Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) Algorithm Description

Open-File Report 2013–1057

U.S. Department of the Interior
U.S. Geological Survey

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By Gail Schmidt, Calli Jenkerson, Jeffrey Masek, Eric Vermote, and Feng Gao

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)
kilogram per square meter (kg/m^2)	0.2048	pound per square foot (lb/ft^2)
gram per square centimeter (g/cm^2)	xxx	xxx

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32

Vertical coordinate information is referenced to the World Geodetic System 1984 (WGS 84).

Horizontal coordinate information is referenced to the World Geodetic System 1984 (WGS 84).

Abbreviations and Acronyms

6S	Second Simulation of a Satellite Signal in the Solar Spectrum
ACCA	Automated Cloud Cover Assessment
ACCESS	Advancing Collaborative Connections for Earth System Science
AOT	aerosol optical thicknesses
CDR	Climate Data Record
DDV	dense dark vegetation
DEM	digital elevation model
DN	digital number
ECV	Essential Climate Variable
ENVI	Exelis Visualization Solutions
EROS	Earth Resources Observation and Science
ETM+	Enhanced Thematic Mapper Plus
GCM	Global Climate Model
GeoTIFF	Georeferenced Tagged Image File Format
GMT	Greenwich Mean Time
GNEW	Gain variable for Landsat 5 TM – new
GOLD	Gain variable for Landsat 5 TM – old
GSFC	Goddard Space Flight Center
HDF	Hierarchical Data Format
IDL	Interactive Data Language
lat/long	latitude/longitude
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
LMAX	Spectral radiance scaled to maximum QCAL
LMIN	Spectral radiance scaled to minimum QCAL

LPGS	Level 1 Product Generation System
LUT	look up table
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NDSI	normalized difference snow index
NLAPS	National Landsat Archive Production System
NOAA	National Oceanic and Atmospheric Administration
OMI	Ozone Monitoring Instrument
QA	quality assurance
QCAL	Quantized calibrated pixel value in DN
SWIR	shortwave infrared
TIROS	Television and Infrared Observation Satellite
TM	Thematic Mapper
TOA	top of atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
UL	upper left
UMD	University of Maryland
USGS	U.S. Geological Survey
WO	work order

Acknowledgments

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The authors would also like to acknowledge John Dwyer of the USGS for his support of the on-demand processing and Landsat CDRs and ECVs, including the surface reflectance CDR.4.

Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) Algorithm Description

By Gail Schmidt[1], Calli Jenkerson[2], Jeffrey Masek[3], Eric Vermote[4], Feng Gao[5]

Abstract

The Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software was originally developed by the National Aeronautics and Space Administration–Goddard Space Flight Center and the University of Maryland to produce top-of-atmosphere reflectance from Landsat Thematic Mapper and Enhanced Thematic Mapper Plus Level 1 digital numbers and to apply atmospheric corrections to generate a surface-reflectance product. The U.S. Geological Survey (USGS) has adopted the LEDAPS algorithm for producing the Landsat Surface Reflectance Climate Data Record. This report discusses the LEDAPS algorithm, which was implemented by the USGS.

Introduction

The U.S. Geological Survey (USGS) is developing science-quality, applications-ready, key terrestrial variables and will produce them on an operational basis using historical, current, and future Landsat observations. The terrestrial variables will follow the guidelines established through the Global Climate Observing System and include Climate Data Records (CDRs), which represent geophysical transformations of Landsat data, and Essential Climate Variables (ECVs), which represent specific geophysical and biophysical land properties. CDRs and ECVs offer a framework for producing long-term Landsat datasets suited for monitoring, characterizing, and understanding land-surface change over time.

This document provides a description of the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS; Wolfe and others, 2004; Vermote and Saleous, 2007; National Aeronautics and Space Administration, 2007) algorithm, which was implemented by the USGS to produce a Landsat Surface Reflectance CDR.

Background

The LEDAPS software was originally developed in 2006 at National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the University of Maryland with funding from the NASA Terrestrial Ecosystems and Applied Sciences Programs. A February 2011 version was released through the NASA Advancing Collaborative Connections for Earth System Science (ACCESS) Program (Masek and others, 2006), with a contribution from the USGS Landsat Program. The USGS Earth Resources Observation and Science (EROS) Center used that version to create a baseline version of LEDAPS: 1.0.0.

[1]Stinger Ghaffarian Technologies (SGT), contractor to the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD, work performed under contract G10PC00044.

[2]ERT, contractor to USGS EROS Center, Sioux Falls, SD, work performed under contract G10PC00044.

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[5]U.S. Department of Agriculture, Agricultural Research Service, Hydrology and Remote Sensing Laboratory, 10300 Baltimore Avenue, Beltsville, MD.

LEDAPS 1.0.0 produces top-of-atmosphere (TOA) reflectance from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) Level 1 digital numbers (DN) and applies atmospheric corrections to generate a surface-reflectance product. The corrections are based on the Second Simulation of a Satellite Signal in the Solar Spectrum (6S; Kotchenova and others, 2006; Vermote and others, 1997) radiative-transfer model used by the Moderate Resolution Imaging Spectroradiometer (MODIS) Land Science Team. Examples of the results, compared to TOA reflectance, are displayed in figure 1.

