

IMAGING REFLECTANCE SPECTROSCOPY IN THE NATIONAL ECOLOGICAL OBSERVATORY NETWORK'S AIRBORNE OBSERVATION PLATFORM

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Abstract

The National Ecological Observatory Network (NEON) is a planned facility of the National Science Foundation. NEON's mission is to enable understanding and forecasting of the impacts of climate change, land use change and invasive species on continental-scale ecology. Airborne remote sensing plays a critical role in this scaling strategy by making measurements at the scale (1-3 meters) of individual shrubs and larger plants over hundreds of square kilometers. The NEON airborne remote sensing instrumentation is designed to bridge scales from organism and stand scales, as captured by plot and tower observations, to the scale of satellite based remote sensing. The Airborne Observation Platform will include imaging spectroscopy, to quantify plant species identity and function, canopy waveform LIDAR to measure vegetation structure and heterogeneity, and airborne panchromatic photography to retrieve land use, roads, impervious surfaces, and built structures. NEON will build three AOP systems to allow for routine national coverage of NEON sites (60 sites nationally) and capacity to respond to investigator requests for specific projects.

Introduction

The National Ecological Observatory Network (NEON) is a planned facility of the National Science Foundation. NEON's mission is to enable understanding and forecasting of the impacts of climate change, land use change and invasive species on continental-scale ecology. NEON links observations of environmental change (land use, climate and invasive species) to population, community, genomic, phenological, biogeochemical and ecohydrological responses. The NEON infrastructure includes access to continental-scale data from spaceborne and national survey programs, airborne remote sensing at regional scales and site-based measurements at carefully selected sites representative of much of the eco-climatic variability of the United States (Keller et al 2008). NEON is designed to produce continental-scale estimate of ecological states and processes by linking site-based to geospatial information via next-generation models and analyses. The program is designed around a scaling or extrapolation strategy designed to infer processes at organismal scales and analyze their consequences at regional and larger scales.

Airborne remote sensing plays a critical role in this scaling strategy by making measurements at the scale (1-3 meters) of individual organisms (shrubs and larger plants) over hundreds of square kilometers. The NEON airborne remote sensing instrumentation is designed to bridge scales from organism and stand scales, as captured by plot and tower observations, to the scale of satellite based remote sensing. The Airborne Observation Platform (AOP) will achieve sub-meter to meter scale spatial resolution that will allow measurements at the level of individual plant canopies or small groups of organisms. The NEON AOP will include imaging spectroscopy, to quantify plant species identity and function, canopy waveform LIDAR to measure vegetation structure and heterogeneity, and airborne panchromatic photography to retrieve key co-registered aspects of land use, roads, impervious surfaces, and built structures. NEON will build three AOP systems to allow for routine national coverage of NEON sites (60 sites nationally) and capacity to respond to investigator requests for specific projects.

The NEON AOP will contribute to our understanding of ecosystem forcings and responses as represented by vegetation states and processes. Invasive plants can be detected both through their spectral properties and their structural properties (Asner and Vitousek, 2005; Asner et al. 2008). Pest and pathogen outbreaks, changes in competitive relations, responses to disturbances like wildfire, and many features of land use are also readily observed and quantified using the powerful combination of biochemical and structural information provided by spectroscopy and waveform LiDAR. The AOP remote sensing system is driven by the strong synergy between hyperspectral imaging and scanning waveform LiDAR. For example, while canopy structure is often a major contributor to hyperspectral reflectance signatures of vegetation, the biochemical and physiological properties observed from the hyperspectral instrument can be affected by structure and the resulting shadows that occur within and between vegetation canopies. In contrast, waveform LiDAR can provide direct measurements of canopy height and crown shape that are key determinants of structure, shadowing, and biomass, but cannot easily distinguish between species or plant functional types or differences in vegetation biochemical and physiological properties.

