



NASA Cold Land Processes Experiment (CLPX 2002/03): Spaceborne Remote Sensing

ROBERT E. DAVIS,* THOMAS H. PAINTER,⁺ DON CLINE,[#] RICHARD ARMSTRONG,[@] TERRY HARAN,[@]
KYLE McDONALD,& RICK FORSTER,⁺ AND KELLY ELDER**

* *Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, Hanover, New Hampshire*
+ *Department of Geography, University of Utah, Salt Lake City, Utah*

[#] *National Operational Remote Sensing Hydrology Center, National Weather Service, Chanhassen, Minnesota*
[@] *National Snow and Ice Data Center, University of Colorado, Boulder, Colorado*

& *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California*

** *Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colorado*

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ABSTRACT

This paper describes satellite data collected as part of the 2002/03 Cold Land Processes Experiment (CLPX). These data include multispectral and hyperspectral optical imaging, and passive and active microwave observations of the test areas. The CLPX multispectral optical data include the Advanced Very High Resolution Radiometer (AVHRR), the Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Multi-angle Imaging Spectroradiometer (MISR). The spaceborne hyperspectral optical data consist of measurements acquired with the NASA *Earth Observing-1 (EO-1)* Hyperion imaging spectrometer. The passive microwave data include observations from the Special Sensor Microwave Imager (SSM/I) and the Advanced Microwave Scanning Radiometer (AMSR) for Earth Observing System (EOS; AMSR-E). Observations from the *Radarsat* synthetic aperture radar and the SeaWinds scatterometer flown on *QuikSCAT* make up the active microwave data.

1. Introduction

Current spaceborne sensors have limitations in remotely sensing some aspects of the cryosphere, particularly at frequent repeat intervals and fine-to-moderate spatial resolution. No single measurement system provides the key properties—snow extent, snow water equivalent, and freeze–thaw state—that hydrologists and climate modelers need. The Cold Land Processes Experiment (CLPX) had the objective of acquiring and compiling spaceborne remote sensing, airborne remote sensing, and field data to serve as the basis for validating current and emerging algorithms, as well as developing a cryosphere-specific spaceborne imaging program to address the limitations mentioned above. Most recent algorithms for snow property mapping have not been tested under a wide variation of snow cover prop-

erties, land cover, and terrain. This has prevented a thorough quantification of the confidence, or skill, of different approaches and has prevented a comprehensive determination of the conditions limiting the recovery of snow properties and freeze–thaw timing. We summarize here the primary spaceborne remote sensing data collected during the CLPX in four classes of sensing modality—multispectral and hyperspectral optical, and passive and active microwave—that will be used in conjunction with the airborne remote sensing and field data in further investigations.

2. Multispectral optical imaging

Pure snow has a distinctive spectral signature in the reflective solar spectrum, is one of the brightest of natural substances in the visible and near-infrared, and is among the darkest targets in the shortwave infrared. In the visible and near-infrared part of the spectrum, we have seen robust methods for mapping snow extent, estimated as binary classes of snow or no snow (Dozier 1989; Hall et al. 1995, 2002). Since the 1990s, the litera-

Corresponding author address: Robert Davis, Cold Regions Research and Engineering Laboratory, USACE, 72 Lyme Road, Hanover, NH 03755-1290.

E-mail: robert.e.davis@erdc.usace.army.mil

TABLE 1. Matrix of specifications for the spaceborne instruments used for the CLPX.

