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# The Short Wave Aerostat-Mounted Imager (SWAMI): A novel platform for acquiring remotely sensed data from a tethered balloon

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#### Abstract

We describe a new remote sensing system called the Short Wave Aerostat-Mounted Imager (SWAMI). The SWAMI is designed to acquire colocated video imagery and hyperspectral data to study basic remote sensing questions and to link landscape level trace gas fluxes with spatially and temporally appropriate spectral observations. The SWAMI can fly at altitudes up to 2km above ground level to bridge the spatial gap between radiometric measurements collected near the surface and those acquired by other aircraft or satellites. The SWAMI platform consists of a dual channel hyperspectral spectroradiometer, video camera, GPS, thermal infrared sensor, and several meteorological and control sensors. All SWAMI functions (e.g. data acquisition and sensor pointing) can be controlled from the ground via wireless transmission. Sample data from the sampling platform are presented, along with several potential scientific applications of SWAMI data.

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#### 1. Introduction

Remote sensing is an indispensable tool for studying terrestrial biophysical and biogeochemical processes from the local to global scale. Flux towers are being used to study material and energy exchanges between the biosphere and the atmosphere over landscape scales. Although advances in multispectral and hyperspectral remote sensing technology over the past three decades have enabled the study of ecosystem structure and function across a wide range of spatial and temporal scales, there still exists a gap between canopy scale processes and landscape level satellite remote sensing measurement.

To derive biophysical parameters relevant to ecosystem structure and function from coarse-scale spectral data, it is often necessary to use algorithms developed from in situ spectral reference data acquired at the plot level. Reference data collection methodologies can be separated into two categories.

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In the first approach, often employed where the vegetation canopy top is relatively low (<1.5 m), spectral data is gathered near the ground using portable spectrometers positioned above specific surface plots. Biophysical characteristics (e.g. photosynthetic and non-photosynthetic biomass, leaf angle distribution, leaf area index) of these entire plots can then be thoroughly quantified to develop empirical relationships with the observed spectra (e.g. Asrar et al., 1986; Middleton, 1991). A main drawback to this sampling approach is that the instrument ground instantaneous field of view (GIFOV) is limited in size, and often is too small to investigate spectral changes associated with varying densities and other characteristics of larger plant functional groups (i.e. trees and shrubs) at a scale coars enough to link spectral data with biogeochemical measurements such as watershed-scale hydrology and ecosystem-atmosphere trace gas fluxes.

To characterize areas containing taller plant canopies (i.e. trees and large shrubs), a second type of field sampling approach is often employed. Biophysical characteristics are measured at a greater number of locations without concurrent ground-based spectroradiometric measurements, but close in

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time to sensor overflight (e.g. Cohen et al., 2003). The measurement locations are later co-registered with the overflight image, and relationships between the image data and ground parameters are derived. However, inherent to this approach are errors that stem from the fact that the exact amount of overlap between pixel and sample plot locations is often impossible to quantify due to geometric and radiometric constraints. Furthermore, because vegetation water status and biosphere-atmosphere material fluxes often vary as a function of hour and day, improving correlations between fluxes and spectral data requires concurrent measurement at the appropriate scale within the tower footprint (Rahman et al., 2003). Given these considerations, it is important to develop new remote sensing techniques to bridge the spatial gap between ground measurements and high-altitude aircraft or spaceborne observations, as well as to narrow the temporal gap that may limit the applicability of locally derived spectral algorithms to predict fluxes at regional and global scales (e.g. Gamon et al., 2004).

Remote sensing instruments capable of flying on the tether line of a sturdy tethered balloon can help bridge such sampling gaps. Because the flight altitude of a tethered balloon can be precisely controlled and rapidly changed, a balloon-mounted remote sensing platform can acquire surface spectral data at a variety of nested spatial scales ranging from the plot level (<5 m diameter GIFOV) to the level of moderate resolution satellite sensors (ca. 500 m diameter GIFOV). In addition, tethered balloon remote sensing allows for continuous data collection above a fixed ground location as the sun angle changes over the course of a day, therefore serving as a cost-effective method for acquiring experimental data with which to evaluate, validate, and improve canopy radiative transfer models. In this paper, we describe the Short Wave Aerostat-Mounted Imager (SWAMI), a new remote sensing system that can be mounted to the tether line of a tethered balloon. The SWAMI is designed to acquire quantitative hyperspectral, photographic, and a suite of ancillary data that can be used to study both basic remote sensing questions (e.g. Chen & Vierling, 2006-this issue) as well as to link ecosystem level trace gas fluxes with spatially appropriate spectral observations in real time.