Each AOP consists of an aircraft platform carrying a remote sensing instrumentation package designed to bridge scales from organism and stand scales to the scale of satellite based remote sensing. The AOP instrumentation is designed to measure the effects of land use change, changes in vegetation state and performance including the presence and effects of invasive species. The optimum available instrumentation to implement these capabilities are a high-fidelity visible to shortwave infrared spectrometer, and a waveform LiDAR together with a high-resolution digital camera. A separate ancillary upward-looking solar spectrometer provides information on incoming solar radiation at the flight altitude needed for quantitative data processing. Data from this sensor support atmospheric correction of the measured spectral radiance from the ground-viewing imaging spectrometer and can be diagnostic of higher level clouds that may introduce artifacts in the data. In addition, atmospheric characteristics will be collected via a sun-photometer and weather station equipment at each core and relocatable site for input into a radiative transfer model for atmospheric correction.

The high cost of aircraft operations limits the frequency of airborne surveys of individual NEON sites. To detect interannual trends, NEON will seek to overfly each core and relocatable site annually. To minimize the phenological contribution to the signal, flights will be designed to collect remote sensing data over each site during a period of peak greenness which is currently defined as the range of dates where Moderate Resolution Imaging Spectrometer (MODIS) normalized vegetation difference index (NDVI) for the site is within 90% of the site maximum. A preliminary assessment of typical peak greenness periods at each of the NEON sites helps to schedule flights (Fig. 1). Annual observations of the NEON sites inevitably miss important site-level signals such as phenology. Higher frequency data on vegetation function is for example, available from field measurements, or from satellite measurements at a coarser resolution. Meter-scale AOP measurements serve to bridge these scales and measurements conducted over the course of the growing season and can capture changes in phenology. We expect future satellite remote sensing to provide relatively frequent (days to weeks) moderate resolution multi-spectral data at the 500 to 1000 m spatial scale. A sufficiently large area must be flown by AOP for reliable comparison to satellite measurements. Currently we estimate that each AOP site mission will cover up to 300 km² at 1 to 3 meter ground resolution, a compromise between area coverage and cost.

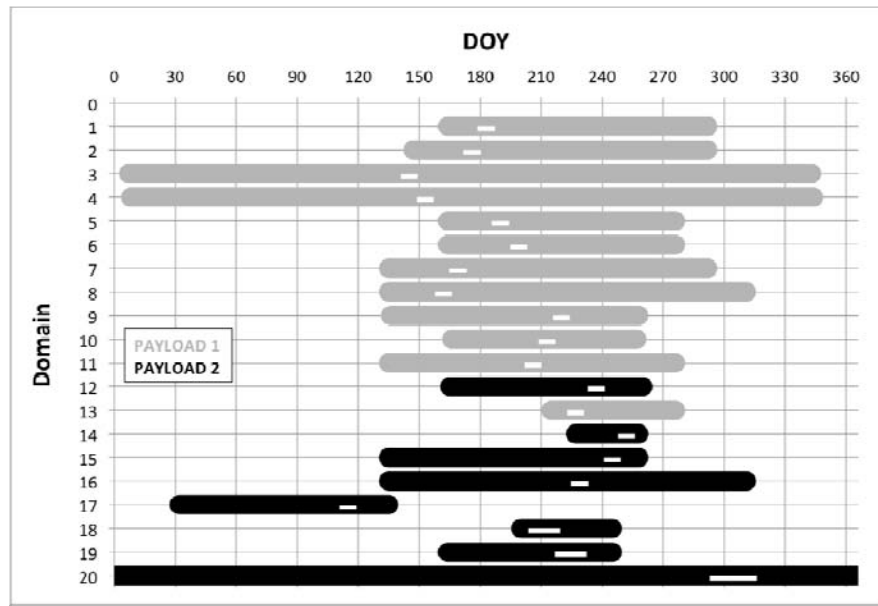


Figure 1: MODIS NDVI data are used to determine the available estimated peak green period for each domain. Grey and black bars represent days of the year (DOY) that meet peak greenness criteria (see text) for AOP payloads 1 and 2 respectively. The white bars indicate baseline planned flight days for operations in each domain.