Sensor	Spectral range and full width at half maximum	Spatial resolution	Temporal frequency	Angular range
AVHRR	0.58–12.5 μm 0.1–1.0 μm	1.1 km	Subdaily	$\pm 40^\circ$
MODIS	0.405–14.385 μm 0.015–0.5 μm	250 m (B1, B2) 500 m (B3–7) 1 km (B8–36)	Daily (2 days)	$\pm 55^\circ$
TM/ETM+	0.4–2.2 μm	30 m (B1–5, 7) 120 m (B6)	16 days	$\pm 0.5^\circ$
MISR	0.446–0.866 μm 0.04–0.08 μm	275 m	9 days	9 angles
Hyperion	0.4–2.5 μm 0.01 μm	30 m	16 days	$\pm 0.225^\circ$
SSM/I	19.35, 22.2, 37.0, and 85.5 GHz	25 km	Subdaily	53.1°
AMSR-E	6.9, 10.65, 18.7, 23.8, 36.5, and 89.0 GHz	6–40 km	Daily	55°
<i>Radarsat-1</i>	5.3 GHz	12.5 m	3–4 days; 24-day repeat cycles	19° – 49°
<i>QuikSCAT</i>	13.4 GHz	25 km	Subdaily	46° HH (inner beam) and 54° vertical-vertical polarization (outer beam)

ture has reported techniques for estimating snow-covered area per pixel (Nolin et al. 1993; Rosenthal and Dozier 1996; Painter et al. 2003; Salomonson and Appel 2004). Recent progress has reported on how to estimate snow surface grain size and wetness as well (Green et al. 2002; Painter et al. 2003). However, snow reflectance in the visible and near-infrared region is insensitive to snow water equivalent (except for shallow snow) because the radiation in these wavelengths does not significantly penetrate. Furthermore, visible and near-infrared sensing requires solar illumination and cannot see through clouds or forest elements. The CLPX collected measurements from a variety of spaceborne multispectral instruments. Table 1 summarizes the wave bands, whereas Table 2 summarizes the periods of collection, or intensive observation periods (IOPs). IOP-1 was conducted from 17 to 24 February 2002, IOP-2 from 24 to 30 March 2002, IOP-3 from 17 to 25 February 2003, and IOP-4 from 25 March to 1 April 2003. All IOPs measure the earth's radiance in the reflected solar spectrum (visible through shortwave infrared) and emitted terrestrial spectrum (thermal infrared).

The Landsat dataset consists of observations with 30-m resolution in six reflective solar bands collected in two row-path combinations over the large regional study area (LRSA; Davis 2003). Data were collected between 10 November 2001 and 9 January 2003, using the Enhanced Thematic Mapper Plus (ETM+) sensor on *Landsat-7* and the Thematic Mapper (TM) sensor

on *Landsat-5*. Data consist of level 1G imagery products (radiance) that have been radiometrically and geometrically corrected.

The National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR/2 and AVHRR/3) data have high temporal but moderate spatial resolution (daily global coverage at 1.1-km resolution). The CLPX dataset consists of AVHRR High-Resolution Picture Transmission (HRPT) brightness temperatures and reflectances in continuous coverage over the LRSA. Data are gridded to the LRSA at 1.1-km (or 30 arc-second) resolution (Cline 2003). Data were collected between November 2001 and May 2003 (Table 2).

TABLE 2. Matrix of spatial coverage and acquisition periods for the spaceborne instruments used for the CLPX.

Sensor collection dates	Spatial coverage	IOP-1	IOP-2	IOP-3	IOP-4
AVHRR	All LRSA	X	X	X	X
MODIS	All LRSA	X	X	X	X
TM/ETM+	Each MSA	X	X	X	X
MISR	All LRSA	X	X	X	X
Hyperion	Fraser MSA	X	X		
SSM/I	All LRSA	X	X	X	X
AMSR-E	All LRSA			X	X
<i>Radarsat-1</i>	Each MSA			X	X
<i>QuikSCAT</i>	All LRSA	X	X	X	X

