



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

DON CLINE,* SIMON YUEH,⁺ BRUCE CHAPMAN,⁺ BOBA STANKOV,[#] AL GASIEWSKI,[#] DALLAS MASTERS,[#]
 KELLY ELDER,[@] RICHARD KELLY,[&] THOMAS H. PAINTER,^{**} STEVE MILLER,⁺⁺ STEVE
 KATZBERG,^{##} AND LARRY MAHRT^{@@}

*NOAA/NWS/National Operational Hydrologic Remote Sensing Center, Chanhassen, Minnesota

⁺Jet Propulsion Laboratory, Pasadena, California

[#]University of Colorado, Boulder, Colorado

[@]Rocky Mountain Research Station, USDA Forest Service, Fort Collins, Colorado

[&]University of Waterloo, Ontario, Canada

^{**}University of Utah, Salt Lake City, Utah

⁺⁺Johnson, Kunkel & Associates, Eagle, Colorado

^{##}NASA Langley Research Center, Langley, Virginia

^{@@}Oregon State University, Corvallis, Oregon

(Manuscript received 29 January 2007, in final form 22 April 2008)

ABSTRACT

This paper describes the airborne data collected during the 2002 and 2003 Cold Land Processes Experiment (CLPX). These data include gamma radiation observations, multi- and hyperspectral optical imaging, optical altimetry, and passive and active microwave observations of the test areas. The gamma observations were collected with the NOAA/National Weather Service Gamma Radiation Detection System (GAMMA). The CLPX multispectral optical data consist of very high-resolution color-infrared orthoimagery of the intensive study areas (ISAs) by TerrainVision. The airborne hyperspectral optical data consist of observations from the NASA Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). Optical altimetry measurements were collected using airborne light detection and ranging (lidar) by TerrainVision. The active microwave data include radar observations from the NASA Airborne Synthetic Aperture Radar (AIRSAR), the Jet Propulsion Laboratory's Polarimetric K_u-band Scatterometer (POLSCAT), and airborne GPS bistatic radar data collected with the NASA GPS radar delay mapping receiver (DMR). The passive microwave data consist of observations collected with the NOAA Polarimetric Scanning Radiometer (PSR). All of the airborne datasets described here and more information describing data collection and processing are available online.

1. Introduction

Airborne sensors provide many unique observing capabilities to help understand cold land processes. Aircraft platforms provide flexibility in data collection not generally found with spaceborne systems, improving opportunities for coordinating remote sensing observations with ground observations and for adapting to changing conditions. Seven airborne sensors (Table 1) were used to observe the surface and near-surface of the study areas of the Cold Land Processes Experiment (CLPX) during

four intensive observing periods (IOPs). Some of these are close analogs to current spaceborne sensors, providing similar spectral observations with greater spatial resolution. Others currently have no spaceborne counterpart. All provide observations of the snow, land, and terrain in CLPX that will be used to better understand cold land processes, improve the use of current spaceborne measurements, and develop new and improved observation capabilities. IOP1 was conducted from 17 to 24 February 2002, IOP2 from 24 to 30 March 2002, IOP3 from 17 to 25 February 2003, and IOP4 from 25 March through 1 April 2003. In this paper, we summarize the CLPX airborne remote sensing datasets from four categories that span three spectral regions: gamma radiation observations, multi- and hyperspectral optical imaging and optical altimetry, and passive and active microwave.

Corresponding author address: Don Cline, NOAA/NWS/National Operational Hydrologic Remote Sensing Center, 1735 Lake Drive West, Chanhassen, MN 55317.
 E-mail: donald.cline@noaa.gov

TABLE 1. Airborne remote sensing datasets collected for CLPX. (Descriptions of the sensor and data handling methods and more detailed information on the actual data collected can be found online at <http://nsidc.org/data/clpx>; see the metadata link associated with each dataset.)

Dataset/product	Similar spaceborne counterpart	Spatial coverage	IOP				Data volume	Parameters
			1	2	3	4		
Airborne gamma snow and soil moisture surveys	n/a	Each MSA	X3		X4	X	1 MB	SWE
Infrared orthoimagery and lidar topographic mapping	n/a	Each ISA				X2	4.31 GB	Soil moisture Terrain elevation Snow depth
AVIRIS	Hyperion	Swaths intersect ISA		X1	X	X	22.52 GB	Apparent surface reflectance Sub-pixel snow-covered area Grain size
AIRSAR	ALOS	Each MSA	X	X		X	POLSAR 300 MB, TOPSAR 1 GB per flight line; 92.61 GB total	Polarimetric (POLSAR) and cross-track interferometry (TOPSAR) radar data at P, L, and C bands
POLSCAT	n/a	Each MSA	X		X	X	2.94 MB	Geolocated normalized radar cross section for VV, HH, VH, and HV polarizations
Airborne GPS bistatic radar	n/a	Each MSA	X		X	X	280 MB	Snow cover Soil moisture
Multiband PSR imagery	AMSR-E	Each MSA	X		X	X	2.4 GB	Brightness temperature Snow cover

¹ Scenes collected shortly after IOP2.