Airborne Observation Platform Overview

The major functional elements of the AOP are the aircraft platforms, three identical remote sensing instrument payloads, the sensor maintenance and calibration facility, a data processing, archiving and distribution facility, and flight operations. Each instrument payload will consist of an imaging spectrometer, a small footprint waveform LiDAR, an airborne digital camera and a dedicated Global Positioning System (GPS) and Inertial Measurement Unit (IMU) subsystem. An integrated GPS-IMU is required to precisely measure instrument payload position and attitude during remote sensing data collection. This information will be combined with knowledge of the relative orientation of the optical sensors in the GPS-IMU reference frame to compute the line-of-sight trajectory of each laser shot, and spectrometer and camera detector element at a specific time. The common time reference for sensor observations will come from the GPS unit. Data collected over each site will be stored on removable hard drives and sent to the NEON Headquarters for input to the NEON data processing facility and subsequently available to the public via the NEON web portal.

Instrumentation

The AOP spectrometer measures the reflectance of the Earth in several hundred narrow spectral bands between 380 and 2500 nm, providing the capability to reliably remotely measure the subtle biochemical and biophysical properties of vegetation from an airborne platform. The hyperspectral data provided by the imaging spectrometer provides the capability to assess vegetative species diversity and classify vegetation to plant functional types or species levels [19]. The inclusion of the shortwave infrared provides enhanced capability for discriminating tropical and temperate tree species [20,21] and the discrimination of senesced plant materials, wood, or bark from background soils. Spectral bands within the visible to near-infrared portion of the spectrum provide the capability for characterizing canopy chemistry, physiology, and type.

A trade study conducted early in the NEON development resulted in the selection of the pushbroom implementation for the imaging spectrometer. This trade was driven by the need for a wide field of view, high spatial resolution, uniformity, and high signal-to-noise requirements. Systems trades have resulted in an instrument with the full 380 to 2500 nm spectral band being dispersed over a single focal plane array, sampled at 5 nm and operating at a spectral resolution of 10 nm. With an instantaneous field of view of 1 milliradian, the imaging spectrometer provides a ground resolution of between 1 to 3 meters and ground swath of 700 to 2200 m depending on flight altitude, thereby providing a critical link in scaling from individual plant or canopy attributes, to plot or stand level observations across the 20 NEON eco-climate domains, and ultimately, when combined with satellite observations, extrapolation to continental scales.

The imaging spectrometer design utilizes a single spectrometer module and focal plane array to achieve the required uniformity. The entire imaging spectrometer will be housed in a vacuum chamber and cryogenically cooled to 150 K to minimize background noise and dark noise to meet the high signal-to-noise required, in addition to providing a controlled thermal environment for the spectrometer during flight operations. An on-board calibration subsystem is integral to each imaging spectrometer providing the capability for flat fielding for every imaging spectrometer data set, traceability to laboratory calibration standards, and a means for conducting trend analysis to monitor imaging spectrometer performance over time. The on-board calibrator, in conjunction with the NEON laboratory calibration facility also provides a means for cross calibrating between replacement sensors over the lifetime of the 30-year NEON observatory and between sensors flying on separate airborne platforms.

Airborne LiDAR directly measure the three-dimensional distribution of plant canopies, as well as sub-canopy topography, providing high-resolution mapping of vegetation height, cover, and canopy structure. The basic measurement made by a LiDAR device is the distance between the sensor and a target surface, which is obtained by determining the elapsed time between the emission of a short duration laser pulse and the arrival of the reflection of that pulse (the return signal) at the sensor's receiver. In the early 1970s laser altimeters were first flown to measure the topography of the Moon. This technology has since developed such that it can be utilized to measure not only physical surface topographies, but also vegetation canopy structure. These discrete return LiDAR data have been used in the forestry and ecological sciences in the past decade for gaining a better understanding of ecological parameters by measuring canopy heights in forested regions. The number of recordable pulse reflections is limited, however, with the discrete return LiDAR. Airborne laser altimeters that have pushed the boundaries of this measurement technology include the Airborne Topographic Laser Altimeter System (ATLAS) and the Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) (36,37). While discrete-return LiDAR provide single or a small number of vertical positions, the waveform LiDAR records the entire time-varying intensity of the returned energy from each laser pulse. The waveform captures the entire height distribution of the objects illuminated by the laser pulse. Full-waveform LiDAR are currently gaining more attention as they allow for the detection of understory structure in forested environments and give a more complete measurement of topographic vertical structure throughout the vegetation. The Laser Vegetation Imaging Sensor (LVIS) uses a full-waveform laser altimeter to measure surface topography, and vegetation height and structure within a 10–30 m footprint. More recently, small footprint waveform LiDAR have been used to determine ecological parameters such as tree height and species classification, leaf area index, and even to measure fuel loads of coarse woody debris on the forest floor.

