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Technical Report Series on the Boreal Ecosystem-Atmosphere Study (BOREAS)

Forrest G. Hall and Jeffrey A. Newcomer, Editors

Volume 90

BOREAS Level-2 NS001 TMS Imagery: Reflectance and Temperatures in BSQ Format

Brad Lobitz and Michael Spanner, Johnson Controls, Inc.
Richard Strub, Raytheon ITSS

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

September 2000

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BOREAS Level-2 NS001 TMS Images: Reflectance and Temperatures in BSQ Format

Brad Lobitz, Michael Spanner, Richard Strub

Summary

For BOREAS, the NS001 TMS images, along with the other remotely sensed data, were collected to provide spatially extensive information over the primary study areas. This information includes detailed land cover and biophysical parameter maps such as fPAR and LAI. Collection of the NS001 images occurred over the study areas during the 1994 field campaigns. The level-2 NS001 data are atmospherically corrected versions of some of the best original NS001 imagery and cover the dates of 19-Apr-1994, 07-Jun-1994, 21-Jul-1994, 08-Aug-1994, and 16-Sep-1994. The data are not geographically/geometrically corrected; however, files of relative X and Y coordinates for each image pixel were derived by using the C130 INS data in an NS001 scan model. The data are provided in binary image format files.

Note that some of the data files on the BOREAS CD-ROMs have been compressed using the Gzip program. See Section 8.2 for details. Note also that the top portion of the ASCII header file in each level-2 NS001 image product indicates the band 8 data to be 'Scaled Reflectance' when in fact they are 'Scaled Temperatures'.

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1. Data Set Overview

1.1 Data Set Identification

BOREAS Level-2 NS001 TMS Images: Reflectance and Temperatures in BSQ Format

1.2 Data Set Introduction

The BOReal Ecosystem-Atmosphere Study (BOREAS) Staff Science effort covered those activities that were BOREAS community-level activities or required uniform data collection procedures across

sites and time. These activities included the acquisition, processing, and archiving of 8-band NS001 Thematic Mapper Simulator (TMS) Multispectral Scanner (MSS) data collected on the National Aeronautics and Space Administration's (NASA) C-130 aircraft. The NS001 provided spectral image data very similar to that of the Landsat Thematic Mapper (TM).

1.3 Objective/Purpose

For BOREAS, the NS001 TMS imagery, along with the other remotely sensed images, was collected to provide spatially extensive information over the primary study areas. This information includes detailed land cover and biophysical parameter maps such as fraction of Photosynthetically Active Radiation (fPAR) and Leaf Area Index (LAI). The level-2 products contain atmospherically corrected reflectance and temperature bands in addition to 'good' relative X and Y coordinates of each pixel.

1.4 Summary of Parameters

NS001 level-2 data in the BOREAS Information System (BORIS) consist of 21 files per flight line and as a set they contain the following parameters:

Descriptive information as American Standard Code for Information Interchange (ASCII) text records, reflectance values for image bands 1 to 7, temperature values for image band 8, housekeeping information for each band, per pixel relative X and Y pixel coordinates, and per pixel view zenith and azimuth angles.

1.5 Discussion

BORIS personnel processed the NS001 TMS level-0 images by:

- Extracting pertinent header information from the level-0 image product and placing it in an ASCII file on disk.
- Reading the information in the disk file and loading the online data base with needed information.
- Developing software to calculate the relative X and Y pixel positions from the C130 Inertial Navigation System (INS) data and providing it to NASA Ames Research Center (ARC) personnel.

Ames personnel created the level-2 NS001 TMS imagery by:

- Obtaining the pertinent level-0 NS001 imagery from BORIS.
- Obtaining optical depth data from BORIS.
- Obtaining radiosonde data from BORIS.
- Modeling the path transmittance and path radiative emission (thermal channel) using a Moderate Resolution Model of LOWTRAN7 (MODTRAN).
- Modeling the path water vapor column concentration and downwelling irradiance using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S).
- Processing the imagery using NASA ARC's Image Atmospheric Correction (Imagecor) program.
- Using the BORIS software and C130 INS data to calculate files of X and Y coordinates.
- Returning the processed files to BORIS.

1.6 Related Data Sets

BOREAS Level-0 C-130 Navigation Data
BOREAS Level-0 C-130 Aerial Photography
BOREAS RSS-02 Level-1b ASAS Imagery: At-sensor Radiance in BSQ Format
BOREAS Level-1B MAS Imagery: At-sensor Radiance, Relative X and Y Coordinates
BOREAS Level-2 MAS Imagery: Reflectance and Temperatures in BSQ Format
BOREAS Level-0 TIMS Imagery: Digital Counts in BIL Format

2. Investigator(s)

2.1 Investigator(s) Name and Title
BOREAS Staff Science

2.2 Title of Investigation
BOREAS Staff Science Aircraft Data Acquisition Program

2.3 Contact Information

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3. Theory of Measurements

The NASA Earth Resources Aircraft Program at ARC operates the C-130 aircraft to acquire data for Earth science research. The NS001 MSS used on the C-130 aircraft collects radiance measurements in the seven Landsat-4 and -5 TM bands plus a band from 1000 to 1300 nm. Therefore, when reflected or emitted radiation from Earth surface features is measured from the aircraft, inferences can be made about Landsat satellite measurements.

