BOREAS Scanning Lidar Imager of Canopies by Echo Recovery: Level-3 Data

Summary

SLICER data were acquired in support of BOREAS at all of the TF sites in the SSA and NSA, and along transects between the study areas. Data were acquired on 5 days between 18-Jul and 30-Jul-1996. Each coverage of a tower site is typically 40 km in length, with a minimum of 3 and a maximum of 10 lines across each tower oriented in a variety of azimuths. The SLICER data were acquired simultaneously with ASAS hyperspectral, multiview angle images. The SLICER Level 3 products consist of binary files for each flight line with a data record for each laser shot composed of 13 parameters and a 600-byte waveform that is the raw record of the backscatter laser energy reflected from Earth's surface. The SLICER data are stored in a combination of ASCII and binary data files.

Note that the SLICER data are not contained on the BOREAS CD-ROM set. An inventory listing file is supplied on the CD-ROM to inform users of the data that were collected. See Sections 15 and 16 for information about how to acquire the data.

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1. Data Set Overview

1.1 Data Set Identification

BOREAS Scanning Lidar Imager of Canopies by Echo Recovery: Level-3 Data

1.2 Data Set Introduction

Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) is an airborne laser altimeter and surface lidar instrument that acquires canopy height, vertical structure, and ground elevation data along transects that are approximately 50 m wide. The data have a horizontal resolution of approximately 10 m and a vertical resolution of approximately 1 m. Each laser footprint is individually georeferenced by combining the laser ranging data with orientation and positional information provided by the Inertial Navigation System (INS) and

Global Positioning System (GPS), respectively. SLICER was flown onboard a National Aeronautics and Space Administration (NASA) C130-Q aircraft on 5 days between 18-Jul and 30-Jul-1996, acquiring data along transects crossing all the Tower Flux (TF) sites in the Southern and Northern Study Areas (SSA and NSA, respectively) of the BOReal Ecosystem-Atmosphere Study (BOREAS) study region (Harding, 1998).

1.3 Objective/Purpose

The objectives of this activity were to (1) provide the BOREAS project with measurements of canopy structure and ground topography, which are not readily achievable by ground-based or other remote sensing techniques, and (2) utilize BOREAS ground-based canopy measurements to assess SLICER performance and capabilities. Canopy architecture plays a fundamental role in controlling the exchanges of radiative energy, sensible heat, water, carbon dioxide, and trace gases between the surface and the lower atmosphere. Canopy architecture also plays an important role in controlling remote sensing image characteristics, such as the self-shadowing effects on at-sensor radiance observed by passive optical imagers. However, the importance of canopy architecture has rarely been directly quantified due to the difficulty in obtaining consistent, regional observations of three-dimensional canopy structure. The SLICER data collection for BOREAS provides the opportunity to incorporate such observations in an integrated study of the boreal ecosystem.

1.4 Summary of Parameters and Variables

The SLICER data provided to the BOREAS project are a Level 3 product consisting of a mixture of raw and derived parameters for each laser shot yielding a valid return along the flight. The data record for each laser shot consists of 13 parameters and a 600-byte waveform that is the raw record of the backscatter laser energy reflected from Earth's surface. Level 3a consists of all shots along the flight lines that yielded a valid reflection from Earth's surface. Automated software has been applied to identify the ground reflection within each waveform. Level 3b consists of segments extracted from the Level 3a data that are in the vicinity of the TF sites. The Level 3b data have been manually inspected and edited to refine the identification of the ground reflection within the waveforms.

The 13 parameters are the laser shot number; across-track beam position; energy of the transmitted pulse; time of pulse transmission; diameter of the laser footprint on the surface; azimuth and inclination of the laser pointing vector; latitude and longitude of the footprint; elevation of the highest surface within the footprint (e.g., canopy top, or ground where unvegetated); and the distance along the laser vector from the highest surface to what is inferred to be the start, peak, and end of the laser reflection from the ground.

1.5 Discussion

SLICER acquired data on flight lines that crossed each of the TF sites in both the SSA and the NSA in the BOREAS study region. Data on a minimum of 3 and a maximum of 10 flight lines were acquired for each tower site. Additional data were acquired on transect flights between study areas and for calibration purposes. Data for each flight line, which are typically 40 km in length, are contained in individual binary files (Level 3a). For ease of use, where the ground track is close to a BOREAS TF site, the data were extracted from the full flight lines, edited for ground return identification, and stored in separate files (Level 3b). Each file contains 1,001 laser shots centered near a tower, extending approximately 1 km outward from the tower.

The BOREAS SLICER data are available for distribution on two CD-ROMs; one contains the SSA and transect data and the other contains data for the NSA. The CD-ROMs also contain acquisition and processing notes, aircraft flight trajectory data, summary flight line location maps for each study area and tower site, summary plots of each flight line that include line location, aircraft attitude, surface elevation, and return pulse width (a measure of vegetation height), and software for interactively viewing the data in the Interactive Data Language (IDL).

1.6 Related Data Sets

BOREAS RSS-02 Extracted Reflectance Factors Derived from ASAS Imagery
BOREAS RSS-02 Level-1b ASAS Imagery: At-sensor Radiance in BSQ Format

SLICER Level 0, 1, and 2 data are archived and distributed on CD-ROM by the Laser Altimeter Processing Facility (LAPF) at NASA's Goddard Space Flight Center (GSFC). Level 0 consists of raw GPS, INS, and altimetry ranging data as recorded during a flight. Level 1 consists of the aircraft trajectory, derived by a kinematic differential solution applied to the raw GPS records, and INS and altimetry data converted to physical units and segmented into individual flight segments. Level 2 consists of geolocation results (position and elevation) for each laser shot, derived by merging the GPS, INS, and altimetry data, along with some engineering data not included in Level 3. Nadir-viewing VHS video records of the SLICER flight lines are also archived by the LAPF.

The LAPF maintains a World Wide Web (WWW) site at http://denali.gsfc.nasa.gov/lapf that shows location maps and profiles for each flight line. Refer to http://denali.gsfc.nasa.gov/lapf/slicer/slicer.html for SLICER information. The latest software version of a browser for viewing and editing the Level 3 data within IDL is also distributed at the WWW site, along with a sample Level 3 data set for the NSA Old Jack Pine (OJP) site.

2. Investigator(s)

2.1 Investigator(s) Name and Title

David J. Harding, Principal Investigator

2.2 Title of Investigation

The SLICER data acquisition was not a formal part of BOREAS Experiment Plan. It was approved as a no-cost, add-on experiment entitled Airborne Laser Altimeter Characterization of Canopy Structure and Sub-canopy Topography at BOREAS Tower Flux Sites.

2.3 Contact Information

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3. Theory of Measurements

The principles of laser altimetry are rather simple and are based on precise timing of the round-trip travel time of a short duration laser pulse (Bufton, 1989). By combining the range distance, derived from the travel time, with knowledge of the laser pointing vector and the platform position, the horizontal and vertical position of the reflecting target is established in an absolute reference frame (Figure 1). Topographic profiles or images can then be constructed showing the elevation of the reflecting target.

The SLICER instrument extends this altimeter capability by recording a lidar waveform. The lidar waveform is a record of the amplitude of backscattered laser energy received as a function of time (Figure 2). Unlike traditional lidar, where returns from the entire atmospheric column are recorded at low vertical sampling, SLICER records reflections only from Earth's surface (in the absence of clouds). The return signal is recorded at very high vertical sampling, thus providing a finely sampled measure of the vertical distribution of illuminated surface area within the footprint, including plant area throughout the vegetation canopy (Figure 3). Where laser energy penetrates to the canopy floor and is reflected back to the receiver, a measure of canopy height is obtained for that laser pulse from the travel-time between canopy top and ground reflections. The waveform amplitude decreases with depth through the canopy due to occlusion (reflection and absorption) of the transmitted laser energy; less laser energy per unit area penetrates into the canopy with increasing depth. The amount of occlusion at a specific depth into the canopy is dependent on the amount of canopy area encountered higher in the canopy.

The intensity of the received backscatter return at a given depth in the canopy depends on the amount of laser illumination penetrating to that depth, and on the reflectivity of the intercepted surfaces at the wavelength of the laser. Also, the spatial distribution of laser energy is not constant across a laser footprint, but instead has a circular, Gaussian distribution. Therefore, the horizontal organization of reflecting surfaces with respect to the laser energy spatial distribution affects the intensity of the return. In summary, the time history of backscatter energy is a measure of the vertical distribution of illuminated surface area, projected in the direction of the laser vector, weighted by the reflectance of the surfaces at the monochromatic laser wavelength and the spatial distribution of laser energy across the footprint. The vertical resolution of the backscatter waveform is a function of the duration (i.e., pulse width) of the transmitted laser pulse and the bandwidth (i.e., response time) of the detector used to convert the backscatter energy into an analog signal. The vertical sampling of the backscatter waveform is a function of the sampling rate of the digitizer used to convert the analog signal to a digital record.

The received laser energy reflected from the surface consists of returns due to both single and multiple-scattering events. Single-scattering events consist of photons that encounter only one surface and are reflected directly back to the receiver at 0_ phase angle (parallel illumination and view angles; i.e., hot spot orientation). Multiple-scattering events consist of photons that encounter more than one surface before being reflected back to the receiver, as can be the case for laser energy that is transmitted through foliage and is subsequently reflected from another surface. Laser energy reflected from the ground consists of single-scattered photons, where a gap extends through the entire canopy to the ground in the direction of the transmit pulse, as well as some fraction of multiple-scattered photons. The path for multiple-scattered photons is longer than the straight-line path between instrument and target (the single-scattering path) and thus those photons appear delayed in the waveform compared to single-scattered photons.

The relative strength of the canopy and ground returns provides information on canopy closure. The term canopy closure is used here to mean the fraction of plant area per unit area, projected along the direction of the transmitted laser pulse. It is equal to one minus the gap fraction. The cumulative height distribution of canopy energy, normalized by the total return energy, is a relative measure of canopy closure as a function of height (Figure 3). The measure is relative because the reflectance of the surfaces encountered at 0_ phase angle, at the wavelength of the transmitted laser pulse, determines the return signal strength from each surface. Independent knowledge of the average reflectance of the canopy and ground surfaces within the laser footprint is necessary to convert the cumulative distribution to an absolute measure of canopy closure. The cumulative distribution also makes the simplifying assumption that only single-scattering events contribute to the return signal. Furthermore, the closure measure depends on the spatial organization of plant area and gaps with respect to the Gaussian energy distribution across the footprint. For an equal amount of plant area within a footprint, the plant area concentrated in the center of the footprint will yield a higher measure of closure as compared to that concentrated at the outer edges of the footprint (Figure 4).

See Harding et al. (in review) for a more complete discussion of the measurement theory of surface lidar in the presence of vegetation.

4. Equipment

4.1 Sensor/Instrument Description

The SLICER airborne lidar altimeter system consists of a ranging component and ancillary instrumentation for geolocation. The components of the SLICER system are schematically illustrated in Figure 5. The ranging component consists of a laser transmitter, scan mechanism, receiver telescope, detector, timing electronics, waveform digitizer, and an instrument control and data collection system. The SLICER laser transmitter (Coyle and Blair, 1995; Coyle et al., 1995) is a cavity-dumped, Q-switched, diode-pumped, Nd:YAG oscillator-amplifier. The laser outputs a short duration pulse (4 nsec full-width at half-max pulse width) with a beam divergence of approximately 2 mrad at a wavelength of 1064 nm (near-infrared) and at pulse rates up to 80 Hz. A high-speed oscilloscope is used to visually monitor the temporal character and amplitude of the transmitted and received pulses. The scan mechanism consists of optional lenses for changing the beam divergence, a fixed turning mirror and an oscillating mirror that is rotated by means of a computer-controlled galvanometer. The receiver is a 200-mm aperture refracting telescope with a focal length of 245 mm with aft optics that increase the f-number to 3.65. The detector is an EG&G C30955E silicon avalanche photodiode (Si:APD) that converts optical energy into an output analog voltage with a bandwidth of 50 MHz. The timing electronics consist of a Lecroy 4204 time interval unit (TIU) that has a 156.25-picosec resolution (equivalent to 2.3-cm ranging resolution in a one-way travel sense). The waveform digitizer is a Lecroy 6880B analog-to-digital converter capable of sampling at a rate up to 1.348 giga samples per second. The TIU and digitizer modules are housed in a Camac crate. The instrument control and data collection system is based on a 486DX PC-compatible mother board with the altimetry data stored to hard disk and backed up on 8-mm tape.