Recording the continuous waveform also minimizes the 2-3 meter range ambiguity associated with discrete return LiDAR allowing improved detection of low stature shrubs. Both types of systems have

been used extensively for estimating vegetation structure, however the capability of waveform-LiDAR to provide highly accurate estimates of vegetation height, cover, and canopy structure at fine spatial resolution was deemed necessary to generate fused lidar-hyperspectral products for three-dimensional studies of ecosystems. The desire for high-resolution, 3-dimensional detail of vegetation structure (e.g. canopy height, volume and crown shapes) and underlying topography, as well as for the potential data products that can be produced by combining these data with that collected by the AOP imaging spectrometer, drove the requirement for rapidly scanning small-footprint waveform LiDAR.

High-resolution digital imagery is useful for determining land use and allows for full visualization of the morphology of site locations. Image resolution that is at least three times finer than the spectrometer resolution (e.g. ≤ 30 cm on the ground for a flight altitude of 1000 m) will be provided. The digital camera will be a commercial off-the-shelf, moderate format camera of appropriate focal length and field of view to match the swath width of the other AOP sensors.

Measurements made by the remote sensing instruments must be accurately registered in a common geographic coordinate system during ground data processing. This requires the relative alignment of the optical sensors be accurately known and remain stable during flight. Precise 3-dimensional measurements of the payload position are provided by a Global Position System (GPS) sensor mounted with the optical sensors. An Inertial Measurement Unit (IMU) is integrated with the GPS to provide precise information on changes in the relative orientation of the payload. Information on payload position and attitude are combined with knowledge of the relative orientation of the sensors determined during ground calibration and updated in-flight. The relative sensor alignment must be maintained during flight to enable the optical boresights to be accurately related to the GPS-IMU measurements. The integrated GPS-IMU must be capable of achieving very high accuracy and precision in measuring the position, velocity and attitude of the aircraft payload. The GPS measurements must be made at 10 Hz or greater. Inertial measurements must be made at 200 Hz or greater. An output time stamp signal from the GPS-IMU will be input to the waveform LiDAR, digital camera, and imaging spectrometer measurement data streams to ensure a common time reference frame during ground processing.

The design approach for integrated sensor measurements is to mount the instrumentation onto a common mechanical structure to maintain their relative alignment and provide a mechanical interface to attach the structure to the inside the aircraft cabin in the proper orientation along the flight track and to view through an open port in the cabin floor during flight. The structure will provide a common mechanical interface for holding the imaging spectrometer, waveform LiDAR, digital camera and GPS-IMU during flight. The structure is rigid to maintain relative mechanical alignment between sensors and isolates the instrumentation from aircraft mechanical vibrations.

Data Processing

Processing the sensor data requires several steps before high quality geophysical data products can be produced. The output of each processing step becomes the input to the next higher level of data processing. After each step increasingly more sophisticated analyses and diagnostics are performed to ensure that the output data meet the expected accuracies before proceeding to the next processing step.

