_A$

Spectral radiance at the sensor's aperture [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$Q_{\text{cal}}$

Quantized calibrated pixel value [DN].

$Q_{\text{cal min}}$

Minimum quantized calibrated pixel value (DN = 0) corresponding to LMIN <sub>$\lambda$</sub> .

$Q_{\text{cal max}}$

Maximum quantized calibrated pixel value (DN = 255) corresponding to LMAX <sub>$\lambda$</sub> .

LMIN <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal min}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

LMAX <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal max}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

Manuscript received January 27, 2007; revised March 12, 2007. This work was supported in part by the NASA Landsat Project Science Office (LPSO) under Dr. Darrel Williams, Project Scientist, and in part by the U.S. Geological Society (USGS) Center for Earth Resources Observation and Science (EROS) Landsat Project under Kristi Kline, Project Manager. The work of G. Chander was supported by the USGS under Contract G03RCN0001.

G. Chander is with the Science Applications International Corporation (SAIC) at the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: gchander@usgs.gov).

B. L. Markham is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

J. A. Barsi is with Science Systems and Applications, Inc., Greenbelt, MD 20771 USA.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/LGRS.2007.898285

1545-598X/07/\$25.00 © 2007 IEEE

Authorized licensed use limited to: University of Minnesota. Downloaded on August 28, 2009 at 15:54 from IEEE Xplore. Restrictions apply.

Remote Sensing of Environment 113 (2009) 893–903

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: [www.elsevier.com/locate/rse](http://www.elsevier.com/locate/rse)

Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors

Gyanesh Chander<sup>a,\*</sup>, Brian L. Markham<sup>b</sup>, Dennis L. Helder<sup>c</sup>

<sup>a</sup> SGT, Inc., contractor to the USGS, Sioux Falls, SD 57198 USA

<sup>b</sup> National Aeronautics and Space Administration, Greenbelt, MD 20771 USA

<sup>c</sup> South Dakota State University, Brookings, SD 57007 USA

Abstract

The Landsat series of satellites have been collecting images of the Earth's surface for nearly 40 years. These images have been invaluable for characterizing and detecting changes in the land cover and land use of the world. Although initially conceived as primarily picture generating sensors, even the early sensors were radiometrically calibrated and spectrally characterized prior to launch and incorporated some capabilities to monitor their radiometric calibration once on orbit. Recently, as the focus of studies has shifted to monitoring Earth surface parameters over significant periods of time, serious attention has been focused toward bringing the data from all these sensors onto a common radiometric scale over this 40-year period. This effort started with the most recent systems and then was extended back in time. Landsat-7 Enhanced Thematic Mapper (ETM+) is the best-characterized sensor of the series prior to launch and once on orbit, and the most stable system to date, was chosen to serve as the reference. The Landsat-7 project was the first of the series to build an image assessment system into its ground system, allowing systematic characterization of its sensors and data. Second, the Landsat-5 Thematic Mapper (TM) (still operating at the time of the Landsat-7 launch and continues to operate) calibration history was reconstructed based on its internal calibrator, vicarious calibrations, pseudo-invariant sites and a tie to Landsat-7 ETM+ at the time of the commissioning of Landsat-7. This process was performed in two iterations: the earlier one relied primarily on the TM internal calibrator. When this was found to have some deficiencies, a revised calibration was based more on pseudo-invariant sites, though the internal calibrator was still used to establish the short-term variations in response due to contaminant build up on the cold focal plane. As time progressed, a capability to monitor the Landsat-5 TM was added to the image assessment system. The Landsat-4 TM, which operated from 1982 to 1992, was the third system to which the radiometric scale was extended. The limited and broken use of the Landsat-4 TM made this analysis more difficult. Eight-day separated image pairs from Landsat-5 combined with analysis of pseudo-invariant sites established this history. The fourth and most challenging effort was making the Landsat 1–5 Multi-Spectral Scanner (MSS) sensors' data internally radiometrically consistent. This effort was particularly complicated by the age of the MSS data, varying formats and processing levels in the archive, limited datasets, and limited documentation available. Ultimately, pseudo-invariant sites were identified in North America and used for this effort. Note that most of the Landsat MSS archived data had already been calibrated using the MSS internal calibrators, so this processing was embedded in the result. The final effort was developing an absolute scale for Landsat MSS similar to what was already established for the "TM" sensors. This was accomplished by using simultaneous data from Landsat-5 MSS and Landsat-5 TM, accounting for spectral differences between the sensors using EO-1 Hyperion data. The recalibrated history of the Landsat data and implications to users are discussed. The key result from this work is a consistently calibrated Landsat data archive that spans nearly 40 years with total uncertainties on the order of 10% or less for most sensors and bands.

Index Terms—Landsat, radiometric calibration, Landsat-5 TM, Landsat-7 ETM+, Landsat-4 TM, Landsat-1 MSS, Landsat-2 MSS, Landsat-3 MSS, Landsat-4 TM, Landsat-5 TM, Landsat-7 ETM+, Landsat-1 MSS, Landsat-2 MSS, Landsat-3 MSS, Landsat-4 TM, Landsat-5 TM, Landsat-7 ETM+.

1. Introduction

The Landsat series of satellites have been collecting images of the Earth's surface for nearly 40 years. These images have been invaluable for characterizing and detecting changes in the land cover and land use of the world. Although initially conceived as primarily picture generating sensors, even the early sensors were radiometrically calibrated and spectrally characterized prior to launch and incorporated some capabilities to monitor their radiometric calibration once on orbit. Recently, as the focus of studies has shifted to monitoring Earth surface parameters over significant periods of time, serious attention has been focused toward bringing the data from all these sensors onto a common radiometric scale over this 40-year period. This effort started with the most recent systems and then was extended back in time. Landsat-7 Enhanced Thematic Mapper (ETM+) is the best-characterized sensor of the series prior to launch and once on orbit, and the most stable system to date, was chosen to serve as the reference. The Landsat-7 project was the first of the series to build an image assessment system into its ground system, allowing systematic characterization of its sensors and data. Second, the Landsat-5 Thematic Mapper (TM) (still operating at the time of the Landsat-7 launch and continues to operate) calibration history was reconstructed based on its internal calibrator, vicarious calibrations, pseudo-invariant sites and a tie to Landsat-7 ETM+ at the time of the commissioning of Landsat-7. This process was performed in two iterations: the earlier one relied primarily on the TM internal calibrator. When this was found to have some deficiencies, a revised calibration was based more on pseudo-invariant sites, though the internal calibrator was still used to establish the short-term variations in response due to contaminant build up on the cold focal plane. As time progressed, a capability to monitor the Landsat-5 TM was added to the image assessment system. The Landsat-4 TM, which operated from 1982 to 1992, was the third system to which the radiometric scale was extended. The limited and broken use of the Landsat-4 TM made this analysis more difficult. Eight-day separated image pairs from Landsat-5 combined with analysis of pseudo-invariant sites established this history. The fourth and most challenging effort was making the Landsat 1–5 Multi-Spectral Scanner (MSS) sensors' data internally radiometrically consistent. This effort was particularly complicated by the age of the MSS data, varying formats and processing levels in the archive, limited datasets, and limited documentation available. Ultimately, pseudo-invariant sites were identified in North America and used for this effort. Note that most of the Landsat MSS archived data had already been calibrated using the MSS internal calibrators, so this processing was embedded in the result. The final effort was developing an absolute scale for Landsat MSS similar to what was already established for the "TM" sensors. This was accomplished by using simultaneous data from Landsat-5 MSS and Landsat-5 TM, accounting for spectral differences between the sensors using EO-1 Hyperion data. The recalibrated history of the Landsat data and implications to users are discussed. The key result from this work is a consistently calibrated Landsat data archive that spans nearly 40 years with total uncertainties on the order of 10% or less for most sensors and bands.

2. Radiometric Calibration Procedure

Data continuity requires consistency in the interpretation of image data acquired by different sensors. Calculation of radiance is the fundamental step in putting data from multiple sensors and platforms onto a common radiometric scale. The following is a partial list of variables used for radiometric calibration.

$Q$

Raw quantized voltage or response [DN].

$G$

Detector gain or responsivity [DN/(W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$B$

Detector bias or background response [DN].

$L_A$

Spectral radiance at the sensor's aperture [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$Q_{\text{cal}}$

Quantized calibrated pixel value [DN].

$Q_{\text{cal min}}$

Minimum quantized calibrated pixel value (DN = 0) corresponding to LMIN <sub>$\lambda$</sub> .

$Q_{\text{cal max}}$

Maximum quantized calibrated pixel value (DN = 255) corresponding to LMAX <sub>$\lambda$</sub> .

LMIN <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal min}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

LMAX <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal max}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

Manuscript received September 11, 2011; revised version April 18, 2012; accepted for publication May 16, 2012. This work was supported by the NASA Landsat Project Science Office (LPSO) under Dr. Darrel Williams, Project Scientist, and in part by the U.S. Geological Society (USGS) Center for Earth Resources Observation and Science (EROS) Landsat Project under Kristi Kline, Project Manager. The work of G. Chander was supported by the USGS under Contract G03RCN0001.

G. Chander is with the Science Applications International Corporation (SAIC) at the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: gchander@usgs.gov).

B. L. Markham is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

D. L. Helder is with the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: dhelder@usgs.gov).

D. Aaron is with the Brookings, SD 57007 USA (e-mail: daaron@usgs.gov).

J. S. Czaplinski is with the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: jsczaplinski@usgs.gov).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1016/j.rse.2009.01.007

0034-4257/\$ – see front matter. Published by Elsevier Inc.

doi:10.1016/j.rse.2009.01.007

Remote Sensing of Environment 122 (2012) 30–40

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: [www.elsevier.com/locate/rse](http://www.elsevier.com/locate/rse)

Forty-year calibrated record of earth-reflected radiance from Landsat: A review

Brian L. Markham<sup>a,\*</sup>, Dennis L. Helder<sup>b,1</sup>

<sup>a</sup> Biophysical Sciences Laboratory, Code 618, NASA/GSFC, Greenbelt, MD 20771, United States

<sup>b</sup> College of Engineering, South Dakota State University, Brookings, SD 57007, United States

Abstract

Sensors on Landsat satellites have been collecting images of the Earth's surface for nearly 40 years. These images have been invaluable for characterizing and detecting changes in the land cover and land use of the world. Although initially conceived as primarily picture generating sensors, even the early sensors were radiometrically calibrated and spectrally characterized prior to launch and incorporated some capabilities to monitor their radiometric calibration once on orbit. Recently, as the focus of studies has shifted to monitoring Earth surface parameters over significant periods of time, serious attention has been focused toward bringing the data from all these sensors onto a common radiometric scale over this 40-year period. This effort started with the most recent systems and then was extended back in time. Landsat-7 Enhanced Thematic Mapper (ETM+) is the best-characterized sensor of the series prior to launch and once on orbit, and the most stable system to date, was chosen to serve as the reference. The Landsat-7 project was the first of the series to build an image assessment system into its ground system, allowing systematic characterization of its sensors and data. Second, the Landsat-5 Thematic Mapper (TM) (still operating at the time of the Landsat-7 launch and continues to operate) calibration history was reconstructed based on its internal calibrator, vicarious calibrations, pseudo-invariant sites and a tie to Landsat-7 ETM+ at the time of the commissioning of Landsat-7. This process was performed in two iterations: the earlier one relied primarily on the TM internal calibrator. When this was found to have some deficiencies, a revised calibration was based more on pseudo-invariant sites, though the internal calibrator was still used to establish the short-term variations in response due to contaminant build up on the cold focal plane. As time progressed, a capability to monitor the Landsat-5 TM was added to the image assessment system. The Landsat-4 TM, which operated from 1982 to 1992, was the third system to which the radiometric scale was extended. The limited and broken use of the Landsat-4 TM made this analysis more difficult. Eight-day separated image pairs from Landsat-5 combined with analysis of pseudo-invariant sites established this history. The fourth and most challenging effort was making the Landsat 1–5 Multi-Spectral Scanner (MSS) sensors' data internally radiometrically consistent. This effort was particularly complicated by the age of the MSS data, varying formats and processing levels in the archive, limited datasets, and limited documentation available. Ultimately, pseudo-invariant sites were identified in North America and used for this effort. Note that most of the Landsat MSS archived data had already been calibrated using the MSS internal calibrators, so this processing was embedded in the result. The final effort was developing an absolute scale for Landsat MSS similar to what was already established for the "TM" sensors. This was accomplished by using simultaneous data from Landsat-5 MSS and Landsat-5 TM, accounting for spectral differences between the sensors using EO-1 Hyperion data. The recalibrated history of the Landsat data and implications to users are discussed. The key result from this work is a consistently calibrated Landsat data archive that spans nearly 40 years with total uncertainties on the order of 10% or less for most sensors and bands.

Index Terms—Landsat, radiometric calibration, Landsat-5 TM, Landsat-7 ETM+, Landsat-4 TM, Landsat-1 MSS, Landsat-2 MSS, Landsat-3 MSS, Landsat-4 TM, Landsat-5 TM, Landsat-7 ETM+.

1. Introduction

The Landsat series of satellites have been collecting images of the Earth's surface for nearly 40 years. These images have been invaluable for characterizing and detecting changes in the land cover and land use of the world. Although initially conceived as primarily picture generating sensors, even the early sensors were radiometrically calibrated and spectrally characterized prior to launch and incorporated some capabilities to monitor their radiometric calibration once on orbit. Recently, as the focus of studies has shifted to monitoring Earth surface parameters over significant periods of time, serious attention has been focused toward bringing the data from all these sensors onto a common radiometric scale over this 40-year period. This effort started with the most recent systems and then was extended back in time. Landsat-7 Enhanced Thematic Mapper (ETM+) is the best-characterized sensor of the series prior to launch and once on orbit, and the most stable system to date, was chosen to serve as the reference. The Landsat-7 project was the first of the series to build an image assessment system into its ground system, allowing systematic characterization of its sensors and data. Second, the Landsat-5 Thematic Mapper (TM) (still operating at the time of the Landsat-7 launch and continues to operate) calibration history was reconstructed based on its internal calibrator, vicarious calibrations, pseudo-invariant sites and a tie to Landsat-7 ETM+ at the time of the commissioning of Landsat-7. This process was performed in two iterations: the earlier one relied primarily on the TM internal calibrator. When this was found to have some deficiencies, a revised calibration was based more on pseudo-invariant sites, though the internal calibrator was still used to establish the short-term variations in response due to contaminant build up on the cold focal plane. As time progressed, a capability to monitor the Landsat-5 TM was added to the image assessment system. The Landsat-4 TM, which operated from 1982 to 1992, was the third system to which the radiometric scale was extended. The limited and broken use of the Landsat-4 TM made this analysis more difficult. Eight-day separated image pairs from Landsat-5 combined with analysis of pseudo-invariant sites established this history. The fourth and most challenging effort was making the Landsat 1–5 Multi-Spectral Scanner (MSS) sensors' data internally radiometrically consistent. This effort was particularly complicated by the age of the MSS data, varying formats and processing levels in the archive, limited datasets, and limited documentation available. Ultimately, pseudo-invariant sites were identified in North America and used for this effort. Note that most of the Landsat MSS archived data had already been calibrated using the MSS internal calibrators, so this processing was embedded in the result. The final effort was developing an absolute scale for Landsat MSS similar to what was already established for the "TM" sensors. This was accomplished by using simultaneous data from Landsat-5 MSS and Landsat-5 TM, accounting for spectral differences between the sensors using EO-1 Hyperion data. The recalibrated history of the Landsat data and implications to users are discussed. The key result from this work is a consistently calibrated Landsat data archive that spans nearly 40 years with total uncertainties on the order of 10% or less for most sensors and bands.

2. Radiometric Calibration Procedure

Data continuity requires consistency in the interpretation of image data acquired by different sensors. Calculation of radiance is the fundamental step in putting data from multiple sensors and platforms onto a common radiometric scale. The following is a partial list of variables used for radiometric calibration.

$Q$

Raw quantized voltage or response [DN].

$G$

Detector gain or responsivity [DN/(W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$B$

Detector bias or background response [DN].

$L_A$

Spectral radiance at the sensor's aperture [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

$Q_{\text{cal}}$

Quantized calibrated pixel value [DN].

$Q_{\text{cal min}}$

Minimum quantized calibrated pixel value (DN = 0) corresponding to LMIN <sub>$\lambda$</sub> .