The ranging instrumentation is augmented by an INS for precise determination of laser beam pointing, GPS receivers for differential, kinematic determination of aircraft position and for use as a time source, and video equipment for image documentation of the ground track. The INS for BOREAS was a Litton LTN-92 laser ring gyro system. Gyroscopically determined accelerations are converted to roll, pitch, and yaw by the INS and reported at a rate of 64 Hz. The INS data stream is sampled by the altimetry data system at the time of each laser pulse fire, and the roll, pitch, and yaw data are recorded as a part of the altimetry data record for each laser pulse. For position and time data, Ashtech Z-12 dual-frequency GPS receivers were utilized at BOREAS, with the GPS data recorded to laptop computer hard disks. For redundancy, two receivers were deployed both on the aircraft and at the ground base station. The dual aircraft receivers were connected via a signal splitter to a single Ashtech avionics GPS antenna mounted on top of the aircraft fuselage on the airframe centerline. Similarly, the dual ground receivers were connected to a single Ashtech ground plane antenna mounted on a surveyor's tripod above a geodetic benchmark. One of the onboard Ashtech receivers provides time-referencing data for the altimetry data stream. Absolute time is output from the receiver as a GGA message page that is received by a clock box and reformatted for recording by the altimetry data system. In addition, a 1 pulse per second time mark from the GPS receiver is used as a 1-second counter that, in conjunction with a PC timer card containing a GHz oscillator time source, yields 0.016-msec resolution on the laser pulse transmit time. The second in-flight GPS receiver provides real-time position data that are utilized by flight manager software running on a separate laptop computer. The flight manager displays navigation information to the pilot on a color monitor. Color video imagery, acquired using a video camera pointing at nadir, was recorded on to VHS tapes with time annotated on each video frame using an external time-stamp generator that was manually synched to GPS time.

4.1.1 Collection Environment

Data were collected with the SLICER instrument mounted in the interior of a pressurized aircraft. Temperature, although controlled, did vary within the aircraft interior during the course of a flight mission. The temperature variations were not monitored. Although the laser ranging function of the SLICER instrument is not temperature sensitive, the recorded amplitude of the received backscatter laser energy is potentially affected by temperature variations (see Section 11.1).

4.1.2 Source/Platform

The aircraft used for BOREAS was a C130-Q turboprop stationed at NASA GSFC's Wallops Flight Facility (WFF). The aircraft was based at the Prince Albert Airport during the BOREAS deployment. SLICER acquisitions in Iceland, the Azores, and Florida also used the WFF C130-Q aircraft. Remaining SLICER acquisitions utilized a Sabreliner T-39 twin engine jet, also stationed at WFF.

4.1.3 Source/Platform Mission Objectives

The primary mission objective at BOREAS was acquisition of Advanced Solid-state Array Spectroradiometer (ASAS) multilook angle, hyperspectral images of the TF sites. The aircraft was flown on specific headings across the towers in order to acquire ASAS images parallel, perpendicular, and oblique to the solar principal plane. SLICER was operated at nadir on each of the flight lines as ASAS images were acquired. SLICER data were also acquired during transect flights between the SSA and NSA while ASAS acquired nadir view-zenith-angle images. Additionally, specific flight lines were flown to acquire SLICER calibration data.

4.1.4 Key Variables

The principal quantities measured by SLICER are:

1) The round-trip travel time of a short-duration 1064-nm pulse of laser light, from the aircraft platform to the first surface that reflects sufficient laser light above a detection threshold at the receiver.
2) The intensity of the backscatter return reflected from the surface as a function of time.
3) The orientation of the laser pointing vector, obtained from the orientation of the laser scan mirror and an INS measurement of instrument attitude based on gyroscope-determined accelerations.
4) The trajectory of the aircraft, obtained from a kinematic differential solution of dual-frequency GPS observations.
5) Observation time for each of the above quantities.

4.1.5 Principles of Operation

A short-duration, 1064-nm laser pulse (4 nsec full width at half the maximum peak amplitude) is generated by the laser transmitter at rates up to 80 Hz. The laser transmitter is commanded to fire at a specified repetition rate by computer control using an interrupt-driven fire command for each pulse. The transmit time of each laser pulse is established using two time sources. Absolute time is reported by an onboard GPS receiver at 2 Hz and recorded by the altimetry data system. A relative transmit time is measured with 0.016-msec resolution by using a time counter which is based on a PC timer card containing a GHz oscillator that is synched using a 1 pulse per second time mark provided by the GPS receiver. The laser transmitter includes a photodiode detector that samples a small fraction of the output pulse energy at a point within the transmit beam. The voltage signal from the photodiode detector is accumulated in an integrator, yielding a measure of output pulse energy as a single byte value. After exiting the laser transmitter, the intensity of the transmit pulse is modulated by the use of filters in order to achieve a backscatter energy below the saturation limit of the receiver detector. Filters are manually inserted into the transmit beam path by the instrument operator in order to optimize the return signal level. The filter used is not recorded in the data structure.

Output pulses are directed downward and scanned across the aircraft flight direction by means of a galvanometer-driven scan assembly. The computer-controlled galvanometer rotates a small mirror to a specified angular position prior to initiation of each laser pulse fire command. Laser pulse energy that is backscattered from a reflecting surface at 0_ phase angle (i.e., the hot spot orientation) is collected by a receiver telescope and focused onto a 50-MHz Si:APD that converts optical energy into an output voltage.

The output voltage from the detector is split between a TIU and an analog-to-digital digitizer. The TIU precisely measures the time interval between the transmitted laser pulse and the received backscattered pulse based on a leading-edge, threshold-detection scheme. The TIU contains a high-frequency internal oscillator that yields 156.25 picosecond timing resolution of the pulse round-trip travel time, equivalent to a one-way range resolution of 2.3 cm. A start-pulse fiber optic transfers a small portion of the transmit laser pulse energy into the receiver telescope, where it is focused onto the Si:APD detector. The TIU starts when the leading edge of the transmit pulse rises above a start-pulse threshold value, which is established by the instrument operator. The TIU stops when the output voltage of the detector rises above a stop-pulse detection threshold, which is also established by the instrument operator. The detector output voltage can exceed the stop-pulse detection threshold due to a valid return from a reflecting surface or due to instrument electronic noise and/or background solar illumination. A range gate is used to define a ranging time over which the stop-pulse detection threshold will be applied. A signal greater than the detection threshold occurring before or after the range gate does not stop the TIU. The range gate is established by the operator to bracket the distance to the anticipated target (e.g., land surface), given the known flight altitude above the ground. In some cases, no detector output voltage above the threshold occurs within the range gate, yielding a no-range result. The stop-pulse detection threshold and range gate are established to maximize the frequency of ranging to valid returns and minimize the number of noise and no-range results. Valid returns are received from the first encountered surface that backscatters sufficient transmitted laser energy to exceed the stop-pulse detection threshold. This can be an optically dense cloud layer, a vegetation canopy top, bare ground in unvegetated areas, or an ice or water surface.

Upon detection of a signal above the stop-pulse threshold, the TIU measure of the start to stop time interval is recorded, which corresponds to the round-trip travel time of the transmitted laser pulse. A value of zero is recorded for no-range results. In addition to TIU ranging to the first detected return, SLICER implements a surface lidar function by digitizing the time history of the energy backscattered from the surface. Upon detection of the stop pulse, a constant number of bins are read from the digitizer, yielding a waveform for that laser shot that records return amplitude as a function of time. The digitizer continuously samples the detector output and scales the voltage to an 8-bit value. A constant offset is added after scaling to displace the detector mean background noise level, which is zero-referenced, to yield all positive values. The scale factor in the analog-to-digital conversion and the offset applied typically remain constant during a SLICER flight mission, but could vary between flight missions. Upon detection of the TIU stop event, a specified number of bins are read from the digitizer and stored, yielding a waveform that records the return amplitude as a function of time. For most SLICER acquisitions, including BOREAS, 600 digitizer bins were stored.

The vertical resolution of the backscatter waveform is a function of the duration (i.e., pulse width) of the transmitted laser pulse and the bandwidth (i.e., response time) of the detector used to convert the backscatter energy into an analog signal. Vertical resolution refers to the separation required between surfaces in order to distinguish backscatter energy reflected from each of the surfaces. The convolution of the transmit pulse shape in time with the broadening caused by the detector response (defined by its bandwidth) yields an impulse response, theoretically the narrowest possible return signal for reflection from a perfectly smooth, flat surface. The 4-nsec (full-width at half-max) SLICER pulse width and 50-MHz detector bandwidth combine to yield an impulse response pulse width of approximately 6 nsec (full-width at half-max), equivalent to a width of 1.8 m. Note, however, that the width of the impulse response increases with increasing optical energy received (i.e., as the peak amplitude increases). The vertical resolution of the system is one-half the impulse response (0.9 m), because the travel distance of the laser pulse down-and-back between two surfaces is twice their vertical separation.

The vertical sampling of the backscatter waveform is a function of the sampling rate of the digitizer used to convert the analog signal to a digital record. The digitizer samples the detector output voltage at a rate of 1.348 GHz, with a resulting temporal sampling of 0.742 nsec. Because the digitizer is recording the two-way transit time of light (e.g., down through a canopy and back out), the vertical sampling distance is half the temporal sampling (i.e., 0.371 nsec), equivalent to 0.1112 m per waveform bin. The waveform is normally stored at the full digitizer bin resolution (0.1112 m). In some cases, digitizer bins are averaged together before storing in the waveform array, yielding a waveform sampling distance increased by an integer averaging factor. No digitizer averaging was applied to the BOREAS data.

The bins read from the digitizer correspond in time to a range of bins referenced to the TIU stop event, with the stop event assigned in the acquisition software to a specific waveform bin position. For BOREAS, that position is bin 28, using an array-labeling convention where the initial position is bin 0. Bins 0 to 27 of the waveform correspond to the detector output voltage recorded prior to the stop event (i.e., background noise before the start of the return). The remaining bins from the TIU stop event to the end of the waveform (bins 28 to 599) correspond to a height range of 63.6064 m (572 bins x 0.1112 m/bin), which is significantly greater than the height of the canopies studied. Thus, the waveform extends beyond the distance at which the ground return is expected. The last portion of the waveform, therefore, corresponds to background noise occurring after any ground reflection. The digitizer implementation in SLICER is flexible, permitting adjustment in the number of total bins, distance resolution per bin, and bin position of the TIU stop event. The values reported here are specific to the BOREAS data set. Appropriate digitizer factors for other data sets are contained in the header record of each Level 3 data file.

The location of the laser footprint, referenced to the first detected reflection, is determined by combining the TIU ranging data with knowledge of the laser pointing angle and the absolute position of the aircraft derived from a GPS trajectory. The laser pointing angle is determined by combining the scan mirror angle with a measurement of instrument orientation, obtained using a Litton LTN-92 INS. The INS reports roll, pitch, and yaw parameters computed from gyroscope-determined accelerations at a rate of 64 Hz The INS data stream is sampled by the altimetry data system at the time of each laser pulse fire, and the roll, pitch, and yaw data are recorded as a part of the altimetry data record for each shot. The aircraft trajectory is determined by postflight processing of 2-Hz differential kinematic GPS data employing GPS receivers on the aircraft and at a fixed base station. Ashtech Z-12 dual-frequency receivers were used for this study.