² Data collected shortly after IOP4 and in September 2004.

³ Background data collected prior to these flight lines in September 2001.

⁴ Background data collected prior to these flight lines in September 2002.

2. Gamma radiation snow and soil moisture surveys

Natural terrestrial gamma radiation is emitted from the potassium, uranium, and thorium radioisotopes in the upper 20 cm of soil. The principal contributors to terrestrial gamma rays are the ^{40}K , ^{238}U , and ^{232}Th series. The radiation is sensed from a low-flying aircraft flying 150 m above the ground. The terrestrial gamma rays are attenuated by the atomic cross section of the intervening mass—water (any phase), vegetation, and air—between the ground and the aircraft. Observation of the attenuation (i.e., between measurements over dry soil and measurements over moist soil or snow) is a reliable basis for soil moisture and snow water equivalent (SWE) measurements. The technique of pairing the Gamma Radiation Detection System (GAMMA) with observations has been used operationally by the U.S. National Weather Service (NWS) since 1979 to measure the mean areal snow water equivalent and soil moisture along flight lines (Peck et al. 1980; Jones and Carroll 1983; Carroll 1987). The instrument and aircraft are operated by the NWS National Operational Hydrologic Remote Sensing Center (NOHRSC).

The GAMMA dataset consists of SWE observations collected in a series of flight lines within each of the three mesocell study areas (MSAs): North Park, Rabbit

Ears, and Fraser. Initial background terrestrial gamma radiation measurements were collected under relatively dry soil conditions with no snow cover present in September 2001 for 84 flight lines in the North Park MSA, 22 flight lines in the Rabbit Ears MSA, and 23 flight lines in the Fraser MSA. Coincident ground observations of gravimetric soil moisture were collected to estimate the mean areal soil moisture along each flight line. This estimation was then used to calibrate the background radiation measurement to account for the attenuation effects of the existing soil moisture. The absorption and reradiation of gamma radiation by intervening vegetation mass is accounted for in the calibration. Subsequent measurements of terrestrial gamma radiation over the calibrated flight lines during the experiment were used to determine the attenuation of the radiation signal solely a result of the intervening water mass in the snow and soil. The observations included in the dataset assume the same subnivean soil moisture that existed at time of the background calibration. In situ subnivean soil moisture observations collected in snow pits during each IOP may be used to adjust the SWE observations using the relationship

$$\text{SWE} = \frac{1}{A} \left[\ln \frac{C_0}{C} - \ln \left(\frac{100 + 1.11M}{100 + 1.11M_0} \right) \right] \text{g cm}^{-2}, \quad (1)$$