$Q_{\text{cal max}}$

Maximum quantized calibrated pixel value (DN = 255) corresponding to LMAX <sub>$\lambda$</sub> .

LMIN <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal min}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

LMAX <sub>$\lambda$</sub>

Spectral radiance that is scaled to  $Q_{\text{cal max}}$  [W/(m<sup>2</sup> · sr ·  $\mu\text{m}$ ))].

Manuscript received September 11, 2011; revised version April 18, 2012; accepted for publication May 16, 2012. This work was supported by the NASA Landsat Project Science Office (LPSO) under Dr. Darrel Williams, Project Scientist, and in part by the U.S. Geological Society (USGS) Center for Earth Resources Observation and Science (EROS) Landsat Project under Kristi Kline, Project Manager. The work of G. Chander was supported by the USGS under Contract G03RCN0001.

G. Chander is with the Science Applications International Corporation (SAIC) at the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: gchander@usgs.gov).

B. L. Markham is with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

D. L. Helder is with the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: dhelder@usgs.gov).

D. Aaron is with the Brookings, SD 57007 USA (e-mail: daaron@usgs.gov).

J. S. Czaplinski is with the U.S. Geological Survey Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198 USA (e-mail: jsczaplinski@usgs.gov).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1016/j.rse.2011.06.026

0034-4257/\$ – see front matter. Published by Elsevier Inc.

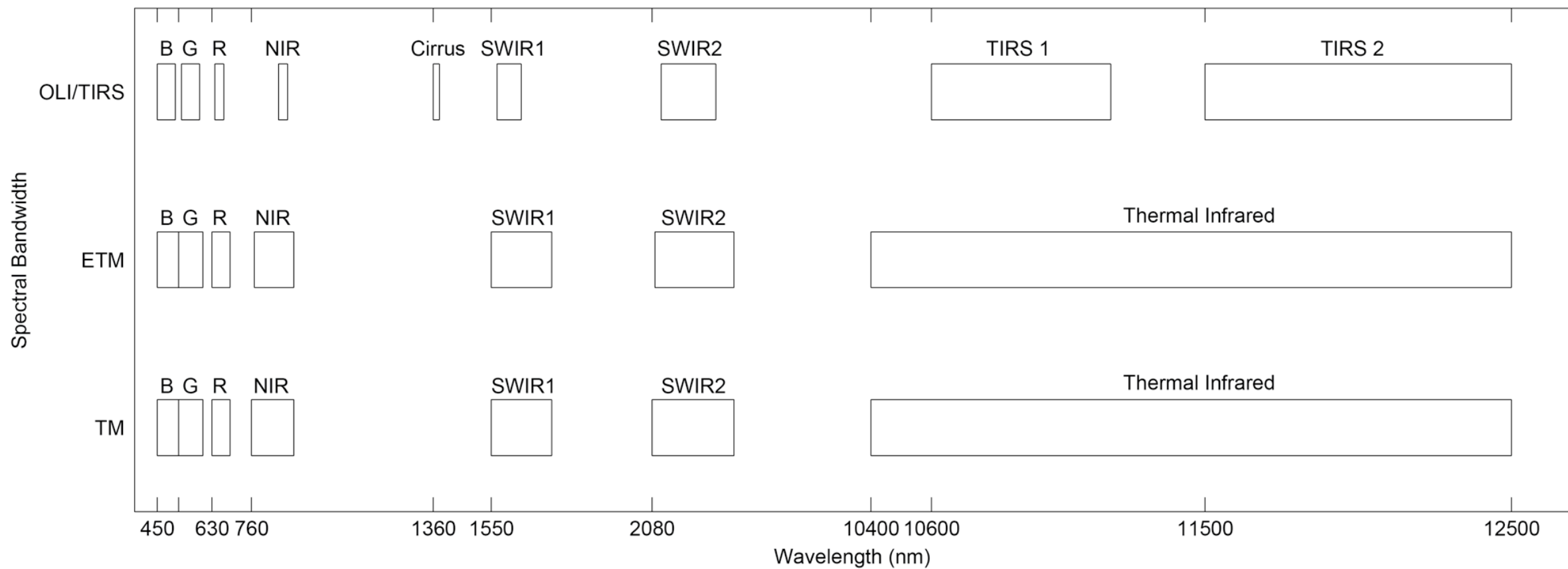
doi:10.1016/j.rse.2011.06.026

snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP I)

Tuesday, July 22, 2014



# Spectral Bandwidths, Gain Settings, and Detector Saturation



<a href="#">Sun Elevation</a>	35.55225754
<a href="#">Data Type Level 1</a>	ETM+ L1T
<a href="#">Sun Azimuth</a>	159.78796387
<a href="#">Full Aperture Calibration</a>	N
<a href="#">Gain Band 1</a>	H
<a href="#">Gain Band 2</a>	H
<a href="#">Gain Band 3</a>	H
<a href="#">Gain Band 4</a>	L
<a href="#">Gain Band 5</a>	H
<a href="#">Gain Band 6 VCID 1</a>	L
<a href="#">Gain Band 6 VCID 2</a>	H
<a href="#">Gain Band 7</a>	H
<a href="#">Gain Band 8</a>	L
<a href="#">Gain Change Band 1</a>	HH
<a href="#">Gain Change Band 2</a>	HH

## Snow and Clouds

255	255	255
237	255	255
208	221	255

# Heritage Automated Cloud-Cover Assessment (ACCA) Algorithm

## Landsat 7 Automatic Cloud Cover Assessment

Richard R. Irish\*

Science Systems and Applications, Inc.

NASA's Goddard Space Flight Center, Greenbelt, Maryland

### ABSTRACT

An automatic cloud cover assessment algorithm was developed for the Landsat 7 ground system. A scene dependent approach that employs two passes through ETM+ data was developed. In pass one, the reflective and thermal properties of scene features are used to establish the presence or absence of clouds in a scene. If present, a scene-specific thermal profile for clouds is established. In pass two, a unique thermal signature for clouds is developed and used to identify the remaining clouds in a scene. The algorithm appears to be a good cloud discriminator for most areas of the Earth. Some difficulty has appeared in imagery over Antarctica, and snow at high illumination angles is occasionally mistaken for cloud.

Keywords: Landsat, ETM+, clouds, classification, ACCA, algorithm

### 1. INTRODUCTION

A primary goal of the Landsat 7 mission is to provide a global seasonal archive of cloud-free imagery over the Earth's landmasses. To achieve this goal, 250 images or scenes are acquired each day by the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) and archived. Mission success is determined by the cloud-free nature of each scene acquired. An automatic cloud cover assessment (ACCA) algorithm was deployed for ascertaining the cloud component of each ETM+ image prior to archiving. The resulting cloud cover assessment scores are subsequently used by mission planners to reschedule failed acquisitions, and by users to filter cloudy scenes from database queries.

Discerning clouds from underlying terrain seems intuitively straightforward. Clouds are white and colder than the land surface they obscure and these properties match up well with the multispectral response characteristics of the ETM+. Cloud and land surface variability, however, creates problems. Wide reflectance and temperature profiles for clouds do occur within and between scenes. A cloud signature that works well for one scene may be ineffective for another. Accurate cloud identification is also affected by surface features (e.g. snow, white sand) that have reflectance signatures that are similar and in some cases identical to clouds in the ETM+ bands.

A scene dependent approach for identifying clouds was developed for Landsat 7 to minimize the effects of cloud variability. The algorithm handles the cloud population in each scene uniquely by examining the image data twice. The first pass through the data is designed to capture clouds and only clouds. Eight different filters are used to isolate clouds and to eliminate cloudless areas and problem land surface features such as snow and sand. The pass one goal is to develop a reliable cloud signature for use in pass two where the remaining clouds are identified.

### 2. EARLIER WORK

The General Electric Corporation built one of the first Landsat 4 and 5 ground processing systems for the U.S. Government. The primary payload of these two satellites is the Thematic Mapper (TM) and the ground system was aptly name the Thematic Mapper Image Processing System (TIPS). The original ACCA algorithm was incorporated as part of TIPS.<sup>1</sup> Processing limitations of early 1980 computers imposed constraints on the TM ACCA algorithm. To reduce computational load, only three bands were examined, and these were sub-sampled by a factor of 16. The original scenes, 6112 samples by 5984 lines in size, were reduced to 382 by 374 images for determining cloud statistics.

## Characterization of the Landsat-7 ETM+ Automated Cloud-Cover Assessment (ACCA) Algorithm

Richard R. Irish, John L. Barker, Samuel N. Goward, and Terry Arvidson

### Abstract

*A scene-average automated cloud-cover assessment (ACCA) algorithm has been used for the Landsat-7 Enhanced Thematic Mapper Plus (ETM+) mission since its launch by NASA in 1999. ACCA assists in scheduling and confirming the acquisition of global "cloud-free" imagery for the U.S. archive. This paper documents the operational ACCA algorithm and validates its performance to a standard error of ±5 percent. Visual assessment of clouds in three-band browse imagery were used for comparison to the five-band ACCA scores from a stratified sample of 212 ETM+ 2001 scenes. This comparison of independent cloud-cover estimators produced a 1:1 correlation with no offset. The largest commission errors were at high altitudes or at low solar illumination where snow was misclassified as clouds. The largest omission errors were associated with undetected optically thin cirrus clouds over water. There were no statistically significant systematic errors in ACCA scores analyzed by latitude, seasonality, or solar elevation angle. Enhancements for additional spectral bands, per-pixel masks, land/water boundaries, topography, shadows, multi-date and multi-sensor imagery were identified for possible use in future ACCA algorithms.*

### Introduction

A primary goal of the Landsat-7 (L7) mission is to populate the U.S.-held Landsat data archive with seasonally refreshed, essentially cloud-free Enhanced Thematic Mapper Plus (ETM+) imagery of the Earth's landmasses. To achieve this goal, the Landsat Project Science Office (LPSO) at NASA's Goddard Space Flight Center (GSFC) developed the Long-Term Acquisition Plan (LTAP): a mission-long imaging strategy designed to optimize the 250 scenes acquired each day by the ETM+ (Arvidson *et al.*, 2001, Arvidson *et al.*, 2006). An optimized scene acquisition has two primary characteristics: a priority for acquisition on that date and a low estimate of cloud contamination. A key element in the LTAP is a 12-month global analysis of vegetation derived from

Advanced Very High Resolution Radiometer (AVHRR) observations using the Normalized Difference Vegetation Index (NDVI) (Goward *et al.*, 1999). Use of the resulting seasonality increases the probability of ETM+ collects during periods of heightened biological activity. Another key element of the LTAP strategy is to use cloud-cover (CC) predictions to reduce cloud contamination in acquired scenes.

In addition to the LTAP, acquisition scheduling by mission planners also requires reliable CC reports for imagery that is already acquired. Therefore, an automated cloud-cover assessment (ACCA) algorithm was created for determining the cloud component of each acquired ETM+ scene. The resulting CC assessment scores are used to monitor LTAP performance and reschedule acquisitions as necessary. The purpose of this paper is to document and evaluate the operational ACCA algorithm and to suggest potential enhancements for future Landsat-type missions.

### Landsat-7 Mission Planning

To predict the probability of clouds in upcoming acquisitions, the L7 LTAP employs historical CC patterns developed by the International Satellite Cloud Climatology Project (ISCCP) and daily predictions provided by NOAA's National Centers for Environmental Prediction (NCEP). Candidate LTAP acquisitions are prioritized according to the forecasted cloud environment normalized against the historical CC average, as well as other system and resource constraints (Arvidson *et al.*, 2006). The priority for a candidate acquisition receives a boost if the forecasted CC is lower than the historical average (Gasch and Campana, 2000). The result of the scheduling process is an imaging schedule for the top 250 (on average) prioritized scenes. A schedule is transmitted to the satellite every 24 hours and forms the basis for operating the ETM+ during its 17 percent maximum daily duty cycle.

These 250 scenes, once acquired, are transmitted to the U.S. Geological Survey's Earth Resources Observation and Science (USGS/EROS) facility in Sioux Falls, South Dakota. The Landsat Processing System (LPS) processes the raw data into radiometrically uncalibrated and geometrically unresampled imagery; generates the associated browse imagery, ACCA scores, and other metadata; and sends the data set to the Landsat Archive Manager (LAM) for storage and eventual distribution.

Photogrammetric Engineering & Remote Sensing  
Vol. 72, No. 10, October 2006, pp. 1179–1188.  
0099-1112/06/7210-1179/\$3.00/0  
© 2006 American Society for Photogrammetry  
and Remote Sensing

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING

October 2006 1179

Note: a per-pixel version of the heritage ACCA has been developed for TM, ETM+, and OLI/TIRS with some refinements (a paper is in draft)



# Projected Cloud Shadows using Solar Geometry

1388

JOURNAL OF ATMOSPHERIC AND OCEANIC TECHNOLOGY

VOLUME 26

## A Geometry-Based Approach to Identifying Cloud Shadows in the VIIRS Cloud Mask Algorithm for NPOESS

KEITH D. HUTCHISON

Center for Space Research, The University of Texas at Austin, Austin, Texas

International Journal of Remote Sensing  
Vol. 31, No. 20, 20 October 2010, 5449–5464



### Automated masking of cloud and cloud shadow for forest change analysis using Landsat images

CHENGQUAN HUANG\*†, NANCY THOMAS†, SAMUEL N. GOWARD†, JEFFREY G. MASEK‡, ZHILIANG ZHU§, JOHN R. G. TOWNSHEND† and JAMES E. VOGELMANN¶

†Department of Geography, University of Maryland, College Park, MD 20742, USA

‡Biospheric Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

§US Geological Survey, 12201 Sunrise Valley Drive, Reston, VA 20771, USA

¶USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, USA

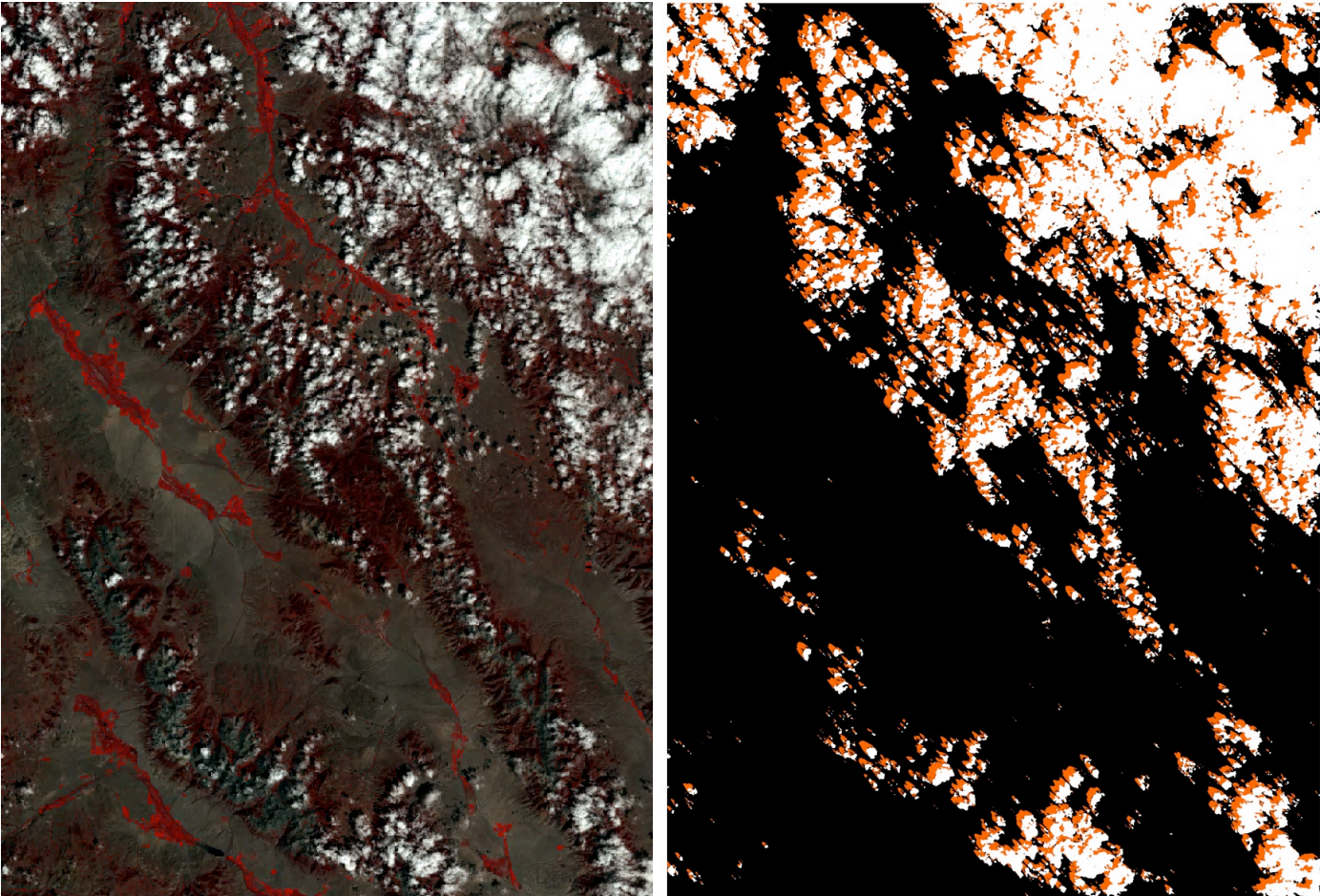
(Received 8 April 2009; in final form 6 August 2009)

Accurate masking of cloud and cloud shadow is a prerequisite for reliable mapping of land surface attributes. Cloud contamination is particularly a problem for land cover change analysis, because unflagged clouds may be mapped as false changes, and the level of such false changes can be comparable to or many times more than that of actual changes, even for images with small percentages of cloud cover. Here we develop an algorithm for automatically flagging clouds and their shadows in Landsat images. This algorithm uses clear view forest pixels as a reference to define cloud boundaries for separating cloud from clear view surfaces in a spectral-temperature space. Shadow locations are predicted according to cloud height estimates and sun illumination geometry, and actual shadow pixels are identified by searching the darkest pixels surrounding the predicted shadow locations. This algorithm produced omission errors of around 1% for the cloud class, although the errors were higher for an image that had very low cloud cover and one acquired in a semiarid environment. While higher values were reported for other error measures, most of the errors were found around the edges of detected clouds and shadows, and many were due to difficulties in flagging thin clouds and the shadow cast by them, both by the developed algorithm and by the image analyst in deriving the reference data. We concluded that this algorithm is especially suitable for forest change analysis, because the commission and omission errors of the derived masks are not likely to significantly bias change analysis results.