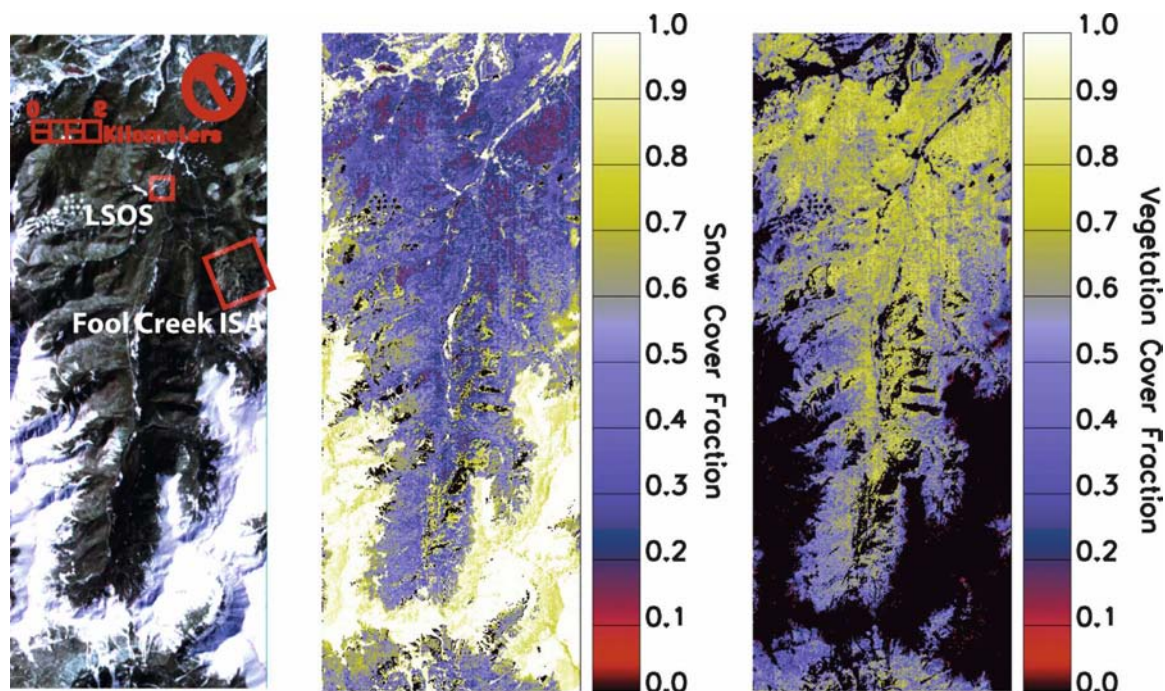


FIG. 1. Snow and vegetation cover fractions retrieved by the spectroscopy mixture model HYPSCAG, a simultaneous retrieval of snow fraction and grain size (Painter 2003), from NASA *EO-1* Hyperion imaging spectrometer data (acquired 19 Mar 2002).

The Moderate Resolution Imaging Spectroradiometer (MODIS) provides near daily global coverage in 36 spectral bands, with resolution varying from 250 to 1000 m. MODIS data for CLPX consist of geographic (GEO) and universal transverse mercator (UTM) grids covering the LRSA (Haran 2003). The data cover the period 15 February (yearday 046) through 15 May (yearday 135), for a total of 90 days for both study years (2002–03; Table 2). Data were resampled from the original Hierarchical Data Format–Earth Observing System (HDF–EOS) product files containing either swath data or gridded data; the parameters include calibrated radiances, surface reflectance, snow cover (Hall et al. 2006), surface temperature/emissivity, and vegetation indices.

The Multi-angle Imaging Spectroradiometer (MISR) views the earth at nine widely spaced angles via radiometrically and geometrically calibrated images, in four spectral bands at each of the nine angles, to provide global images with high spatial detail; global spatial sampling is provided at 275 and 1100 m. The MISR instrument orbits the earth about 15 times each day. There are 233 distinct orbits that are repeated every 16 days. These 233 repeating orbits are called paths, and because the paths overlap, near global coverage is obtained in 9 days. The MISR L1B2T (terrain-registered) top of atmosphere–scaled radiance data are available

for the periods November 2001–May 2002 and November 2002–May 2003 (Table 2; Davis 2004).