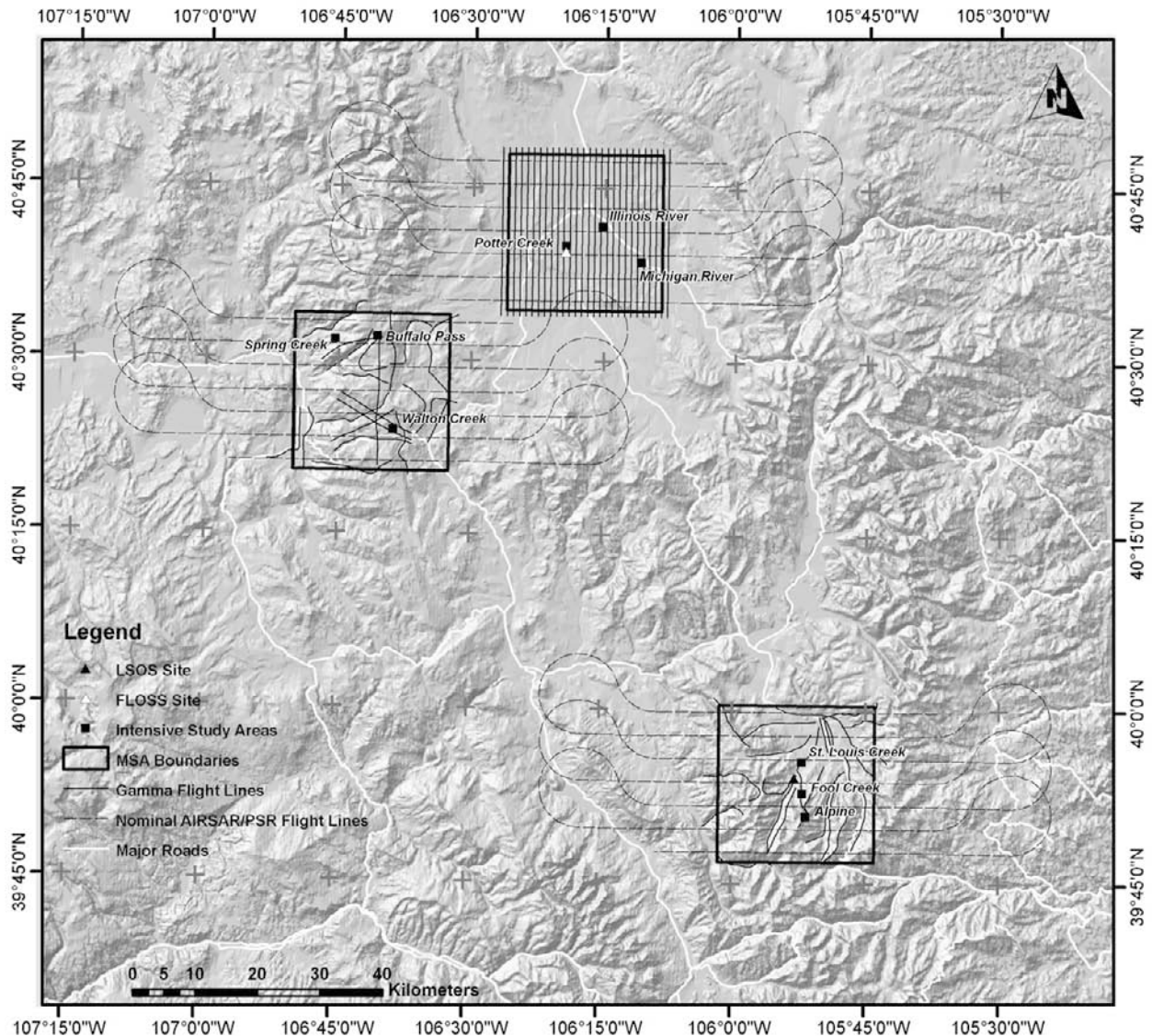


FIG. 1. Map of CLPX study areas where airborne data were collected. Nominal flight tracks for DC-8 and P-3 aircraft (active and passive microwave, including AIRSAR, PSR, and POLSCAT) and for gamma radiation snow surveys are shown.

where:

- 1) C and C_0 = uncollided terrestrial gamma count rates over snow and bare ground;
- 2) M and M_0 = percent soil moisture for snow-covered and bare ground, estimated from in situ measurements (also included in the dataset); and
- 3) A = radiation attenuation coefficient in water ($\text{cm}^2 \text{g}^{-1}$).

The North Park GAMMA flight plan consisted of 28 parallel series of three 9-km flight lines, with each series spaced 1 km apart. Together, these 84 individual SWE samples provide coverage of approximately 30% of the land area in the MSA. In the Rabbit Ears MSA (22 flight lines) and the Fraser MSA (23 flight lines),

ground coverage is much less a result of terrain constraints on low-altitude flights.

Here, the lines generally follow valleys, ridges, and elevation contours. (More information about the GAMMA data collection and processing is available online at <http://www.nohrsc.noaa.gov/>.)

3. Multispectral and hyperspectral optical imaging and altimetry

a. Infrared orthoimagery and lidar topographic mapping

This dataset was collected to provide detailed mapping of surface features, vegetation characteristics, and

TABLE 2. Digital orthoimagery and lidar data collection.

Data collection site	Snow covered		Snow free	
	Date	Local time (MST)	Date	Local time (MST)
Fraser MSA and LSOS	8 Apr 2003	1350–1540	18 Sept 2003	1345–1645
Rabbit Ears MSA	9 Apr 2003	1130–1300	19 Sept 2003	1345–1545
North Park MSA	9 Apr 2003	0945–1115	19 Sept 2003	0945–1245

topography within the intensive study areas (ISAs) and to test the concept of measuring snow depth using aerial light detection and ranging (lidar). The dataset consists of color-infrared orthophotography (high-resolution topographic mapping and aerial photography with 15-cm pixel resolution provided by Terrain-Vision), lidar elevation returns (raw/combined, filtered to bare ground/snow, and filtered to top of vegetation), elevation contours (0.5 m), and snow depth contours (0.1 m). Observations were made in the ISAs, the local scale observation site (LSOS), and at a site adjacent to the National Center for Atmospheric Research (NCAR) flux tower (close to the southeast corner of the Potter Creek ISA; Fig. 1; Table 2). Data were collected on 8–9 April (snow-covered sites) and 18–19 September 2003 (snow-free sites). Data are available for all sites except for snow depth contours at the site adjacent to the NCAR flux tower. Elevation data were acquired from approximately 1280 m above ground level (AGL) via airborne lidar, normalized to ground controls and processed to remove noise and redundancies (Corbley 2003). The elevation observations have approximately 1.5-m horizontal spacing and approximately 0.05-m vertical tolerances. The pixel size of the orthophotographs is 0.15 m. The snow-free and snow-covered elevation

data with the orthoimagery provide detailed information about the distribution of snow depth in relation to vegetation distribution and height characteristics (Fig. 2).