#### 1. Introduction

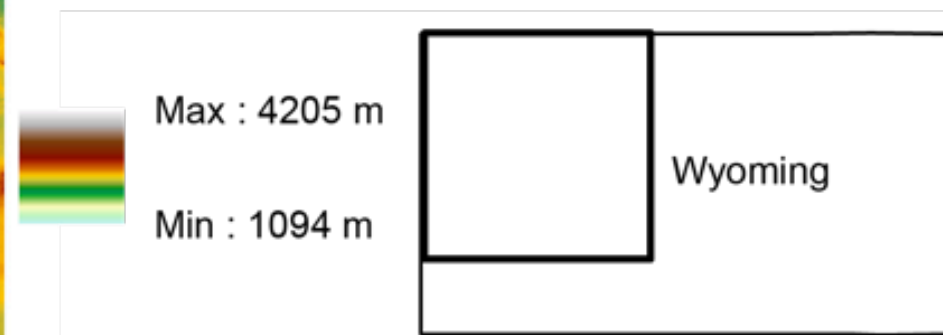
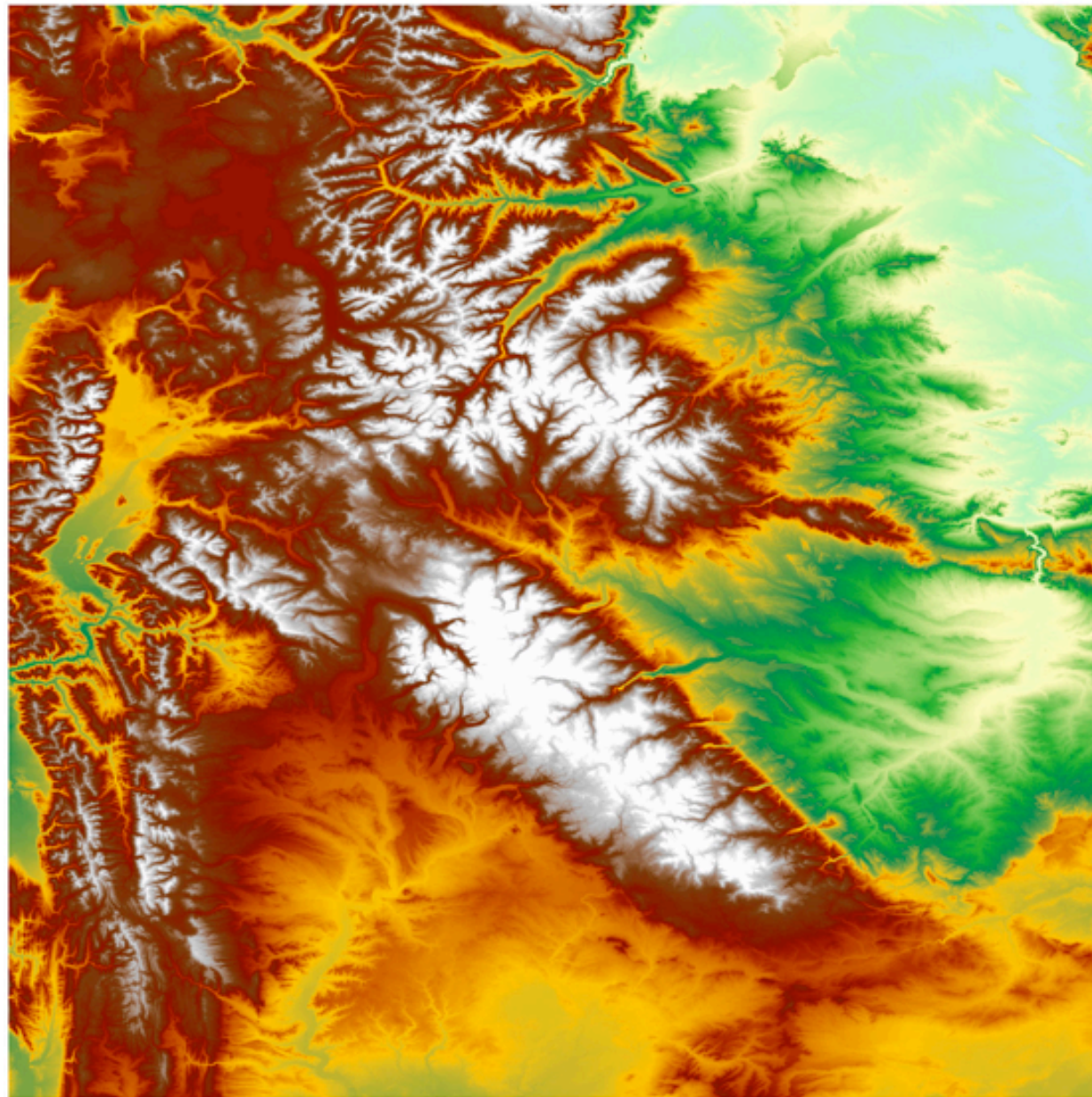
The usefulness of optical remote sensing images for land surface studies is often hindered by the presence of cloud and shadow. Little or no information of the surface can be derived from observations contaminated by cloud or shadow. To minimize the impact of such contaminations, cloud-free images are often preferred over cloudy images in land remote sensing applications. For areas that suffer constant cloudy conditions, however, cloud-free images are not always available. This problem is

\*Corresponding author. Email: cqhuang@umd.edu





# Western Wyoming Study Region

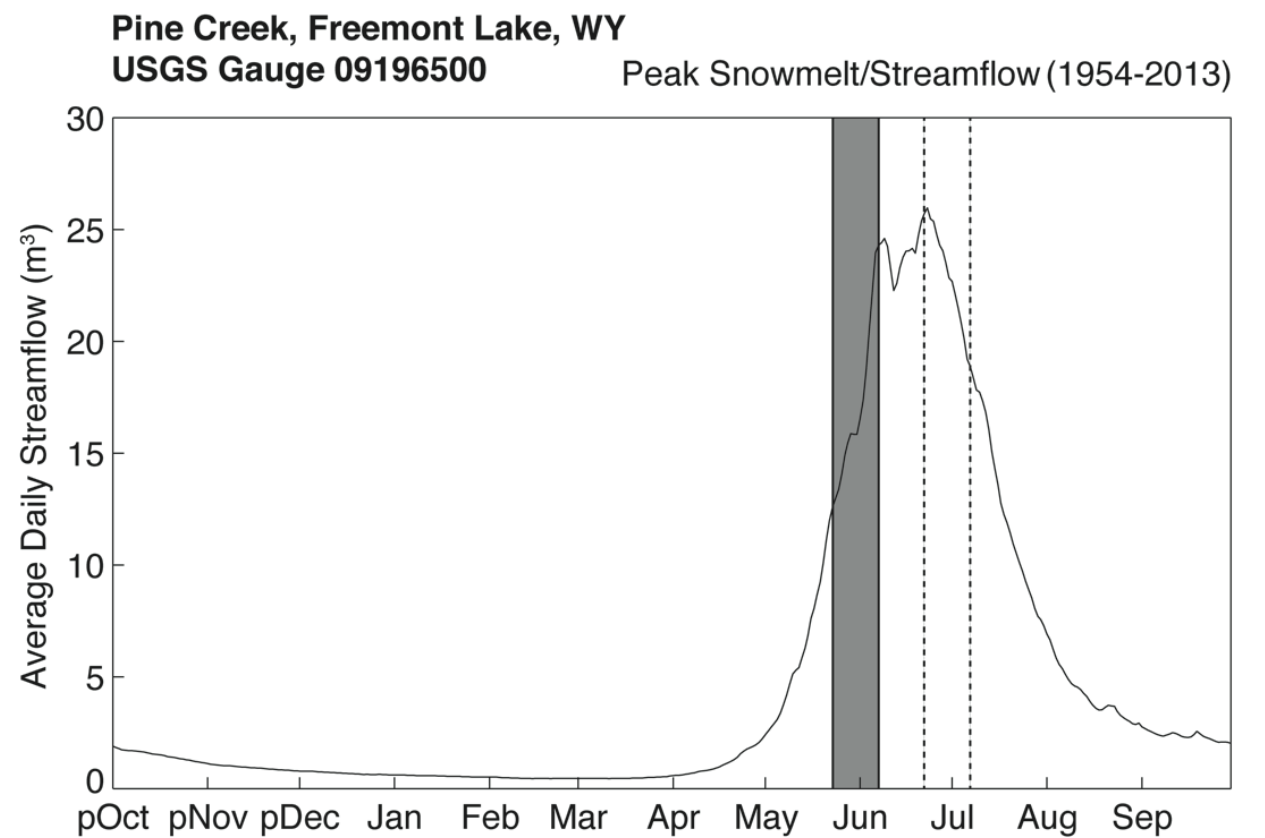
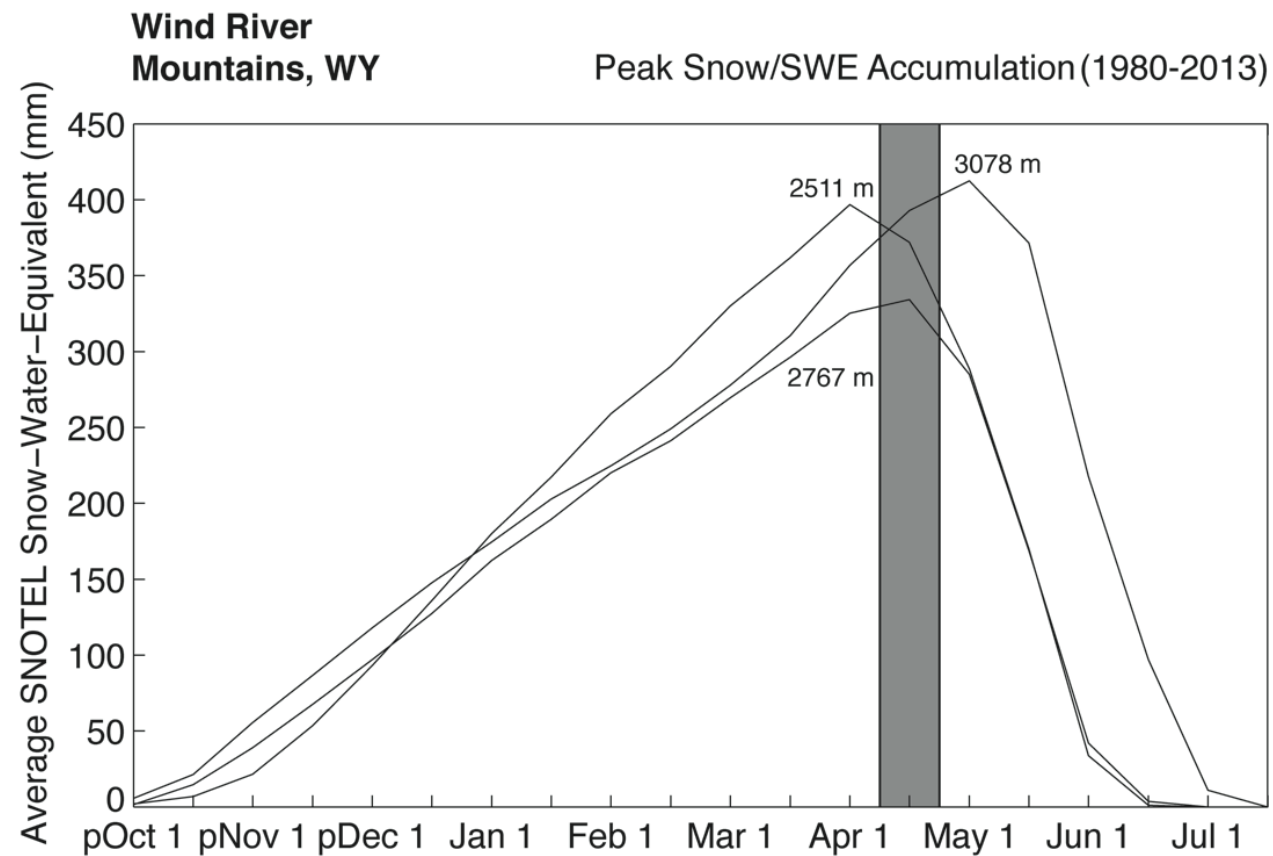


Temporal Scale: Julian peak snow accumulation (98-112) and melt (143-158) intervals from 2000-2014