## 1.1. Background

The use of tethered balloons in remote sensing science dates to the birth of aerial remote sensing itself, when in 1858 Gaspard Felix Tournachon manually collected an aerial photograph near Paris while aboard a tethered hot air balloon. Numerous aerial photographic surveys using manned tethered balloons followed in the 1860s, establishing this method as a viable means for collecting airborne data for municipal, military, aesthetic, and scientific purposes (Newhall, 1969). Timed and remote methods of camera shutter control have enabled smaller unmanned tethered balloons to be employed for remote sensing science. Expanded application of such data in recent years includes photogrammetric quantification of periglacial geomorphology (Boike & Yoshikawa, 2003), measurement of the area of melt ponds perched upon sea ice (Derksen et al., 1997), and quantitation of plant biomass and

vegetated canopy area (e.g. Buerkert et al., 1996; Friedli et al., 1998; Gerard et al., 1997). Although tethered balloons do present some unique deployment challenges, their continued use to conduct remote sensing science for more than 140 years attests to the many advantages of tethered balloons over other airborne platforms, including: (1) extended flight duration (allowing continuous observations to be made over a given location for an indefinite amount of time, ranging from hours to weeks), (2) the highly controllable flight altitude (i.e. GIFOV size), (3) ease of use in remote and/or international locations, where logistical and/or political constraints may preclude the use of other aircraft, (4) relative low cost, (5) relative ease of moving the platform (e.g. Buerkert et al., 1996 used a camel harnessed by a tow rope to guide their balloon across the Sahelian landscape), (6) no high-frequency vibration as with helicopter platforms, and (7) wireless target selection and spectrometer control from the ground, enabling unmanned data collection and its inherent safety benefits. However, while numerous studies have employed relative radiometric methods for gathering and classifying surface information via tethered balloons using both RGB and IR-sensitive films and charge coupled devices (CCDs), to our knowledge no such systems have ever before been deployed to quantify absolute hyperspectral or multispectral radiance or reflectance. The SWAMI carries instrumentation that can image an area using videography, as well as gather hyperspectral radiometric measurements that can be precisely co-located with the imagery. Some applications of these data are described in detail in this paper.

In addition to their utility for collecting remote sensing data, measurements collected with tethered balloons can also fill a critical scale gap in the quantification of landscape level trace gas fluxes. Pioneering tethered balloon work to quantify meteorological variables throughout the planetary boundary layer (Emmitt, 1978; Wylie & Ropelewski, 1980) has been combined with advances in atmospheric trace gas sampling to derive trace gas fluxes representing upwind footprints of tens to hundreds of square kilometers (e.g. Davis et al., 1994; Zimmerman et al., 1988). Over the past decade, fluxes of methane (Beswick et al., 1998; Choularton et al., 1995), nonmethane hydrocarbons (Davis et al., 1994; Greenberg et al., 1999; Guenther et al., 1996; Spirig et al., 2004; Zimmerman et al., 1988), and carbon dioxide (Kuck et al., 2000) have been calculated using measurements from tethered balloons. Collecting remote sensing data from balloons, therefore, can allow for simultaneous spectral and flux measurements representing large flux footprints collected via balloons and towers. This explicit link between spectra and fluxes at the landscape scale may allow improved scaling of flux tower results from the local to landscape scale.

Here, we provide details pertaining to the design and manufacturing of the SWAMI, as well as the tethered balloon platform currently used to fly the platform. Fundamental elements of the mechanical design and construction are presented. Electrical and computer systems that enable sensor stability control, communications routing, and remote operation of the spectrometer are also described. Sample data are presented in the context of their applications for conducting

both basic remote sensing research as well as how they may be applied to the scaling of biosphere—atmosphere flux data of relevance to the FLUXNET and SpecNet communities. In addition to the general description here, we also provide detailed instructions for the design and construction of SWAMI on the Internet (www.cnr.uidaho.edu/remotesensing) to encourage duplication and improvement of this sampling package by others.