b. Airborne Visible/Infrared Imaging Spectrometer

The NASA Jet Propulsion Laboratory's (JPL) AVIRIS measures reflected radiance in 224 spectral bands across the wavelength range 0.4–2.5 μm with a 1 Mrad field of view. The AVIRIS acquisitions over the CLPX mesocell study area had 7.5-km swaths and 100-km lengths (Painter 2002). Initially, the AVIRIS data will be converted to apparent surface reflectance using the High-Accuracy Atmospheric Correction for Hyperspectral Data (HATCH) atmospheric correction model (Qu et al. 2003). The apparent surface reflectance data will be inverted for subpixel snow-covered area and subpixel snow grain size using the technique described in Painter et al. (2003).

The Multiple Endmember Snow-Covered Area and Grain Size (MEMSCAG) model (Painter et al. 2003) uses the multiple endmember spectral mixture analysis (MESMA) described in Roberts et al. (1998) to determine the subpixel coverage of snow and the grain size of the fractional snow cover. The MESMA approach allows the number of endmembers and the endmembers themselves to vary on a pixel-by-pixel basis to

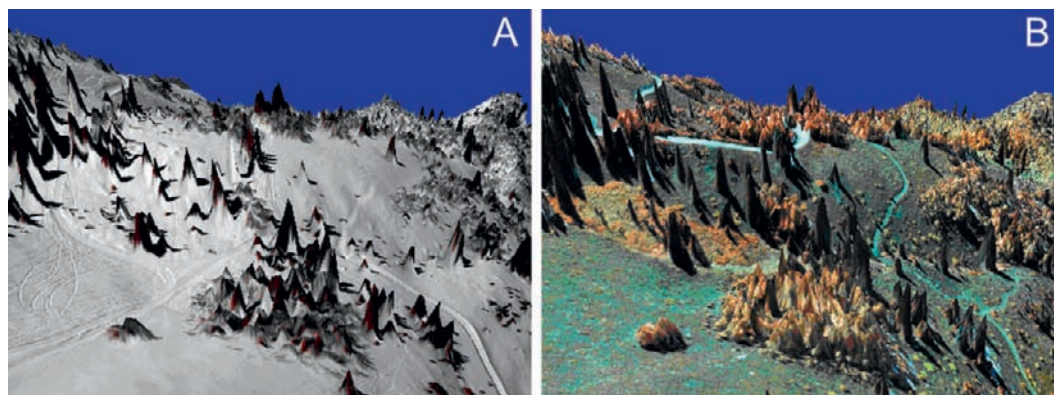


FIG. 2. High-resolution color-infrared orthoimagery of a portion of the Spring Creek ISA (view to southwest) draped over 2-m resolution unfiltered lidar DEM for (a) April and (b) September 2003. The orthoimagery lidar elevation datasets provide quantitative information about vegetation distribution, height, and structure. Potential applications of this information include investigation of vegetation structure on snow distribution, effects of vegetation on remote sensing signals, and estimation of snow height using unfiltered and filtered (aka “bald earth”) DEMs.

accommodate spatial and temporal variability in surface cover. The MEMSCAG model uses spectral reflectance endmembers for snow that are modeled with the discrete ordinate radiative transfer (DISORT) model (Stamnes et al. 1988), with grain radii ranging from 10 to 1100 μm at 10- μm intervals. Vegetation, rock, soil, and lake ice spectral endmembers were measured in the field and laboratory with an Analytical Spectral Devices, Inc. FR field spectroradiometer.

4. Active and passive microwave

Both active and passive microwave sensors have demonstrated sensitivity to snow properties and the freeze/thaw status of soils. Microwave signal response is influenced by snow depth, density, wetness, crystal size and shape, ice crusts and layer structure, surface roughness, vegetation characteristics, soil moisture, and soil freeze/thaw status. These characteristics make microwave remote sensing attractive for providing spatially distributed snow information. Microwave datasets were collected in CLPX to help improve the understanding of microwave signal response to snow and soil properties, develop and test retrieval algorithms, and advance the use of microwave remote sensing data in models.