365 image samples from TM, ETM+ and OLI/TIRS



# Peak Snow Accumulation and Melt Intervals for Western Wyoming, USA



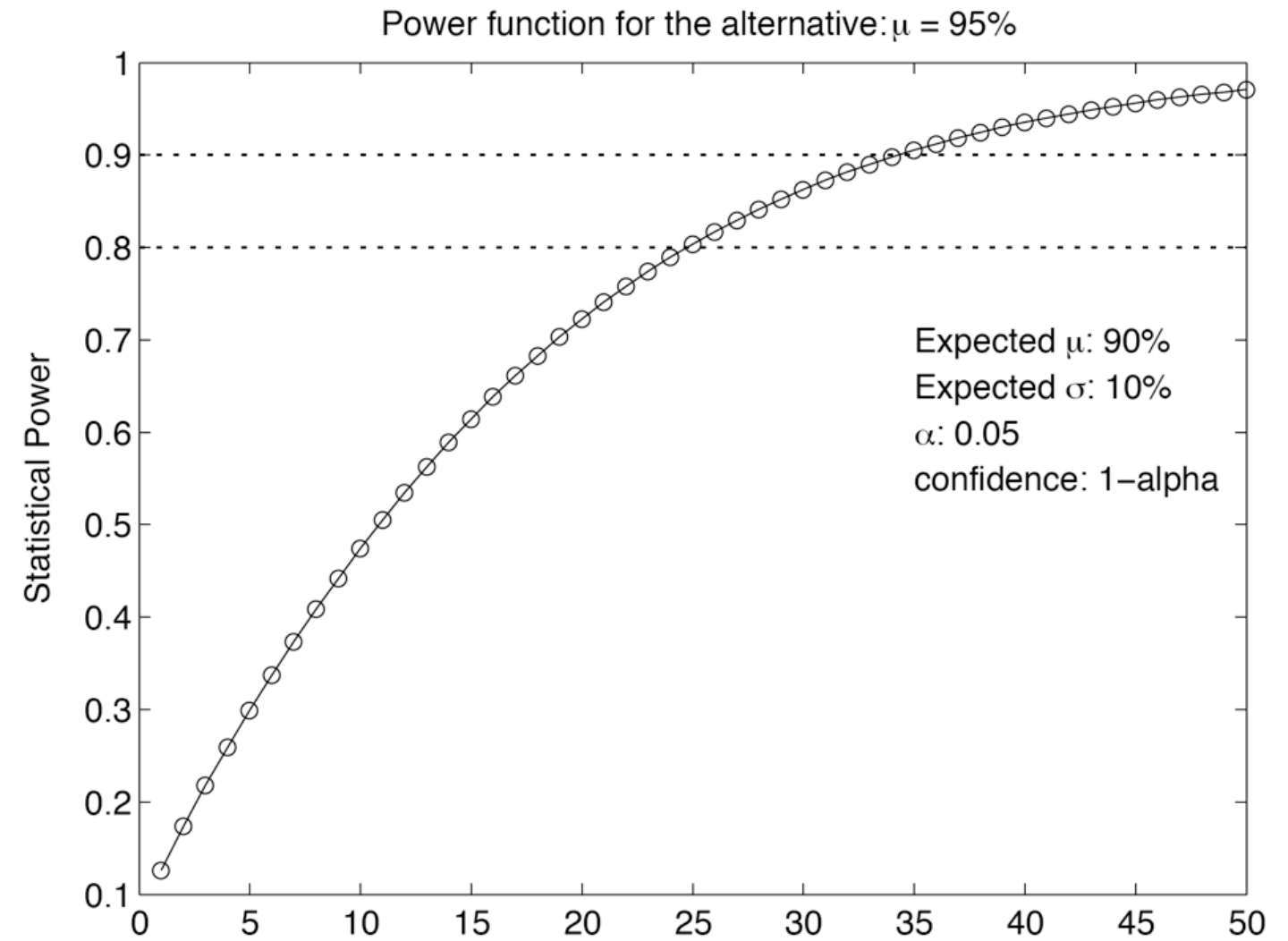
# Method: Cloud/Shadow Accuracy Assessment

## Heritage ACCA Population Sample

## Thematic Sample Size: Binomial Probability Theory

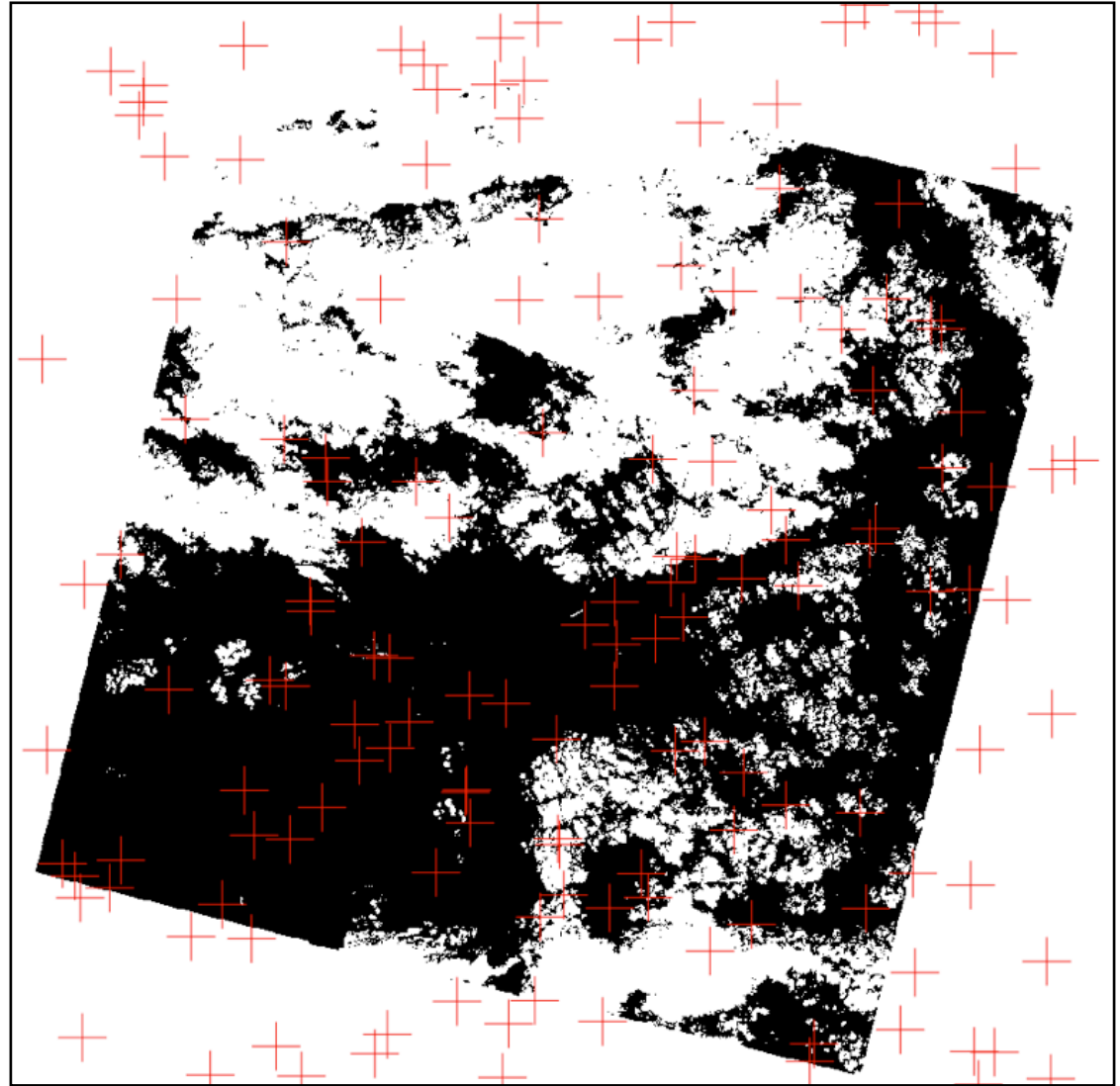
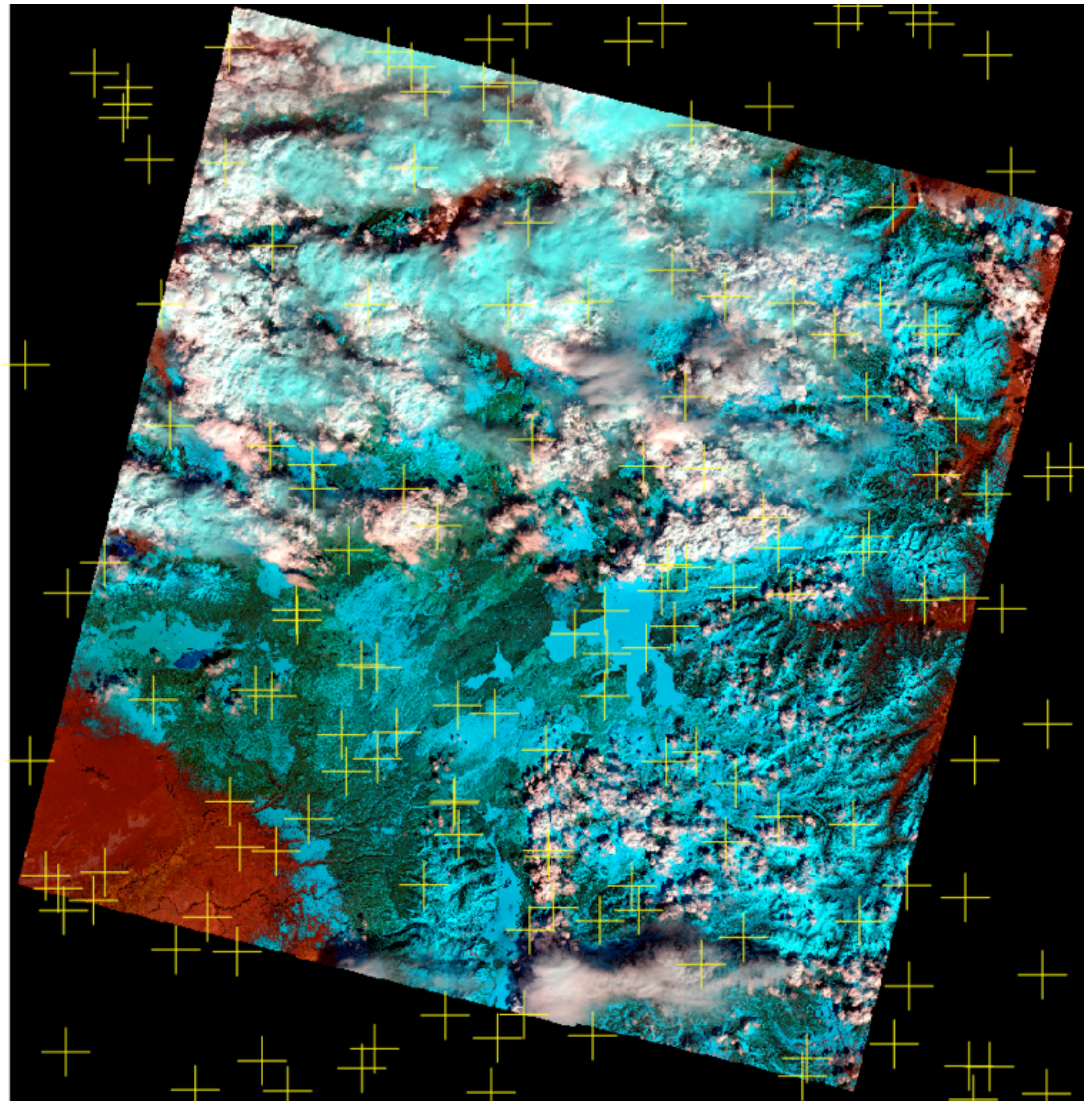
$$N = \frac{Z^2(p)(q)}{E^2} = \frac{1.96^2(90)(10)}{10^2} = 35 \text{ samples}$$

Z: standard normal deviate  
p: expected map accuracy  
q: 100-p  
E: allowable error





# Error Matrix: Visual Interpretation vs. ACCA

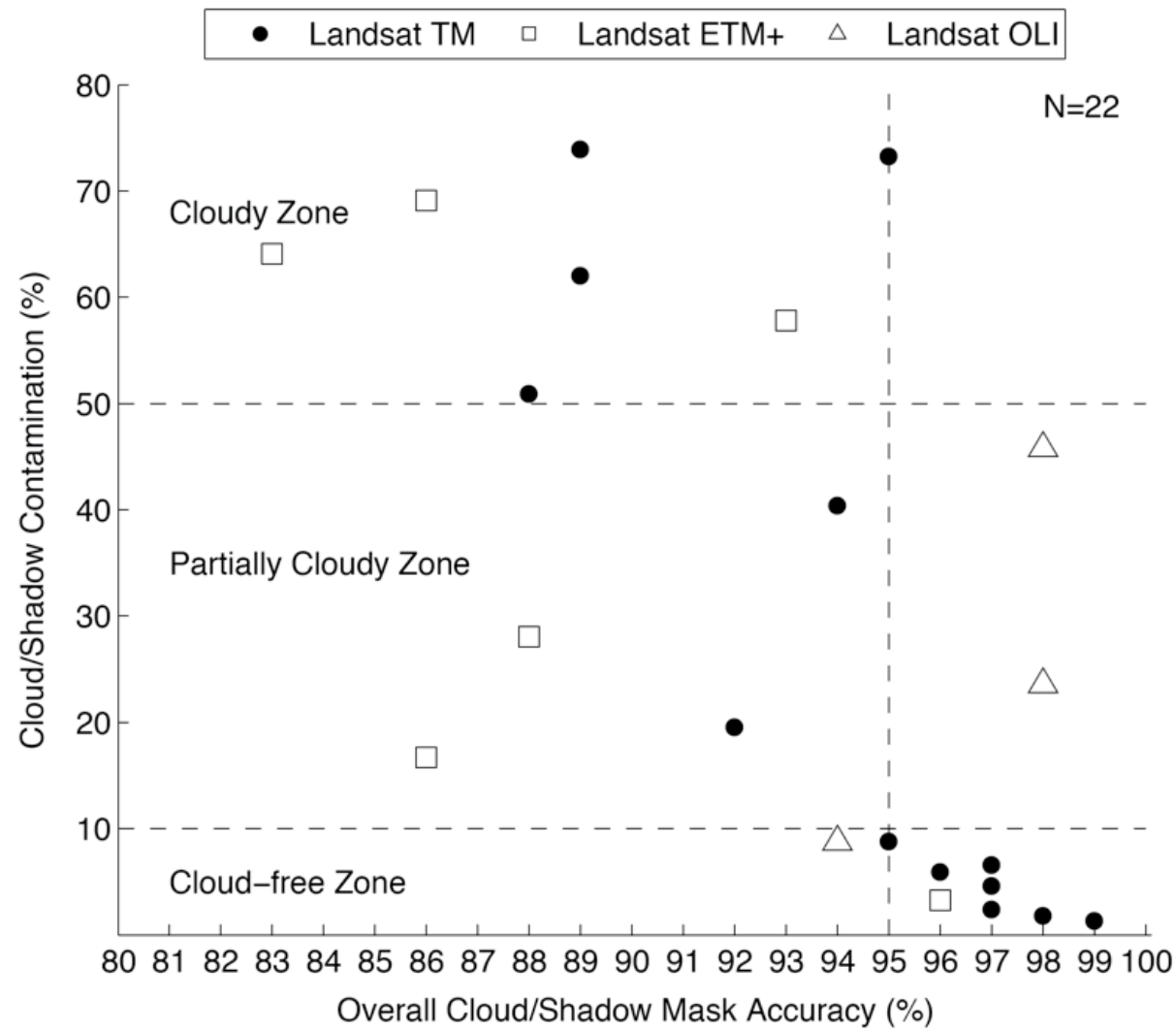


## Class Assignments

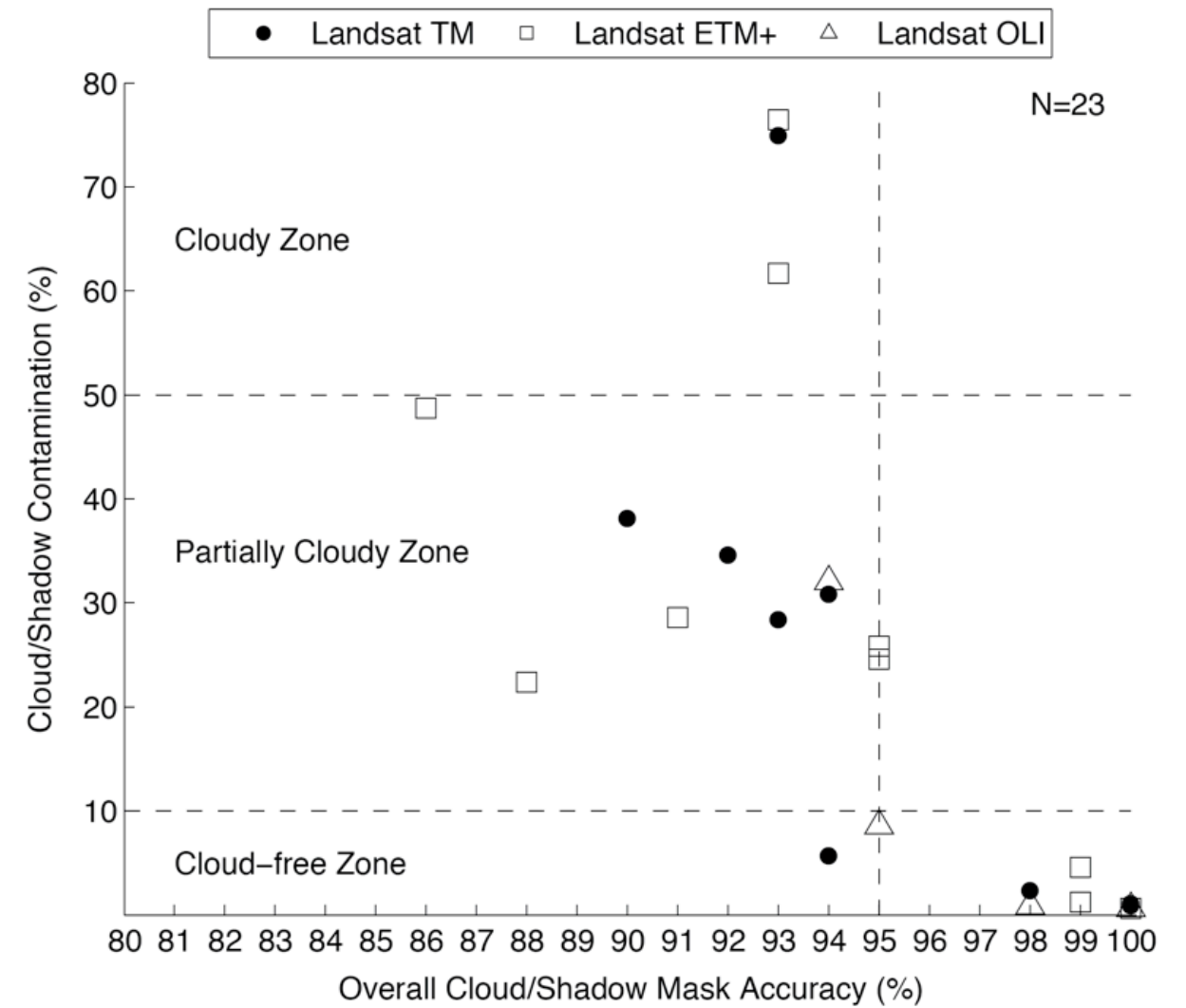
Cloud/Shadow-Free Pixels: Snow Surface (**SS**) or Snow-Free Land (**SFL**)