4.1.6 Sensor/Instrument Measurement Geometry

The GPS avionics antenna is mounted on top of the aircraft fuselage on the airframe centerline. The x, y, and z offsets from the GPS antenna to the laser altimeter receiver are established with a measuring tape. For BOREAS, the base station GPS receiver was installed over a permanent survey mark selected by the GPS technician (Earl Frederick, NASA GSFC EG&G contractor) near the Prince Albert Airport runway. The following published position for the survey mark, in WGS84 coordinates, was used to compute the trajectories: 53_ 12" 59.160480' N, 105_ 39" 37.141840', elevation 402.6360 meters. The GPS tripod and antenna were reinstalled over the survey mark for each flight, and the height of the antennae above the mark was measured on each flight day.

The laser transmitter, receiver, and INS are all mounted on an optical bench in order to maintain alignment between these devices. The optical bench is mounted inside the aircraft above an optical-quality, fused-silica window that is 17 inches in diameter. The laser transmitter, mounted on top of the optical bench, generates a horizontally transmitted laser pulse. Spatially each laser pulse is circular in cross-section with a Gaussian distribution of energy. The divergence of the laser beam ranged from approximately 2 mrad, defined as the angle at which the pulse energy has fallen off to $1/e^2$ times (13.5%) that at the beam center. Temporally, the laser pulse has a Raleigh distribution with a fast leading-edge rise time, on the order of 1.5 nsec, and a trailing-edge that falls off more slowly asymptotically.

The transmit beam scan assembly is attached to the laser transmitter box at the exit aperture of the laser beam. Lenses can be installed in a mount in the scan assembly that causes the laser beam to diverge more than the nominal 2-mrad transmit divergence. Lenses producing beam divergence of approximately 3 mrad, 8 mrad, and 10 mrad are available. All but one flight line at BOREAS were acquired using the standard divergence of approximately 2 mrad. One flight line flown at a low altitude (line 8 on 29-Jul) was acquired using the lens yielding a divergence of approximately 10 mrad. The horizontally transmitted laser pulses are reflected downward in the scan assembly and pass through a tube that extends from the scan assembly to the window. The laser pulses are scanned in a direction perpendicular to the aircraft flight direction by means of a small mirror that is rapidly rotated to fixed angular positions using a galvanometer. The laser transmitter is triggered by computer control to fire a single laser pulse after the mirror is rotated to a specified position. For BOREAS, five laser pulses were typically fired for each cross-track scan (Figure 6), although for two flight lines the galvanometer was held fixed at nadir, yielding a single-beam profile (lines 6 and 8 on 29-Jul). The resulting pattern of laser footprints on the ground depends on their size and along-track and cross-track spacing (Figure 6). The footprint size depends on the laser divergence and aircraft altitude above ground. The nominal flight altitude above ground at BOREAS was 4500 m, yielding footprints nominally 9 m in diameter. Cross-track footprint spacing is determined by the angular separation between successive transmitted pulses and aircraft altitude above ground. The angular separation is determined by the programmed angular positions of the mirror and aircraft roll. For this work, the galvanometer was controlled to yield footprints that are contiguous across the track during level flight (i.e., 2-mrad cross-track angle yielding 9-m cross-track spacing). However, low-frequency roll excursions of several degrees during data acquisition, combined with the high-frequency galvanometer scanning, make the cross-track pattern of footprints non-uniform. Along-track spacing is determined by laser pulse repetition rate, number of cross-track footprints, aircraft ground speed, and changes in pitch attitude. Changes in pitch were small and thus have an insignificant effect on along-track spacing. With five cross-track footprints and a laser pulse repetition rate of 80 Hz, the typical ground speed resulted in a nominal along-track spacing of approximately 10 m. However, wind speed and direction at the aircraft altitude affects ground speed and the resulting along-track spacing.

Laser illumination backscattered from reflecting surfaces within each footprint is collected in a receiving telescope that has an aperture diameter of 20 cm and a 10 mrad field-of-view (FOV). The telescope housing extends downward from optical bench to just above the window. The amount of backscatter energy collected by the telescope depends on its aperture and the distance to the reflecting target, decreasing with the square of the distance assuming Lambertian scattering from the target. The five contiguous, cross-track footprints (each having 2-mrad divergence) were aligned to fit across the 10-mrad receiver FOV. The receiving telescope's optical efficiency is uniform across most of the FOV but declines at the edges by approximately 15%, so the backscatter energy collected for the outer scan footprints is slightly lower than for the central footprints.

The backscattered laser light and any background reflected solar illumination collected by the receiver telescope is focused through a bandpass filter onto a 1-mm-diameter Si:APD. The bandpass filter significantly reduces background solar illumination by only permitting transmission of light in a narrow, 2-nm-wide wavelength range centered at the laser wavelength. The Si:APD detector converts input optical energy into an output voltage. The high bandwidth of the detector (50 MHz) achieves temporal resolution of the backscattered laser energy that is nearly equal to the duration of the transmitted pulse. The combination of narrow laser pulse width and high detector bandwidth yields a vertical resolution of approximately 0.9 m, where vertical resolution refers to the separation required between surfaces in order to distinguish backscatter energy reflected from each.

4.1.7 Manufacturer of Sensor/Instrument

The SLICER system was designed and integrated by personnel at NASA GSFC. Bryan Blair (Code 924, (301) 614-6741, bryan@avalon.gsfc.nasa.gov) led the development of the SLICER system, adapting the Airborne Topographic Laser Altimeter System (ATLAS), a profiling laser altimeter, developed by Jack Bufton (Code 920, (301) 286-8591, jbufton@pop900.gsfc.nasa.gov). ATLAS was first modified by the addition of a new laser transmitter and the waveform acquisition capability (Blair et al. 1994), and subsequently by the addition of the scanning capability.

The manufacturers of the principal components in SLICER are:

Laser transmitter:
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Scan mechanism:
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Galvanometer in scan mechanism:
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109 Smith Place
Cambridge, MA 02138
(617) 441-0600

Receiver telescope:
NASA GSFC, Jack Bufton, lead

Code 920, (301) 286-8591, jbufton@pop900.gsfc.nasa.gov

Detector:
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45 William Street
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(781) 237-5100

Timing electronics and waveform digitizer:
LeCroy Corporation
700 Chestnut Ridge Rd
Chestnut Ridge, NY 10977
(800) 553-2769

Inertial Navigation System:
Litton Industries, Inc.
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(818) 598-5000

GPS Receivers:
Magellan Corp./Ashtech Precision Products
471 El Camino Real
Santa Clara, CA 95050-4300
(408) 615-5100

GPS to altimeter clock box:
NASA GSFC, John Ward, lead
Code 571, (757) 824-1010

4.2 Calibration

Calibration of the SLICER system includes measurement of laser pulse divergence and temporal quality, time and angle biases between the INS unit and the laser transmitter, a system delay range bias, and laser pulse transmit energy.

Precise measurement of far-field laser beam divergence is difficult. For the SLICER laser transmitter, divergence was measured in the laboratory for the as-transmitted divergence (approximately 2 mrad), and with lenses in place that are used to increase the divergence (to approximately 3, 8, and 10 mrad). Several standard divergence measurement methods were used, yielding inconsistent results; the reported divergence values are accurate only at the 10% level.

Temporal beam quality (pulse shape and duration) is calibrated by measurement in the laboratory using high-speed detectors and an oscilloscope. Components of the laser transmitter are individually aligned in order to minimize the pulse width (at approximately 4 nsec full-width at half-max) and to yield a Raleigh distribution of energy with time having a minimal 'back porch' effect (see Section 11.2).

INS-to-altimeter time and attitude biases are calibrated using roll and pitch maneuver data (typically +/- 5 degrees for each axis) acquired in-flight over water, which provides a flat, level reference surface. Small lakes in or near the SSA and NSA were utilized in the case of BOREAS. The roll and pitch maneuvers cause systematic variations in the ranging distance to the water surface. Biases are found by iteratively varying each until the resulting elevation for the water derived from the geolocation process is level (exclusive of wave structure). The degree to which the water surface is level in the geolocation results is qualitatively assessed by visually examining elevation profiles. Time delays between firing of a laser pulse and the recorded roll, pitch, and yaw parameters are established first. The time delays for each of the attitude parameters consists of two components, an INS instrument reporting delay and a synch-up delay between the constant INS data rate and the software-controlled laser fire rate. The INS instrument reporting delay is constant for each parameter and is determined by applying a time offset that yields level water. The synch-up delays change between each data file and are determined by an iterative shifting and interpolation of the recorded attitude parameters with respect to the laser fire times that is done automatically as a part of the geolocation processing. Roll and pitch alignment biases are also established by iteratively varying each until a sufficiently level water surface results. The geolocation results are insensitive to small errors in yaw, so no yaw bias is established or applied to the attitude data.

The TIU range data are corrected for a range bias due to a system timing delay caused by optical and electronic signal delays, which vary between installations of the instrument. The system delay is found by solving for the elevation of a surface at a known distance. Typically, data acquired in a flight across a site with an established geodetic benchmark are used, such as the location of the GPS base station, yielding an end-to-end system delay measurement. The system delay established for the BOREAS installation was 15.4 m.

The transmit energy per pulse was measured in a laboratory prior to installation on the aircraft using an external energy meter. The transmit energy per pulse is nominally 0.7 mJ. However, the transmit energy jitters from shot to shot by about 10% due to random effects. During flight, the laser output energy per shot is monitored by an internal photodiode detector and recorded in the data structure, but the noise level on this monitor is very high (as much as 50% of signal), greatly exceeding the actual energy variation due to shot-to-shot jitter.

In addition to random shot-to-shot jitter, laboratory results document that the laser output energy varies significantly as a function of laser temperature. The transmitter operates most efficiently when the laser diodes are at 30 _C; below and above this temperature, the transmitter is less efficient and pulse energy is reduced. Excess heat is generated during operation of the transmitter, so a thermal management system (thermal electric coolers, copper heat strapping to a heat sink, and fans) is used to remove the excess heat, maintaining the diodes at or near 30 _C. The shot energy monitor does show long-term variations during the course of a flight line acquisition that is likely due to changes in laser transmitter temperature. A fairly rapid increase in laser energy over several minutes at the start of an acquisition is likely due to the diode temperature increasing from ambient conditions up to 30 _C. A gradual decrease in shot energy then often occurs, probably as the diode temperature slowly exceeds 30 _C. However, the observed variations may also be artifacts due to thermally induced mechanical flexure of the photodiode detector mount. In addition, mechanical instability of the pulse energy monitor has been observed, where aircraft attitude variations (especially during pitch calibration maneuvers) cause significant variation in the recorded pulse energy levels. Also, in some instances the long-term trend in laser transmit energy is abruptly offset in amplitude. The amplitude offset is constant and applies to large, continuous segments of laser shots (100's to 1000's of shots). The abrupt offsets are probably not actual changes in transmit energy. The cause of the offset is not known but is likely due to a gain or bias shift in the start pulse energy detection electronics.

4.2.1 Specifications

The waveform digitizer sampling rate, defining the 0.1112 m vertical sampling per waveform bin, has not been independently calibrated. Factory specification of the digitizer is relied on for this value.

Factory specifications for the LTN92 INS unit are a sampling resolution of 0.1 mrad and a drift rate of 0.17 mrad per axis per hour during operation.

4.2.1.1 Tolerance

Due to problems detailed above, the laser pulse energy measure contained within the Level 3 data structure should be considered unreliable. Furthermore, the intensity of the transmit pulse is modulated by the use of filters in order to achieve a backscatter energy below the saturation limit of the receiver detector. Filters are manually inserted into the transmit beam path by the instrument operator in order to optimize the return signal level. The filter is inserted in the beam path after the position of the internal pulse energy monitor, and the filter used is not recorded in the data structure. Therefore, the pulse energy measure in the data structure is both unreliable and incomplete.