3. Hyperspectral optical imaging

The National Aeronautics and Space Administration (NASA) *Earth Observing-1* (*EO-1*) Hyperion instrument is a high-resolution hyperspectral imager capable of resolving 220 spectral bands (from 0.4 to 2.5 μm) with a 30-m spatial resolution, in formation with Landsat ETM+. The instrument images a 7.5 km $\times$ 100 km land area per image and provides detailed spectral mapping across all 220 channels, with high radiometric accuracy. The Hyperion acquisitions over the CLPX Fraser mesocell study area (MSA) had 7.5-km swaths and a 100-km length (Painter 2003). The retrieved Hyperion parameters include spectral surface reflectance, fractional snow-covered area, vegetation-covered area, rock-covered area, and grain size (Painter et al. 2003; Fig. 1). Hyperion data were acquired for the CLPX IOP-1 (15 February 2002) and IOP-2 (19 March 2002).

4. Passive microwave

The measurements of the cryosphere in the microwave spectral domain have attracted a great deal of attention because of their insensitivity to weather con-

ditions and solar illumination. Microwave sensors appear well suited to measure cold land properties because the microwave signal responds to the dielectric constant of surface materials, which in turn depends on the phase of water, ice, or liquid. Typically, snow measurements require two frequencies for snow property retrieval: one at moderate-to-low frequency to penetrate the snow and another at higher frequency to interact with the snow volume (Chang and Rango 2000). Passive microwave observations have demonstrated sensitivity to snow water equivalent (Chang et al. 1987; Goodison 1989; Nagler and Rott 1992; Grody and Basist 1996; Tait 1998; Pulliainen and Hallikainen 2001). Snow cover products derived from microwave measurements have a legacy dating back 25 yr or more (Frei and Robinson 1999). However, they currently have coarse spatial resolutions that limit their use in hydrologic modeling to the larger river basins. The coarse spatial resolution also leads to complex mixed pixels over much of the temperate latitudes, which presents some of the more difficult current challenges to algorithm developers (Chang et al. 1996). Passive microwave sensing has also shown promise for assessing the freeze–thaw state of the land surface (Zhang and Armstrong 2001; McDonald et al. 2004).

The Air Force Space and Missile Systems Center runs the Defense Meteorological Satellite Program (DMSP). As part of the DMSP, the Special Sensor Microwave Imager (SSM/I) consists of a seven-channel, four-frequency, linearly polarized, passive microwave radiometric system. The CLPX dataset has been gridded to the geographic (latitude–longitude) and UTM grids of the LRSA, with observations consisting of brightness temperatures from frequencies at 19, 22, 37, and 85 GHz (Brodzik 2003a). Grid resolution is 25 km, which approximates the sampling resolution of the original swath data. Backus–Gilbert optimal interpolation is used to artificially increase (16 times) the density of brightness temperature measurements in the satellite swath reference frame. This process uses actual antenna patterns to create the oversampled array, and the net effect is as if the additional samples had been made by the satellite radiometer itself; that is, the beam patterns and spatial resolutions of the interpolated data approximate those of the original samples. This method is based on the earlier work of Galantowicz and England (1991) and Poe (1990).

The NASA EOS *Aqua* satellite includes the Advanced Microwave Scanning Radiometer–EOS (AMSR-E). The AMSR-E has the SSM/I as its immediate heritage. It covers the same mid- and high-frequency spectral range, with the addition of lower frequencies (6.925 and 10.65 GHz) not found on the SSM/I.

The CLPX dataset includes AMSR-E passive microwave brightness temperatures gridded to the geographic (latitude–longitude) and UTM grids of the LRSA. The data consist of passive microwave frequencies at 6.9, 10.7, 18.7, 23.8, 36.5, and 89.0 GHz, separated by ascending and descending satellite passes and include time files (Brodzik 2003b). These data are interpolated from swath space using inverse distance squared resampling, with a grid resolution of approximately 25 km. Temporal coverage ranges from 1 February to 31 May 2003.