## 2. Platform overview and flight infrastructure

The Short Wave Aerostat-Mounted Imager (SWAMI) consists of an aluminum frame that can be attached to a gimbaled stabilization mount clamped to the balloon tether line. The SWAMI frame contains four bays suitable for holding instrumentation, communications hardware, power supplies, and a pointable, actively stabilized viewing hatch for remote sensing purposes (Fig. 1). Primary instrumentation of the SWAMI includes a hyperspectral spectroradiometer (Fieldspec Dual UV/VNIR, Analytical Spectral Devices, Boulder, CO), miniature color video camera (Supercircuits, Inc., Model PC169XS, Leander, TX), and thermal infrared sensor (Model EW-39669-00, Cole-Parmer, Vernon Hills, IL). Sensor heads of each of these primary instruments are carefully mounted to the viewing hatch in the same focal plane to ensure target colocation. Environmental sensors complementing these remote sensing instruments include an OEM-grade global positioning system receiver (Model Svee Eight Plus, Trimble Navigation Ltd., Sunnyvale, CA), humidity sensor and thermometer, cup anemometer, and barometer. The open frame nature of the system allows for modular additions or substitutions of other sensors should they be required for a particular application.

The tethered balloon flight system used to carry the SWAMI instrument platform is robust. Flight infrastructure used to fly the balloon includes a 5-m-long flatbed trailer (Fig. 2) that carries a fairlead (pulley-based pivot system) and a heavy-duty hydraulic marine winch (Sea-Mac, Houston, TX) fitted with a level-line spooling mechanism. The winch holds more than 2000 m of high-density linear polyethylene line (SPECTRA<sup>TM</sup>)



Fig. 2. SWAMI tethered balloon platform with required flight infrastructure.

sheathed in nylon (Cortland Line Company, Cortland, NY). The line has a diameter of about 9mm with a failure load of approximately 1100 kg. The trailer-mounted system, designed for operation in remote locations, is powered using a 12-KVA Honda diesel generator.

The balloon envelope is manufactured with a durable polymer-coated nylon fabric (Hypalon<sup>TM</sup>) with an internal volume of 1000 m³ (Model TIF-3500, Aerostar International, Sioux Falls, SD). The balloon contains an expandable belly and spring-loaded pressure relief valve to enable flight to altitudes >2000 m above ground level (AGL). When filled with helium, the balloon is 12 m long and 4.3 m wide, and is capable of attaining 78 kg free lift at sea level. The aerodynamic design of the balloon allows flight in laminar winds of >11 m s<sup>-1</sup>, which can increase the instantaneous payload carrying capacity to >300 kg at sea level. However, surface winds exceeding 4.5 m s<sup>-1</sup> can cause difficulty in preparing the balloon for flight. Translation movements of the balloon are tolerable through swiveling of the pulley fairlead about its axis. A slack take-up

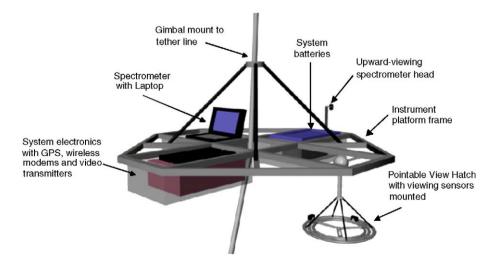


Fig. 1. Schematic of the SWAMI platform with instrumentation and stabilized viewing hatch.

mechanism is also situated between the winch and fairlead to keep the tether line taught during downdrafts; without such a mechanism it is possible for the line to derail from the pulleys and cause catastrophic failure. Additional site requirements include clearance to fly in the given airspace and a clearing of approximately 50 m minimum diameter. This balloon system has previously carried a variety of atmospheric sampling packages along its tether line so as to characterize tropospheric trace gas compound concentrations and fluxes (e.g. as in measurements presented in Greenberg et al., 1999).