a. Airborne Synthetic Aperture Radar imagery

The AIRSAR is a side-looking imaging P-, L-, and C-band radar flown aboard the NASA DC-8 aircraft (Lou et al. 2001). Two modes of AIRSAR data were collected in CLPX: 1) fully polarimetric mode [polarimetric synthetic aperture radar (POLSAR)] at P-, L- and C-band simultaneously, and 2) cross-track interferometry mode [XTI, or topographic synthetic aperture radar (TOPSAR)] at C-band simultaneously. The CLPX AIRSAR missions were flown at a nominal altitude of 8 km AGL over the three MSAs: Rabbit Ears, North Park, and Fraser. The nominal flight lines for each MSA consisted of three overlapping east–west lines to provide full MSA coverage and one north–south line crossing the three east–west lines to help fill radar shadow areas. A total of 171 TOPSAR and POLSAR flight lines were flown in February, March, and September of 2002 and in March 2003. All of the flight lines were processed using standard AIRSAR processing procedures. The resulting POLSAR datasets are in slant range projection, and the TOPSAR datasets are in ground range projection. The POLSAR and TOPSAR datasets have also been converted to universal transverse Mercator (UTM) map coordinates; both the native and the UTM-projected datasets are available. For POLSAR data transmitted at 40-MHz bandwidth (L- and C-band), the azimuth pixel spacing

TABLE 3. POLSCAT parameters. Note that actual incidence angle depends on aircraft attitude.

Parameter	Characteristics
Frequency	13.95 GHz
Polarization	VV, HH, HV, VH
Nominal incidence angle*	40°
Antenna beamwidth	5°
Antenna peak gain	28 dB
Antenna sidelobe	<−30 dB
Polarization isolation	>35 dB
Footprint size	1 km × 0.7 km at 8 km altitude
Radar transmit peak power	6 W at OMT flange
Radar transmit PRF	2857 Hz
Radar transmit pulse length	27 μs
Noise equivalent σ_0	−35 dB at 8 km altitude
Receiver A/D converter	12 bits

is 9.26 m, and the range pixel spacing is 3.3 m (18 looks taken during processing). At 20 MHz bandwidth (P-band), the azimuth pixel spacing is 9.26-m, and the range pixel spacing is 6.6-m. The azimuth and range pixel spacing of the TOPSAR data is 5 m.

The CLPX AIRSAR datasets provide opportunities to explore mid- to low-frequency radar response to a wide variety of snowpack conditions. All of AIRSAR's frequencies have large penetration depths in dry snow, so they can help improve our understanding of the effects of roughness at the snow–ground interface on radar response. High-resolution digital elevation maps (DEMs) produced during TOPSAR processing for each MSA are also available and have the potential for a wide variety of applications. (More information about the AIRSAR data collection and processing is available online at <http://nsidc.org/data/nsidc-0153.html>.)

b. Polarimetric K_u -band scatterometer

The POLSCAT instrument is a K_u -band polarimetric scatterometer operating at 13.95 GHz (Yueh et al. 2002). Flights were flown on the NASA DC-8 on 19, 21, and 23 February 2002 (during IOP1), 25 March 2002 (IOP2), and 25, 28, and 30 March 2003 (IOP4). A total of 205 flight lines of data were collected over Fraser, North Park, and Rabbit Ears MSAs. The POLSCAT antenna, mounted on a 62° port in the DC-8, pointed approximately at the center of the AIRSAR swath. Most of the POLSCAT data were collected on AIRSAR flight lines at a nominal altitude of 8000 m AGL, yielding a nominal footprint size of approximately 1000 m. During IOP1, several low-altitude flight lines were flown at 1500 m AGL, yielding smaller nominal footprints of approximately 100 m. Flight line details are given by Yueh (2003).

TABLE 4. PSR bands, polarizations, and 3-dB antenna beamwidths for CLPX. The multiple subband channels on PSR/CX are used for interference mitigation.

Scanhead	Band (GHz)	Polarizations	Beamwidths
PSR/CX	5.8–7.3 (four subbands)	v, h	10°
	10.6–10.8 (four subbands)	v, h	6.5°
PSR/A	10.6–10.8	v, h	8°
	18.6–18.8	v, h	8°
	21.4–21.7 (H ₂ O wing)	v, h	8°
	36–38	v, h	2.3°
	86–92	v, h	2.3°
	9.6–11.5 μ m IR	Unpolarized	7°

The raw data from POLSCAT's CLPX flights were processed to produce the normalized radar cross section (σ_0) of the terrain. The range from the target to the antenna was calculated using the aircraft altitude, aircraft GPS altitude, and a digital elevation map. In-flight calibration was performed using a calibration loop consisting of one waveguide attenuator and two directional waveguide couplers in the radar's front end, which leaks a small transmit signal into the receivers. Tests conducted in the laboratory—and aircraft flight data—suggest that the calibration loop measurements were very stable, with a drift of less than 0.1 dB over several hours. The key parameters of POLSCAT are described in Table 3.