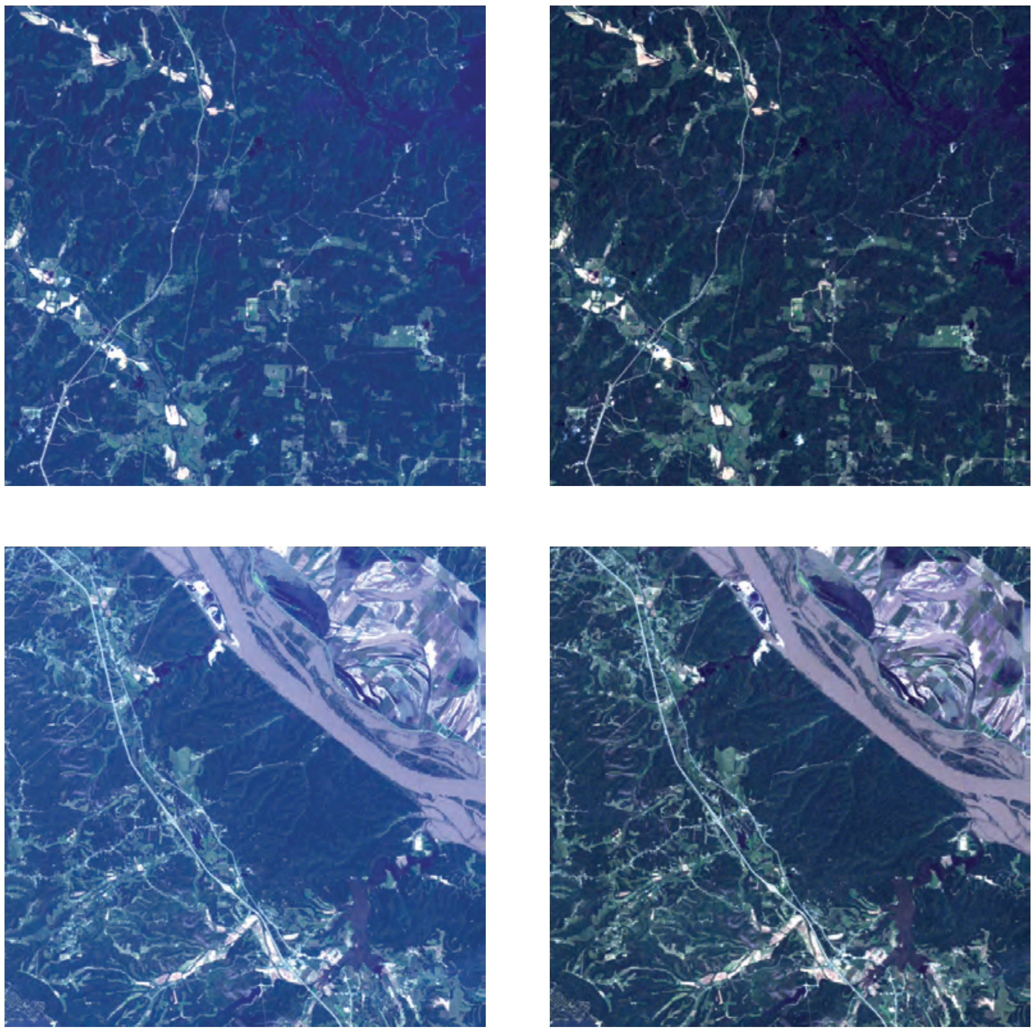

Figure 1. Examples of atmospheric correction results. All images are Landsat 5 Thematic Mapper acquired May 30, 1995 in Path 23, Row 34 spanning the Mississippi River in Missouri. The images in the right column are surface reflectance data derived from the atmospheric correction of the top of atmosphere reflectance shown in the left column.

Description of LEDAPS Modules

LEDAPS is written in six modules to execute the following three key steps:

1. Convert DN to TOA reflectance
2. Detect cloud pixels based on the TOA reflectance
3. Correct to surface-reflectance from TOA reflectance and auxiliary datasets

The modules provided in the LEDAPS software are described below, and the overall processing flow is depicted in figure 2.

Module 1 Parameter.—“lndpm” parses the Landsat metadata file and creates the necessary input files for each of the downstream LEDAPS modules.

Module 2 Calibration.—“lndcal” calibrates Landsat data from DN to TOA reflectance (and brightness temperature for the thermal band).

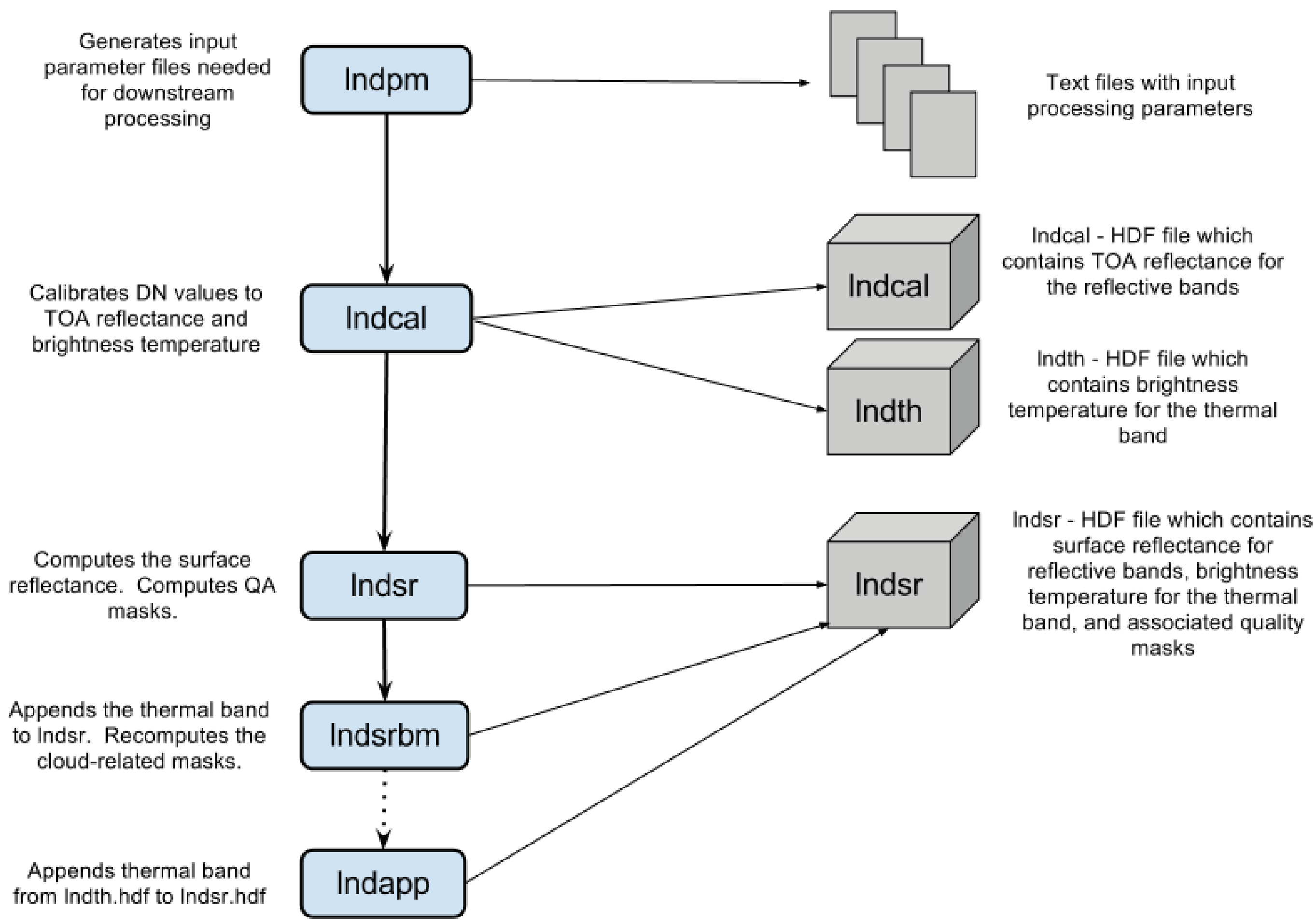

Figure 2. Algorithm processing flow.