Cloud/Shadow Pixels: Cloud over Snow-Free Land (**CSFL**), Cloud Edge over Snow-Free Land (**CESFL**), Cloud over Snow Surface (**CSS**), Cloud Edge over Snow Surface (**CESS**), Shadow over Snow-Free Land (**SSFL**), and Shadow Edge over Snow-Free Land (**SESFL**)

# Peak Snow Accumulation



# Peak Snowmelt





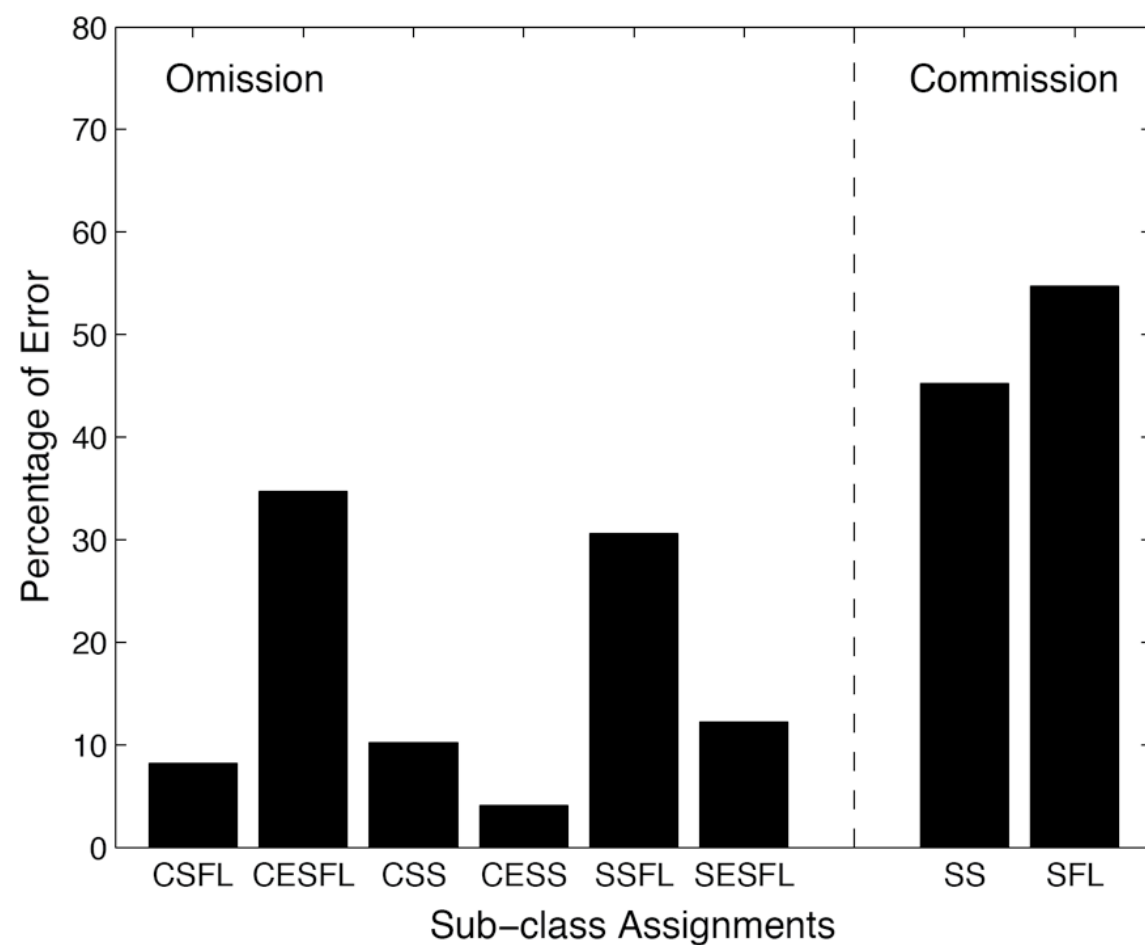
## Peak Snow Accumulation

Heritage ACCA	Visual Reference Images (N=22)			
	Cloud/Shadow-free	Cloud/Shadow		User Accuracy
	Cloud/Shadow-free	1436	49	1485
	Cloud/Shadow	95	563	658
		1531	612	1999
	Producer Accuracy	<b>0.94</b>	<b>0.92</b>	<b>0.93</b>

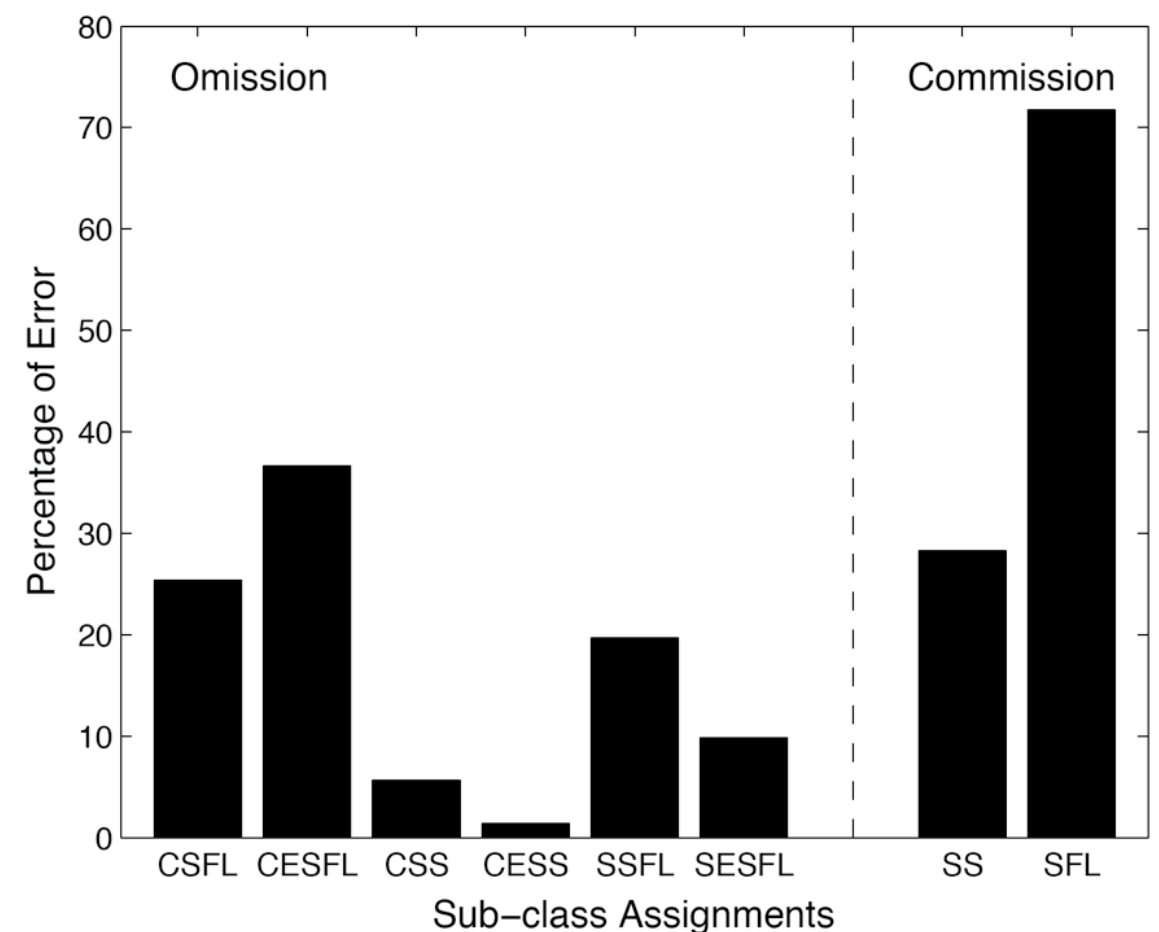
## Peak Snowmelt

Heritage ACCA	Visual Reference Images (N=23)			
	Cloud/Shadow-free	Cloud/Shadow		User Accuracy
	Cloud/Shadow-free	1708	71	1779
	Cloud/Shadow	46	506	552
		1754	577	2214
	Producer Accuracy	<b>0.97</b>	<b>0.88</b>	<b>0.95</b>

## Error Distribution



## Error Distribution



**Objective #2** Determine the importance of topographic normalization for Landsat TM, ETM+, and OLI/TIRS images during snowmelt



# Topographic Normalization for Local Solar Illumination

J. A. SMITH  
TZEU LIE LIN  
K. J. RANSOM  
College of Forestry and Natural Resources  
Colorado State University  
Fort Collins, CO 80523

## The Lambertian Assumption and Landsat Data

The Lambertian assumption is often used when analysis is required for varying illumination angles.

INTRODUCTION  
THE LANDSAT SENSOR requires imagery over a wide range of data acquisition times.

ABSTRACT:

## ON THE SLOPE-ASPECT CORRECTION OF MULTISPECTRAL SCANNER DATA

by P.M. Teillet, B. Guindon and D.G. Goodenough

Canada Centre for Remote Sensing

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 28, NO. 5, SEPTEMBER 1990

963

## Rapid Calculation of Terrain Parameters For Radiation Modeling From Digital Elevation Data

JEFF DOZIER, ASSOCIATE, IEEE, AND JAMES FREW, MEMBER, IEEE

**Abstract**—Digital elevation models are not terrain parameters to determine incoming radiation for use in surface climate models, interpolation, and parameters in hydrologic models. Interpolation of points in an elevation grid, fast algorithm computation time. We describe rapid method azimuth, solar illumination angle, horizon, radiation from sky and terrain. Calculation of algorithms and lookup tables.

### I. USE OF DIGITAL ELEVATION MODEL CALCULATIONS

IN ALL but very gentle terrain, significant variations in the surface climate and in remote sensing results from local topographic effects. Factors to this variation are solar and lunar radiation, although there are also variations in wind speed and soil moisture. Topographic effects on solar irradiance are illumination angle and shadowing from the thermal part of the electromagnetic emission from surrounding slopes and bottoms to receive more thermal radiation in structured areas. Problems in calculating mountainous areas have been addressed in the last two decades [1], [2].

Most radiation calculations over the terrain are aided by digital elevation grids, which are represented by a matrix. In the United States, they are available as Digital Elevation Models from the U.S. Geological Survey [3]. The grids for the entire U.S. are available at 63.5 m (0.01 in. at map scale) quadrangles are available at 30-m commercial firms sell software which

Manuscript received October 8, 1989. This work was supported by NASA. J. Dozier is with the Center for Remote Sensing, University of California, Santa Barbara, CA 93106, and with the University Space Research Association, NASA Johnson Space Flight Center, Greenbelt, MD 20771. J. Frew is with the Center for Remote Sensing, University of California, Santa Barbara, CA 93106. IEEE Log Number 9035826.

0

Authorized licensed use limited to: University of Minnesota.

Peter Meyer<sup>1,\*</sup>, Klaus I. Itten<sup>1</sup>, Tobias Kellenberger<sup>1</sup>, Stefan Sandmeier<sup>1</sup> and Ruth Sandmeier<sup>1</sup>

## Radiometric corrections of topographically induced effects on Landsat TM data in an alpine environment

Four radiometric correction methods for the reduction of slope-aspect effects in a Landsat TM data set are tested in a mountainous test site with regard to their physical soundness and their influence on forest classification, as well as on the visual appearance of the scene. Excellent ground reference information and a fine-resolution DEM allowed precise assessment of the applicability of the methods under investigation. The results of the study presented here demonstrate the weakness of the classical cosine correction method for radiometric correction in rugged terrain. The statistical, Minnaert and C-correction approaches, however, yielded an improvement of the forest classification and an impressive reduction of the visual topography effect.

### 1. Introduction

The overutilization of tropical forests as well as the problems of deterioration of the health of forests in mid latitudes, have warned mankind that an important ecological factor, i.e., an important natural resource is endangered and may not be so renewable as was anticipated. In recent years, much emphasis was laid on the mapping and inventorying of forests and forest damage. On a local level, colour-infrared air photographs have been used with great success, and on larger scales, be they regional, continental or even global, satellite studies show quite encouraging results.

In this study the feasibility of Landsat TM forest classifications in an alpine environment is tested versus excellent ground reference data. It has been shown in the past that terrain-induced illumination variations have hindered an easy and straightforward solution of the distinction of forests versus non-forest backgrounds, and also to separate a forest into its major classes. Four methods to correct the impact of illumination have been tested in order to improve the accuracy of forest classifications. Since a correction of the at-

mospheric effects based on 5S (Tanré et al., 1986) did not result in a significant improvement of the forest classification (Leu, 1991), no atmospheric correction was applied in this study.

### 2. Basis of the study

#### 2.1. Selection of test sites and associated ground reference data

The base dataset consists of a 7-band TM scene (194-27) of 3 July, 1985. Fall, winter or spring imagery is not suited for forest classification due to the lower sun angles which cast shadows, and the fact that the foliage of the various forest types is not fully developed. Within the selected cloud-free scene, the "Beckenried" site was selected, situated in the mountainous pre-Alps of the Canton of Nidwalden in Central Switzerland. The terrain elevation in the 12.0 km by 17.5 km test site varies from 434 to 2404 m with pronounced steep slopes.

For this test site the green plates, containing the class forest, of the 1:50,000 Swiss Federal Office topographic maps were scanned. Additionally, maps of forest stands were digitized which had been generated by the Swiss Sanasilva Project using colour-infrared air photographs at a scale of 1:10,000 and flown on 25 July, 1985 (353 ha) and 13 August, 1987 (572 ha). Thus, well timed ground reference information was available, which in part

<sup>1</sup> Remote Sensing Laboratories, Department of Geography, University of Zurich—Irchel CH-8057 Zurich, Switzerland.