4.2.2 Frequency of Calibration

Beam divergence has been measured only one time for the SLICER instrument, in 1995, due to the difficulty of the measurement. Beam temporal quality and transmit energy are typically measured immediately prior to installation of the instrument in the aircraft, as was done for BOREAS.

Roll and pitch maneuvers over water are normally conducted at least once on each flight day. The INS reporting delay remained constant as expected during the BOREAS deployment. Ideally, alignment biases should also remain constant for the duration of an installation. However, small alignment bias variations have been observed from day to day, and even during a single flight, so roll and pitch biases specific for each flight day are used in the geolocation processing. The cause of the alignment bias variations is unknown, but is likely related to the unexplained drift between the transmit pulses and receiver FOV (see Section 11.1) and/or to temporal drifts in the INS attitude solution.

Flights across the GPS base station to establish the range bias due to the system delay were conducted on several days at BOREAS, but only one flight yielded a SLICER ground track close enough to the base station to be used to establish the bias.

4.2.3 Other Calibration Information

The LTN92 INS unit is maintained by the Aircraft Operations Branch at WFF. It is periodically returned to the manufacturer for recalibration on a routine maintenance schedule.

5. Data Acquisition Methods

A SLICER flight mission typically consists of the following steps:

1) Collect GPS data at both the fixed base station and onboard the aircraft while the aircraft is not moving for a period of approximately 30 minutes, in order to provide static differential data to initialize the forward kinematic solution.
2) Initialize the INS unit while the aircraft is not moving.

3) After takeoff, fly over a water surface at approximately 10,000 ft in level flight to align the laser footprints within the receiver FOV by manually adjusting mirror mounts to maximize the return energy for each footprint (returns off of a water surface are normally used as it provides a flat reference target with uniform albedo).
4) Acquire data over a water surface at approximately 10,000 ft, conducting a sequence of roll maneuvers and pitch maneuvers (typically +/- 5 degrees for each axis) to be used in data postprocessing to establish time and angle biases between the laser altimeter and INS unit.
5) Acquire data across the target sites, typically at an altitude of 17,500 ft (approx. 5,000 m) above mean sea level, using a flight management system that displays aircraft position (obtained from a GPS receiver) relative to a programmed flight line (at BOREAS the desired flight line was defined by preprogrammed coordinates for the tower positions and a flight orientation through a tower site established in-flight by ASAS requirements for a specified azimuth with respect to the solar principal plane); data acquisition is typically initiated several minutes prior to reaching the target location and terminated several minutes after passing the target (flight time to a target location is reported by the flight management system).
6) Prior to landing, acquire data across the GPS base station location to be used in data postprocessing to establish the system range bias.
7) After landing, collect GPS data at both the fixed base station and onboard the aircraft while the aircraft is not moving for a period of approximately 30 minutes, in order to provide static differential data to initialize the backward kinematic solution.

Due to time constraints imposed by ASAS acquisition requirements, steps 3 through 6 were not necessarily completed in that order nor were all those steps always completed for every flight mission.

6. Observations

6.1 Data Notes

Data processing notes for production of the Level 3 data for each flight line are included on the Level 3 CD-ROMs in day-specific subdirectories in the Procdata directory.

The file fluxtowr.sum in the Documnts directory on the Level 3 CD-ROMs contains a summary that lists, for each SLICER flight line, the BOREAS TF site(s) crossed by that flight line, and the approximate laser shot number in the data record closest to the tower.

6.2 Field Notes

Instrument operator log notes for each flight day are included on the Level 3 CD-ROMs in the Documnts directory.

7. Data Description

7.1 Spatial Characteristics

7.1.1 Spatial Coverage

A SLICER flight line typically consists of a 45-m-wide swath composed of five cross-track laser footprints (Figure 6). For BOREAS acquisitions, the length of each flight line varies, but is typically about 40 km. In a few cases, profile data were acquired (no cross-track scanning of the footprints). Flight lines across all TF sites in the SSA and NSA were acquired, with a minimum of 3 lines and a maximum of 10 lines per site. Data were also acquired on transect lines between the study areas, and for calibration purposes. The North American Datum of 1983 (NAD83) coordinates for the tower sites are:

Site	Longitude	Latitude
NSA-BVP	98.02747° W	55.84225° N
NSA-FEN	98.42072° W	55.91481° N
NSA-OBS	98.48139° W	55.88007° N
NSA-OJP	98.62396° W	55.92842° N
NSA-YJP	98.28706° W	55.89575° N
SSA-FEN	104.61798° W	53.80206° N
SSA-OBS	105.11779° W	53.98717° N
SSA-OJP	104.69203° W	53.91634° N
SSA-YJP	104.64529° W	53.87581° N
SSA-9OA	106.19779° W	53.62889° N
SSA-9YA	105.32314° W	53.65601° N

7.1.2 Spatial Coverage Map

The SLICER Level 3 CD-ROMs contain summary flight line location maps for each study area and detailed maps for each tower site, as well as summary plots of each flight line that include a location map.

7.1.3 Spatial Resolution

Each illuminated laser footprint is circular and is nominally 9 m in diameter. The cross-track spacing between footprints is variable, but is nominally 9 m. The along-track spacing is also variable, but is nominally 10 m. See Section 4.1.6 for a discussion of parameters that influence footprint diameter and spacing.

7.1.4 Projection

Each laser footprint is individually georeferenced with latitude, longitude, and elevation to the World Geodetic System of 1984 (WGS84) ellipsoid. Latitude and longitude in the WGS84 ellipsoid reference frame are essentially identical to those referenced to the NAD83 ellipsoid. The two can be considered to be identical for all practical purposes.

7.1.5 Grid Description

Not applicable.

7.2 Temporal Characteristics

7.2.1 Temporal Coverage

SLICER data were acquired on five flight days between 18-Jul and 30-Jul-1996.

7.2.2 Temporal Coverage Map

Data were acquired for NSA sites on 18-Jul and 24-Jul; for the SSA sites on 20-Jul, 29-Jul, and 30-Jul; and on transects between the study areas on 18-Jul and 24-Jul-1996.

7.2.3 Temporal Resolution

In SLICER's typical operating mode, the laser pulse repetition rate is 80 pulses per second. Each laser pulse yields a unique observation. The time between flight lines across a tower site on a flight day varied between tens of minutes and several hours.

7.3 Data Characteristics

Data characteristics are defined in the companion data definition file (lidar3.def).

7.4 Sample Data Record

Sample data format shown in the companion data definition file (lidar3.def).

8. Data Organization

8.1 Data Granularity

The smallest unit of SLICER data that can be ordered is a CD-ROM of SLICER data and associated ancillary files. On the CD-ROMs the smallest unit of data is the Level 3b flight line, which is binary data files corresponding to data near flux towers. These files each contain 1,001 laser shots centered near a tower, extending approximately 1 km outward from the tower. The Level 3a binary files, containing all data along a flight line, contain tens of thousands of laser shots typically extending for 40 km.

8.2 Data Format(s)

The BOREAS CD-ROM inventory listing file consists of numerical and character fields of varying length separated by commas. The character fields are enclosed with single apostrophe marks. There are no spaces between the fields.

The GPS aircraft trajectory files are stored as ASCII data. A trajectory file consists of ASCII data composed of one header record and then a data record for each GPS epoch. The header record consists of one parameter and a data record consists of eight parameters. The naming convention for these files consists of an eight-character name and a .trj suffix. The eight characters consist of YY_MM_DD, where YY is the last two digits of the year in which the data were collected, MM is the month of the year, and DD is the day of the month. The trajectory files are located in the Gps_misc directory on the SLICER CD-ROMs.

The SLICER data files are stored as binary data. A SLICER data file consists of binary data composed of one header record and then a data record for each laser shot. The header record consists of 4 signed long integers and a data record consists of 13 signed long integers and a byte array composed of 600 elements. The long integer byte order follows the Motorola (UNIX or Macintosh) convention. The bytes must be swapped for use on systems following the Intel convention (PC or VAX). Some of the parameters are stored as scaled integers and must be divided by a scale factor per the following table in order to be converted to the units as defined in Section 7.3.3. Note that scale factors of sufficient precision must be used to achieve the necessary precision for the output results.

Parameter	Stored As	Bytes	Scale Factor Divisor	Scale Factor Precision	Output As	Bytes
header record:						

tiu_bin	long	4	none	-	long	4
dig2wf	long	4	none	-	long	4
wvfm_bins	long	4	none	-	long	4
numshots	long	4	none	-	long	4
data records:						
shotnum	long	4	none	-	long	4
beam	long	4	none	-	long	4
starten	long	4	none	-	long	4
gpstime	long	4	1.00E+04	double flt	double flt	8
diameter	long	4	1.00E+06	float	float	4
azimuth	long	4	1.00E+06	float	float	4
inclination	long	4	1.00E+06	float	float	4
latitude	long	4	1.00E+06	double flt	double flt	8
longitude	long	4	1.00E+06	double flt	double flt	8
elevation*	long	4	1.00E+06or04*	float	float	4
grndstart	long	4	1.00E+06	float	float	4
grndpeak	long	4	1.00E+06	float	float	4
grndend	long	4	1.00E+06	float	float	4
waveform	byte array	600	none	-	byte array	600
Data Record Total:		652				664

* NOTE: The elevation scale factor of 1.00E+06 limits the highest elevation that can be stored as a signed long integer to be 2,147.48 m (i.e., [2^32]/2*1E-6). This is an adequate maximum elevation for the BOREAS data, but is inadequate for sites where the topography exceeds this limit. SLICER Level 3 CD-ROMs for non-BOREAS sites where the topography exceeds the limit along any data line for that site were created using a scale factor of 1.00E+04, yielding a maximum permissible elevation of 214,748 m. Flight days using the 1.00E+04 elevation scale factor are 19-Sep, 20-Sep, 24-Sep, 28-Sep, and 30-Sep in 1995, and 21-Feb-1997. Also, all flight days in 1993 use the 1.00E+04 factor. The latest version of the SLICER browser software available from http://denali.gsfc.nasa.gov/lapf/slicer/browser.html automatically applies the appropriate elevation scale factor when reading the data into IDL.

SLICER data files consists of two types. Level 3a data consist of all valid laser returns along a flight line. The location of the ground return in these files has been identified by automated signal processing software. The naming convention for these files consists of an eight-character name and a .dat suffix. The eight characters consist of YYMMDDLL, where YY is the last two digits of the year in which the data were collected, MM is the month of the year, DD is the day of the month, and LL is the flight line number on that day. Flight lines are numbered in sequence in the order in which they were collected. Some line numbers refer to instrument calibrations, either done on the ground (pre- or postflight) or in-flight (fiber calibrations), during which no surface returns are collected. These calibration lines have not been included in the SLICER data, so flight line numbers can be skipped. In some cases, flight lines are broken into segments for processing purposes, designated by a and b as part of the LL label. The Level 3a files (.dat extensions) are located in flight-day specific subdirectories within the Procdata directory on the SLICER CD-ROMs.

Level 3b data consist of segments of laser shots copied from the Level 3a flight lines. These files each contain 1,001 laser shots centered near a BOREAS flux tower, extending approximately 1 km outward from the tower. The automated identification of the ground return for each laser shot has been visually inspected on a plot of the backscatter waveform; errors in ground identification have been corrected by interactive selection of the ground position on the plot (using the IDL data browser routines included on the CD-ROM). The file format is the same as that of the Level 3a data. The naming convention is changed, consisting of an eight-character name and an .edt suffix to indicate the data was edited. The eight characters consist of a four-letter designation of the tower site followed by DDLL (day and line number). The four-letter designation follows the BOREAS site abbreviation conventions (i.e., NOBS, SOBS, SOJP). The Level 3b files are located in the Towr_edt subdirectory within the Sitedata directory on the SLICER CD-ROMs.