Module 3 Cloud Shadow Mask.—"lndcsm" produces a cloud mask based on a pre-2004 C translation of an Interactive Data Language (IDL) Automated Cloud Cover Assessment (ACCA) algorithm. Note that this is an outdated and inaccurate ACCA algorithm intended for use as a preliminary cloud filter and the USGS implementation of LEDAPS 1.0.0 excludes this module.

Module 4 Surface Reflectance.—"lndsr" computes the surface-reflectance for the TM and ETM+ reflectance bands and produces a quality mask for fill, dark dense vegetation (DDV), snow, and land/water data. It includes a derivation of select internal cloud mask values used in production, but these are reset in the "lndsrbm" module.

Module 5 Surface Reflectance Based Mask.—"lndsrbm" detects and creates masks for cloud, cloud shadow, and adjacent clouds using a surface-reflectance based algorithm.

Module 6 Append.—"lndapp" appends the thermal brightness temperature band to the surface-reflectance output product.

Dependencies

The LEDAPS modules are designed to work with formatting specific to Landsat TM and ETM+ scenes and the auxiliary datasets needed to perform atmospheric corrections. Processing is dependent upon

- Properly formatted Landsat TM or ETM+ metadata files,
- Georeferenced Tagged Image File Format (GeoTIFF) band data, and
- Air pressure, water vapor, air temperature, ozone, and digital elevation model (DEM) data.

Table 1. Algorithm inputs.

Module	Description	Units	Source	Type
lndpm	Landsat metadata file		LPGS, NLAPS, NLAPS WO, UMD (TM or ETM+)	Text file.
	Path to the auxiliary files: GCMDEM, OMI/TOMS, NCEP REANALYSIS data, and GOLD/GNEW calibration files for TM		ANC_PATH	Environment variable.
	Read UL corner, number of rows and columns, and resolution from Band 1 (if GeoTIFF from LPGS) or metadata if from NLAPS		LPGS, NLAPS, NLAPS WO, UMD	GeoTIFF or metadata file.
lndcal	Calibration input parameter file (lndcal.txt)		lndpm	Text file.
	Input metadata file (metadata.txt)		lndpm	Text file.
	L1 Landsat imagery (bands 1-7, includes band 6 for the thermal band, include band 8 if ETM+)	DN, (band 6 is Kelvin), unsigned byte	LPGS, NLAPS (TM or ETM+)	GeoTIFF file, one band per file.
	GOLD, GNEW, GOLD_2003 (if processing TM data)	Gains per band, W/(m2 sr micron)	Landsat cal/val team	Text file.
lndcsm	Cloud mask input parameter file (lndcsm.txt)		lndpm	Text file.
	Landsat calibrated TOA reflectance (bands 1-7)	Reflectance	lndcal	HDF4 file.
	Landsat thermal band brightness temperature	°Celsius	lndcal	HDF4 file.
lndsr	TOA reflectance for all reflective bands (lndcal.hdf)	Reflectance, signed 16-bit integer, scale factor 0.0001	lndcal	HDF4 file.
	QA bits to indicate band saturation (lndcal.hdf)	Flag, unsigned byte	lndcal	HDF4 file.
	Brightness temperature for thermal band (lndth.hdf)	°Celsius, signed 16-bit integer, scale factor 0.01	lndcal	HDF4 file.
	QA bits to indicate band saturation (lndth.hdf)	Flag, unsigned byte	lndcal	HDF4 file.
	OMI/TOMS ozone data	Dobson, signed 16-bit integer, scale factor 1.0	OMI, TOMS data centers	HDF4 file.
	NCEP REANALYSIS data (pressure, water vapor, air temperature)	Signed 16-bit integer, pressure in Pascals, scale factor 1.0, water vapor in kg/m2, scale factor 0.01, air temperature in Kelvin, scale factor 0.01	NCEP REANALYSIS	HDF4 file.
	Global GCMDEM	Meters		HDF4 file.
lndsrbm	Surface reflectance input parameter file (lndsr.txt)		lndpm	Text file.
	Landsat surface reflectance product	Reflectance	lndsr	HDF4 file.
	Landsat thermal band brightness temperature	°Celsius	lndcal	HDF4 file.
	NCEP REANALYSIS data (pressure, water vapor, air temperature)	Signed 16-bit integer, pressure in Pascals, scale factor 1.0, water vapor in kg/m2, scale factor 0.01, air temperature in Kelvin, scale factor 0.01	NCEP REANALYSIS	HDF4 file.
lndapp	Landsat surface reflectance product	Reflectance	lndsr	HDF4 file
	Landsat thermal band brightness temperature	°Celsius	lndcal	HDF4 file

[*]DEM digital elevation model, DN digital number, ETM+ Enhanced Thematic Mapper Plus, GCM Global Climate Model, GeoTIFF Georeferenced Tagged Image File Format, GNEW new revised gain variable for Landsat 5 TM, GOLD old gain variable for Landsat 5 TM, HDF Hierarchical Data Format, HDF4 HDF version 4, L1 level 1, LPGS Level 1 Product Generation System, NCEP National Centers for Environmental Prediction, NLAPS National Landsat Archive Processing System, OMS Total Ozone Mapping Spectrometer, QA quality assurance, TM Thematic Mapper, TOA top of atmosphere, UL upper left, UMD University of Maryland, WO work order.

Table 2. Algorithm outputs.