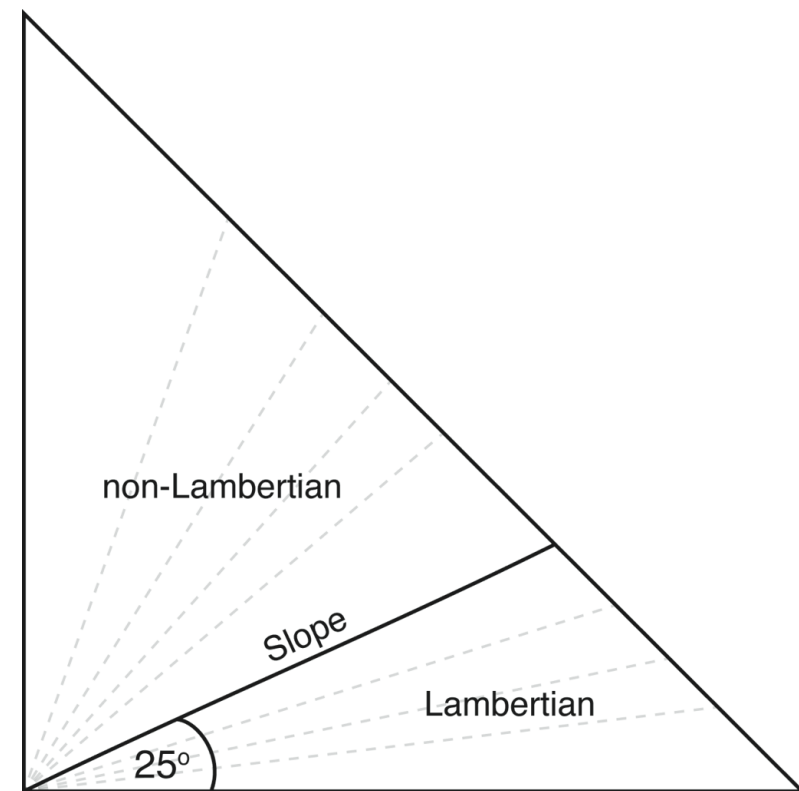
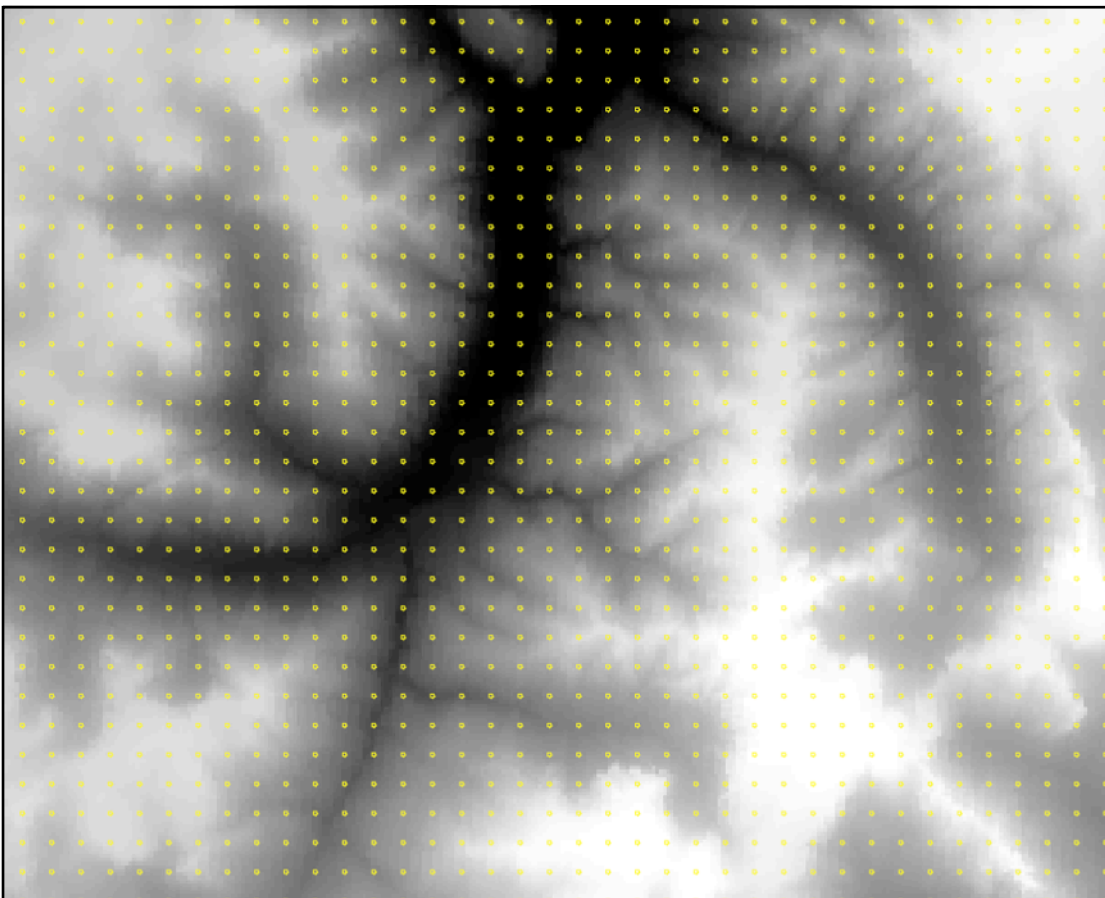
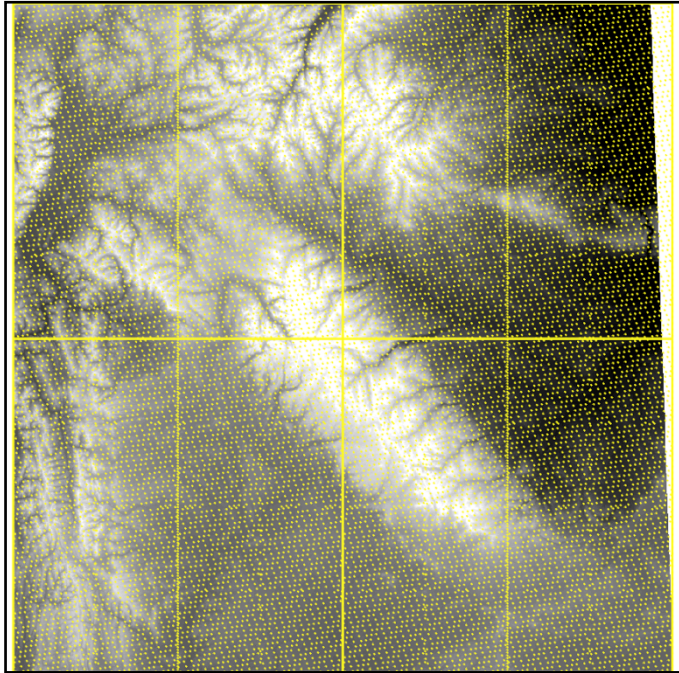
\* Present address: Jet Propulsion Laboratory, California Institute of Technology, MS 169-315, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.



photo: christopher j. crawford



# Method: Sample Size / Minnaerts Correction



$$L_H = L_T * \frac{\cos(sz)^k}{\cos(i)}$$

$L_H$ : path radiance for horizontal surface

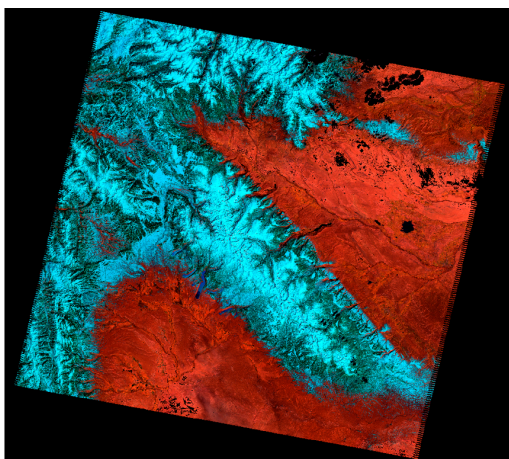
$L_T$ : path radiance over sloped terrain

$\cos(sz)$ : sun's zenith angle

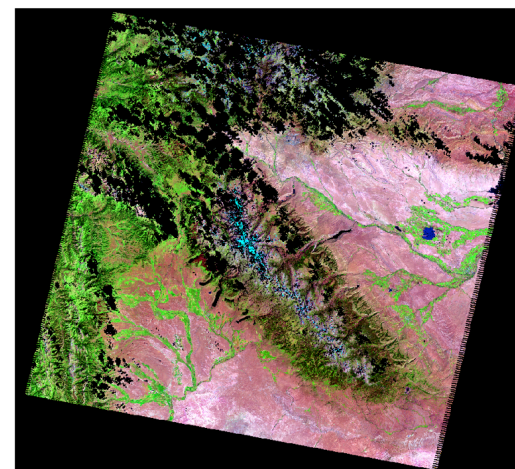
$\cos(i)$ : sun's incidence angle



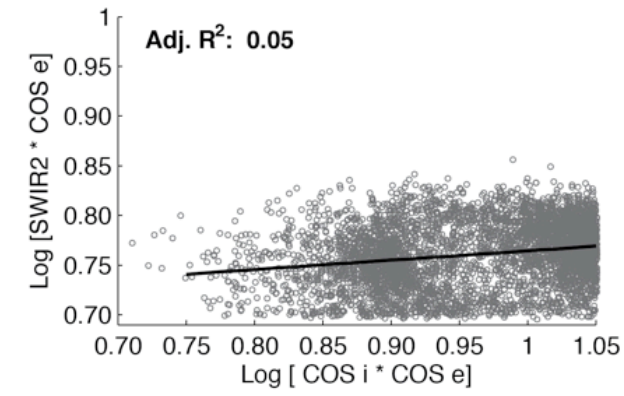
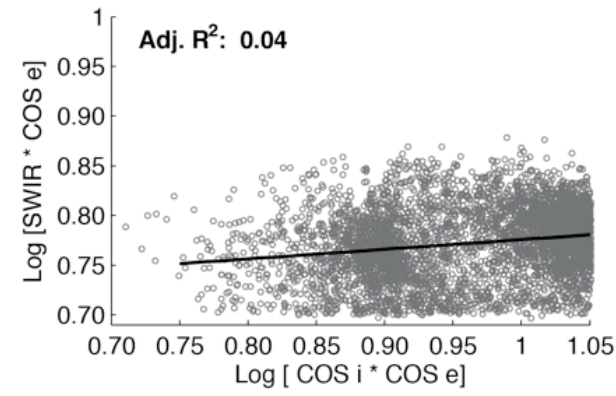
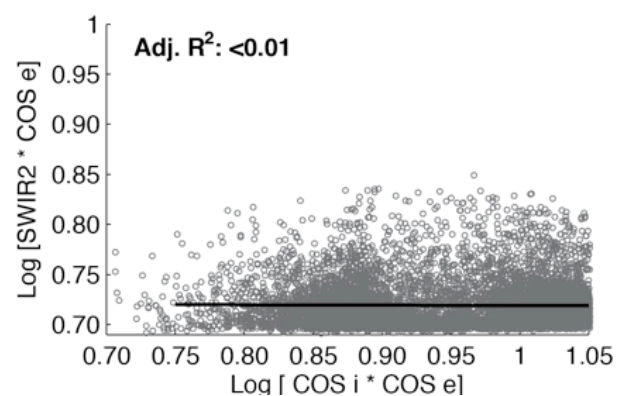
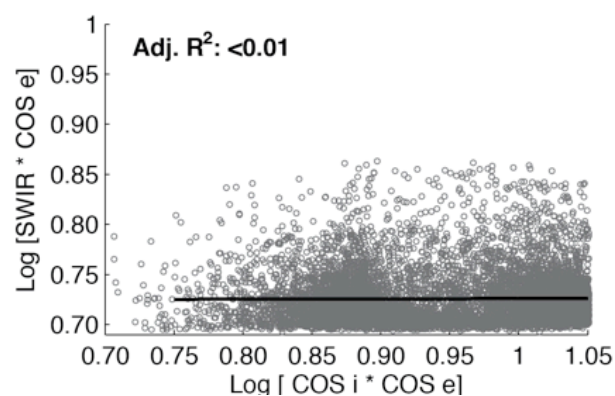
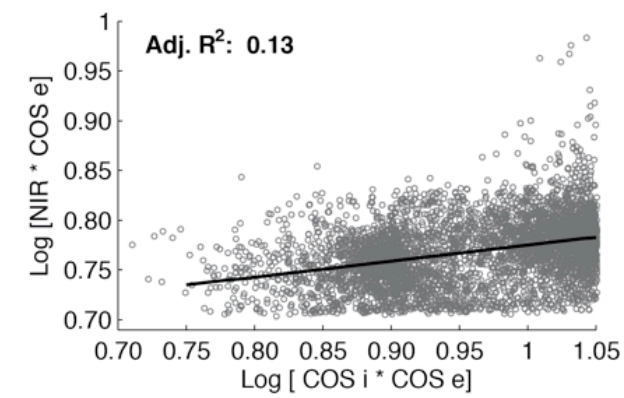
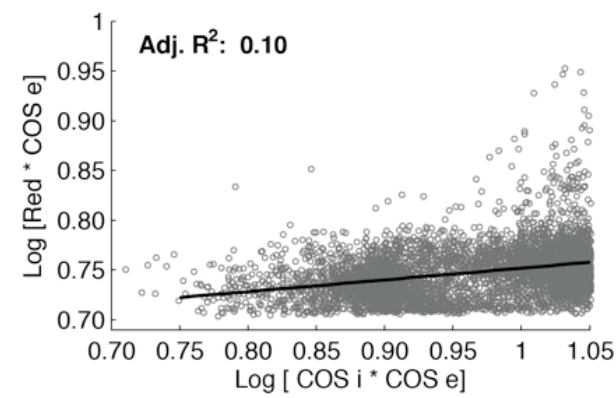
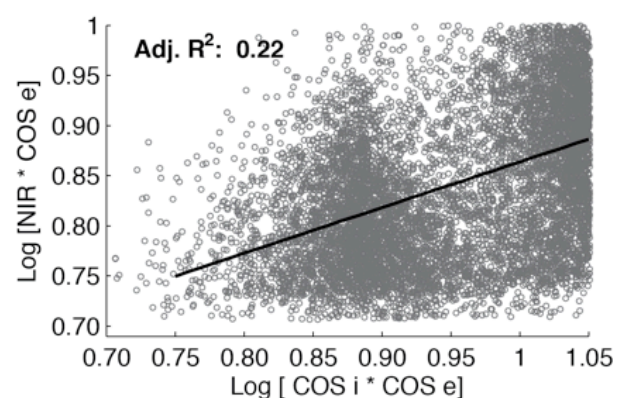
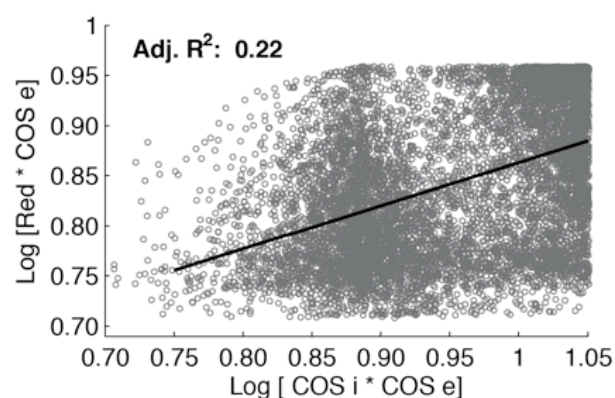
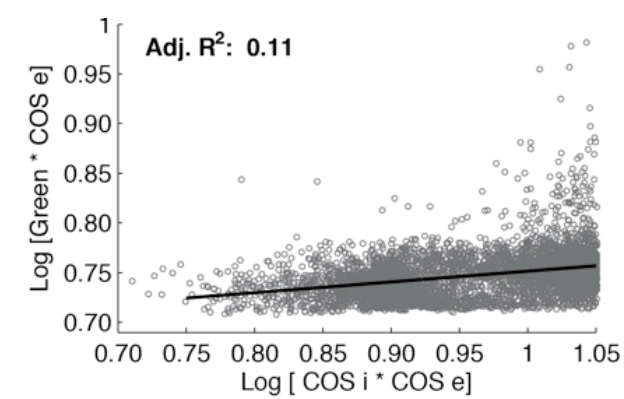
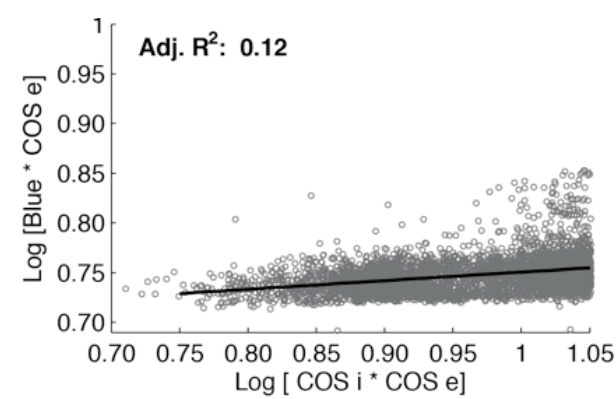
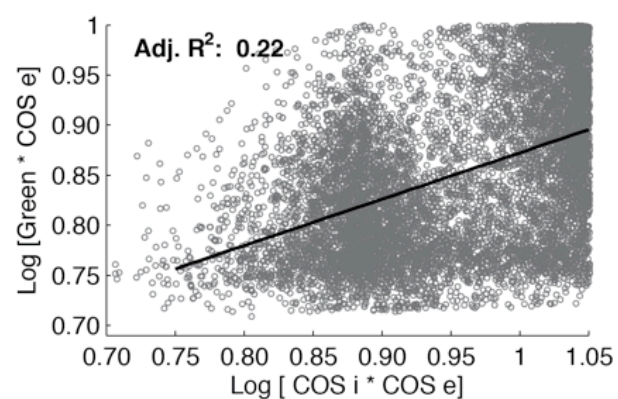
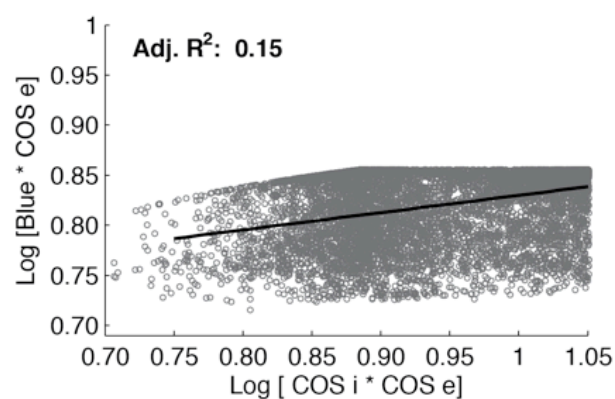
# Landsat TM and the Lambertian Assumption