The convention for data levels is to assign Level-0 to the raw, unprocessed data recorded at the output of the sensor (Table 2). After applying calibration factors, these data are transformed into meaningful physical units in Level-1 data. Calibration factors are provided by the sensor manufactures and updated during routine sensor calibration. Calibration coefficient tables and formulas for applying

coefficients are developed and coded in the processing scheme. The Level-1 data is captured with the native sampling characteristics with little or no editing for data artifacts. In addition to physical units, the data is referenced to a standard geographic coordinate system. In the NEON data products definition, Level-2 data consists of temporally gap-filled data, typically from a single instrument or sensor (e.g., temperature sensors mounted on FIU towers) and is not applicable to AOP data stream. Level-3 data consisting of sensor data derived from the Level-1 data will be mapped onto a uniform 5-meter sampling grid (or fixed geographic locations) with missing spatial data filled in. Level-4 data products are derived products using Level 1, 2 and/or 3 data. Products at this level may combine observations from more than one NEON instrument, observer, and/or sampling area.

Level-1 data volume for the AOP instrument suite for a single NEON site survey is estimated at 480 gigabytes, resulting in a yearly data volume of approximately 38 terabytes. This includes the standard observations of the 60 sites composing the full NEON observatory and up to 8 Terabytes of data from directed flights. To handle this volume of data, the remote sensing data processing segment will be integrated into the NEON Observatory Cyberinfrastructure. Higher-level data products, in addition to calibrated, ortho-georectified spectral reflectances, radiances and LiDAR waveforms (Level-1 data) for all sites will be publically available via a web server. The NEON Observatory Cyberinfrastructure will include all the computing power, storage capacity, networking capability from sensor to the Web, and specialized software and hardware environments needed to conduct NEON research. It also includes the people required to operate and maintain the equipment, develop and support software, create standards and best practices, and deliver security, user help-desk support, and other services.

Table 2: Representative Data Products Derived from AOP

L level	Product	Description
L-0	Raw sensor output data	Uncalibrated data from the spectrometer, LiDAR, and camera
L-1	Geo-located, calibration sensor data (1-3 meter)	Sensor spectral radiance: 380-2500 nm, 10 nm resolution Surface reflectance: 380 to 2500 nm, 10 nm resolution LiDAR vertical waveform Panchromatic imagery (15 to 30 cm resolution)
L-3	Mapped 5-meter sensor data	Surface reflectance: 380 to 2500 nm, 10 nm resolution “Nearest neighbor” LiDAR waveform 5-meter averaged LIDAR waveform 50-cm resolution imagery (zoom to Level-1 resolution)

AOP Science Data Products

The airborne instrumentation is designed to support research on a range of important themes in ecology in response to grand challenges in the study of biodiversity, biogeochemistry, climate change, ecohydrology, infectious disease, invasive species, and land use change. These science goals require observational data of a wide range of ecosystem attributes ranging from plant functional types, vegetative biochemical and biophysical properties, canopy structure to ecosystem functioning and response. In addition to AOP-specific science data products, higher-level data products will combine information from other NEON science facilities and satellite data. Some of these products will use

primarily AOP data (Table 3) while AOP data will contribute to other products such as ecosystem productivity and biomass estimates.

The AOP-specific data algorithms will be jointly developed through partnerships with universities or research institutions having the demonstrated experience with processing spectroscopic and waveform LiDAR data for ecosystem and land surface studies. To support development of specialized AOP data processing algorithms and early processing of commissioning data, a computer testbed will be developed during the NEON construction phase. Transition of research-grade algorithms into operational software including AOP-specific quality assurance, quality control and diagnostic components to be run on the Cyberinfrastructure computer facility will be developed in-house by NEON scientists and software engineers using the computer testbed. Once operational software has been sufficiently tested and reviewed, it will be transitioned to the NEON Cyberinfrastructure for routine processing.