Following CLPX, the POLSCAT instrument was upgraded with scanning capability to provide K_u -band imagery. As part of the testing of this upgrade, test flights were made over the CLPX ISAs during August 2004. The snow-free K_u -band imagery provides ground-scattering information and additional opportunities for exploring the retrieval of snowpack properties based on temporal change in K_u -band backscatter.

c. Airborne GPS bistatic radar

The GPS bistatic radar delay mapping receiver (DMR) was used in the 2002 and 2003 flights over the CLPX MSAs to measure GPS signals reflected from the earth's surface. The DMR tracks and measures the direct line-of-sight right-hand circularly polarized (RHCP) signal of a GPS satellite. It also simultaneously measures the delayed Earth-reflected, near-specular left-hand circularly polarized (LHCP) GPS signal. These measurements are a form of bistatic radar. Data were collected on 19 and 21 February 2002 from the NASA DC-8 and on 22–24 February and 25, 30, 31 March 2003 from the NASA P-3 aircraft. The receiver position is computed from either the more accurate of an external navigation source or the receiver's own GPS navigation solution. The GPS surface reflections are georeferenced to a composite Earth consisting of the WGS-84 ellipsoid, the EGM96 geoid, and the GTOPO30 elevation model. The spatial resolution of these data is variable, depending on airborne height and scattering regime (specular or rough). The reflections collected were from a variety of terrain, including dry plains, rugged mountains, valleys, snow-covered mountains, valleys, and lakes. The primary objective was to observe the quality of GPS bistatic radar reflections from snow-covered mountainous terrain to perhaps sense liquid water. The measurements can be used to estimate the surface scattering coefficient and the path delays between the direct and reflected GPS signals. Over land, scattering coefficients can be used to estimate changes in surface soil moisture. Over water surfaces, the reflected pulses can be used to sense roughness and derive wind speeds. The bistatic range measurements can also be used to estimate the receiver height above the surface in a form of aircraft altimetry.

TABLE 5. Catalog of PSR observations of MSAs during three CLPX field campaigns (IOPs 1, 3, and 4). MSAs are Rabbit Ears (RE), Fraser (F), and North Park (NP). Variations in surface elevation of up to ± 1 km within each MSA resulted in a band-dependent range of 3-dB spatial resolutions.

Experiment and configuration	Date	Observation times (UTC)	MSA(s) imaged	No. flight lines	Nominal flight altitude (km AGL)	3-dB spatial resolution
						range (m) at 37, 89/10, 18, 21 GHz
CLPX IOP1 PSR/A on NASA DC-8	19 Feb 2002	2118–2235	RE	7	2.34	88/308 to 209/728
	21 Feb 2002	1645–1849	F	7	2.10	55/191 to 234/812
	23 Feb 2002	1657–1834	NP	7	2.10	54/184 to 203/708
CLPX IOP3 PSR/A on NASA P-3B	22 Feb 2003	1835–2035	NP	7	3.93	184/642 to 334/1161
	23 Feb 2003	1735–2137	NP, RE, F	21	2.18	65/229 to 215/749
	24 Feb 2003	2030–2305	NP, RE	14	2.22	71/246 to 206/718
	25 Feb 2003	1730–2100	NP, RE, F	21	2.18	65/229 to 215/749
	25 Feb 2003	1730–2100	NP, RE, F	21	2.18	65/229 to 215/749
CLPX IOP4 PSR/A and PSR/CX on NASA P-3B	25 Mar 2003	1750–2205	NP, RE, F	21	2.18	65/229 to 215/749
	30 Mar 2003	1810–2230	NP, RE, F	21	2.18	65/229 to 215/749
	31 Mar 2003	1750–2150	NP, RE, F	21	2.18	65/229 to 215/749