April 20, 2009  
snow-on



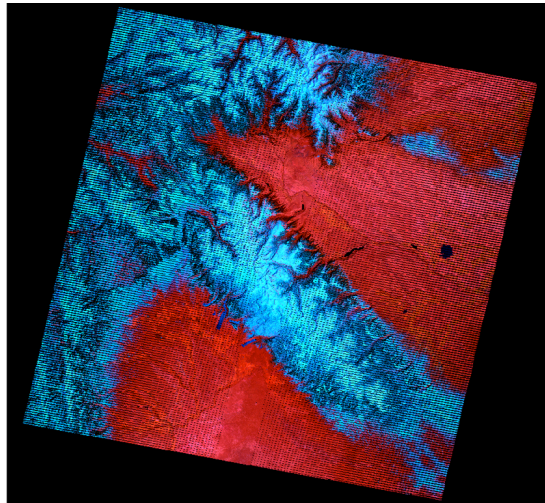
August 10, 2009  
snow-off



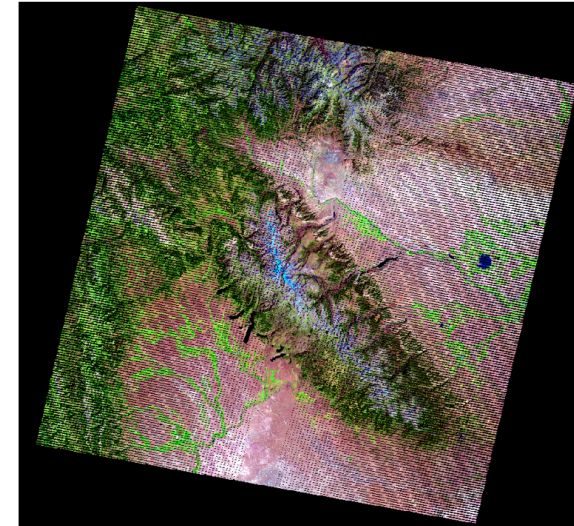
snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP I)



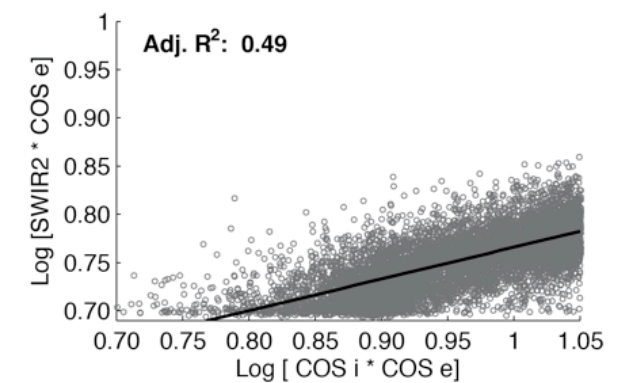
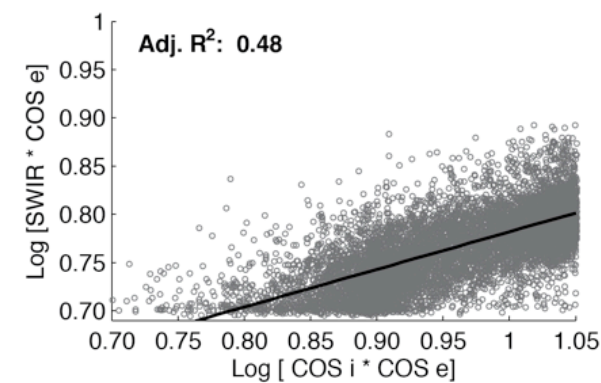
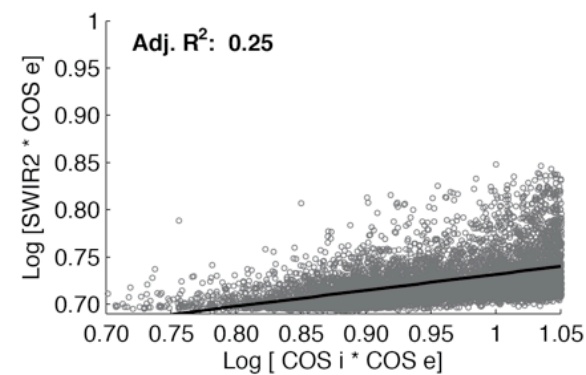
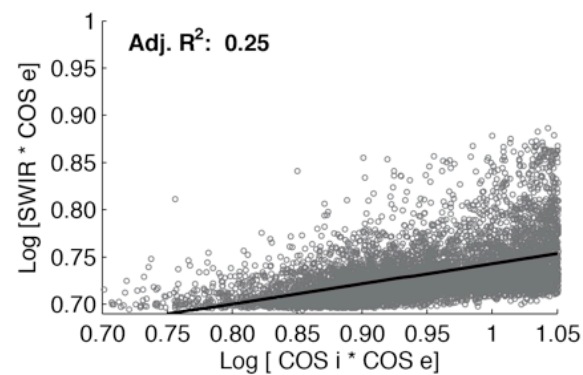
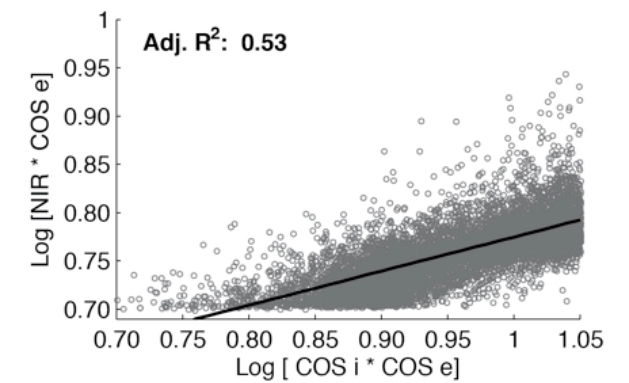
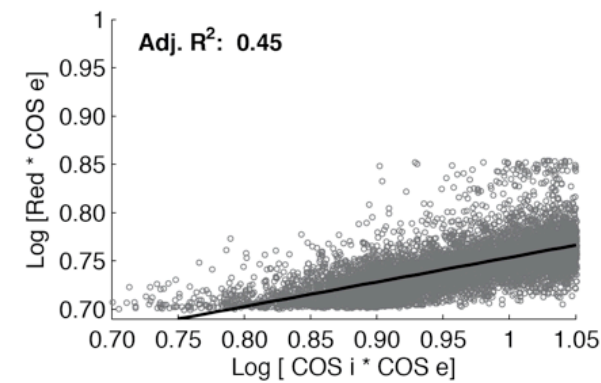
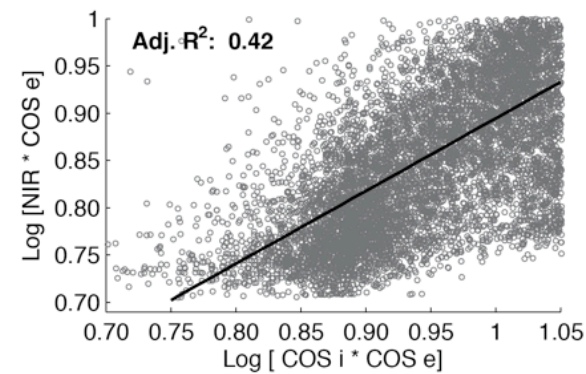
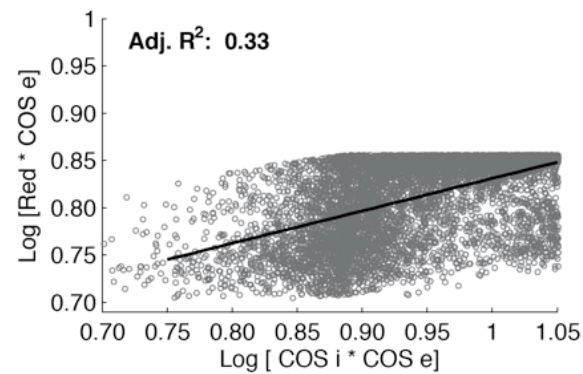
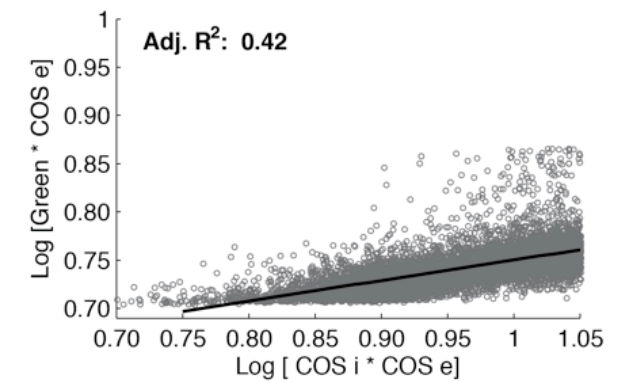
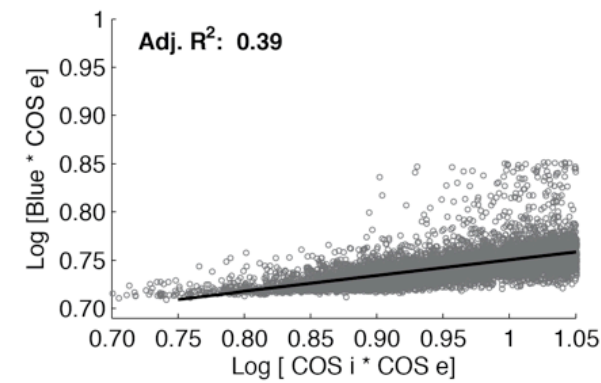
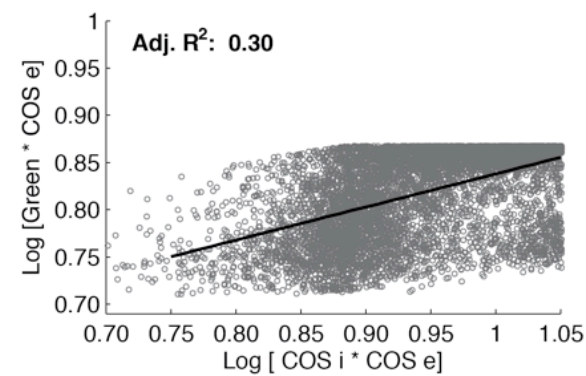
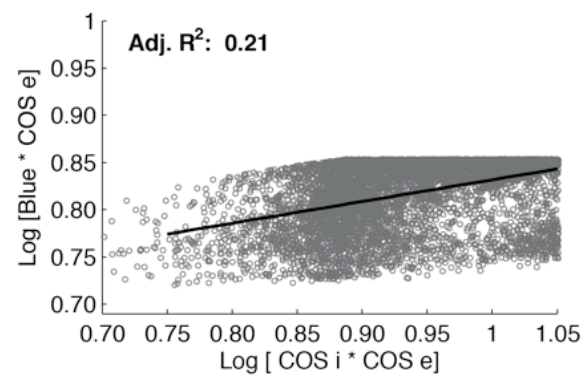
# Landsat ETM+ and the Lambertian Assumption