Module	Description	Units	Target	Type
lndpm	Input files for each of the downstream LEDAPS modules (metadata.txt, lndcal.txt, lndcsm.txt, lndsr.txt)		lndcal, lndcsm, lndsr	Text file.
	ENVI header file for each of the output HDF files (lndcal.hdf, lndcsm.hdf, lndth.hdf, lndsr.hdf)		lndcal, lndcsm, lndsr	Text file.
	LogReport file to track the matching metadata parameters		User info	Text file.
lndcal	TOA reflectance for all reflective bands (lndcal.hdf)	Reflectance, signed 16-bit integer, scale factor 0.0001	lndcsm, lndsr	HDF4 file.
	QA bits to indicate band saturation (lndcal.hdf)	Flag, unsigned byte	lndcsm, lndsr	HDF4 file.
	Brightness temperature for thermal band (lndth.hdf)	°Celsius, signed 16-bit integer, scale factor 0.01	lndcsm, lndsr	HDF4 file.
	QA bits to indicate band saturation (lndth.hdf)	Flag, unsigned byte	lndcsm, lndsr	HDF4 file.
lndcsm	ACCA cloud/snow mask			
0=land, 1=cloud, 2=shadow, 4=water, 8=snow, 255=fill	8-bit, unsigned byte	lndsr, optional	HDF4 file	
	Intermediate band 6 temp file	8-bit, unsigned byte	User info	Raw binary file.
	Intermediate clmaskb temp file	8-bit, unsigned byte	User info	Raw binary file.
	Intermediate clmaskb2 temp file	8-bit, unsigned byte	User info	Raw binary file.
	Intermediate clmask temp file (ultimately contains the same values as the HDF4 ACCA cloud/snow mask file)	8-bit, unsigned byte	User info	Raw binary file.
	Cloud mask log file		User info	Text file.
lndsr	Surface reflectance for all reflective bands (lndsr.hdf)	Reflectance, signed 16-bit integer, scale factor 0.0001	User info	HDF4 file.
	QA bands to indicate band features and quality for fill, dark dense vegetation, cloud, cloud shadow, snow, land/water, and adjacent cloud (lndsr.hdf)	Flag, unsigned byte	User info	HDF4 file.
lndsrbm	Updated cloud, cloud shadow, and adjacent cloud QA bands in Landsat surface reflectance product (lndsr.hdf)	Flag, unsigned byte	User info	HDF4 file.
	Updated Landsat surface reflectance product to contain thermal brightness temperature band (lndsr.hdf)	°Celsius, signed 16-bit integer, scale factor 0.01	User info	HDF4 file.
lndapp	Updated Landsat surface reflectance product to contain thermal brightness temperature band (lndsr.hdf)	°Celsius, signed 16-bit integer, scale factor 0.01	lndsrbm	HDF4 file.

*ACCA Automated Cloud Cover Assessment, ENVI Exelis Visualization Solutions, HDF Hierarchical Data Format, HDF4 HDF version 4, LEDAPS Landsat Ecosystem Disturbance Adaptive Processing System, QA quality assurance, TOA top of atmosphere.

Inputs

The inputs required for each of the LEDAPS software modules are listed in table 1. The modules build upon each other, using output from one as input to another, as well as incorporating auxiliary datasets, as needed.

LEDAPS atmospheric correction utilizes external inputs from

- National Centers for Environmental Prediction (NCEP) meteorological reanalysis data,
- NASA GSFC Ozone Monitoring Instrument (OMI),
- NASA GSFC Meteor-3 and Nimbus-7 Total Ozone Mapping Spectrometer (TOMS),
- National Oceanic and Atmospheric Administration (NOAA) Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS), and
- Global Climate Model (GCM) DEM.

The daily atmospheric inputs to LEDAPS 1.0.0 are needed for the acquisition date of the desired Landsat scene. OMI, TOMS, and NCEP REANALYSIS from 1980 to 2013 are available for download from their respective data centers. In cases where TOMS data are not available (for example, 1994–96), TOVS data are used. Scripts developed at USGS EROS are used to download the inputs, sort the files by years, save them to subdirectories, and reformat them into Hierarchical Data Format (HDF). USGS EROS also holds the GCMDEM HDF file delivered with the LEDAPS source code.

Table 1 includes listings for "GOLD" and "GNEW" auxiliary files. These are gain variables for each spectral band utilized to recalibrate the Landsat 5 TM products, but because LEDAPS pulls gain and bias values from the input-product metadata, the default is to skip this recalibration function. The "old" versus "new" is used to distinguish between the file applied to remove the original calibration values and the one that correctly recalculates them. The GOLD_2003 file is applied to products acquired after 2003. These files are delivered with the LEDAPS source code and can be obtained from USGS EROS, if needed.

LEDAPS is configured to read all standard Landsat metadata, as generated by Level 1 Product Generation System (LPGS), National Landsat Archive Production System (NLAPS), or the University of Maryland (UMD). Files with extensions "*MTL.txt" or "*.met" are treated as ETM+ metadata from LPGS. Extensions "*H1," "*.hdr," "*_WO," and "*.prodreport" are treated as TM metadata from NLAPS. UMD metadata file extensions are simply "*.umd" or "*.UMD," but the USGS implementation of LEDAPS 1.0.0 phased out handling UMD input files.

Outputs

As mentioned previously, the LEDAPS modules build upon each other by producing files or information that are used as input in the subsequent steps. The outputs are listed in table 2.

Prototype Code

LEDAPS 1.0.0, as implemented by the USGS, was derived from a February 2011 prototype version of LEDAPS, which was adapted by Feng Gao and available at *ftp://hydrolab.arsusda.gov/pub/fgao/Ledaps/* (accessed November 9, 2012).

Verification Methods

Given that the LEDAPS software is already in place and validated (Masek et al., 2006), the production version of LEDAPS, which is used for Landsat Surface-Reflectance generation, can be validated against the existing software. Any changes made to the baseline LEDAPS 1.0.0 code will need to be independently validated, based on the type of change that is made.

Maturity

The LEDAPS software is stable, and the USGS expects only limited and (or) minor modifications from the original developers of the code. Future enhancements are planned to support additional Landsat satellites (such as Landsat 8, 2013).

Procedure

LEDAPS 1.0.0 strings six software modules together to step through the processes of creating TOA and surface-reflectance with quality information. A general description of each module is provided below, followed by programming details, as necessary. “Module 3 Cloud Shadow Mask (lndcsm)” is included for posterity though that software is not used in LEDAPS 1.0.0 (owing to its outdated and inaccurate calculations).