Thematic considerations dictated, within technical constraints, the choice of spectral band position and width in the NS001 sensor. Eight bands were selected; seven of which correspond to Landsat TM bands. These bands were chosen after many years of analysis for their value in discrimination of several Earth surface features. A blue (0.45 to 0.52 µm) band provides increased penetration of water bodies as well as supporting analyses of land use, soil, and vegetation characteristics. The lower-wavelength cutoff is just below the peak transmittance of clear water, while the upper-wavelength cutoff is the limit of blue chlorophyll absorption for healthy green vegetation. Wavelengths below 450 nm are substantially influenced by atmospheric scattering and absorption.

A green (0.52 to 0.60 µm) band spans the region between the blue and red chlorophyll absorption bands and therefore corresponds to the green reflectance of healthy vegetation. A red (0.63 to 0.69 µm) band includes the chlorophyll absorption band of healthy green vegetation and represents one of the most important bands for vegetation discrimination. The latter is also useful for soil boundary and geological boundary delineations. A reflective-infrared (0.76 to 0.90 µm) band is especially responsive to the amount of vegetation biomass present in a scene. It is useful for crop identification and emphasizes soil-crop and land-water contrasts.

Two of the three mid-infrared (1.00 to 1.30; 1.55 to 1.75 µm) bands are sensitive to the turgidity or amount of water in plants. Such information is useful in crop drought studies and in plant vigor

investigations. In addition, these are two of the few bands that can be used to discriminate between clouds, snow, and ice, which is very important in hydrologic research. The other mid-infrared band (2.08 to 2.35 µm) is important for the discrimination of geologic rock formations. It has been shown to be particularly effective in identifying zones of hydrothermal alteration in rocks. Finally, the thermal infrared (10.4 to 12.5 µm) band measures the amount of infrared radiant flux emitted from surfaces. The apparent temperature is a function of the emissivities and true or kinetic temperature of the surface. It is useful for locating geothermal activity, thermal inertia mapping for geologic investigations, vegetation classification, vegetation stress analysis, and soil moisture studies.

4. Equipment

4.1 Sensor/Instrument Description

The NS001 TMS instruments are designed to simulate spectral, spatial, and radiometric characteristics of the TM sensor on the Landsat-4 and -5 spacecraft. The NS001 is generally flown at medium altitudes aboard NASA's C-130 aircraft based at NASA ARC and provides 12.2-meter resolution at nadir at an altitude of 4,878 meters (16,000 feet).

The NS001 sensor differs slightly from the Landsat TM instruments. It has 7 spectral channels that are very similar to those of the TM sensor, but it has an additional infrared channel, as follows:

NS001 Channel	Wavelength, µm	Comparable Landsat TM Band
1	0.45-0.52	1
2	0.52-0.60	2
3	0.63-0.69	3
4	0.76-0.90	4
5	1.00-1.30	-
6	1.55-1.75	5
7	2.08-2.35	7
8	10.40-12.5	6

4.1.1 Collection Environment

The C-130 aircraft flies at altitudes ranging from 5000 to 7000 meters.

4.1.2 Source/Platform

NASA's C-130 Earth Resources Aircraft.

4.1.3 Source/Platform Mission Objectives

The original objectives of the scanner were to provide low-altitude data in the Landsat TM bands for analysis prior to the launch of the satellite and to provide calibration information from under-flights subsequent to the launch of the satellite.

4.1.4 Key Variables

Emitted radiation, reflected radiation, and temperature.

4.1.5 Principles of Operation

Design parameters of the NS001 are based on the specifications of the Landsat TM with respect to spectral band characteristics. A single spectrometer disperses the energy to cover the first six bands from 0.45 µm to 1.75 µm. An array, employing silicon, germanium, and indium antimonide detectors, is used. Band 7 is separated by a dichroic bandpass filter. The eighth band, in the 10.4 µm to 12.5 µm region, is detected by a cooled mercury-cadmium-telluride detector.

Variable velocity over height (V/H) conditions are compensated by a variable speed motor that drives the scan mirror.

Each channel employs a preamplifier to provide initial video amplification. Gain and level control of video signals are adjustable from the operator's control panel. Each channel is digitized to an 8-bit resolution and is multiplexed with calibration and housekeeping data.

4.1.6 Sensor/Instrument Measurement Geometry

IFOV	2.5 mrad
Total Scan Angle	100 degrees
Pixels/Scan Line	699

Sensor footprint is 12.2 by 12.2 m at nadir at 4878 meters altitude.

4.1.7 Manufacturer of Sensor/Instrument

NASA/Lyndon B. Johnson Space Center
Houston, TX

Lockheed Electronics Company, Inc.
Systems and Services Division
Houston, TX

4.2 Calibration

The NS001 includes two full-aperture blackbodies and one integrating sphere within the scan mirror cavity. They are viewed each scan by the instrument and the responses are embedded in the data stream. Blackbody temperatures and lamp current data are multiplexed with scanner output data. The blackbody irradiance is determined by its monitored temperature and estimated emissivity. The blackbodies are also cross-checked periodically by comparing the NS001 responses to the blackbodies and an external precision blackbody. The internal sphere is calibrated by reference to an external light source.