## 3. Design specifications

To enable successful deployment of the SWAMI, several design specifications that specifically pertain to balloons must be followed. Many of these considerations apply to any remote sensing system to be deployed on a tethered balloon. Platform specifications include:

- Lightweight frame structure. In order to fly under all weather conditions, the complete package and fastening system is designed to have a mass <20 kg. Although the balloon is capable of more free lift at sea level, the acceptable payload mass decreases with site elevation and with line weight at higher flight altitude. Low SWAMI structural mass also enables additional instrumentation to be concurrently flown, to enable trace gas or other atmospheric sampling during remote sensing measurement.
- Easy, reliable connection to balloon tether line. Because irradiance and radiance are simultaneously measured by the FieldSpec Dual instrument, the SWAMI platform is connected to the tether line at least 200 m below the balloon. With this geometry, the fraction of sky obscured by the balloon at the height of the sensor is <0.1% of the entire sky hemisphere. Surface winds can make connecting the platform to the tether line difficult as a result of line movement. In addition, due to the great lift of the balloon, the line cannot be wrapped around an attachment mechanism; instead, a nonslip line attachment clamp must be used. Because a small amount of slippage can create enough heat to melt synthetic line materials such as Spectra<sup>TM</sup>, much care must be made in implementing a robust, yet simple and easily removable attachment.
- Sensor stability. The platform and viewing hatch must be stable while in flight to enable viewing of the same surface features while spectroradiometer data are being recorded. We achieve an acceptable amount of stability (i.e. where >90% of the target area remains the same during spectral measurement acquisition) using both passive and active control mechanisms.
- Wireless ground control. Practical considerations preclude the use of any wires to directly connect the ground control station with the platform. The SWAMI ground control station therefore utilizes two-way wireless data transmission to monitor target characteristics, steer the viewing hatch, send commands to the instrumentation package, and receive all sensor data in real time. The ground control system thus

- serves to not only acquire data, but also to troubleshoot and correct problems that may occur in mid-flight.
- Pointable viewing hatch. To acquire measurements across a range of viewing geometries, the SWAMI is designed to measure surface features at view zenith angles ( $\theta_v$ ) of up to  $60^\circ$  in any direction.
- Power efficiency. Batteries are the only practical means of supplying power to the electronic system during flight.
   Because superfluous batteries contribute excess weight to the platform, the electronic system must be as efficient as possible. Long flight times are desirable in order to characterize surface features at multiple altitudes and sunsensor geometries over the course of a day.







Fig. 3. Structural components of the SWAMI including (a) center mount for tether line attachment, (b) platform skeleton without instrumentation, and (c) viewing hatch shown during deployment.

## 4. SWAMI platform description

## 4.1. Mechanical components and design

The essential elements of the SWAMI mechanical support system consist of the center mount line attachment clamp, platform frame, and viewing hatch (Fig. 3). The center mount attachment clamp is a 1.8-kg modified gimbal mount fabricated of solid aluminum using a computer numerical control (CNC) mill. All edges on the mount (as well as on the platform as a whole) have been rounded to prevent abrasion or other damage to the tether line. Four nylon ropes connect the center mount to the platform and can be readily adjusted to enable static leveling of the platform. The platform frame is an octagonal skeleton measuring 1.5 m across, constructed of square tube extruded aluminum. Three of the four platform instrument bays contain lightweight, flexible, yet formable rigid plastic baskets. These three baskets hold the spectroradiometer, batteries, and the majority of the electronic instruments and control systems. The fourth bay contains the instrument viewing hatch. The viewing hatch consists of an aluminum ring approximately 25 cm in diameter and an interior Plexiglas mount surface for alignment of the optical instruments and dual axis tilt sensor to measure  $\theta_{v}$ . The outer aluminum ring and the inner Plexiglas mount are configured with axes normal to one another; servo motors are used to control the pitch and roll of the radiometric sensors via direct drive to these

axes. A third servo motor for yaw control is utilized to correct for azimuthal twisting about the tether line. This servo is placed such that it can swivel the view hatch about the third (vertical) principal axis (not visible in figure).