Module 1 Parameter

The lndpm application reads the input Landsat TM or ETM+ metadata and LEDAPS-related environment variables, calculates the gain and bias (for LPGS products), and generates the parameter files needed for each of the downstream-processing applications. The algorithm processes through these steps:

- Determine the location of the auxiliary files (DEM, OMI/TOMS, REANALYSIS, etc.)
- Read desired fields from the input Landsat metadata or work-order file
- Calculate the band gain and bias, if processing the LPGS products; otherwise use the gain and bias settings in the metadata file
- Read the upper left (UL) corner coordinates, number of lines/samples, and resolution from band 1
- Always convert/use the UL corner of the UL pixel in LEDAPS
- Write the metadata to the meatadata.txt file
- Write the ENVI header files for each of lndcal.hdf, lndth.hdf, and lndsr.hdf
- Create the lndcal.txt metadata file
- Create the lndth.txt metadata file
- Create the lndsr.txt metadata file

Module 2 Calibrate

The lndcal application reads the sensor and scene information from the input parameter and metadata files. Gains, biases, and other reflectance parameters are read from the input parameter and metadata files. In the unlikely event these parameters are not available in the metadata, LEDAPS has functionality to perform recalibration based on the band and sensor using the “GOLD” and “GNEW” files. The brightness temperature is computed and written to lndth.hdf, with saturated and fill values being modified in the output and flagged in the quality-assurance (QA) band. The TOA reflectance values are calculated for each band and written to lndcal.hdf, with saturated and fill values being modified in the output and flagged in the QA band. Associated metadata is written to both files. The application also outputs statistics—such as the minimum and maximum reflectance per band—to the user. There are three steps to complete processing in this module: calibration, computation of brightness temperature, and TOA reflectance.

<u>Calibration</u>

- Read the input header file (metadata.txt), which contains sensor, acquisition date, solar angles, path/row, scene information, projection information, and gain/bias information
- Set the thermal gain to 0.0551583 and bias to 1.2377996
- Set the line minimum and maximum (LMIN/LMAX) values for each band and sensor (this includes different LMIN/LMAX values for ETM+ before/after July 1, 2000)
- Set the relative sun-earth distance values for each band and sensor
- Verify the acquisition date based on the sensor type
- Set the qcalmin = 1 (assume LPGS) and qcalmax = 255
- Compute the gain/bias for each band, based on the band and sensor-specific variables
    - Set gain = (lmax – lmin) / (qcalmax – qcalmin)
    - Set bias = lmin – (gain * qcalmax)
- If the satellite is Landsat 1–3 and the gain/bias for a particular band is less than delta (0.00001), then recompute the gain/bias based on band and sensor-specific variables
    - Set gain = 10.0 * (lmax – lmin) / 254.0
    - Set bias = 10.0 * lmin
    - If processing Landsat 1 and band 4
        - Set gain = 0.6024
        - Set bias = 10.0 * (lmax – lmin) / 254.0
- If the satellite is Landsat 4 or 5 and the gain/bias for a particular band is less than delta (0.00001), then recompute the

gain/bias based on band and sensor-specific variables
  - If this is band 1
    - Set the K1 and K2 constants to sensor-specific values
  - Else
    - Set gain = 10.0 * (lmax – lmin) / 254.0
    - Set bias = 10.0 * lmin
- If processing Landsat 5 TM and the recalibrate flag was set, read the old and new calibration coefficients from GOLD/GOLD_2003 and GNEW
- Create and open the output files (lndcal.hdf and lndth.hdf)

<u>Computation of Brightness Temperature</u>

- Compute the brightness temperature for band 6; keep track of min/max band statistics
  - If dnout is set
    - Set scale = (dn_map[3] – dn_map[2] + 1) / (dn_map[1] – dn_map[0] + 1)
  - Set rad = gain * current thermal pixel value
  - Set temp = K2 / (log (1.0 + K1/rad))
  - Set temp = 273.15
  - If dnout is set
    - Set brightness temp = dn_map[2] + (current thermal pixel value – dn_map[0]) * scale) + 0.5
  - Else
    - Set brightness temp = temp * 100.0 + 0.5
- If the input thermal value is ≥ 254, then set the QA saturated band flag for band 6 and mark the output pixel value as “saturated” (i.e., 20,000)
- If the input thermal value is fill, then set the QA fill flag for band 6 and mark the output pixel value as “fill” (i.e., −9999)
- Write the temp to the HDF file
- Write the stats to the screen
- Write the QA band to the HDF file
- Write the band 6 metadata

<u>Computation of TOA Reflectance</u>

- Compute the TOA reflectance for each of the reflective bands; keep track of min/max band statistics
  - If dnout is set
    - Set scale = (dn_map[3] – dn_map[2] + 1) / (dn_map[1] – dn_map[0] + 1)
  - If the GOLD and GNEW files are available, and the recal flag is set
    - If the work order flag is set
      - Set alpha = final_gain for this band
      - Set grescale = DN_to_Radiance_gain for this band
      - Set gold = alpha/grescale
    - Else
      - Set gold = GOLD gain for this band
      - Set gnew = GNEW gain for this band
    - End if
  - Else
    - Set gold = 1.0
    - Set gnew = 1.0
  - End if
- Set gain = gain
- Set bias = bias * gold / gnew
- Set ref_conv = (PI * dsun2) / (esun * cos_sun_zenith)
- If the input reflective value is 255, then set the QA saturated band flag for this band, and mark the output pixel value as “saturated” (i.e., 20,000)
  - Else If the input reflective value is fill, then set the QA fill flag for this band and mark the output pixel value as “fill” (i.e., −9999)
- Else
  - Set rad = (gain * current pixel value) + bias

    - Set ref = rad * ref_conv
- If the dnout is set
    - Set the output for the current pixel and band = (dn_map[2] + (current pixel value – dn_map[0]) * scale) + 0.5
- Else
    - Set the output for the current pixel and band = (ref * 10,000.0) + 0.5
- Write the TOA reflectance to the HDF file
- Write the stats for each band to the screen
- Write the QA band to the HDF file
- Write the reflective band metadata

Module 3 Cloud Shadow Mask

A description of this module is included herein for posterity. It was formerly used as a preliminary cloud filter in production, but was deactivated in LEDAPS 1.0.0 because it uses a C translation of pre-2004 heritage ACCA code and was not particularly successful in its calculations. The lndcsm application opens, reads, and applies a scale factor to the lndcal and lndth values. The brightness temperature values are converted from degrees Celsius (°C) to Kelvin. All fill pixels are marked as such, otherwise the pixels are initialized as land pixels. Various band ratios are then computed for each pixel (such as the normalized difference snow index (NDSI)) and compared to known threshold values for cloud-, snow-, and water-related pixels. The respective QA mask is then written to the lndcal.hdf file, along with associated metadata.