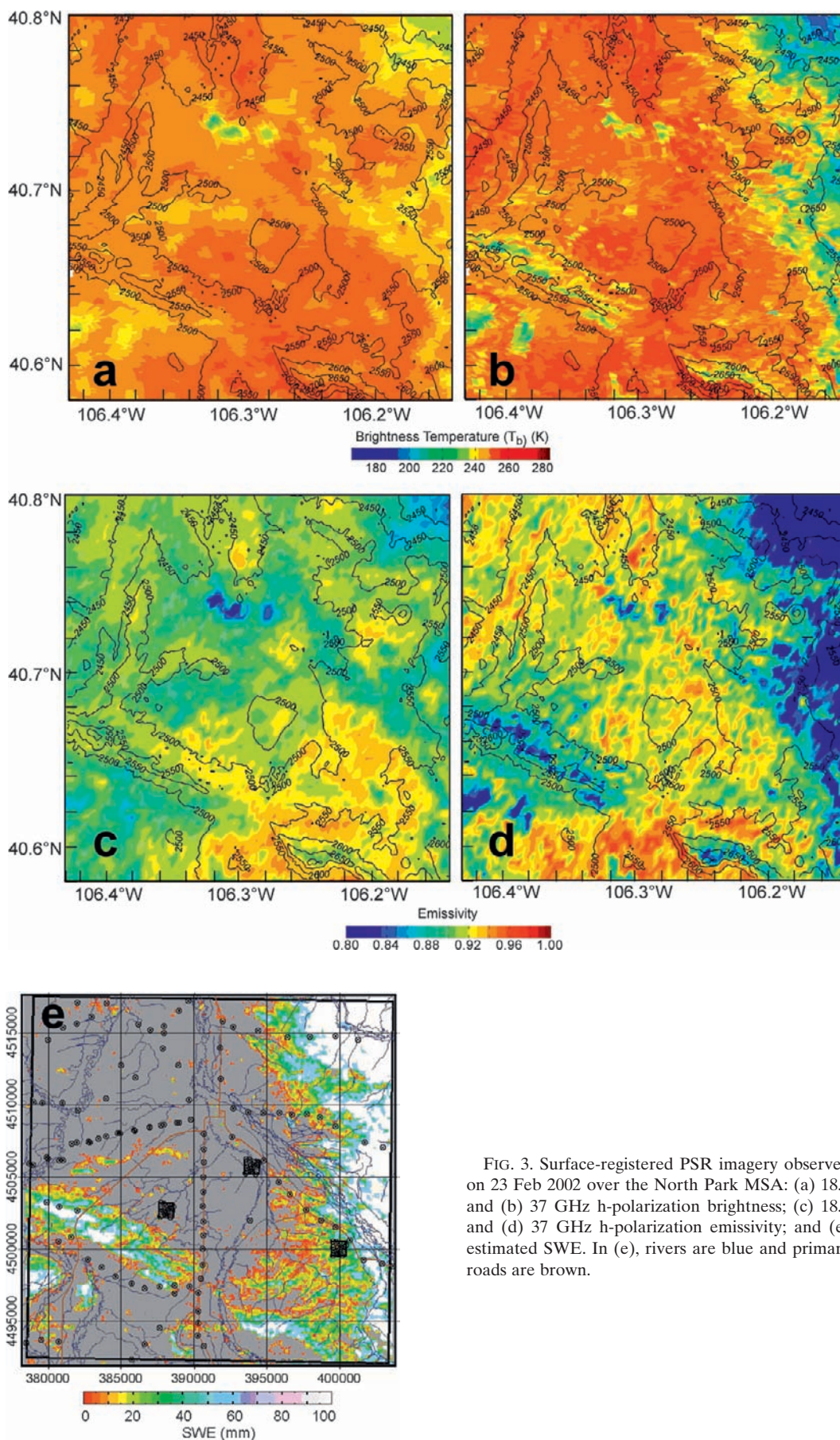


FIG. 3. Surface-registered PSR imagery observed on 23 Feb 2002 over the North Park MSA: (a) 18.7 and (b) 37 GHz h-polarization brightness; (c) 18.7 and (d) 37 GHz h-polarization emissivity; and (e) estimated SWE. In (e), rivers are blue and primary roads are brown.

d. Multiband Polarimetric Scanning Radiometer imagery

The NOAA PSR is a versatile airborne radiometer with multiple scanheads that provide measurements across a range from 5.8 to 92 GHz (Piepmeier and Gasiewski 2001; Stankov et al. 2003). In 2002, a single scanhead (PSR/A) was used to provide frequencies most commonly used for snow measurement. In 2003, a second scanhead (PSR/CX) was flown to provide full polarimetric and spectral simulation of the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) sensor aboard the NASA *Aqua* satellite (Table 4). For CLPX, the instrument was operated in conically scanned mode at an incidence angle of 55° from nadir. The PSR configuration for each IOP is listed in Table 5. A three-stage calibration process was used to provide an estimated absolute accuracy of nominally ± 1 K for the range of brightness temperature values encountered during CLPX. The PSR datasets were georegistered to UTM coordinates using positioning information collected on board the aircraft and a high-resolution digital elevation model.

The PSR datasets can provide insights into snowpack spatial and temporal variation and microwave polarization and spectral behavior. For example, mosaicked PSR maps over the North Park MSA observed on 23 February 2002 (Figs. 3a–d) reveal significant spatial variation of brightness temperatures at grid scales as small as the PSR resolution (a few hundred meters). The associated microwave emissivity variations are up to 20%–25%. The estimation of SWE from the 18 and 37H GHz PSR channels (Fig. 3e) using the methodology of Chang et al. (1987) and Kelly et al. (2003) reveals similarly high spatial variability of snowpack water storage.