5. Active microwave

Spaceborne active microwave observations of the CLPX region were acquired by *Radarsat-1* and SeaWinds on *QuikSCAT*. *Radarsat-1* orbits the earth at an altitude of 798 km and at an inclination of 98.6° to the equatorial plane. The satellite's synthetic aperture radar (SAR) operates at C band (5.4 GHz) and horizontal–horizontal (HH) polarization and has a steerable beam providing an incidence angle that can be varied from 10° to 60°, with swath widths of 45–500 km, and spatial resolutions ranging from 8 to 100 m. *Radarsat-1* imagery collected for the CLPX consist of 12.5-m resolution, standard beam backscatter images with incidence angles ranging from 19° to 49°, and a swath width of approximately 100 km. Both ascending and descending passes were acquired, spanning from February to June 2003.

In contrast to the spaceborne SARs, spaceborne scatterometers have a nominal spatial resolution of tens of kilometers and revisit times of subweekly to subdaily, depending upon sensor swath width, orbit configuration, and latitude. Although they were originally developed for characterization of ocean winds, the high temporal repeat observation capability of scatterometers makes them ideal for studying quickly varying conditions, such as the progression of snowmelt and the freeze–thaw state of the land surface over large areas. The SeaWinds scatterometer onboard *QuikSCAT* operates in a sun-synchronous and 497-mile, near-polar orbit, circling the earth every 100 min, taking approximately 400 000 measurements over 93% of the earth's surface every day. Operating at Ku band (13.4 GHz), SeaWinds measures an 1800-km swath. *QuikSCAT* was launched in June 1999 as a “quick recovery” mission to fill the gap created by the loss of its predecessor, the NASA Scatterometer (NSCAT), which suffered a catastrophic power failure in June 1997. Prior to *QuikSCAT*, both NSCAT and the scatterometers on board European Remote Sensing satellites 1 and 2 (*ERS-1* and *ERS-2*) had been used to map wet snow and freeze–thaw transitions (Frolking et al. 1999).