#### 4.2. Electrical sensors, components, and circuitry

Several instruments have been integrated with the SWAMI control system to provide an array of information about the viewing target and surrounding environment. In order to collect and transmit data from each instrument to the ground in real time, sub-platforms utilizing custom computer programs were designed and manufactured. The following list details the key SWAMI sensors, data management/control components, and data transmission devices. Electronic circuitry showing the relations among these sensors is depicted in Fig. 4. Additional detail regarding the electrical engineering of the SWAMI can be found on the Internet at www.cnr.uidaho.edu/remotesensing.

#### 4.3. Radiometric sensors

Radiometric sensors on the platform are comprised of:

 A dual channel hyperspectral field spectroradiometer. The Fieldspec Dual UV/VNIR measures wavelengths from 350

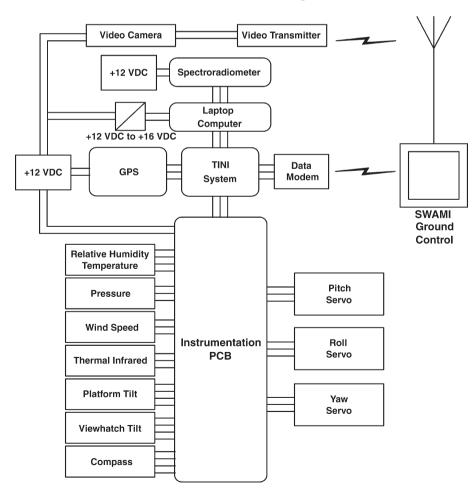


Fig. 4. Schematic of the SWAMI electrical system.

to 1050 nm with approximately 3 nm spectral resolution (i.e. 3 nm full width half maximum of a single signal emission line). The instantaneous field of view (IFOV) of the downward-pointing spectrometer can be adjusted by fitting the fiber optic tip with factory-calibrated cylinder type foreoptics of 10° or 18°, while the upward pointing spectrometer cable is deployed within a "remote cosine receptor" diffusing cap. This dual nature of the spectroradiometer allows for reflectance factors to be calculated remotely and in real time using concurrent measures of radiance and irradiance from the two sensors, which have been previously cross-calibrated in the laboratory using a standard reflectance panel. Introduction of error to the downwelling signal from balloon shadowing interference is highly unlikely, due to the fact that the balloon blocks < 0.1% of the sky above the sensor platform.

- An RGB microvideo camera. This camera employs a CCD to record data at 460 lines of resolution. The camera can be fitted with lenses of various focal length so as to allow data collection closely matching the hyperspectral GIFOV. For example, an 8-mm lens (Supercircuits model ML-8.0 MM) best coincides with the hyperspectral GIFOV when using an 18° foreoptic (see Chen & Vierling, 2006-this issue). Therefore, the video resolution available for GIFOV ground cover classification is maximized while maintaining complete GIFOV coverage within the video.
- A thermal infrared sensor. The miniature thermal infrared sensor can measure temperatures ranging from 0 to 180 °C with an accuracy of  $\pm 3$  °C. The sensor is sensitive to the spectral range of 7.6–18  $\mu$ m, with adjustable emissivity settings between 0.02 and 1.00. The IFOV of the sensor is  $\sim 30^{\circ}$ .

## 4.4. Other sensors

#### Other SWAMI sensors include:

- A GPS receiver. An OEM-grade 8-channel continuous tracking GPS receiver is utilized with a micropatch antenna (Miniature 5V antenna model, Trimble Inc.) to record the three dimensional position of the platform. The real-time position accuracy of the instrument is rated at 25 m.
- Tilt sensors. Two dual axis tilt sensors (CXTA02, Crossbow Technology, San Jose, CA) are used on the SWAMI. One sensor is located on the platform skeleton to provide data about the platform movement, while the other is fastened to the viewing hatch Plexiglas mount surface to provide data necessary to stabilize the view angle of the radiometric sensor heads. The tilt sensors can measure  $\theta_{\rm v}$  to  $\pm 75^{\circ}$  at  $0.5^{\circ}$  accuracy.
- An analog compass sensor. This sensor (Model 1655, Dinsmore Sensors, Girard, PA) provides the azimuth angle of the SWAMI viewing hatch so as to monitor and provide data necessary for view azimuth angle (Ψ<sub>v</sub>) control via servo motor.
- Meteorological sensors. Relative humidity, temperature, barometric pressure, and wind speed data are collected