5. Summary

Airborne remotely sensed data collected for the CLPX provide high-resolution observations of snow, land, and terrain to better understand cold land processes, improve the use of current spaceborne measurements, and develop new and improved observing capabilities. The airborne remote sensing data archive includes gamma radiation measurements of snow water equivalent and soil moisture, multispectral and hyperspectral optical imaging data, optical altimetry data, and active and passive microwave data. The National Snow and Ice Data Center distributes the CLPX airborne archive in addition to satellite and field measurements.

Acknowledgments. This work was funded through the cooperation of many agencies and organizations including the National Aeronautics and Space Administration's (NASA) Earth Science Enterprise, Terrestrial Hydrology Program, Earth Observing System Program, and Airborne Science Program; the National Oceanic and Atmospheric Administration's Office of Global Programs; the U.S. Army Corps of Engineers' Civil Works Remote Sensing Research Program; the U.S. Army's Basic Research Program; the National Space Development Agency of Japan (NASDA); the Japan Science and Technology Corporation; and the National Assembly for Wales, Strategic Research Investment Fund. A portion of this work was conducted at the Jet Propulsion Laboratory at the California Institute of Technology, which was under contract to NASA.

More than 200 people participated in the planning and execution of CLPX 2002/03. Their efforts are very much appreciated.

REFERENCES

- Carroll, T., 1987: Operational airborne measurements of snow water equivalent and soil moisture using terrestrial gamma radiation in the United States. *Proc. Symp. on Large-Scale Effects of Seasonal Snow Cover*, Vancouver, BC, Canada, Int. Association of Hydrological Sciences, IAHS Publication 166, 213–223.
- Chang, A. T. C., J. L. Foster, and D. K. Hall, 1987: Nimbus-7 derived global snow cover parameters. *Ann. Glaciol.*, **9**, 39–44.
- Corbely, K. P., 2003: Project case study—LIDAR for elevation mapping. *CE News*, **14**, 40–41.
- Jones, W., and T. Carroll, 1983: Error analysis of airborne gamma radiation soil moisture measurements. *Agric. For. Meteorol.*, **28**, 19–30.
- Kelly, R. E. J., A. T. C. Chang, L. Tsang, and J. L. Foster, 2003: A prototype AMSR-E global snow area and snow depth algorithm. *IEEE Trans. Geosci. Remote Sens.*, **41**, 230–242.
- Lou, Y., Y. Kim, and J. van Zyl, 2001: The NASA/JPL Airborne Synthetic Aperture Radar System. NASA Jet Propulsion Laboratory, Pasadena, CA, digital media. [Available online at <http://airsar.jpl.nasa.gov>.]
- Painter, T. H., 2002: Cold Land Processes Field Experiment: AVIRIS data. National Snow and Ice Data Center, Boulder, CO, digital media. [Available online at www.nsidc.org/data/clpx.]
- , J. Dozier, D. A. Roberts, R. E. Davis, and R. O. Green, 2003: Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data. *Remote Sens. Environ.*, **85**, 64–77.
- Peck, E., T. Carroll, and S. Vandermark, 1980: Operational aerial snow surveying in the United States. *Hydrol. Sci. Bull.*, **25**, 51–62.
- Piepmeier, J. R., and A. J. Gasiewski, 2001: High-resolution passive microwave polarimetric mapping of ocean surface wind vector fields. *IEEE Trans. Geosci. Remote Sens.*, **39**, 606–622.

- Qu, Z., B. C. Kindel, and A. F. H. Goetz, 2003: The high accuracy atmospheric correction for hyperspectral data (HATCH) model. *IEEE Trans. Geosci. Remote Sens.*, **41**, 1223–1231.
- Roberts, D. A., M. Gardner, R. Church, S. Ustin, G. Scheer, and R. O. Green, 1998: Mapping chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. *Remote Sens. Environ.*, **65**, 267–279.
- Stamnes, K., S.-C. Tsay, W. J. Wiscombe, and K. Jayaweera, 1988: Numerically stable algorithm for discrete-ordinate method radiative transfer in multiple scattering and emitting layered media. *Appl. Opt.*, **27**, 2502–2509.
- Stankov, B. B., A. J. Gasiewski, M. Klein, V. Leuski, B. Weber, V. Irisov, D. Cline, and A. Yevgrafov, 2003: Airborne measurement of snow cover properties using the Polarimetric Scanning Radiometer during the Cold Land Processes Experiments (CLPX02-03). *Proc. Int. Geoscience and Remote Sensing Symp.*, Toulouse, France, IEEE, 683–685.
- Yueh, S., 2003: CLPX-Airborne: Polarimetric ku-band scatterometer (POLSCAT) data. National Snow and Ice Data Center, Boulder, CO, digital media. [Available online at www.nsidc.org/data/clpx.]
- , W. Wilson, and S. Dinardo, 2002: Polarimetric radar remote sensing of ocean surface wind. *IEEE Trans. Geosci. Remote Sens.*, **40**, 793–800.