The Towr_dat subdirectory within the Sitedata directory on the SLICER CD-ROMs consists of exact copies of the Level 3a data for the 1,001 shot segments near the towers. The automated identification of the ground return location within the waveform has been retained; no manual editing of the ground return location was done. The naming convention follows that of the Level 3b data, except that the .dat suffix is preserved to indicate no editing was done.

9. Data Manipulations

9.1 Formulae

Not provided. Contact D. Harding for information on specific formulae used in data processing.

9.1.1 Derivation Techniques and Algorithms

Derivations in the SLICER Level 3 data products consist of three types: geolocation of the laser footprint, determination of the laser pointing vector orientation, and identification of the ground return in the backscatter waveform.

The laser footprint latitude, longitude, and elevation are derived using geolocation methods adapted by Bryan Blair from those described in Vaughn et al. (1996). Postflight processing software uses rotation matrices to compute the laser footprint in coordinates referenced to the WGS84 ellipsoid, by combining the absolute position of the aircraft platform, the distance to the surface, and the laser pointing vector (Figure 1).

The laser vector inclination and azimuth are computed based on a Euler angle rotational transformation from the roll, pitch, and yaw parameters obtained from the INS.

A sequence of processing steps establishes the ground return position in the backscatter waveform. First, to improve the signal-to-noise ratio of the distribution, the raw digitizer count amplitudes are summed by accumulating the signal in adjacent waveform bins. Typically, four adjacent bins are summed when the data have a bin resolution of 0.1112 m, yielding a 0.44-m vertical sampling, which is approximately one-half the vertical resolution defined by the laser pulse width and detector response. Note that the 6-nsec-wide (1.8-m) impulse response is expressed in the digitized waveform as 0.9 m wide because time in the waveform is divided by two to convert two-way, down-and-back pulse travel to a one-way distance. Next, the mean of the background noise is established using a portion of the waveform not expected to have a signal. Due to the short stature of much of the vegetation in the BOREAS region, the final 10% of the waveform is used beyond any potential last ground return. For other SLICER data sets, where tall canopies can cause a signal return to the end of the waveform, the portion of the waveform prior to the TIU_BIN is used if a statistically sufficient number of bins occur before TIU_BIN. The mean background noise is subtracted from the summed distribution, yielding a signal above the noise level. Negative results, where the variance in the noise causes the waveform signal to be less than the mean noise, are set to zero. The ground reflection in the signal is identified by assuming that it is the last return above noise. The end of the last return is defined as the latest signal above a threshold that is a multiple of the maximum noise in the portion of the waveform used to define the mean noise level. The multiplication factor is adjusted depending on desired detection sensitivity (a higher factor causes fewer false triggers of noise but misses more low ground returns, whereas a smaller factor causes more false triggers of noise after the true ground return but misses fewer low ground returns). The appropriate multiplication factor depends on signal-to-noise and is determined by visual examination of ground profile results for a selected set of test cases. The peak of the last return is defined to be the first inflection in signal strength prior to the end of the last return, identified using its first derivative. The start of the last return cannot be uniquely identified from the raw distribution because backscatter return from low vegetation could be convolved in time with the ground return. Therefore, the start of the last return is identified based on the width characteristics of the asymmetric, Raleigh-shaped system impulse response. The impulse response is the theoretical signal recorded from a smooth and flat surface and depends on the convolved effects of pulse width and detector response. The SLICER impulse response is established from minimum-width returns from water surfaces. A ratio is determined for the impulse response between the width from the signal end to peak compared to the width from peak to start. The observed end-to-peak width of the last return is scaled by this ratio in order to define the start position of the last return. This method accounts for any pulse broadening of the last return due to slope or roughness of the ground within the footprint.

The distances to the ground return start, peak, and end are referenced to the TIU_BIN waveform position. This is the waveform bin corresponding to the first return received above the instrument detection threshold that causes the TIU stop event (i.e., canopy top in the presence of vegetation). The latitude, longitude, and elevation parameters defining the location of the laser return are specific to this TIU_BIN position in the waveform. The TIU stop-pulse bin position is assigned in software and is constant for a data file, but it can vary significantly between files if instrument operational parameters are changed. The waveform bin position corresponding to the TIU stop-pulse time is not recorded in the data system; instead, it is established for a data file by visually assessing multiple, overplotted waveform records. Typically, water returns are used to determine in which bin the signal level first consistently increases above the background noise. This observed bin position is the value recorded in the TIU_BIN parameter of the Level 3 data header.

9.2 Data Processing Sequence

9.2.1 Processing Steps

The SLICER data processing sequence is diagrammed and described in Figure 7.

An editing step is applied in converting Level 2 products to Level 3 in order to delete laser shots that did not yield valid returns. Invalid laser shots that are excluded consist of: (1) no-range data, (2) clouds and noise above an elevation threshold set above the highest expected ground, (3) noise below an elevation threshold set below the lowest expected ground, (4) and a few percent of shots with anomalously low start pulse energy (described in Section 11.2). No-range data consist of laser shots for which no backscatter signal was received above the instrument detection threshold. For the BOREAS data, the high and low elevation thresholds to remove cloud returns and noise were 700 and 0 m, respectively.

9.2.2 Processing Changes

None.

9.3 Calculations

9.3.1 Special Corrections/Adjustments

In some instances of very low return amplitudes throughout the waveform, the algorithm described in Section 9.1.1 finds no signal above the ground end detection threshold. In those instances, the ground start, peak, and end positions are assigned to the last three bins at the end of the waveform as a flag to indicate failure to detect any waveform signal above threshold. In other SLICER data sets with tall canopies, the positions are set equal to the TIU_BIN to flag no signal detection.

The standard determination of the ground return position fails for saturated ground returns (see Section 11.2 for a description of saturated returns). In saturated cases, the threshold determination of the end of the ground return often corresponds to a small detector ringing peak after the return. Software checks are included to minimize detection of these false peaks. Also, because the saturated peak does not have a well-defined inflection point, the ground peak is simply set to the mid-point of the saturated portion of the waveform. Thus, the peak to end half-width does not have physical significance. Lacking a valid half-width, the ground start is defined to be the point prior to the peak at which the slope of the waveform record decreases below a constant, but arbitrary, magnitude. The cutoff slope magnitude is selected so that the resulting ground start positions look qualitatively correct. The determination of the ground end, peak, and start is noisier and thus less accurate when the ground return is saturated. Also, the ground start technique for saturated returns will not effectively separate returns from vegetation directly above the ground. However, in most cases saturation of the ground return occurs where the surface is unvegetated and the intensity of the transmit pulse reaching the ground is not diminished by any overlying vegetation.

9.3.2 Calculated Variables

The distance from the instrument to the reflecting target is computed from the TIU round-trip travel time by multiplying by the speed of light through an atmosphere of standard temperature and pressure.

The laser footprint latitude, longitude, and elevation are derived using geolocation methods adapted from those described in Vaughn et al. (1996). Postflight processing software uses rotation matrices to compute the laser footprint in coordinates referenced to the WGS84 ellipsoid, by combining the absolute position of the aircraft platform, the distance to the surface, and the laser pointing vector (Figure 1). The offset between the laser instrument and the GPS antenna (the reference point for the aircraft trajectory) is accounted for in the calculation.

The laser footprint diameter is computed as the tangent of the laser divergence times the ranging distance to the target. A divergence of 2 mrad was inadvertently used for all files, causing an error for those flight lines where a greater divergence was used. See Section 11.2 for a list of those files and the appropriate correction that must be applied.

The laser vector inclination and azimuth are computed based on a rotational transformation from the roll, pitch, and yaw parameters obtained from the INS.

The distance from the first detected return in the backscatter signal to the start, peak, and end of the ground return is derived by multiplying the number of waveform bins times the one-way travel distance represented by each waveform bin. The distance per bin is a function of the sampling rate of the waveform digitizer and any digitizer averaging applied. No averaging was used for the BOREAS data so the bin resolution is always 0.1112 m. If digitizer averaging is applied it is reported in the header record of each data file.

9.4 Graphs and Plots

The SLICER CD-ROMs include several types of plots as PostScript (.ps) files. For each flight day, plots located in the Gps_misc directory show attributes of the aircraft trajectory as a function of GPS time (elevation, elevation difference between successive elevations, quality metrics for the kinematic solution). For each flight line, plots located in the day-specific subdirectories in the Procdata directory show a regional location map and profiles of aircraft attitude, elevation of the laser return, and a preliminary version of the backscatter pulse width (an approximation of vegetation height). These flight line plots are also stored as GIF format files (.gif) in the same subdirectories. Regional summary maps showing the SLICER ground tracks for all flight lines at the SSA and NSA are located in the Tower_ps subdirectory in the Sitedata directory.

Detailed flight line maps showing the location of the laser footprint ground tracks in the vicinity of each TF site are also located in the Tower_ps subdirectory in the Sitedata directory. On these maps, small circles indicate the location of individual laser footprints. Four-digit numbers adjacent to ground tracks indicate the acquisition day and flight line number for that track. Plus signs at the center of the maps indicate the location of the tower for that site. Narrow lines extending from the towers indicate the location of ground transects along which canopy properties where measured by Chen (BOREAS Remote Sensing Science (RSS)-07 team). Open squares on these ground transects indicate the location of plots where stem and hemispherical photo data were measured by Rich (BOREAS Terrestrial Ecology (TE)-23 team). The open triangle indicates the location of the target coordinate that was entered into the flight navigation computer to guide acquisition of the data (the target coordinates were approximations of the tower locations and thus not exactly coincident with the towers).

10. Errors

10.1 Sources of Error

The accuracy of the footprint geolocation results (latitude, longitude, and elevation) depends on the accuracy of the ranging data; pointing knowledge; platform trajectory; and determination of the system, angle, and time biases.

The accuracy of the distance measurements from the first return (e.g., canopy top) to the start, peak, and end of the ground return depends on the signal-to-noise ratio in the backscatter waveform, the implementation of automated signal processing routines to identify the ground return, and the resolution and accuracy of the digitizer sampling rate.

The accuracy of the transmit pulse energy measurement depends on instrumental characteristics of the start pulse energy monitor.

10.2 Quality Assessment

10.2.1 Data Validation by Source

SLICER geolocation and elevation results were assessed by differencing the profiles with respect to a Digital Elevation Model (DEM) for the SSA. The National Imaging and Mapping Agency (NIMA) Digital Terrain Elevation Data (DTED) Level 1 DEM product was used for the comparison. DTED Level 1 has a 30 arc second spatial resolution (approximately 90 m). SLICER profiles were shifted with respect to the DTED grid in order to establish the best-fit location for the SLICER profiles based on a minimization of the root mean square (RMS) difference between the SLICER ground elevations and the DTED elevations. Unlike similar comparisons to 3 arc second United States Geological Survey (USGS) DEMs for the conterminous U.S. (Section 10.2.2), very inconsistent results were obtained using DTED, probably due to the low DTED spatial resolution, its relatively poor height accuracy, and uncertainty about what, if any, correction for vegetation height was applied to the DTED elevations. The relatively poor and uncertain quality of the DTED, combined with the extremely low relief of the BOREAS landscape, cause the DTED to be a poor representation of the topography in the BOREAS region. The SLICER to DTED results were, therefore, judged to be unreliable and not a useful measure of SLICER geolocation accuracy. No such comparison was done for the NSA because DTED data are not available for that region.