April 10, 2009  
snow-on

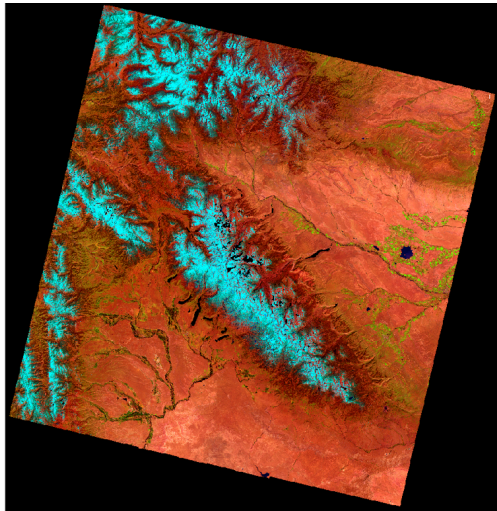


August 10, 2009  
snow-off

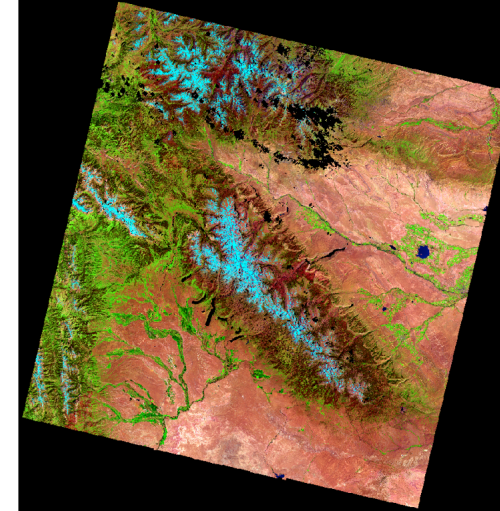




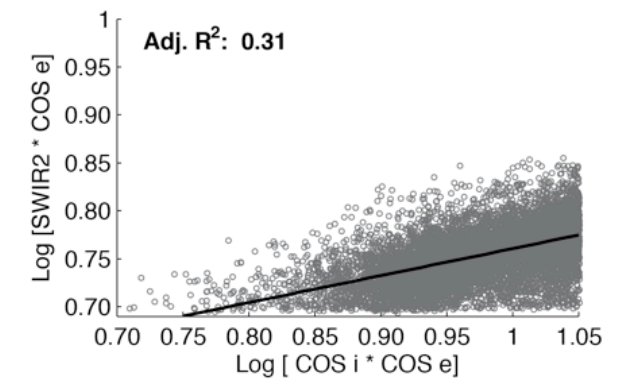
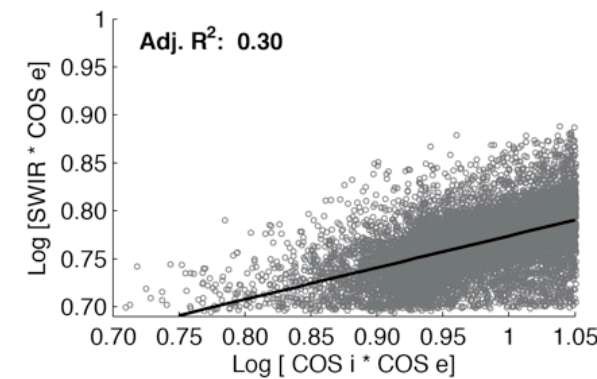
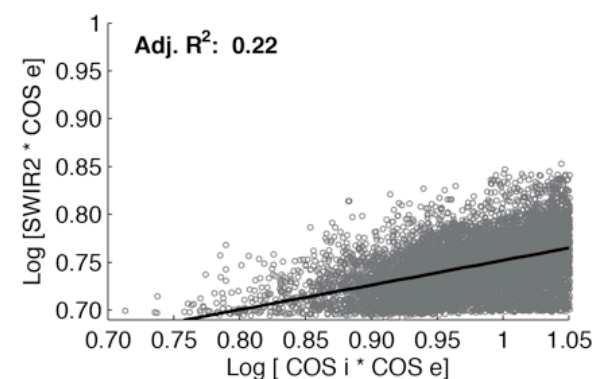
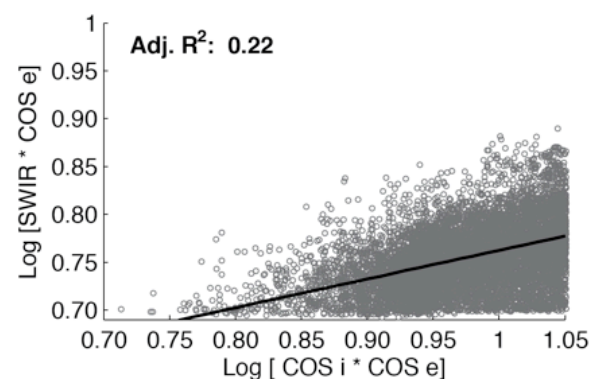
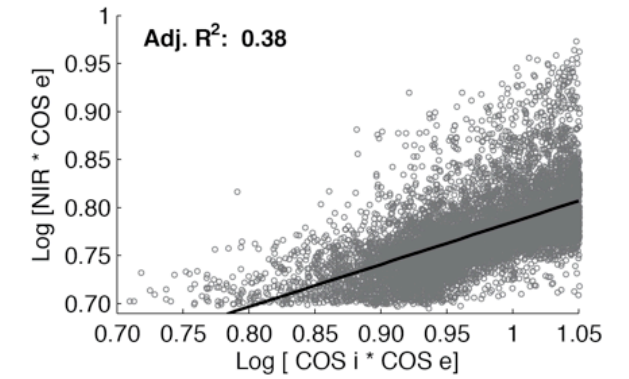
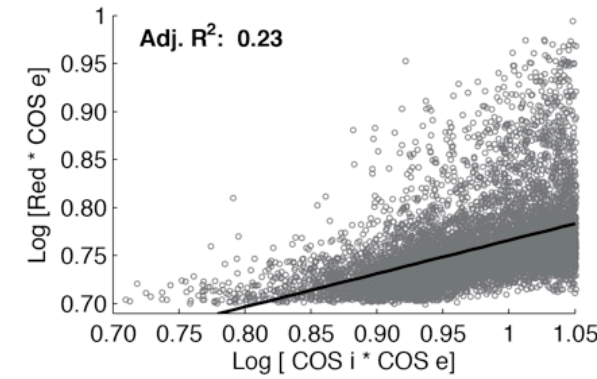
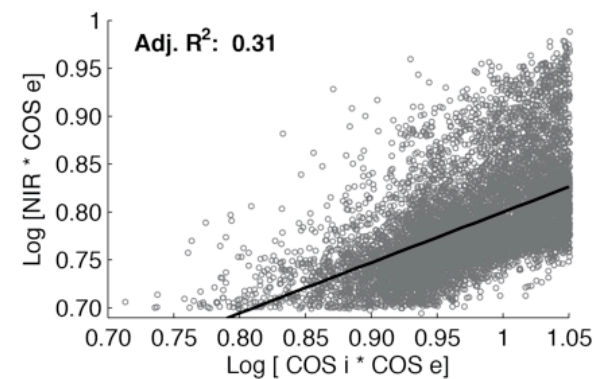
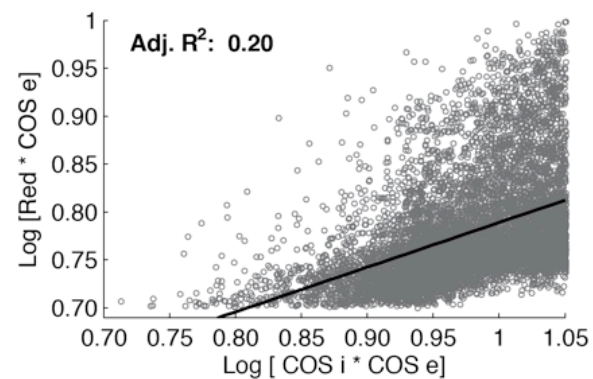
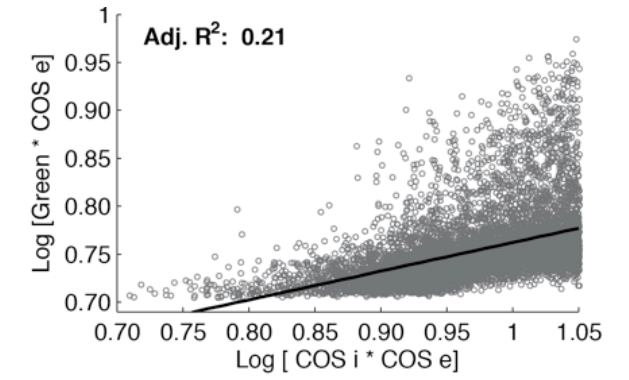
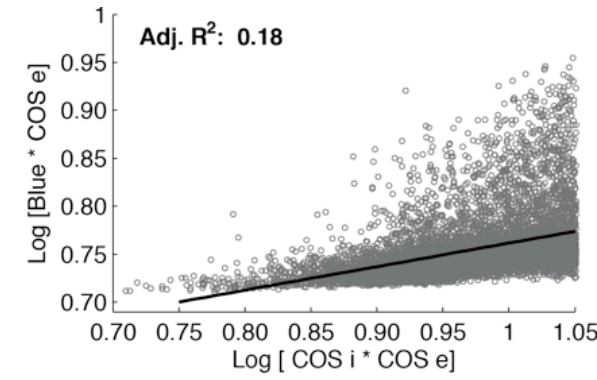
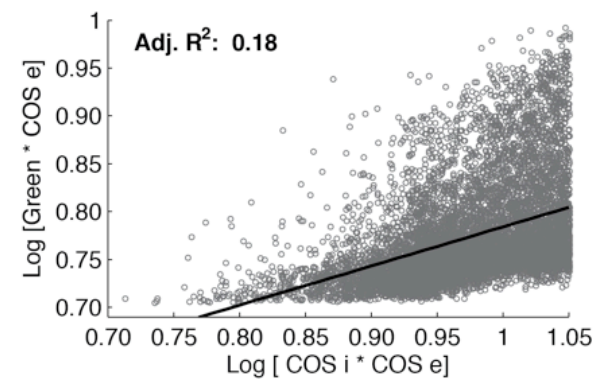
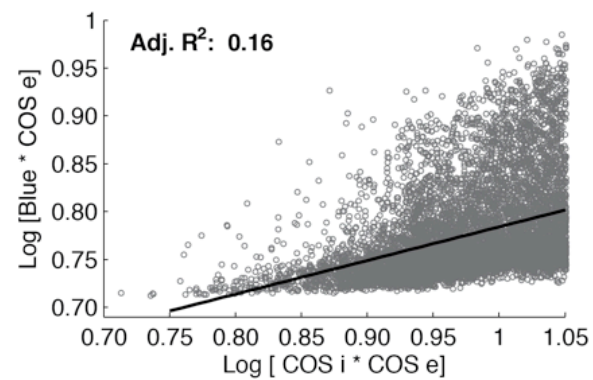
# Landsat OLI and the Lambertian Assumption



June 4, 2014  
snowmelt



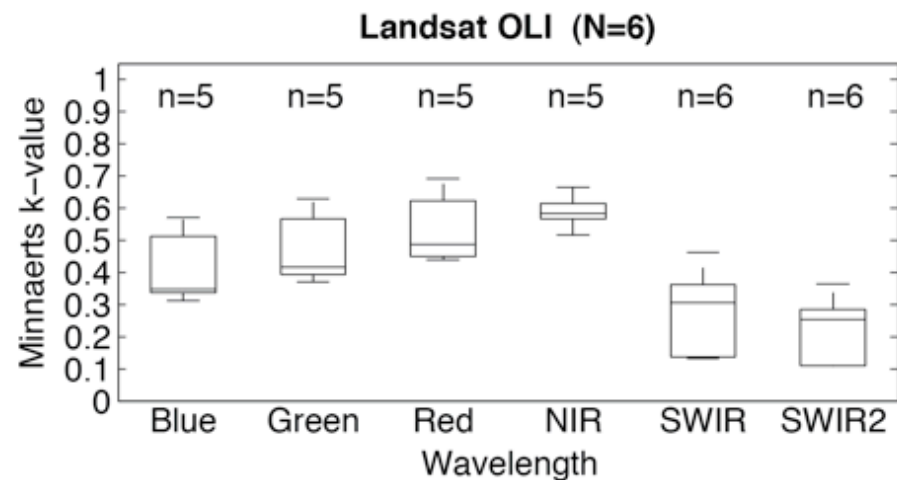
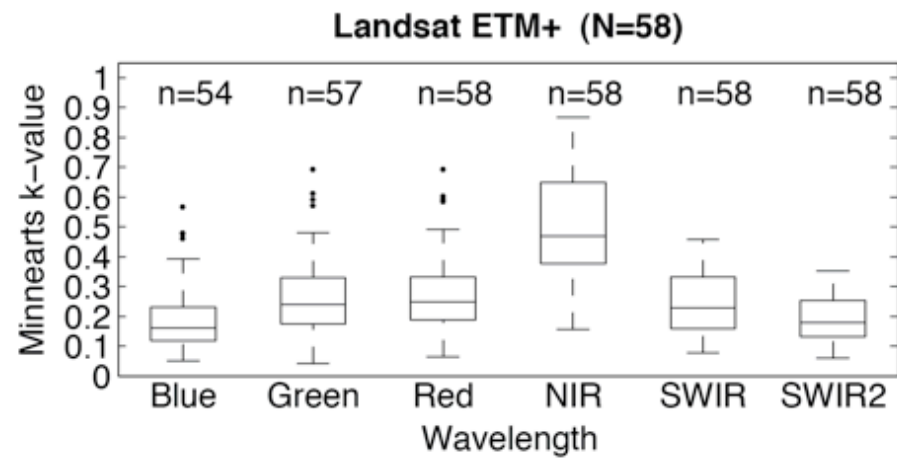
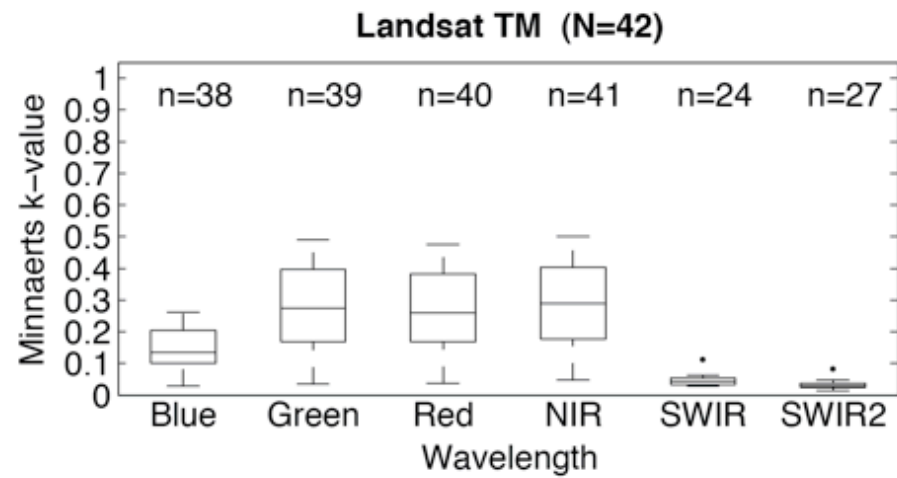
July 7, 2014  
snowmelt



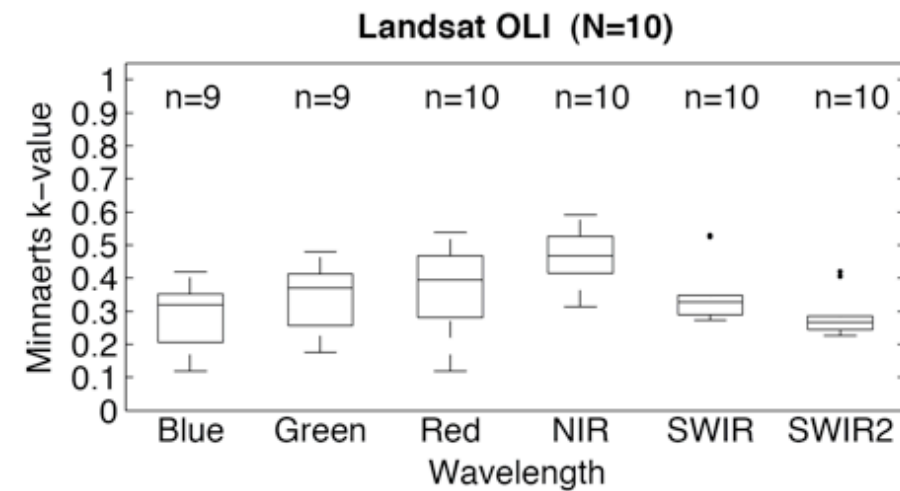
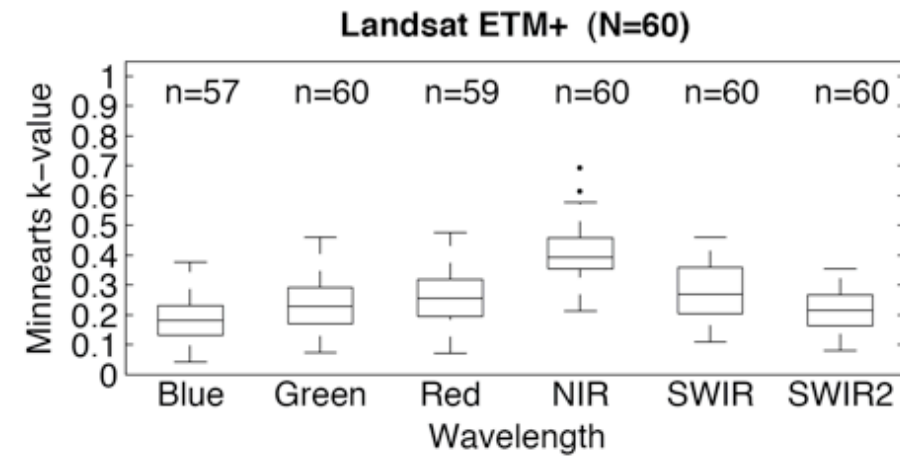
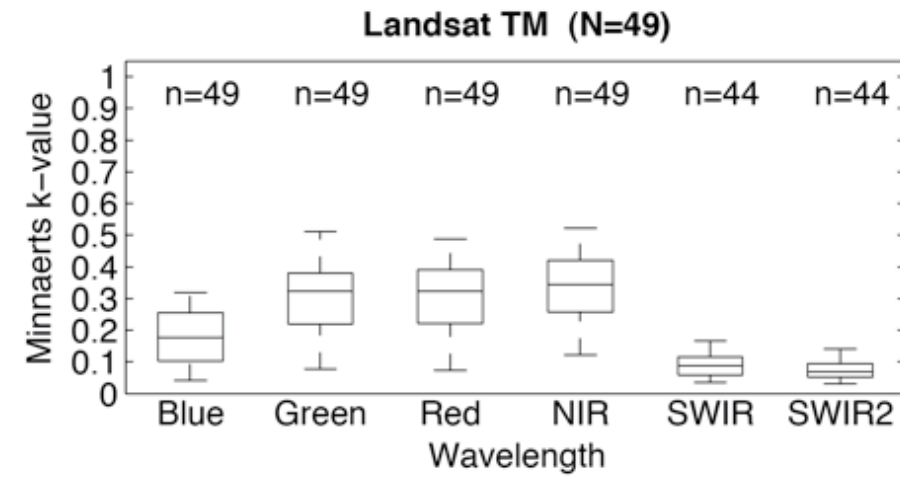
snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP I)

# Wavelength-Dependent Response by Sensor

## Peak Snow Accumulation



## Peak Snowmelt





# Summary and Way Forward

- \* Cloud/cloud shadow omission and commission errors are seasonally dependent and reflect the limits of observation over changing heterogeneous surfaces
- \* Topographic-induced effects on local solar illumination cannot be ignored for higher resolution sensors that exhibit wavelength-dependent responses
- \* Evaluate pixel and sub-pixel snow algorithm performance under partially cloudy conditions



*photo: christopher j. crawford*

*snowpex 1<sup>st</sup> International Satellite Snow Intercomparison Workshop (ISSP I)*