Module 4 Surface Reflectance

The lndsr algorithm performs the atmospheric correction needed to calculate surface-reflectance for Landsat TM and ETM+ data. 6S is run to generate a look up table (LUT) accounting for pressure, water vapor, ozone, and geometrical conditions over the whole scene for a range of aerosol optical thicknesses (AOT). A LUT is created for every band and is used both in the aerosol retrieval process as well as in the correction step. Incorporating the DDV method developed by Kaufman and others (1997), AOT is extracted directly from the imagery based on the physical correlation between chlorophyll absorption and bound water absorption. A linear relation is created between shortwave infrared (SWIR) and surface-reflectance in visible bands so that AOT can be estimated by comparing visible band surface-reflectance with TOA reflectance.

AOT is averaged to 1-kilometer (km) resolution, and candidate dark targets are selected in the image. The relation between blue and SWIR reflectance is derived over the dark targets and propagated across the spectrum using a continental aerosol model. 6S is summarized in figure 3, excerpted from Vermote and Saleous (2007).

- Open and read the input parameter file
- Open the input thermal band
- Open and read the REANALYSIS “PRWV” file
- Open and read the ozone file
- Create the look up table for parameters required as part of the surface-reflectance calculations
- Create and open the output file (lndsr.hdf)
- Determine the scene center latitude/longitude (lat/long) in degrees
- If the acquisition date are known
    - Compute the scene Greenwich Mean Time (GMT) based on the acquisition time
- Else
    - Compute the scene GMT = 10.5 – center_long/15
- If scene GMT is < 0, then adjust scene GMT by 24 hours
- Read the surface pressure, water vapor, and air temperature data and auxiliary metadata from the PRWV file
- Read the auxiliary data and associated metadata from the ozone file
- Convert the surface-pressure values from Pascals to millibars
- Convert the water vapor from kilograms per square meter (kg/m^2) to grams per square centimeter (g/cm^2)

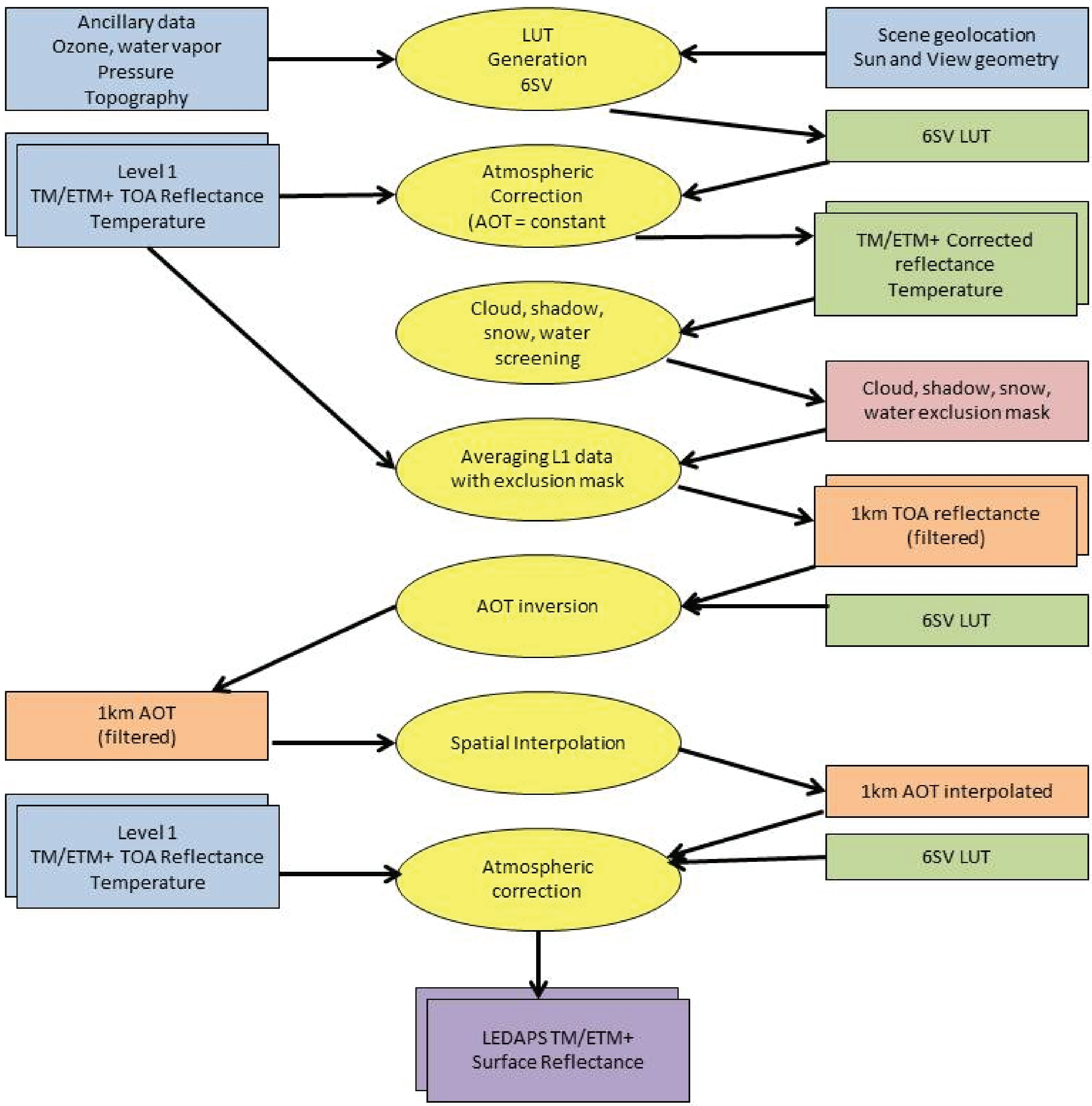

Figure 3. Atmospheric correction flow.