10.2.2 Confidence Level/Accuracy Judgment

Because SLICER employs a threshold detection method for ranging, the range data are affected by an error source known as range walk. Low amplitude returns typically have slower rise times on the leading edge of the return than do high amplitude returns (Figure 8). Thus, for targets at equal distance from the laser transmitter, the detection threshold is crossed slightly later in time for low amplitude returns as compared to high amplitude returns. As a result, the target with a low amplitude return will appear to be at a slightly greater ranging distance, and thus, lower in elevation. A range walk calibration curve is measured during each SLICER flight by transmitting laser pulses of varying intensity through a fiber optic delay cable of fixed length (fiber calibrations). However, range walk corrections can be effectively applied only to returns from discrete, continuous surfaces, such as bare ground or water, that yield a well-behaved waveform leading edge. Diffuse, vertically distributed surfaces, such as an open vegetation canopy, result in broadened returns with complex leading edges that are not easily corrected for range walk. Therefore, SLICER elevation data in the Level 3 data sets are not corrected for range walk. The resulting uncorrected ranging error is typically in the 10's of centimeters, but can be at the meter level for the greatest excursions of return pulse amplitude.

For the BOREAS aircraft trajectories, forward and backward kinematic solutions were computed and combined in order to optimize the resulting accuracy. For short (< 10 km) separations between the receivers, PNAV yields trajectories with cm-level accuracy. However, for the baseline length used at BOREAS (up to 700 km), the trajectory accuracy is probably at the meter-level (horizontal and vertical) based on unpublished comparisons of trajectories derived for common data sets by PNAV and software optimized for long baselines (GITAR trajectories provided by B. Krabill, GSFC Code 972). The PNAV solution is reliable only with a minimum of five satellites observed and a Position Dilution of Precision (PDOP) of less than 4. The RMS position error is only valid in an absolute sense when certain conditions are met (which is probably not the case for these long baseline flights), but it gives a relative sense of where the solution is of poorer accuracy.

The accuracy of the footprint geolocation results depends on the accuracy of the ranging data; pointing knowledge; platform trajectory; and determination of the system, angle, and time biases. For the high altitudes typical of the BOREAS acquisitions (nominally 4.5 km above ground), pointing errors are the largest source of geolocation errors. Based on the specified accuracy of the INS and the magnitude of the unmonitored alignment drifts, the pointing knowledge accuracy should be on the order 2 mrad, yielding position accuracies equivalent to the laser footprint diameter in the nominal five-beam mode. Geolocation accuracies of this order have been verified for non-BOREAS SLICER data sets by comparing SLICER elevation profiles to corresponding image features (e.g., edges of building, forest clear cut boundaries) in several independently georeferenced high-resolution images and to topography in independently georeferenced DEMs. Many SLICER lines in the conterminous U.S. have been compared to USGS 7.5-minute quadrangle DEMs, which have a horizontal resolution of 3 arc second (approximately 30 m). In most cases, the SLICER elevation profiles match the DEMs, indicating that the SLICER geolocation is accurate at least at the DEM pixel scale. In a few cases, unexplained horizontal offsets of the SLICER profiles are observed (see Section 11.2 for a list of flight lines with known geolocation problems).

The precision and accuracy of the identification of the ground return in the backscatter waveform depend on the algorithm employed (see Section 9.1.1). The precision of the ground start, peak, and end distances is reduced from the intrinsic waveform bin resolution (0.1112 m for BOREAS) by the summation of adjacent bins to improve signal-to-noise. Four adjacent bins are typically summed, yielding a precision of 0.44 m for the ground distance parameters. Also, the half-width determination of the start of the ground return is noisy, at the submeter level, due to the sensitivity of the ground end threshold determination. The ground end threshold technique is sensitive to the asymptotic fall-off in energy of the transmit-pulse trailing edge and to the potential presence of a variable amplitude back porch effect during periods of non-optimal beam quality. A peak fitting approach to selection of the last return likely would achieve a more accurate identification of the ground signal.

The accuracy with which the TIU_BIN position in the waveform can be established depends on the visual inspection of multiple, overlaid waveform plots (see Section 9.1.1). The appropriate bin position can only be determined with this method to within several waveform bins due to bin jitter from shot to shot, and the variable range-walk character of the return pulse leading edge as a function of surface conditions. TIU_BIN jitter is caused by inexact timing synchronization between the TIU oscillator and the waveform digitizer oscillator.

10.2.3 Measurement Error for Parameters

None available.

10.2.4 Additional Quality Assessments

Qualitative assessments of data consistency were made by constructing a variety of plots for SLICER data in the vicinity of each flux tower. Plots included three-dimensional perspective views of canopy top and ground elevation profiles, contoured transect plots of the height distribution of canopy surface area and closure, and plots of individual and averaged canopy height profiles derived from the backscatter waveforms (examples shown in Harding, 1998). No anomalous data characteristics were observed in these plots.

10.2.5 Data Verification by Data Center

Verification by BOREAS staff was minimal. The data header files were read and inventory information was extracted (see Section 7.3). These metadata were loaded in the BORIS data base, and files containing the metadata were extracted for inclusion on the CD-ROM.

The IDL software provided by SLICER personnel was used to view some of the .dat files.

11. Notes

11.1 Limitations of the Data

The amplitude of the backscatter signal in the raw waveform is in units of digitizer counts (0-255). These amplitude counts are not calibrated, nor are they consistent as a function of beam position or time. Thus, the waveform cannot be used as an absolute measure of received backscatter energy. Causes of variation in receive energy per digitizer count include:

1) Detector efficiency and gain.
2) Radial fall-off in the efficiency of the receiver telescope.
3) Scanner-to-receiver alignment.
4) Digitizer offset and gain.

A significant reason for lack of calibration of the digitizer counts is varying efficiency of the Si:APD detector. The detector efficiency in converting input energy to output voltage is temperature dependent; the temperature dependence of the SLICER detector has not been calibrated, nor is the detector temperature controlled. It instead varies with ambient and operating conditions. Therefore, the amplitude of the output voltage is not an absolute measure and can vary with time as the temperature of the detector varies. Furthermore, the gain level of the detector, defining the conversion of input energy to volts, could be varied. Detector gain would typically not be varied during a deployment of the instrument, but could be changed between deployments.

In addition, the receiving telescope's optical efficiency is uniform across most of the FOV but declines at the edges by approximately 15%. Therefore, the backscatter energy is less efficiently collected for the outer scan positions as compared to the central footprints (Figure 9). Furthermore, although the laser scan pattern is aligned to fit within the receiver FOV in-flight, typically at the start of a flight mission, the alignment has been observed to drift during flight due to unknown causes. The alignment drift causes unmonitored variations in return signal strength, especially for the two outer footprints in the five footprint configuration as they can fall partially to wholly outside the receiver FOV (Figure 9).

Finally, the analog-to-digital conversion applied by the waveform digitizer depends on offset and gain factors. These factors are not normally altered during a deployment of SLICER, but can vary from deployment to deployment.

For backscatter waveforms with low amplitude ground returns and/or poor signal-to-noise performance, the threshold method used to identify the ground return (see Section 9.1.1) can miss the ground return. Instead, a higher canopy return is identified as the ground return. In some rare cases, the ground end position is properly identified, but the ground peak position misses the maximum ground return and instead identifies a maximum return from a higher canopy layer. The ground start position is then placed higher up into the canopy by the half-width method. A final error is the identification of waveform noise occurring after, and thus below the ground. These various anomalous ground return detections are usually readily identified by examining a profile plot of the canopy top and ground start, peak, and end elevations.

11.2 Known Problems with the Data

The theoretical shape of the transmit pulse in time is Raleigh, with a sharp leading edge rising to a peak and a slower, asymptotic decrease in energy after the peak (Figure 10). However, with non-optimal alignment of laser transmitter elements, the asymptotic fall-off of laser energy can at times be corrupted, yielding a pronounced step-like "back porch" on the pulse trailing edge (Figure 10). The back porch effect can cause problems in properly identifying the end of the ground return and the pulse width. For BOREAS, the laser transmitter elements were well aligned, and the back porch effect is negligible. For some other SLICER missions, the back porch effect can be prominent and a significant source of error in identifying the ground return. The best characterization of pulse shape, and the magnitude of any back porch effect, is achieved by examining the digitized backscatter pulses reflected from flat surfaces such as water bodies. Note that the 6-nsec-wide (1.8-m) impulse response is expressed in the digitized waveform as 0.9 m wide because time in the waveform is divided by two to convert from two-way (down-and-back) pulse travel to one-way distance.

Received backscatter energy can exceed the detection limit of the Si:APD detector, causing saturation of the amplitude signal. Detector saturation is prevented by reducing the transmit pulse energy. This is accomplished by manually inserting neutral density absorbing filters into the transmit laser pulse path prior to the galvanometer scan assembly. An appropriate filter is selected in-flight by the instrument operator (as a function of flight altitude, atmospheric transmissivity, target reflectivity, and pulse broadening due to within-footprint surface height variability) in order to reduce the maximum received backscatter laser energy below the saturation level of the detector. In some cases, the selected filter is insufficient to prevent detector saturation; for example, when changing from a low-amplitude, broadened return from vegetation to a high-amplitude, narrow return from bare ground.

Detector saturation typically causes specific waveform characteristics (Figure 10). The leading-edge component of the signal, up to the point saturation is entered, accurately preserves the backscatter signal input to the detector. Thus, the TIU range to the first detected surface is correct. When saturation occurs, the detector output voltage remains at a high, nearly constant level (but with detector electronic noise still superimposed on the signal). Due to the detector bandwidth, the saturated output voltage continues later in time than the end of the actual received optical energy reflected from the target. The higher the input signal exceeds the saturation limit, the longer the detector stays in a saturated state. After exiting the saturated state, there is no longer any optical input and as a result, the detector output voltage abruptly drops in amplitude. The detector voltage typically overshoots the background mean noise level, creating an anomalous low, and then enters a 'ringing' phase with anomalous amplitude oscillations about the mean noise level damping out with time. This oscillation causes small false peaks above the noise following the saturated return.

Identification of the ground return start, peak, and end in the waveform is less accurate for saturated returns, and the ground start identification will not properly differentiate return energy from the ground versus vegetation directly above the ground (see Section 9.3.1). However, saturated returns most likely occur when the ground is unvegetated.

In some cases, the entire recorded waveform can be extremely noisy, for either saturated or non-saturated returns. The source, or sources, of the noise is uncertain. One source may be radio frequency interference from pilot transmissions. Often the noise is present as alternating high and low amplitudes between even and odd digitizer bin positions. When no averaging of digitizer bins is applied in recording the waveform, as was the case for BOREAS, this noise between even and odd bins appears in the waveform record. Averaging of adjacent waveform bins can be applied by the data user to greatly reduce this noise. The latest version of the SLICER data browser available from http://denali.gsfc.nasa.gov/lapf/slicer/browser.html always applies averaging of the even and odd bins when plotting the waveform, in order to reduce this noise and improve the waveform appearance.

Due to problems detailed in Section 4.2, the laser pulse energy measure contained within the Level 3 data structure should be considered to be unreliable and incomplete.

In rare instances (a few percent), individual laser shots have markedly lower recorded output energy values than the majority of the other shots. The cause of this reduced laser shot energy is not known, but is possibly due to Q-switch mistiming in the transmitter. These single shots do appear to indeed have significantly lower transmit energies because the ranges for those shots are anomalous, being slightly shortened as compared to adjacent shots, probably due to range walk (see Section 10.2.2). Range walk on these rare low-energy transmit pulses causes the TIU start to occur late, and the resulting range measurement is slightly shorter than normal. The derived elevations are slightly higher (10's of cm) than would be determined with a transmit pulse of normal output energy. Because of this ranging error effect, these low-transmit energy pulses have been deleted from the SLICER BOREAS data products. Although present in the BOREAS data, this effect has never been observed in other SLICER data sets.