The principal source used for calibrating the internal sphere for BOREAS in 1994 was a 76-cm-diameter integrating sphere owned by ARC, and calibrated by the Standards and Calibration Office at GSFC. The sphere contains 12 internally mounted quartz halogen lamps. Estimated uncertainty in the calibration of the sphere is +/-5%. The April 1994 calibration of the sphere was used to calibrate the internal calibration source in the NS001 in 1994.

4.2.1 Specifications

The wavelength range (in µm) of the bands for the NS001 are:

Band	Detector	Wavelength	NE(delta P) %
1	Si	0.458 - 0.519	0.5
2	Si	0.529 - 0.603	0.5
3	Si	0.633 - 0.697	0.5
4	Si	0.767 - 0.910	0.5
5	Ge	1.13 - 1.35	1.0
6	Ge	1.57 - 1.71	1.0
7	InSb	2.10 - 2.38	2.0
8	HgCdTe	10.9 - 12.3	NE(delta T) = 0.25 K

DESIGN DATA:

IFOV	2.5 milliradians
Across-track field of view	100 degrees
Nominal aperture diameter	10.16 cm
Effective aperture area	72.4 cm^2
f/number	1.85
Primary focal length	18.8 cm

Inflight calibration	Integrating sphere and two controllable blackbodies
Short wavelength array temperature	255 K
V/H range	Variable 0.025 to 0.25
Scan rate	Variable 10 to 100 scans/sec
Scan speed stability	One-third of the IFOV, scan line to scan line
Data quantization	8-bits (256 discrete levels)
Number of video samples/scan line	699
Roll compensation	+/-15 degrees
Scan mirror	45-degree rotating mirror

4.2.1.1 Tolerance

The NS001 channels were designed for noise-equivalent reflectance differences for the channels, represented by the radiometric sensitivity [NE(delta P) %; NE(delta T) K] shown in Section 4.2.1.

4.2.2 Frequency of Calibration

An integrating sphere and two controllable thermal blackbodies are integral to the NS001 scanner. Each is viewed once during a complete revolution of the scan mirror. The two thermal blackbodies are principally used to span the recorded thermal image, thereby providing a scaling factor for the measured data. The surface of blackbody number 2 is also used to provide the tare value (darkest object viewed per sweep) for the seven nonthermal detectors. Tare value is artificially set above zero counts; e.g., 8-10 counts, to compensate for any system drift. For BOREAS, one of the blackbodies is used for the internal lamp offset. The average of the two blackbodies is used for the scene offset.

4.2.3 Other Calibration Information

None.

4.2.3.1 Reflective Band Calibration

The BB2 View is used for the internal source offset; i.e., the gain is calculated in effect as:

Gain = (Ref. Lamp View - BB2 View) / Ref. Lamp Spectral Radiance

The reference lamp spectral radiance is determined by preseason calibration relative to the integrating sphere. The apparent scene spectral radiance in Watts/(m2 sr µm) can then be calculated as:

(pixel value - (BB1 View + BB2 View) / 2) / Gain

4.2.3.2 Thermal Band Calibration

GSFC Gain (G), Offset (O), as found in the header summary file(s) are calculated as follows:

a) Calculate blackbody radiances, Lw(mW/cm^2/sr/µm) (assume emissivity=1) for BB1 and BB2 temperatures T(K) e.g.

For example:

$$Lw,bb1 = [K1 / (\exp(K2/Tbb1)-1)]$$

where: K1 = 607.05 W/cm^2/sr/µm
K2 = 1258.39 K

K1, K2 were "best fit" parameters for the temperature range of 273-323 K using the 8/87 NS001 spectral data and the Planck equation.

b) $G = [(BB2\ View - BB1\ View) / (Lw,BB2 - Lw,BB1)]$
$(DN/mW/cm^2/sr/\mu m)$

$O = BB1\ View - G * Lw,BB1\ (DN)$

Target Radiance (Lw) can then be calculated as:

$(pixel\ value - O) / G$

and at-sensor apparent temperature as:

$T = [K2 / (\ln(K1/Lw + 1)]$

5. Data Acquisition Methods

As part of the BOREAS Staff Science data collection effort, the ARC Medium Altitude Aircraft Branch collected and processed 8-band NS001 TMS MSS data to BOREAS level-0 products. The NS001 was flown on NASA's C-130 aircraft during BOREAS (see the BOREAS Experiment Plan for flight pattern details and objectives).

Maintenance and operation of the instrument are the responsibility of ARC. The C-130 Experimenter's Handbook (supplemental) produced by the Medium Altitude Aircraft Branch at ARC provides a description of the instrument, calibration procedures, and data format. Data from the level-0 tapes provided by ARC can be decoded based on the contents of the handbook.

NS001 data may be intentionally overscanned, e.g., operated at some integral multiple of the desired scan rate and then subsampled in preprocessing. The subsampling factor is reported under the label "demagnification factor."

6. Observations

6.1 Data Notes

The top portion of the ASCII header file in each level-2 NS001 image product indicates the band 8 data to be 'Scaled Reflectance' when in fact they are 'Scaled Temperatures'.

6.2 Field Notes

Flight summary reports and verbal records on video tapes are available for the BOREAS NS001 data.