- Convert the ozone data to centimeters-atm
- Read the DEM file
- Determine the scene center lat/long, in degrees (duplicate code)
- Compute the true north adjustment
- Interpolate the water vapor auxiliary data to obtain values for the scene center
- Interpolate the ozone auxiliary data to obtain values for the scene center
- Run the 6S code and compute the atmospheric-correction parameters using the following
  - Set target altitude to 0 km (sea level)
  - Set sza to solar zenith, in degrees
  - Set phi to solar azimuth, in degrees
  - Set vza = 0
  - Set month = 9
  - Set day = 15
  - Set srefl = 0.14
- Interpolate the water vapor, ozone, and surface pressure auxiliary data to obtain values for each of the aerosol grid cells (40x40 window)
- Get the surface pressure DEM data values for each of the aerosol grid cells (40x40 window)
- Update the auxiliary surface-pressure values in the aerosol grid = surface pressure DEM * surface pressure auxiliary / 1,013.0
- Compute the atmospheric parameters with aot550 = 0.01 for each point in the aerosol grid cell, using the parameters in the 6S tables
- For each image line
  - Read the reflectance band data for the current line
  - Read the QA data for the current line
  - Read the thermal band for the current line
  - Interpolate the air temperature for every point in the aerosol grid
  - Run the first pass cloud screening and compute the statistics/diagnostics for the CELLHEIGHT_5KM x CELLWIDTH_5KM (160x160) grid
- For each line in the cloud diagnostics grid
  - For each sample in the cloud diagnostics grid
    - If (nb_tb_clear ≤ 0)
      - Set avg_t6_clear = −9999
      - Set avg_b7_clear = −9999
      - Set std_t6_clear = −9999
      - Set std_b7_clear = −9999
      - Continue
    - Set coef = (scene_gmt – air_temp_time[current_layer]) / air_temp_time_resolution
    - Interpolate the air temperature for the current pixel
    - Set the airtemp_2m = (1-coef) * air_temp[current_layer] + coef*air_temp[current_layer+1]
    - Set sum_value = average of the clear temperature (b6) values for the current pixel in the grid
    - Set sumsq_value = stddev clear temperature (b6) value for the current pixel in the grid

        - Compute the avg_t6_clear value = sum_value / number of clear temp (b6) values for the current pixel in the grid
        - If the number of clear temp (b6) values for this pixel is greater than 1
            - Set std_t6_clear = (sumsq_value – sum_value**2 / number of clear temp (b6) values) / (number of clear temp (b6) values – 1)
            - Set std_t6_clear = sqrt (fabs(std_t6_clear))
        - Else
            - Set std_t6_clear = 0
        - Set sum_value = average of clear b7 values for the current pixel in the grid
        - Set sumsq_value = stddev of clear b7 values for the current pixel in the grid
        - Set avg_b7_clear = sum_value / nb_t6_clear
        - If the number of clear temp (b6) values for this pixel is greater than 1
            - Set std_b7_clear = (sumsq_value – sum_value**2 / number of clear temp (b6) values) / (number of clear temp (b6) values – 1)
            - Set std_b7_clear = sqrt (fabs(std_b7_clear))
        - Else
            - Set std_b7_clear = 0
- Fill in (interpolate) the missing value in the t6_clear grid based on existing values
- Create the dark target temporary file
- For each image line in the aerosol region
    - Read the reflectance band data for the current line
    - Read the QA data for the current line
    - Read the thermal band for the current line
    - Run the second pass cloud screening
    - Dilate the cloud shadow mask for the adjacent 5x5 window
    - Write the dark target information to the temporary file
- Close the temporary file
- Reopen the dark target temporary file
- For each line
    - Read the DDV from the temporary file for the current aerosol region
    - Read each band for the current aerosol region
    - Compute the aerosol for the region (function call)
    - Write the dark target map to the temporary file
- Close the dark target temporary file
- Fill the gaps in the coarse resolution aerosol product for bands 1, 2, and 3
- Compute the atmospheric coefficients for the whole scene using the retrieved AOT
- Reopen the dark target temporary file
- For each line
    - Read the current line for each reflective band
    - Read the current line for the thermal band
    - Compute the surface-reflectance for the current line and stats (function call)

- For each line
  - For each sample
    - For each band
      - If the current pixel in the current band is not the max SR value
        - Set rho = current pixel / 10,000.0
        - Set rho = rho / atmos_coef_tg0G – atmos_coef_rho_ra
        - Set tmpflt = atmos_coef_tgH20 * atmos_coef_td_ra * atmos_coef_tu_ra
        - Set rho = rho / tmpflt
        - Set rho = rho / (1 + atmos_coef_S_ra * rho)
        - Set line_out for the current pixel and band to rho * 10,000.0
      - Else
        - Set line_out for the current pixel and band to max SR value
      - Compute the min/max statistics

- Read the dark target information for the current line from the temporary file
- For each sample
  - Initialize the QA data (fill, DDV, cloud, shadow, snow, water, adjacent cloud) for the current pixel to OFF
  - If the current pixel is not fill
    - Interpolate the AOT for the current pixel from the aerosol grid
    - If the DDV value AND 0x01 then turn on the dark target flag
    - If the DDV value AND 0x10 then
      - Turn off the land flag
    - Else
      - Turn on the water flag
    - If the DDV value AND 0x20 then turn on the internal cloud mask flag
    - Copy the aerosol stats band 1 to the output DARK band
    - Copy the aerosol stats band 2 to the output AVG_DARK band
    - Copy the aerosol stats band 3 to the output STDDEV_DARK band
  - Else
    - Set the output values for this pixel to fill
  - Reset the cloud shadow and adjacent cloud values to OFF
  - Set anom = band1 current pixel – band 3 current pixel / 2.0
  - Set t6 = thermal current pixel / 100.0 + 273.0
  - Set t6s_seuil = 280.0 + (1,000.0*0.01)
  - If (((anom > 300) AND (band5 current pixel > 300) AND (t6 < t6s_seuil)) OR ((band 3 current pixel > 5,000) AND (t6 < t6s_seuil)))
    - Turn cloud flag to ON
  - Else
    - Turn cloud flag to OFF

- Write each of the output reflective bands as 16-bit products

- Write each of the output QA bands as unsigned 8-bit products
- Print the statistics for each band
- Write the output metadata for each band
- Close all the files
- Write the spatial metadata to the HDF file

Module 5 Surface-Reflectance Based Mask

The lndsrbm application includes the process that appends the brightness temperature band to the surface-reflectance product. The surface-reflectance product is read, along with the metadata, and the scene center is computed. The auxiliary data are read for the scene center and acquisition date. The air temperature, solar zenith, solar azimuth, northern adjustment, and pixel size are all used to determine cloud-related properties. The cloud-related QA band values are reset/cleared, ignoring what was previously set in the lndsr application. Bands 1, 3, 5, and 6 are used to determine cloudy pixels, and the average clear temperature is computed for the non-cloudy pixels. For every cloudy pixel, the 5x5 surrounding window is marked as adjacent cloud, unless the pixel is already marked as a cloud. For every cloudy pixel, the cloud shadows are determined. For every cloud shadow, the 3x3 surrounding window is marked as cloud shadow if it is not already cloud or adjacent cloud. The updated cloud-related QA information and associated metadata are written to the surface-reflectance product, overwriting the previous cloud-related QA bands.