Table 1 SWAMI meteorological sensor specifications

Sensor	Company	Model	Range	Output
Relative humidity	Vaisala	Humitter® 50Y	0% to 100%	0-1 VDC
Temperature	Vaisala	Humitter® 50Y	−40 to 60 °C	0–1 VDC
Barometric pressure	Setra	276	600 to 1100 mb	0–5 VDC
Anemometer	Cole-Parmer	P-99780-10	0 to 50 m s <sup>-1</sup>	4-20 mA

aboard the SWAMI; the specifications for these sensors are displayed in Table 1.

## 4.5. Data management and control system components

These components include:

- A laptop computer. A small laptop computer (Fujitsu Montego) is dedicated to operating and managing data collected by the Dual UV/VNIR spectroradiometer. Data from the spectroradiometer are transferred directly to the laptop computer via parallel cable.
- Wireless video transmission. The Eagle Series VTX2400 wireless transmitter and VRX2400 wireless receiver (Trango Systems, Inc., San Diego, CA) is a 2.4-GHz wireless video transmission system used to obtain real-time video data. The system is capable of operation on four different channel frequencies and can transmit composite NTSC or PAL video signals. The RF output power of the transmitter is +6.0 dBm ±3 dB, allowing for line-of-sight data transmission for platform altitudes up to 2 km. A 14-dB patch antenna receives the video signal for ground viewing and recording.
- Wireless data transmission. A pair of serial data modems (CDR-915M, Coyote DataCom, West Sacramento, CA) serve to transfer two-way data streams between the platform and ground control station. The transmitter output power of 200 mW allows for a line-of-sight transmission range up to 16 km.
- Tiny Internet Interface (TINI). The TINI (Dallas Semiconductor Corp., Sunnyvale, CA) is a data networking platform capable of managing and routing data among many hardware devices. A powerful chip-set and a Java programmable runtime environment is utilized to create the TINI data network (Loomis, 2001). The chip-set is located on a 72-pin single in-line memory module (SIMM). The SIMM is inserted onto a Eurocard 20 (E20) socket board (Dallas Semiconductor Corp., Sunnyvale, CA) along with other hardware devices to enable reliable operation. On the SWAMI, two TINI boards are interfaced with a custom printed circuit board (PCB) containing instrumentation circuitry to provide enough ports to manage all necessary data flows.
- Customized SWAMI printed circuit board (PCB). This board acquires meteorological and other sensor data and operates the viewing hatch stability control system (Fig. 4). Major components of the instrumentation PCB include inputs for

the SWAMI sensors, a multiplexer, two microcontrollers, and outputs for the servo motors, as briefly explained below:

- Sensor inputs—The wind, pressure, temperature, relative humidity, thermal infrared, analog compass, and platformmounted tilt sensor connect to the instrumentation PCB through a 16-channel single ended input analog multiplexer (MPC506, Texas Instruments, Dallas, TX). Many of these sensors require +12 VDC for their operation, which is supplied by the PCB.
- Microcontrollers—The two microcontrollers utilized by the PCB include one PIC16F876 (Microchip Technology Inc., Chandler, Arizona) to manage sensor data and one PIC18F252 chip for servo motor control. These microcontrollers are programmable in C to perform all analogto-digital conversions required by the TINI to allow for 2way data transmission between the SWAMI platform and ground control station.
- Servo motor outputs—Three servo motors (models HS605BB and HS805BB, Hitec RCD USA Inc., Poway, CA) are utilized to stabilize  $\Psi_{\rm v}$  and  $\theta_{\rm v}$  of the radiometric sensor viewing hatch via microcontroller output. Each servo requires a +5 VDC input provided by the instrumentation PCB.
- Power system. Three different sets of +12 VDC batteries power the electrical systems. The spectroradiometer is equipped with its own 7-A h nickel cadmium battery. All other instrumentation is run off of a 7.2-A h lead acid battery. The laptop computer is the regulating factor of maximum flight time because of its large current drain on the power system. Its internal battery lasts only for about a half-hour, so