7. Data Description

7.1 Spatial Characteristics

The BOREAS level-2 NS001 TMS images cover portions of the Southern Study Area (SSA) and the Northern Study Area (NSA).

7.1.1 Spatial Coverage

The geographic orientation of each image depends on the direction of the aircraft line of flight. Pixels and lines progress left to right, and top to bottom so pixel n, line n is in the lower right-hand corner of each scene.

The North American Datum of 1983 (NAD83) corner coordinates of the SSA are:

	Latitude	Longitude
Northwest	54.321 N	106.228 W
Northeast	54.225 N	104.237 W
Southwest	53.515 N	106.321 W
Southeast	53.420 N	104.368 W

The NAD83 corner coordinates of the NSA are:

	Latitude	Longitude
Northwest	56.249 N	98.825 W
Northeast	56.083 N	97.234 W
Southwest	55.542 N	99.045 W
Southeast	55.379 N	97.489 W

7.1.2 Spatial Coverage Map
Not available.

7.1.3 Spatial Resolution
Typical altitudes for BOREAS were around 5000 m, producing a 12.5-m pixel at nadir given the NS001's 2.5-mrad IFOV.

7.1.4 Projection
The BOREAS level-2 NS001 images are stored in their original data collection frame with increasing pixel sizes from nadir to the scanning extremes based on the scan angle.

7.1.5 Grid Description
The BOREAS level-2 NS001 images are stored in their original data collection frame with increasing pixel sizes from nadir to the scanning extremes based on the scan angle.

7.2 Temporal Characteristics

7.2.1 Temporal Coverage
The level-2 NS001 images were acquired during 5 days from 19-Apr-1994 to 16-Sep-1994.

7.2.2 Temporal Coverage Map

Date	Study Area
19-Apr-1994	SSA
07-Jun-1994	NSA
21-Jul-1994	SSA
08-Aug-1994	NSA
16-Sep-1994	SSA

7.2.3 Temporal Resolution

Date	Start Time	End Time	Number of images
19-Apr-1994	19:29	20:59	10
07-Jun-1994	18:14	19:18	9
21-Jul-1994	15:46	17:31	10
08-Aug-1994	14:32	15:13	7
16-Sep-1994	18:11	19:39	10

7.3 Data Characteristics

7.3.1 Parameter/Variable

- Scaled Reflectance (Bands 1 to 7)
- Scaled Surface Temperature (Band 8)
- Housekeeping data (Bands 1 to 8)
- Relative X coordinate
- Relative Y coordinate
- Scaled View zenith
- Scaled View Azimuthh

7.3.2 Variable Description/Definition

Scaled Reflectance

The ratio of reflected radiant energy from the target to the incident radiant energy at the time of data collection in the specific NS001 wavelength regions.

Scaled Surface Temperature

The derived surface temperature at the time of data collection in the specific NS001 thermal infrared wavelength regions.

Housekeeping Data

Housekeeping information extracted from the raw image files: one line of ASCII data per image line. Contains radiance per count calibration value, scan line number, blackbody counts, blackbody temperatures, scan speed, Greenwich Mean Time (GMT), air temperature, channel number, blackbody radiance counts, reference lamp voltage, reference lamp current, reference lamp state, reference lamp radiance count, precision radiation thermometer value.

Relative X Coordinate

The X coordinate of the center of the image pixel in relation to the arbitrarily selected origin. The trend of the X coordinates of the pixels is dependent on the direction of flight of the aircraft. The X, Y coordinate system, starts with the nadir pixel location of image line 1 for all flight lines positioned near the origin (0,0) and progresses based on the direction of flight. The flight direction refers to the angle of the flight path relative to magnetic north with north as 0 or 360 degrees, east as 90, south as 180, and west as 270 degrees. For example, the X coordinates for an idealized flight line in the direction of 180 degrees (south) would be increasingly positive to the left of the flight line and increasingly negative to the right of the flight line with the X coordinate for the nadir pixel being approximately 0 (zero).

Relative Y Coordinate

The Y coordinate of the center of the image pixel in relation to the arbitrarily selected origin. The trend of the Y coordinates of the pixels is dependent on the direction of flight of the aircraft. The X, Y coordinate system, starts with the nadir pixel location of image line 1 for all flight lines positioned near the origin (0,0) and progresses based on the direction of flight. The flight direction refers to the angle

of the flight path relative to magnetic north with north as 0 or 360 degrees, east as 90, south as 180, and west as 270 degrees. For example, the Y coordinates for an idealized flight line in the direction of 90 degrees (east) would be increasingly positive to the left of the flight line and increasingly negative to the right of the flight line with the Y coordinate for the nadir pixel being approximately 0 (zero).

Scaled View Zenith

The scaled value of the target-centered view zenith angle (complement of elevation angle). The view zenith indicates the zenith angle at which the radiant energy was traveling when detected by the sensor. The view zenith angle increases from 0 (straight up) to 90 degrees at the horizon.

Scaled View Azimuth

The scaled value of the target-centered view azimuth angle. The view azimuth angle indicates the direction in which the radiant energy was traveling when detected by the sensor. The view azimuth angle increases from 0 to 360 degrees with north as 0 or 360 degrees, east as 90, south as 180, and west as 270 degrees.