Misalignment between the transmitted laser scan pattern and the receiver FOV causes a reduction in receive energy for footprints falling partially outside the receiver FOV. The laser scan pattern is aligned to the receiver FOV in-flight, typically at the start of a flight mission, by manually adjusting mirror mounts to maximize the return energy of each footprint. Laser-to-receiver alignment drift of unknown cause can occur during a flight (Figure 9), causing varying, unmonitored return signal strength, especially of the two outer footprints in the five footprint configuration (as they can fall partially to wholly outside the receiver FOV). For footprints falling partially outside the receiver FOV, the resulting waveform can have an anomalous, low signal-to-noise ratio. The low signal of the return, as compared to the center footprints, also causes greater range walk, and thus an anomalously long TIU range and a resulting low elevation.

The quality of the GPS trajectory for aircraft position depends on the number and angular distribution of observed GPS satellites. The GPS trajectories for each flight day at BOREAS show a large PDOP and RMS excursion near 17 hrs GMT, due to a sub-optimal satellite geometry. The incremental difference of the aircraft altitude, from one altitude measurement to the next, in the GPS trajectory shows little (less than 1 m) to no instantaneous error associated with the onset of these events. However, short-term (seconds to minutes) trajectory errors at the meter-level could be associated with these events due to the Kalman filtering utilized by the PNAV software.

The laser footprint diameter is computed as the tangent of the laser divergence times the ranging distance to the target. A divergence of 2 mrad was inadvertently used in the computation for all files, causing an error for those flight lines where a greater divergence was used to acquire the data. This error is present in one BOREAS file (96072908) and a number of files from other missions. The following files must have the footprint diameter values in the Level 3 files multiplied by the correction factor indicated below to yield the proper diameter. The latest version of the SLICER data browser obtainable from the LAPF Web site automatically corrects the footprint diameters when opening these erroneous files.

YYMMDDLL	Mission Location	Correction
97021912	Puerto Rico	x5
96072908	BOREAS	x5
96072909	BOREAS	x5
95090718	SERC, MD	x5
95092102	Canopy Crane, WA	x5
95092412	Canopy Crane, WA	x5
95092408	Mount Rainier, WA	x1.5
95092410	Canopy Crane, WA	x5
95093004to08	Death Valley, CA	x5
95111603	Orlando, FL	x1.5
95111611to22	Orlando, FL	x5
95111624	Orlando, FL	x5
94082414to17	Performance, MD	x1.5
94082418	Performance, MD	x4
94082419	Performance, MD	x1.5
94100503to07	Duke Forest, NC	x1.5

Many SLICER lines in the conterminous U.S. have been compared to USGS 7.5-minute quadrangle DEMs, which have a horizontal resolution of 3 arc seconds. SLICER lines across the principal target of interest have been compared to the DEMs; lines acquired during transects and calibrations have not been compared. SLICER profiles were shifted with respect to the DEM grid in order to establish the best-fit location for the SLICER profiles based on a minimization of the RMS difference between the SLICER ground elevations and the DEM elevations. SLICER elevations were converted from the WGS84 ellipsoid datum to a mean sea level datum by subtracting the ellipsoid to geoid difference at the footprint location obtained from the Earth Geoid Model 1996 (EGM96). EGM96 was jointly developed by GSFC and the Defense Mapping Agency. In most cases, the position of the best fit match is within +/- one DEM pixel north-south and east-west of the Level 3 geolocation for the SLICER profile. The distance represented by one 3 arc sec DEM pixel is 31 m north-south and is variable east-west, as a function of latitude, but is approximately 24 m. Due to ambiguities in the matching method, one-pixel offsets are probably not significant and do not necessarily imply mislocation of the SLICER data. SLICER data outside the conterminous U.S. have not been assessed in this way due to lack of suitable DEMs. Also, the DEM-matching technique is inaccurate for areas of extremely low relief lacking unique topographic features, such as the BOREAS study areas. In the U.S., low-relief areas where the DEM-matching method failed are the Roanoke River and Performance missions, both acquired on 24-Aug-1994. For the other missions in the conterminous U.S., SLICER lines that matched the DEMs to within +/- one pixel are:

YYMMDD	Mission	Flight Lines

941005	Duke Forest, NC	4, 6, 8
941006	Mahantango, PA	3, 4, 5, 6, 7, 8
950907	SERC, MD	4, 5, 7, 8, 9, 10, 11, 12
950919	Mt. St. Helens, WA	4, 5, 6, 7, 8, 10
950920	Mt. St. Helens, WA	3
950924	Mt. St. Helens, WA	3
950920	Mount Rainier, WA	5, 6, 7, 8, 10, 11, 12, 13
950924	Mount Rainier, WA	5, 6, 7, 8
950921	Canopy Crane, WA	4, 5, 6, 7, 8, 9, 10, 11
950924	Canopy Crane, WA	2, 4, 10
950923	Coast Range, OR	3, 4, 6, 7, 8, 11, 12
950928	Long Valley, CA	2, 3, 4a, 5, 6, 7, 8, 9, 10, 12, 13
950930	Long Valley, CA	2, 3, 4
950903	Death Valley, CA	8, 9
951116*	Orlando, FL	7, 9, 10, 11, 12, 14, 16, 17, 18, 19, 20, 21

* NOTE: SLICER ground elevations for the Orlando mission are consistently below the USGS DEM elevations by an average of 3.0 m. The source of this bias is not known; the most likely sources are use of an incorrect system delay in the SLICER processing and/or use of an incorrect offset between the GPS antenna and SLICER instrument.

In a few cases, horizontal offsets of more than one pixel are observed when comparing the SLICER profiles to the DEMs, indicating unexplained errors in the geolocation results contained in the Level 3 data files. Flight lines known to have errors in geolocation are listed below. The line number, mission, and the offsets between the geolocation position and the best fit to DEM position are given. A positive offset indicates the best-fit match is shifted north and/or east with respect to the geolocation result. If no well-defined minimization of the RMS difference (i.e., convergence) was obtained, 'no convergence' is listed rather than the offsets. Lack of convergence probably indicates that the mislocation offset was larger than the search area over which the SLICER profile was shifted (+/- 30 arc seconds north-south and east-west).

YYMMDDLL	Mission	NS offset	EW offset
94100505	Duke Forest, NC	0.00 m	-49.95 m
94100507	Duke Forest, NC	-30.89 m	-49.93 m
95091912*	Mt. St. Helens, WA	0.00 m	64.11 m
95092401*	Mt. St. Helens, WA	0.00 m	-106.99 m
95092112	Canopy Crane, WA	92.67 m	-128.96 m
95092309	Coast Range, OR	0.00 m	-43.94 m
9509284b	Long Valley, CA	-24.46 m	154.44 m
95092811	Long Valley, CA	no convergence	
95093007	Death Valley, CA	no convergence	
95093010	Death Valley, CA	30.89 m	49.68 m
95111606	Orlando, FL	-123.56 m	-27.10 m
95111608	Orlando, FL	-61.78 m	245.29 m
95111613	Orlando, FL	30.89 m	54.26 m

* NOTE: The caldera dome at Mt. St. Helens experienced significant (100's of meters) growth between the time the acquisition of stereo photos used to construct the DEM and the SLICER mission. This dome change may be biasing the matching results, causing an erroneous offset.

The elevation scale factor of 1.00E+06 (used to convert the signed integer elevation values stored in the Level 3 files to meters) limits the highest elevation that can be stored to 2,147.48 m (i.e., [2^{32}]/2*1E-6). This is an adequate maximum elevation for the BOREAS data, but is inadequate for sites where the topography exceeds this limit. SLICER CD-ROMs for non-BOREAS sites where the topography exceeds this limit along any data line for that site were created using a scale factor of 1.00E+04, yielding a maximum permissible elevation of 214,748 m. The 1.00E+04 elevation scale factor was used on 19-Sep, 20-Sep, 24-Sep, 28-Sep, and 30-Sep-1995, and 21-Feb-1997. Also, all flight days in 1993 use the 1.00E+04 factor. The latest version of the SLICER browser software available from http://denali.gsfc.nasa.gov/lapf/slicer/browser.html automatically applies the appropriate elevation scale factor when reading the data into IDL.

Two flight lines are mislabeled on the map showing the location of ground tracks in the vicinity of the SSA-OJP tower located in the Tower_ps subdirectory in the Sitedata directory. The labels for lines 96072909 and 9607296b are inadvertently switched on the map. Also, the flight log notes for 96072909 should indicate that, like 96072908, it was acquired at approximately 2,400 feet above ground level using a 10-mrad beam divergence in profiling mode.

11.3 Usage Guidance

In order to find SLICER data for a specific BOREAS tower site, refer to the file fluxtowr.sum in the Documnts directory on the SLICER CD-ROMs. It contains a summary that lists for each SLICER flight line the TF site(s) crossed by that flight line, and the approximate laser shot number in the data record closest to the tower. Also, detailed flight line maps, as PostScript files, showing the location of the laser footprint ground tracks in the vicinity of each tower are located in the Tower_ps subdirectory of the Sitedata directory. Each ground track is labeled with a four-digit number corresponding to the flight day of year and line number.

Due to the numerous instrument factors that affect the digitized record of backscatter return (described in preceding sections), the SLICER waveform amplitudes are uncalibrated and should not be used as an absolute measure of return signal strength nor of surface reflectance. Some of the factors affecting return signal strength are constant. In particular, the outward fall-off in receiver telescope sensitivity is constant, and the resulting lower return strength of the outer beams, as compared to the inner beams, could be established by a comparison of returns from a surface of uniform reflectivity, such as water. However, many of the relevant instrument factors are unmonitored and vary slowly over time, including transmit pulse energy, the temperature-dependent detector sensitivity, and alignment drift between the scanned transmit pulses and the receiver telescope FOV. Over short segments of data (seconds to minutes), these slowly varying effects probably do not significantly change instrument performance. Thus, successive shots along a single beam position can be compared in a relative sense. Other unmonitored factors abruptly change digitized signal strength, including filters used to attenuate the transmit beam strength and the digitizer gain setting. Changes in these factors should appear as instantaneous, and usually pronounced, changes in receive energy from shot to shot. However, the attenuation differences between some of the filters are quite small, and the resulting difference in received signal may not be easily recognized. Because of these numerous effects on digitizer amplitude, the most reliable use of SLICER waveforms is to treat each independently and use it only as a relative measure of the vertical distribution of return signal strength for that footprint. Furthermore, for cases of detector saturation, preventing the correct measurement of peak return amplitudes, the waveform record should not be used even in this relative sense.

The Level 3a identification of the ground return start, peak, and end in each waveform is based on automated signal processing software. There are many circumstances in which the ground return can be misidentified (see Section 11.1). In the vicinity of each flux tower, Level 3b products (.edt files in the Towr_edt subdirectory of the Sitedata directory) have been produced where the ground return for each laser return has been visually inspected and edited as needed. Users of Level 3a data, for non-tower data, should inspect, and modify as needed, the automated identification of the ground returns, using the provided IDL-based data browser or other plotting software. Profile plots of individual cross-track beam positions showing the elevation of the canopy top, ground start, ground peak, and ground end (see Section 12) provide a visual indication of incorrectly identified ground return parameters due to inconsistencies from shot to shot along the profile.

In most cases, the SLICER geolocation accuracy is thought to be at the scale of the laser footprint (i.e., approximately 10 m or better). However, some flight lines for non-BOREAS data sets are known to be mislocated by up to 100's of meters based on comparisons with DEMs and georeferenced images (see Section 11.2 for a list of mislocated flight lines in the U.S.). Users of BOREAS SLICER data who are comparing SLICER results to other data at specific locations should confirm the accuracy of the SLICER geolocation results. This is best done by identifying distinctive features in SLICER ground and canopy top elevation profiles, such as distinct forest stand edges, and confirming that these features are consistent with the corresponding features in independently georeferenced high-resolution images.