external power must be provided. However, its power input is +16 VDC rather than +12 VDC accepted by the other electronics. A DC-to-DC voltage converter was designed to alleviate the problem. The converter boosts the +12 VDC output of a 4.5-A h nickel metal hydride battery to +16 VDC at roughly 90% efficiency. The power system and all instrumentation share a common ground so as to minimize the potential for system damage. Under the current platform power configuration, power can be maintained to all system components for approximately 2.5 h.

#### 4.6. Viewing stability control and target selection

The printed circuit board (PCB) monitors and stabilizes the attitude of the radiometric sensor viewing hatch. One PCB microcontroller receives the sensor data from the multiplexer and sends it to the TINI system, where it is then transmitted to the ground control station for user monitoring purposes. The second microcontroller receives tilt sensor data from the viewing hatch and calculates attitude correction factors derived from a proportional control system. These correction factors determine the best position of the three servo motors for negating instabilities. In addition, the automated stability control system can be temporarily overridden by switching to a manual control scheme, allowing the user to choose and then "lock on" to particular targets of interest for selective or repeat measurement.

Because the automated stability control system is driven by changes in viewing hatch roll, pitch, and yaw, platform translation that occurs from gradual balloon drift cannot be detected or corrected without additional inputs. The SWAMI

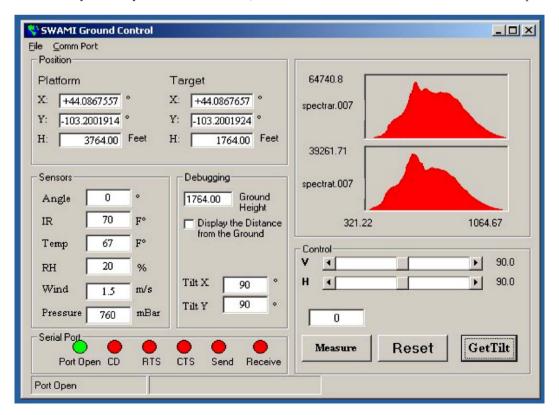


Fig. 5. Computer screen shot of SWAMI ground control software interface.

development team is therefore working to incorporate rapid performance computer vision instrumentation (Acadia I PCI Vision Accelerator Board, Pyramid Vision Technologies, Princeton, NJ) aboard the platform to enable viewing stability via real-time video feedback. The Acadia board detects pixel motion and can be used to produce analog outputs to the servo motors so that they may adjust the attitude of the viewing hatch and return the video target to its original location. This system has been designed, developed, and tested in the laboratory and in controlled field trials.

## 5. SWAMI ground control and example data

The SWAMI ground control instrumentation consists of a wireless data modem and video receiving antenna, a monitor for real-time viewing of the streaming video signal, a video recorder, and a laptop computer. Electrical power necessary to run the ground control system is acquired via the same generator used to run the balloon winch. Custom Windows-based SWAMI software provides the user interface for communicating with the platform, monitoring data streams, and automatically saving data during flight. Fig. 5 shows an example view of the ground control software interface, including readouts for spectral data (shown as raw radiance and irradiance), sensor data, GPS data, communications status, and tilt control.

Target selection for hyperspectral data acquisition may occur in two modes. In the first mode, the servo motors may be manually directed using the software interface to seek the desired ground target as viewed in the video monitor. Once the desired target is selected by the user, the SWAMI uses the concomitant tilt and compass settings as inputs to its stability routine so that the target may be held in view for extended data collection. The second mode of target selection allows the user to input desired azimuth and zenith angles so as to collect data with a known viewing geometry. Regardless of the pointing method, when the desired sample angle is selected, a second software interface window (not shown) allows the user to remotely trigger the spectrometer measurement.