7.3.3 Unit of Measurement

- Scaled Reflectance - Unitless. Look near the end of the ASCII header file for scaling factors.
- Scaled Surface Temperature - Temperature in degrees Celsius. Look near the end of the ASCII header file for scaling factors.
- Relative X coordinate - Tenths of meters
- Relative Y coordinate - Tenths of meters
- Scaled View zenith - Tenths of degrees
- Scaled View Azimuth - Tenths of degrees

7.3.4 Data Source

The values stored in the listed parameters were extracted from the level-0 NS001 files provided to BOREAS and processed to reflectance or surface temperature. The reflectance and surface temperature values are derived from the level-0 data combined with the calibration parameters, so the at-sensor radiance data (level-1) were an intermediate product. View angle values are the result of calibration and processing of the raw NS001 data by NS001 personnel. The relative X and Y coordinates were derived in a joint effort between BORIS and NS001 personnel.

7.3.5 Data Range

Scaled Reflectance and Surface Temperature

Dependent on the particular MAS band of interest due to the wavelength region covered and the scaling factor listed near the end of the ASCII header file.

Relative X coordinate

Dependent on the direction of flight with an absolute minimum of -2,147,483,648 and absolute maximum of 2,147,483,647 for a 32-bit integer field.

Relative Y coordinate

Dependent on the direction of flight with an absolute minimum of -2,147,483,648 and absolute maximum of 2,147,483,647 for a 32-bit integer field.

Scaled View zenith

Minimum - 0
Maximum - 900

Scaled View Azimuth

Minimum - 0
Maximum - 3599

7.4 Sample Data Record

Not applicable to image data.

8. Data Organization

8.1 Data Granularity

The smallest unit of data for level-2 NS001 images is a single image.

8.2 Data Format

8.2.1 Uncompressed Data Files

A single NS001 level-2 image product consist of 21 files:

File 1: An ASCII header file that containing information relating to the mission, location, acquisition time, sensor parameters, aircraft location and attitude, and radiometric calibration parameters.

Files 2-8: Bands 1 to 7 stored as 16-bit integer values in scaled reflectance (low-order byte first). Look near the end of the ASCII header file for scaling factors.

File 9: Band 8 stored as 16-bit integer values in scaled degrees Celsius (low-order byte first). Look near the end of the ASCII header file for scaling factors.

Files 10-17: ASCII files containing the unpacked housekeeping information.

File 18: Relative X coordinates stored as 32-bit integer values in meters (low-order byte first).

File 19: Relative Y coordinates stored as 32-bit integer values in meters (low-order byte first).

File 20: Scaled view zenith values stored as 16-bit integer values in tenths of degrees (low-order byte first).

File 21: Scaled view azimuth values stored as 16-bit integer values in tenths of degrees (low-order byte first).

The geographic orientation of each scene depends on the direction of the aircraft line of flight. Pixels and lines progress left to right and top to bottom so pixel n, line n is in the lower right-hand corner of each scene.

All image files contain a variable number of fixed-length records. The ASCII header files are 80 bytes in length. All binary files for a given flight contain the same number of records. The number of binary records in a flight varies depending on the length of that flight line. Each binary data record in all flights represents 699 image pixels. Therefore, the image and view angle file records contain 699*2 = 1398 bytes and the relative X and Y coordinate files contain 699*4 = 2796 bytes.

8.2.2 Compressed CD-ROM Files

On the BOREAS CD-ROMs, the ASCII header file for each image is stored as ASCII text; however, files 2 to 21 have been compressed with the Gzip compression program (file name *.gz). These data have been compressed using gzip version 1.2.4 and the high compression (-9) option (Copyright (C) 1992-1993 Jean-loup Gailly). Gzip (GNU zip) uses the Lempel-Ziv algorithm (Welch,

1994) used in the zip and PKZIP programs. The compressed files may be uncompressed using gzip (-d option) or gunzip. Gzip is available from many Web sites (for example, ftp site prep.ai.mit.edu/pub/gnu/gzip-*.*) for a variety of operating systems in both executable and source code form. Versions of the decompression software for various systems are included on the CD-ROMs.

9. Data Manipulations

9.1 Formulae

9.1.1 Derivation Techniques and Algorithms

The atmospheric correction algorithm, Imagecor, applied to the NS001 level-0 data is fully documented in Wrigley et al. (1992), which has since been modified to include water vapor and to remove path thermal emission for thermal channels. Imagecor was developed by Robert Wrigley and Robert Slye for the atmospheric correction of First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) data and uses a simple atmospheric model with a modified single-scattering approximation, which permits full image scenes to be processed relatively quickly. Water vapor corrections are based on modeled water vapor transmittance output by 6S combined with water vapor transmittance derived from 940-nm channel sunphotometer data. This transmittance and the spectral response function of the sunphotometer channel were used to determine the equivalent water vapor column content. Imagecor then uses this content to estimate the transmittance across the scene. The thermal channel was corrected by using MODTRAN to model path emission and transmittance at 12 equally spaced angles across the scene and interpolating the path emission between these points.