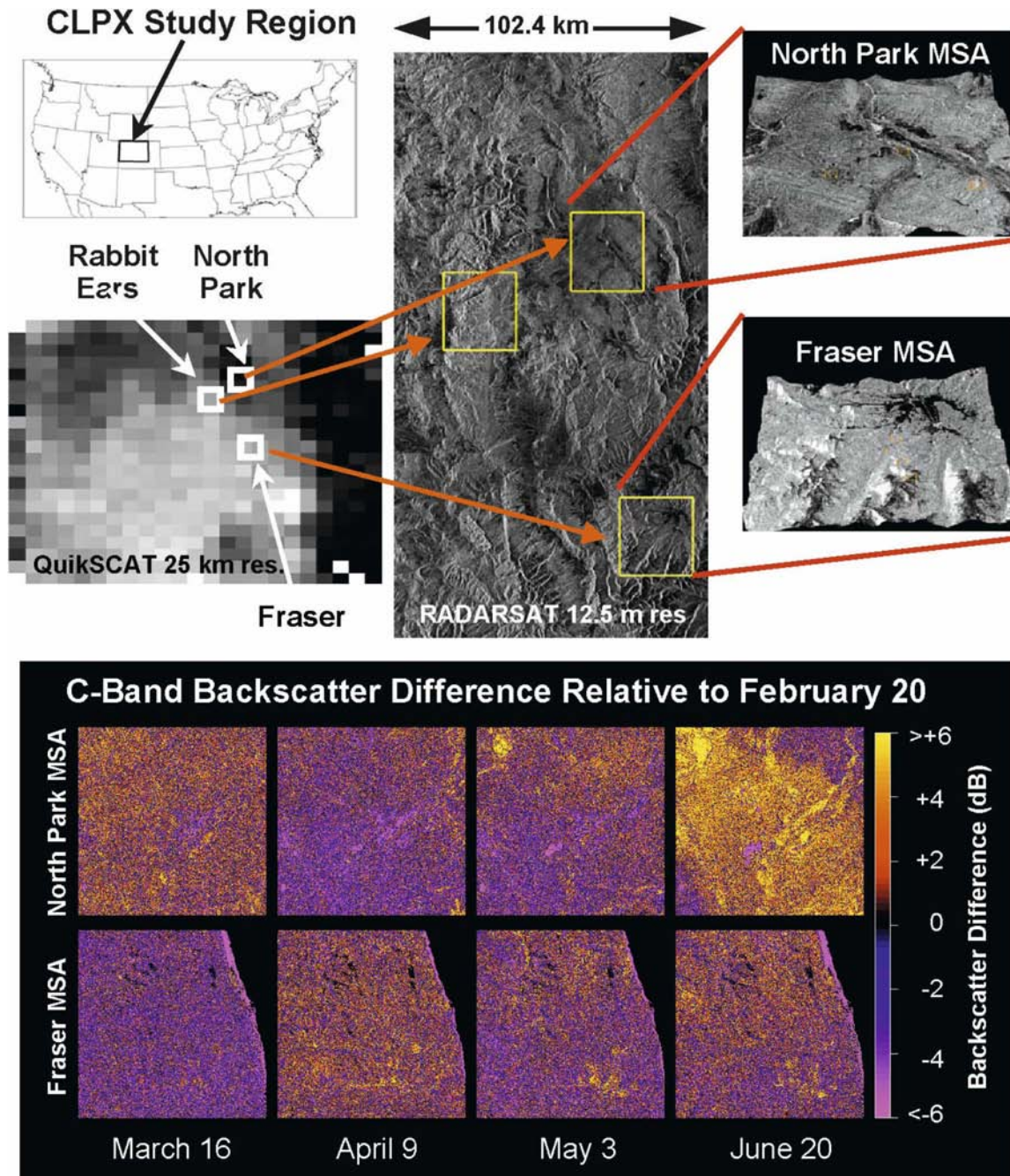


FIG. 2. Spaceborne active microwave datasets collected during CLPX consist of (top left) 25-km resolution Ku-band scatterometer measurements on the entire CLPX study region, acquired by SeaWinds on *QuikSCAT*, and (top right) 12.5-m C-band SAR imagery of the Rabbit Ears, North Park, and Fraser MSAs, acquired by *Radarsat-1*. (bottom) The series of maps show the time series backscatter difference of the 25-km North Park and Fraser MSAs relative to 20 Feb, and elucidate distinct differences in the temporal behavior of the C-band backscatter between these two MSAs as snowmelt and landscape thaw progress. *QuikSCAT* data were obtained from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at NASA's Jet Propulsion Laboratory, Pasadena, California (available online at <http://podaac.jpl.nasa.gov>).

The SeaWinds instrument consists of a rotating pencil-beam antenna that provides contiguous measurement swaths of 1400 (inner beam) and 1800 km (outer beam), covering approximately 70% of the

earth on a daily basis and 90% global coverage every 2 days. Overlapping orbit tracks at higher latitudes improves SeaWinds temporal coverage. For the CLPX, SeaWinds backscatter was compiled as a daily product.

Data for the CLPX are provided as gridded daily backscatter measurements, in American Standard Code for Information Interchange (ASCII) files compiled monthly. Data are provided from ascending and descending nodes, which have equator crossing times of 0600 and 1800 UTC, respectively, allowing for the examination of diurnal backscatter change for both inner and outer beams. See Fig. 2 for examples of active microwave data collected and processed for the CLPX.

6. Summary

Spaceborne remotely sensed data represent a core product suite for the Cold Land Processes Experiment (CLPX), by providing similar measurement footprints, subsets of spectral properties, and view geometries to those anticipated with a potential future Cold Land Processes Pathfinder mission. The CLPX satellite dataset archive includes multispectral and hyperspectral optical data, passive microwave data, and active microwave data. The National Snow and Ice Data Center distributes the CLPX satellite archive, in addition to airborne and field measurements (available online at <http://nsidc.org/data/clpx>).

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