Table 3: Summary table of preliminary Level-4 science data products based primarily on AOP data*

Product	Description
Leaf water content	Upper canopy water content measured as equivalent water thickness; Principal sensor: imaging spectrometer
Leaf nitrogen content	Upper canopy nitrogen content; Principal sensor: imaging spectrometer
Pigment concentrations	Vegetation indices sensitive to concentrations of chlorophyll, xanthophylls, caroteniod and anthocyanin; Principal sensor: imaging spectrometer
fPAR: Fraction of photosynthetic active radiation	Measure of available radiation in specific wavelengths absorbed by canopy; Principal sensor: imaging spectrometer
Albedo	The fraction of total incident radiation striking a surface that is reflected by that surface; Principal sensor: imaging spectrometer
LAI: Leaf area index	Measure of green area per unit ground surface area; Principal sensors: waveform-LiDAR and imaging spectrometer
Canopy height	Horizontal distribution of height profile of canopy components measured as the distance the canopy top and ground; Principal sensor: waveform-LiDAR
Canopy structure	Position, extent, quantity, volume, and shape of aboveground vegetation in both vertical and horizontal directions; Principal sensor: waveform-LiDAR
Cover fraction	Relative amounts of photosynthetic and non-photosynthetic vegetation, including bark, litter, branches, etc.; Principal sensors: waveform-LiDAR and imaging spectrometer
GPP: Gross primary production	Measure of the rate at which an ecosystem's producers capture and store a given amount of chemical energy as biomass in a given length of time; Principal sensors: waveform-LiDAR and imaging spectrometer

*The Level-4 data products presented represent a subset of Level-4 data products using AOP data and generated as standard data products through the NEON data portal.

The NEON AOP in the Context of the Development of Reflectance Spectroscopy

Imaging reflectance spectroscopy was originally developed in the 1970s, based on insights derived from lab analysis of natural materials, and first demonstrated with the Airborne Imaging Spectrometer (AIS) that acquired scientific data from an airborne platform in 1982. Further development over the last decade driven largely by scientific work with the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS), a whiskbroom scanning imaging spectrometer that has been instrumental in the development of terrestrial imaging spectroscopy. More recently, pushbroom imaging spectrometers, such as the Compact Airborne Spectrographic Imager, the Environmental Mapping and Analysis Program sensor (ENMAP) and the Airborne Prism Experiment (APEX) have been developed and become the preferred form for airborne terrestrial remote sensing. While much of the inspiration and impetus for airborne reflectance spectroscopy came from geology, in the 1980s ecologists realized that spectroscopy might also be applicable to retrieving aspects of the chemical or elemental composition of vegetation (Wessman et al 1988, 1989). During the 1990s, NASA and the European Space Agency supported a number of research projects, field campaigns and technology development space missions aimed at establishing the utility of imaging reflectance spectroscopy. Although initially spectroscopy met with enormous skepticism from scientists experienced with targeted band-oriented radiometric techniques, research on spectroscopy continued. Early in this evolution, Alex Goetz and his colleagues realized the need for field-portable, high performance reflectance spectrometers and established ASD to manufacture instruments. Since the early 1990s, ASD instruments have supported virtually every ground, aircraft and spaceborne campaign and have continually expanded their capability. It is entirely appropriate that the community recognize the essential contribution that “commodity” field spectrometers made to the progress of science by joining in this symposium.

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References

- Asner, G. P., R. F. Hughes, P. M. Vitousek, D. E. Knapp, T. Kennedy-Bowdoin, J. Boardman, et al. (2008). Invasive plants transform the three-dimensional structure of rain forests. *Proc. Nat. Acad. Sci.* 105(11), 4519-4523.
- Asner, G. P. and P. M. Vitousek (2005). Remote sensing of biological invasion and biogeochemical change. *Proc. Nat. Acad. Sci.* 102(12), 4383-4386.
- Keller, M., D. S. Schimel, W. W. Hargrove, and F. M. Hoffman (2008). A continental strategy for the National Ecological Observatory Network. *Frontiers in Ecology and the Environment* 6(5): 282-284
- Wessman, C. A., Aber, J. D., Peterson, D. L., Melillo, J. M. (1988). Foliar analysis using near infrared spectroscopy. *Canadian Journal of Forest Research* 18: 6-11.
- Wessman, C. A., Aber, J. D., Peterson, D. L., Melillo, J. M. (1988). Remote sensing of canopy chemistry and nitrogen cycling in temperate forest ecosystems. *Nature* 335: 154-156.