Derivation of the relative X and Y coordinates starts with determining the relative positions of the nadir pixel in each image line. The nadir pixel coordinates are defined to proceed relative to an arbitrary starting X,Y location. Nadir X,Y coordinates are derived as a function of the following parameters:

- Instantaneous Velocities X, Y, and Z from the C130 Navigation data.
- Tracking (actual direction aircraft is pointing) values derived as a function of true heading and drift. To arrive upon nadir pixel tracking, the 1-Hz drift values and 30-Hz true heading values are interpolated to nadir pixel values. Nadir pixel drift is added to the nadir true heading values to obtain nadir pixel tracking values. Note that drift may be a positive or negative value.

The calculations used to derive relative X and Y coordinates of the nadir pixels are:

```
X0        = First (earlier) nadir X location
X1        = Succeeding nadir X location
Y0        = First (earlier) nadir Y location
Y1        = Succeeding nadir Y location
DTime     = Time1 - Time0
            [Delta time stamps between succeeding nadir pixels]
TH0, TH1 = True Heading at succeeding nadir pixels
Dr0, Dr1 = Drift values at succeeding nadir pixels
Tr0, Tr1 = Tracking at succeeding nadir pixels
VX,VY,VZ = Global Positioning System (GPS) velocities in an X, Y and Z GPS
            reference system
Sp0, Sp1 = Ground Speed
            [square root ((VX*VX) + (VY*VY) + (VZ*VZ))]
V0x       = SP0 * cos(TH0 + Dr0)
            [X Velocity at Time0]
V1x       = SP1 * cos(TH1 + Dr1)
            [X Velocity at Time1]
V0y       = SP1 * sin(TH0 + Dr0)
```

```
            [Y Velocity at Time0]
V1y       = SP1 * sin(TH1 + Dr1)
            [Y Velocity at Time1]
AVEV01X   = (V0x + V1x) / 2.0
            [Average X velocity between Time0 and Time1]
AVEV01Y   = (V0y + V1y) / 2.0
            [Average Y velocity between Time0 and Time1]
X         = X0 + (AVE01X * DTime)
            [Succeeding nadir X coordinate]
Y         = Y0 + (AVE01Y * Dtime)
            [Succeeding nadir Y coordinate]
```

The X and Y values along each scan line are projected from the center pixel in both directions, where:

```
AngleIncr       = 100 degrees/699 pixels
x0              = center pixel x coordinate
y0              = center pixel y coordinate
pitch           = pitch of the aircraft interpolated to the center pixel
                  time from the c130 navigation data
ScanAngle       = fabs(AngleIncr * (pixel))
XCoords[pixel] = x0 + alt*tan(pitch)*sin(head) -
                      alt/cos(pitch) * (tan(ScanAngle)) * cos(head)
YCoords[pixel] = y0 + alt*tan(pitch)*cos(head) +
                      alt/cos(pitch) * (tan(ScanAngle)) * sin(head
```

9.2 Data Processing Sequence

9.2.1 Processing Steps

BORIS and ARC personnel created level-2 NS001 image products in an iterative procedure as follows:

- Extract approximate center pixel times from NS001 image files.
- Extract 30-Hz (heading, pitch, roll) and 1-Hz (alt, drift, xyz velocities) data from navigation data files.
- Interpolate navigation data to center pixel times and place into .xy file.
- Create 2 image bands, and X and a Y that contain a coordinate for each of the 699 pixels in each scan line.
- Unpack the 7 reflectance and 1 temperature bands into separate files.

The flight lines were then sent to NASA ARC for atmospheric correction processing, which involved:

- Reading the data tape and exporting the image data to files with system specific byte order.
- Downloading the radiosonde and sunphotometer data from BORIS.
- Modeling the path transmittance and path radiative emission for the thermal channel using a MODTRAN, and modeling the path water vapor column concentration and downwelling irradiance using 6S for visible and near- and mid-infrared channels.
- Processing the image data to reflectance or surface temperature using Imagecor.
- Generating a header file for each of the NS001 flight lines.
- For each flight line, writing to tape each header file and level-2 image data, with housekeeping, X and Y, and zenith and azimuth data.
- Sending the data tape to BORIS.

Finally, BORIS did the following:

- Extracted pertinent header information from each image.
- Loaded inventory information in the relational data base.
- Reviewed random files for content.
- Copied the ASCII and compressed the binary files for release on the CD-ROM.

9.2.2 Processing Changes

None.

9.3 Calculations

9.3.1 Special Corrections/Adjustments

None.

9.3.2 Calculated Variables

See Section 9.1.1.

9.4 Graphs and Plots

None.

10. Errors

10.1 Sources of Error

The NS001 data are calibrated in-flight by reference to the NS001 internal integrating sphere source. Apparent instabilities in this source or its monitoring circuitry, which are not fully understood, are the principal limiting factors in the absolute calibration of NS001 data. Uncertainties due solely to this behavior reached 25% in 1987, though more typically they are expected to be less than 15%. Other identified error sources at the 1-2% level for typical signals include dark current drift along the scan line, hysteresis-like sensitivity changes along the scan line, random noise, scan-speed-induced errors, and nonlinearity of radiance with wavelength.

Channel 7 (2.08-2.35 µm) shows a number of peculiarities that are hysteresis-like, including a change in the apparent dark current drift along scan with scene brightness and a drop in sensitivity in scanning across a bright target of an estimated 8% over the total 100-degree scan angle. Polarization sensitivity of the NS001 was such that for typical atmospheric conditions errors in channel 1 (0.45-0.52 µm) radiances would be up to +/-10% and vary with scan angle; this progressively decreases with increasing wavelength (Markham and Ahmad, 1990).