- Get name of SR_FILE, TEMP_FILE, and PRWV_FILE from the input parameter file and make sure they exist
- Append the thermal band to the surface-reflectance product (using lndapp)
- Get the bounding coordinates from the surface-reflectance file
- Compute the scene center lat/long
- Read the REANALYSIS data from the PRWV_FILE for the scene center and acquisition date
- Get the air temp for the scene center and acquisition date
- Compute the scene orientation
- Compute the deviation between the center and a point 100 pixels north from center (adjnorth)
- Read the solar azimuth and solar zenith from the input metadata
- Read the pixel size from the input metadata
- Write the air temp (tclear) in Kelvin, solar zenith (ts), 0.0 (tv), solar azimuth (fs), adjnorth, and pixel size to a temporary text file
- Set cfac = 6.0
- Set dtr = atan(1.0) / 45.0
- Set default pixsize = 28.5
- Read tclear, ts, tv, fs, tna, and pixsize from the temporary input file
- Subtract 273.0 from tclear to convert Kelvin to °Celsius
- Open the input surface-reflectance product
- Get the number of lines and samples from the cloud QA
- Allocate memory for the various surface-reflectance, temperature, QA bands, and a temporary bit used for the cloud detection
- Read the cloud QA, cloud shadow QA, adjacent cloud QA, snow QA, temperature band, band 1, band 2, band 3, and band 5.
- Reset/clear the cloud, cloud shadow, and adjacent cloud bits (ignoring what was set in the lndsr application)
- # Update the cloud QA bit
- For each line
    - For each sample
        - If band1 pixel is not fill
            - Increment the number of values count by 1
            - Set anom = band1 pixel – band3 pixel / 2.0
            - Set t6 = temperature pixel / 100.0
            - If this is a snow pixel then
                - Continue
            - Else
                - If (anom > 300) and (band5 pixel > 300) and (t6 < tclear) then
                    - Set the cloud QA for this pixel to cloudy

- Increment the number of cloudy pixels count by 1
- Else
- If (band1 > 3,000) and (t6 < tclear) then
  - Set the cloud QA for this pixel to cloudy
  - Increment the number of cloudy pixels count by 1
- Else
  - Increment mclear by t6/10,000.0
  - Increment number of clear pixels count by 1
- End if
- End if
- End if
- End if
- End for samples

- End for line
- If the number of clear pixels > 0
  - Set mclear = mclear * 10,000 / number of clear pixels to produce the average clear temp
- End if
- Set pclear = number of clear pixels * 100 / number of values count to produce the percentage of clear pixels
- If pclear > 5 then
  - Set tclear = mclear
- End if
- # Update the adjacent cloud QA bit
- For each line
    - For each sample
      - If this pixel is a cloud
        - For k = line-5 to line+5
          - For l = sample-5 to sample+5
            - If this window pixel (k,l) is an adjacent cloud or a cloud
              - Continue
            - Else
              - Set this pixel (k, l) as an adjacent cloud pixel
            - End if
          - End for l
        - End for k
      - End if cloudy pixel
    - End for sample
- End for line
- # Compute the cloud shadow
- fack = cosine (fs *dtr) * tangent (ts * dtr) / pixsize
- facl = sine (fs *dtr) * tangent (ts * dtr) / pixsize
- For each line
    - For each sample
      - If the pixel is a cloud
        - Set tcloud = pixel temperature
        - Set cldh = (tclear – tcloud) * 1,000.0 / cfac
        - If cldh < 0 then set cldh = 0
        - Set cldhmin = cldh – 1,000
        - Set cldhmax = cldh + 1,000
        - Initialize minimum band5 value = 9,999
        - For icldh = cldhmin/10, cldhmax/10
          - Set cldh = icldh * 10
          - Set k = line + fack * cldh
          - Set l = sample - facl * cldh
          - If (band5 pixel (k, l) < 800) and (band2 pixel (k, l) – band3 pixel (k, l) < 100)
            - If this is an adjacent cloud or a cloud or a cloud shadow pixel (k, l) then
              - Continue
            - Else

                    - If band5 pixel (k, l) < minimum band5 pixel then
                        - Set minimum band5 pixel = band5 pixel (k, l)
                        - Store line and sample location of the minimum band5 pixel (k, l)
                    - End if
                - End if
            - End if
        - End for icldh
        - If the minimum band5 pixel value was set
            - Set the pixel with the minimum band5 pixel line, sample as a cloud shadow
        - End if
    - End if cloudy pixel
  - End for sample
- End for line
- # Dilate the cloud shadow
- For each line
  - For each sample
    - If this pixel is a cloud shadow
      - For k = line-3 to line+3
        - For l = sample-3 to sample+3
          - If this is an adjacent cloud or a cloud or a cloud shadow pixel (k, l) then
            - Continue
          - Else
            - If tmpbit is set to on for this pixel (k, l) then
              - Continue
            - Else
              - Set tmpbit to on for this pixel (k, l)
            - End if
          - End if
        - End for l
      - End for k
    - End if
  - End for sample
- End for line
- # Update the cloud shadow
- For each line
  - For each sample
    - If tmpbit is set for this pixel then
      - Set this pixel as a cloud shadow
      - Set tmpbit to off for this pixel
    - End if
  - End for sample
- End for line
- Write the new cloud, cloud shadow, and adjacent cloud bands to the surface-reflectance product

Module 6 Append

The lndapp application reads the thermal band from the thermal brightness temperature file (band 6) and appends that band to the surface-reflectance file. Associated metadata for this band also are written. This module is a sub-process within “Module 6 Surface-Reflectance Based Mask.”

- Open the input surface-reflectance file and read metadata from “band1”
- Open the input thermal-brightness file and read metadata from “band6”
- If number of rows and columns from band1 and band6 don’t match, then exit with an error
- Read the image data from band6 in the thermal-brightness file and append to the surface-reflectance product as band6
- Write metadata for band6
- Close surface-reflectance file
- Close thermal-brightness file.

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