SLICER elevations are referenced to the WGS84 ellipsoid. To compare SLICER elevations to topographic data (maps or DEMs) which typically use a vertical datum referenced to mean sea level, an ellipsoid to geoid correction needs to be applied. Because the ellipsoid to geoid separation varies spatially, the correction needs to be applied to each laser footprint as a function of its latitude and longitude. The U.S. National Geodetic Survey distributes software called GEOID which computes the ellipsoid to geoid separation within the conterminous U.S. as a function of latitude and longitude. Similar software is likely available for the BOREAS region from the Canadian geodetic survey. EGM96 provides a global representation of the geoid. EGM96 was jointly developed by GSFC and the Defense Mapping Agency.

Latitude and longitude in the WGS84 ellipsoid reference frame are essentially identical to those referenced to NAD83. The two can be considered to be identical for all practical purposes.

Times in the aircraft trajectory files are with respect to GMT and time in the SLICER data files are with respect to GPS time. GMT times are less than the GPS times by a small, constant number of seconds due to the difference between GMT and GPS time in effect at the time of the flight. GMT progressively falls behind GPS time as leap seconds are added to GMT but not to GPS time. The GPS - GMT time difference during the BOREAS acquisition was 11 seconds. During the period of SLICER operations, the GPS - GMT time difference was as follows after the listed date:

31-DEC-1990	+7 sec
30-JUN-1992	+8 sec
30-JUN-1993	+9 sec
30-JUN-1994	+10 sec
31-DEC-1995	+11 sec
30-JUN-1997	+12 sec
31-DEC-1998	+13 sec

11.4 Other Relevant Information

David Rabine (GSFC Code 924 and SSAI) and Sean Warren (GSFC Code 921) operated the SLICER instrument for the BOREAS deployment. Earl Frederick (GSFC Code 972 and EG&G) operated the GPS base station at Prince Albert Airport.

Funding for the development of SLICER was provided by the Goddard Director's Discretionary Fund and NASA's Solid Earth and Natural Hazards Program. Acquisition of the BOREAS SLICER data was funded by NASA's Terrestrial Ecology Program through an RTOP grant to D. Harding. Processing and generation of BOREAS data products was conducted by the LAPF using funding provided by NASA's Mission to Planet Earth Program Office.

12. Application of the Data Set

The data can be used to construct topographic profiles of the canopy top directly using the elevation parameter, and of the underlying ground using the elevation minus the vegetation height. The canopy top profile consists of the highest detected vegetation surface within each laser footprint. Vegetation height is obtained from the ground start parameter (the distance along the laser vector from elevation to the start of the ground return) corrected for off-nadir pointing by multiplying by the cosine of 90 degrees minus the inclination parameter. The start of the ground return should be used because the TIU ranging component of SLICER is based on leading-edge ranging (i.e., timing is done with respect to the start of the transmit pulse and start of the return pulse). For consistency, ranging to the ground should therefore also be done with respect to the start of the ground return. Using the ground start parameter, the ground profile consists of the highest detected ground surface within each laser footprint.

The broadening of the observed ground return signal as compared to the system impulse response can be used to estimate the height distribution of the ground within the laser footprint. In this way, information on the average within-footprint elevation of the ground and the relief, due to ground slope and/or roughness (Figure 11), can be inferred. This derivation requires deconvolution of the system impulse response from the observed ground return; the data structure parameters of distance to the peak and end of the ground signal include the impulse response pulse width. Therefore, they should not be used directly as measures of the distance to the median and lowest ground surfaces within the footprint.

The vertical distribution of canopy surface area (i.e., within-footprint canopy height profiles) and closure can be estimated from the vertical distribution of backscatter energy recorded in the waveform. Methods for deriving these distributions, and comparisons to ground-truth data, are described in Harding et al. (in review), Lefsky (1997), Lefsky et al. (1998; 1999; in press), and Means et al. (1999).

13. Future Modifications and Plans

None. SLICER was decommissioned in 1998. Experience derived from SLICER was incorporated by Blair et al. (1999) in a completely redesigned, next-generation scanning surface lidar system referred to as the Lidar Vegetation Imaging Sensor (LVIS), which has superseded SLICER. LVIS incorporates a new laser transmitter with a faster pulse repetition rate and a scanned receiver FOV, thus achieving much wider scan patterns, and calibrated measurements of transmit and receive energy. LVIS is primarily used for algorithm development and validation activities in support of the Vegetation Canopy Lidar (VCL), the first mission selected by NASA's Earth System Science Pathfinder Program (ESSP). VCL is scheduled for launch into Earth-orbit in 2000.

14. Software

14.1 Software Description

Aircraft trajectories were produced using PNAV, proprietary software marketed by Magellan Corp./Ashtech Precision Products. PNAV is a Kalman filter-based program that processes GPS observations sequentially by applying carrier-phase processing to dual-frequency, full-wavelength data. Cycle slips are corrected by "on-the-fly" resolution of carrier-phase integer ambiguities.

All other data processing was implemented using IDL, a product of Research Systems, Inc. IDL procedures for processing were written by personnel at GSFC. Geolocation procedures were written principally by Bryan Blair, with contributions from David Rabine and Michelle Hofton. Procedures for identification of ground returns, data editing, formatting, and plotting were written principally by David Harding, with contributions from Jim Roark. David Harding wrote the browser procedures for interactive display and editing of Level 3 data.

14.2 Software Access

PNAV: Magellan Corp./Ashtech Precision Products, 471 El Camino Real, Santa Clara, CA 95050-4300, (408) 615-5100, http://www.magellangps.com.

IDL: Research Systems, Inc., 2995 Wilderness Place, Suite 203, Boulder, CO 80301, (303) 786-9900, http://www.rsinc.com.

IDL processing procedures for SLICER are maintained by the LAPF (contact D. Harding or K. Still; see Section 2.3). IDL procedures constituting the SLICER Level 3 data browser are included on the BOREAS SLICER CD-ROMs. The latest, updated version of the browser is available from http://denali.gsfc.nasa.gov/lapf/slicer/slicer.html.

15. Data Access

15.1 Contact for Data Center/Data Access Information

These BOREAS data are available from the Earth Observing System Data and Information System (EOS-DIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC). The BOREAS contact at ORNL is:

ORNL DAAC User Services
Oak Ridge National Laboratory
(865) 241-3952
ornldaac@ornl.gov
ornl@eos.nasa.gov

15.2 Procedures for Obtaining Data

BOREAS data may be obtained through the ORNL DAAC World Wide Web site at http://www-eosdis.ornl.gov/ or users may place requests for data by telephone, electronic mail, or fax.

15.3 Output Products and Availability

Requested data can be provided electronically on the ORNL DAAC's anonymous FTP site or on various media including, CD-ROMs, 8-MM tapes, or diskettes.

The complete set of BOREAS data CD-ROMs, entitled "Collected Data of the Boreal Ecosystem-Atmosphere Study", edited by Newcomer, J., et al., NASA, 1999, are also available.

16. Output Products and Availability

16.1 Tape Products

None.

16.2 Film Products

None.

16.3 Other Products

Although the inventory is contained on the BOREAS CD-ROM set, the actual SLICER data are not. See Section 15 for information about how to obtain the data.

In addition to the Level 3a and 3b SLICER data files, the SLICER CD-ROMs also contain acquisition and processing notes, aircraft flight trajectory data, summary flight line location maps for each study area and tower site, summary plots of each flight line that include line location, aircraft attitude, surface elevation, and return pulse width (a measure of vegetation height), and programs for use in IDL for interactively viewing and editing the data.

In addition, the LAPF maintains a Web site at http://denali.gsfc.nasa.gov/lapf that shows location maps and profiles for each flight line. Refer to http://denali.gsfc.nasa.gov/lapf/slicer/slicer.html for SLICER information.

17. References

17.1 Platform/Sensor/Instrument/Data Processing Documentation

The SLICER CD-ROMs include instrument and processing documentation in the Docmnts directory as a PostScript file and as a Microsoft Word RTF file. In addition to the material contained herein on Level 3 products, the documentation includes information on Level 2 data products.

17.2 Journal Articles and Study Reports

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Lefsky, M.A., D.J. Harding, W.B. Cohen, G.G. Parker, and H.H. Shugart. 1999. Lidar remote sensing of forest basal area and biomass: application and theory. Rem. Sensing of Environ. 67:83-98.

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17.3 Archive/DBMS Usage Documentation

None.

18. Glossary of Terms

None.

19. List of Acronyms

ASAS - Advanced Solid-state Array Spectroradiometer
ASCII - American Standard Code for Information Interchange
ATLAS - Airborne Topographic Laser Altimeter System
BOREAS - BOReal Ecosystem-Atmosphere Study
BORIS - BOREAS Information System
BSQ - Band Sequential
CD-ROM - Compact Disk - Read-Only Memory
DAAC - Distributed Active Archive Center
DEM - Digital Elevation Model
DTED - Digital Terrain Elevation Data
EGM96 - Earth Geoid Model 1996
EOS - Earth Observing System
EOSDIS - EOS Data and Information System
ESSP - Earth System Pathfinder Program
FOV - Field of View
GIS - Geographic Information System
GMT - Greenwich Mean Time
GPS - Global Positioning System
GSFC - Goddard Space Flight Center
IDL - Interactive Data Language
INS - Inertial Navigation System
LAPF - Laser Altimetry Processing Facility
LVIS - Lidar Vegetation Imaging Sensor
NAD83 - North American Datum of 1983
NASA - National Aeronautics and Space Administration
NIMA - National Imaging and Mapping Agency
NSA - Northern Study Area
OJP - Old Jack Pine
ORNL - Oak Ridge National Laboratory
PANP - Prince Albert National Park
PDOP - Position Dilution of Precision
PNAV - Precise Differential GPS Navigation and Surveying

RMS - Root Mean Square
RSS - Remote Sensing Science
Si:APD - Silicon Avalanche Photodiode Detector
SLICER - Scanning Lidar Imager of Canopies by Echo Recovery
SSA - Southern Study Area
TE - Terrestrial Ecology
TF - Tower Flux
TIU - Time Interval Unit
URL - Uniform Resource Locator
USGS - United States Geological Survey
VCL - Vegetation Canopy Lidar
WFF - Wallops Flight Facility
WGS84 - World Geodetic System of 1984
WWW - World Wide Web

20. Document Information

20.1 Document Revision Date

Written: 04-Apr-1998
Updated: 16-Nov-1999

20.2 Document Review Date(s)

BORIS Review: 27-Aug-1999
Science Review:

20.3 Document ID

20.4 Citation

When using these data, please include the following acknowledgment as well as citations of relevant papers in Section 17.2:

> Development of the SLICER instrument was led by Bryan Blair, and collection and production of the BOREAS SLICER data was led by David Harding, with instrument operations by David Rabine, Sean Warren, and Earl Frederick and data processing by Kathy Still, all at NASA's Goddard Space Flight Center.
>
> Document authors: D.J. Harding, J.B. Blair, D.L. Rabine, and K.L. Still

If using data from the BOREAS CD-ROM series, also reference the data as:

> Harding, D.J., "Airborne Laser Altimeter Characterization of Canopy Structure and Sub-canopy Topography at BOREAS Tower Flux Sites." In Collected Data of The Boreal Ecosystem-Atmosphere Study. Eds. J. Newcomer, D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers. CD-ROM. NASA, 2000.

Also, cite the BOREAS CD-ROM set as:

> Newcomer, J., D. Landis, S. Conrad, S. Curd, K. Huemmrich, D. Knapp, A. Morrell, J. Nickeson, A. Papagno, D. Rinker, R. Strub, T. Twine, F. Hall, and P. Sellers, eds. Collected Data of The Boreal Ecosystem-Atmosphere Study. NASA. CD-ROM. NASA, 2000.

20.5 Document Curator

20.6 Document URL

Keywords:

Laser altimeter
Lidar
SLICER
Vegetation height
Canopy structure
Topography
BOREAS