In addition to these errors, the level-2 errors are dependent on the accuracy of the aerosol optical depth measurements used in the atmospheric correction processing. Errors due to using a single-scattering approximation should be minimal because the BOREAS optical depths were low (met the single-scattering requirement).

10.2 Quality Assessment

10.2.1 Data Validation by Source

Spectral errors could arise due to image-wide signal-to-noise ratio, saturation, cross-talk, spikes, response normalization due to change in gain.

NS001 level-2 pixel data agreed well with helicopter acquired Barnes Modular Multispectral Radiometer (MMR, BOREAS PI: Charles Walthall) data for the BOREAS primary study sites, for the flight lines that coincided the primary sites. With similar geometric and site condition inputs, both 6S and MODTRAN modeled reflectances also were in close agreement to the Imagecor results.

BORIS personnel used the relative X and Y coordinate files to perform forward mapping of several NS001 images as a check of the calculations. Visual assessment of the forward mapped images showed the relative corrections to significantly remove distortions from scan angle and aircraft motion.

Overlay of the forward mapped images on a Landsat TM image showed the features to be in good alignment after nominal shifting and rotation of the image without further stretching or distortion.

10.2.2 Confidence Level/Accuracy Judgment

System optical focus is continually monitored by close observation of the apparent sharpness and resolution of objects appearing in scenes after data processing. Although this is somewhat subjective, the approach has proved to be a viable alternative compared to the classical resolution measurement method.

The latter method requires removing the scanner system from the C-130 airplane with subsequent setup. This is not a practical option during the flying/deployment portion of the year. However, any observed focus degradation would be corrected by focus adjustment.

10.2.3 Measurement Error for Parameters

The Noise Equivalent Spectral Radiance for the channels ranges from 0.08 to 2.77 microwatts per square cm. Uncertainties due to the behavior of the internal integrating sphere reached 25% in 1987, though more typically they are expected to be less than 15%.

10.2.4 Additional Quality Assessments

None.

10.2.5 Data Verification by Data Center

None, other than reviewing the values extracted from the tape files and loading them in the database.

11. Notes

11.1 Limitations of the Data

To date, the following discrepancies/problems been noted in the data:

Certain values in the header information such as MEAN_FRAME_STATUS, MEAN_ and STDV_GSFC, and AMES_GAIN and OFFSETS, especially for bands 7 and 8, were outside the valid range for these parameters. Such values, when found, were entered into the BORIS database as the number -99.0 or -999.0 depending on the data base field width. The problem appears to occur randomly.

11.2 Known Problems with the Data

The top portion of the ASCII header file in each level-2 NS001 image product indicates the band 8 data to be 'Scaled Reflectance' when in fact they are 'Scaled Temperatures'.

11.3 Usage Guidance

The NS001 data are not geometrically corrected. The data contain both panoramic distortion, as a function of the 100-degree total field of view, as well as the other spatial perturbations induced by a moving aircraft. BORIS personnel used the relative X and Y coordinate files to perform forward mapping of several NS001 images as a check of the calculations. Visual assessment of the forward mapped images showed the relative corrections to significantly remove distortions from scan angle and aircraft motion. Overlay of the forward mapped images on a Landsat TM image showed the features to be in good alignment after nominal shifting and rotation of the image without further stretching or distortion.

Before uncompressing the Gzip files on CD-ROM, be sure that you have enough disk space to hold the uncompressed data files. Then use the appropriate decompression program provided on the CD-ROM for your specific system.

11.4 Other Relevant Information

Two in-flight adjustments are made that affect the radiometric calibration of the reflective channels. The primary adjustment is to the postamplifier gain of each channel. This is adjusted by means of a channel specific potentiometer before and between data acquisitions to optimize the spread of the data across the range of the A/D converter (8 bits). The gain settings are continuously variable and are not directly recorded in the data; they are inferred from changes in the instrument response to the integrating sphere. The second adjustment is for scan speed, which is adjusted between 10 and 85 scans per second to maintain contiguous scan lines, or some multiple of contiguous if contiguity is not maintainable at the altitude required for data collection. Typical altitudes for BOREAS in 1994 were 5000 m, which produced 12.5-m pixels at nadir given the NS001's 2.5-mrad IFOV.

12. Application of the Data Set

These data could be used to study the reflectance or temperature characteristics of various surface features.

13. Future Modifications and Plans

None. The NS001 instrument was decommissioned in October 1995.

14. Software

14.1 Software Description

BORIS staff developed software and command procedures for:

- Extracting header information from level-0 NS001 TMS images on tape and writing it to ASCII files on disk.
- Reading the ASCII disk file and logging the level-0 NS001 image products into the Oracle data base tables.

The atmospheric correction software, Imagecor, was written in the C language. It is operational on Sun Microsystems Solaris systems and has few hardware dependencies. Gzip (GNU zip) uses the Lempel-Ziv algorithm (Welch, 1994) used in the zip and PKZIP commands.

14.2 Software Access

Imagecor is written in the C language and is operational on VAX 6410 and MicroVAX 3100 systems at GSFC. The primary dependencies in Imagecor are the tape I/O library and the Oracle data base utility routines. For information on Imagecor, contact one of the individuals listed in Section 2. Gzip is available from many Web sites across the Internet (for example, FTP site prep.ai.mit.edu/pub/gnu/gzip-*.*) for a variety of operating systems in both executable and source code form. Versions of the decompression software for various systems are included on the CD-ROMs.

15. Data Access

The level-2 NS001 TMS images are available from the Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

15.1 Contact Information

For BOREAS data and documentation please contact:

ORNL DAAC User Services
Oak Ridge National Laboratory
P.O. Box 2008 MS-6407
Oak Ridge, TN 37831-6407
Phone: (423) 241-3952
Fax: (423) 574-4665
E-mail: ornldaac@ornl.gov or ornl@eos.nasa.gov

15.2 Data Center Identification

Earth Observing System Data and Information System (EOSDIS) Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) for Biogeochemical Dynamics http://www-eosdis.ornl.gov/.

15.3 Procedures for Obtaining Data

Users may obtain data directly through the ORNL DAAC online search and order system [http://www-eosdis.ornl.gov/] and the anonymous FTP site [ftp://www-eosdis.ornl.gov/data/] or by contacting User Services by electronic mail, telephone, fax, letter, or personal visit using the contact information in Section 15.1.

15.4 Data Center Status/Plans

The ORNL DAAC is the primary source for BOREAS field measurement, image, GIS, and hardcopy data products. The BOREAS CD-ROM and data referenced or listed in inventories on the CD-ROM are available from the ORNL DAAC.

16. Output Products and Availability

16.1 Tape Products

The BOREAS level-2 NS001 TMS data can be made available on 8-mm, Digital Archive Tape (DAT), or 9-track tapes at 1600 or 6250 Bytes Per Inch (BPI).

16.2 Film Products

Color aerial photographs and video records were made during data collection. The video record includes aircraft crew cabin intercom conversations and an audible tone that was initiated each time the sensor was triggered. The BOREAS data base contains an inventory of available BOREAS aircraft flight documentation, such as flight logs, video tapes, and photographs.

16.3 Other Products

These data are available on the BOREAS CD-ROM series.

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17.3 Archive/DBMS Usage Documentation

None.

18. Glossary of Terms

None.

19. List of Acronyms

```
6S       - Second Simulation of the Satellite Signal in the Solar Spectrum
ARC      - Ames Research Center
ASAS     - Advanced Solid-state Array Spectroradiometer
ASCII    - American Standard Code for Information Interchange
BIL      - Band Interleaved by Line
BOREAS   - BOReal Ecosystem-Atmosphere Study
BORIS    - BOREAS Information System
BPI      - Bytes Per Inch
BSQ      - Band Sequential
CCRS     - Canada Centre for Remote Sensing
CCT      - Computer-Compatible Tape
CD-ROM   - Compact Disk-Read-Only Memory
DAAC     - Distributed Active Archive Center
DAT      - Digital Archive Tape
EOS      - Earth Observing System
EOSDIS   - EOS Data and Information System
ERTS     - Earth Resources Technology Satellite
FIFE     - First ISLSCP Field Experiment
fPAR     - fraction of Photosynthetically Active Radiation
GICS     - Geocoded Image Correction System
GIS      - Geographic Information System
```

```
GMT      - Greenwich Mean Time
GPS      - Global Positioning System
GSFC     - Goddard Space Flight Center
HTML     - HyperText Markup Language
IFOV     - Instantaneous Field-of-View
Imagecor - Image Atmospheric Corration (program)
INS      - Inertial Navigation System
ISLSCP   - International Satellite Land Surface Climatology Project
LAI      - Leaf Area Index
MAS      - MODIS Airborne Simulator
MMR      - Modular Multispectral Radiometer
MODIS    - Moderate-resolution Imaging Spectrometer
MODTRAN  - Moderate Resolution Model of LOWTRAN7
MSS      - Multispectral Scanner
NAD83    - North American Datum of 1983
NASA     - National Aeronautics and Space Administration
NSA      - Northern Study Area
ORNL     - Oak Ridge National Laboratory
PANP     - Prince Albert National Park
RSS      - Remote Sensing Science
SSA      - Southern Study Area
TIMS     - Thermal Infrared Multispectral Scanner
TM       - Thematic Mapper
TMS      - Thematic Mapper Simulator
URL      - Uniform Resource Locator
```

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13. ABSTRACT *(Maximum 200 words)*

For BOREAS, the NS001 TMS images, along with the other remotely sensed data, were collected to provide spatially extensive information over the primary study areas. This information includes detailed land cover and biophysical parameter maps such as fPAR and LAI. Collection of the NS001 images occurred over the study areas during the 1994 field campaigns. The level-2 NS001 data are atmospherically corrected versions of some of the best original NS001 imagery and cover the dates of 19-Apr-1994, 07-Jun-1994, 21-Jul-1994, 08-Aug-1994, and 16-Sep-1994. The data are not geographically/geometrically corrected; however, files of relative X and Y coordinates for each image pixel were derived by using the C130 INS data in an NS001 scan model. The data are provided in binary image format files.

14. SUBJECT TERMS
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