The flight altitude trajectory of a SWAMI data acquisition flight that took place during the summer of 2003 is shown in Fig. 6. The flight duration was 70min, during which time hyper-

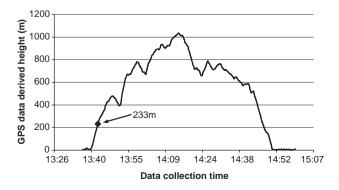


Fig. 6. SWAMI flight profile acquired Summer 2003. The diamond represents the height at which data were collected to perform spectral mixture analyses of a forested ecosystem (Chen & Vierling, 2006-this issue).





Fig. 7. Sample video captures of the surface acquired at altitudes of (a) 233 m AGL and (b) 778 m AGL. The circle inscribed on each image denotes the area of the GIFOV subtended by the hyperspectral measurement. Note that the time stamp of the video represents the time (h:mm:ss) since start of video capture.

spectral data were acquired for 25 ground targets of varying diameter as the platform height was changed. Example video and hyperspectral data collected at 233-m and 778-m altitude are shown in Figs. 7 and 8, and the 233-m data are analyzed in a companion paper (Chen & Vierling, 2006-this issue).

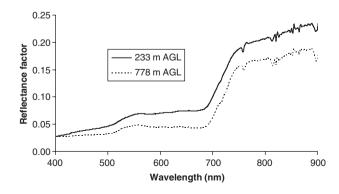


Fig. 8. Sample spectra acquired by the SWAMI corresponding to the areas denoted by the circles in Fig. 7(a,b). Spectral mixture analyses using the spectrum collected at 233 m AGL are reported in Chen and Vierling (2006-this issue).

5.1. Example applications of SWAMI in remote sensing and flux scaling

The unique sampling capabilities enabled by the SWAMI platform allow for a wide range of potential applications in many sampling environments. Example applications include:

- Spectral mixture analysis (SMA). Because the spatial overlap between the hyperspectral signal and the collected image can be quantifiably delineated, hyperspectral and simulated multispectral endmember analyses may occur over tall vegetation canopies to allow for detailed error assessment of linear and nonlinear SMA approaches (e.g. Chen & Vierling, 2006-this issue).
- Investigation of surface anisotropy. By attaching a second tether line to the balloon and moving the SWAMI platform across the sky in a large arc, large-scale goniometer-type measurements could be achieved to study the reflectance anisotropy of tall canopies (after Sandmeier & Itten, 1999). Alternately, continuous nadir or off-nadir measurements collected over the course of an entire day would enable direct field measurements of diurnal variation in field anisotropy over a wide range of surfaces. Diurnal variability in hyperspectral or multispectral vegetation indices of tall canopies could be quantified, thereby assisting in flux tower scaling efforts. Investigations under cloudy skies could be compared with clear sky observations to further investigate the interaction among shadows and trees in SMA (e.g. Chen et al., 2004; Lobell et al., 2002) or retrieval of biophysical parameters using various approaches.
- Atmospheric effects upon surface radiometry. The influence of variable atmospheric scattering upon surface radiometry (e.g. under heavy aerosol conditions) could be investigated by flying the SWAMI at a range of altitudes over homogeneous surfaces.
- Linking trace gas flux measurements to radiometric measurements. The GIFOV attainable by the SWAMI can be large enough to represent pixels from moderate/low resolution sensors (e.g. MODIS, AVHRR). Because this spatial scale of spectral measurement compares well with the scale of a flux tower footprint, explicit links between surface spectral variability and fluxes may be possible at the landscape level. Continuous flight over the course of days to weeks could allow for diurnal variability in fluxes and radiometry to be explored, possibly helping to decouple spectral effects caused by bi-directional reflectance from spectral effects caused by changes in canopy ecophysiology (e.g. foliar water status or pigment activity). Spectral mixture analyses of SWAMI GIFOVs in tower footprints could allow for the abundance of particular endmembers (e.g. plant functional groups) to be related to flux measurements in a temporally explicit manner. Furthermore, adding atmospheric sampling packages (e.g. Greenberg et al., 1999) to the SWAMI tethered balloon during spectral measurement collection near towers could allow for balloon/tower cross comparisons, enabling trace gas fluxes and surface radiometric change to be examined across a hierarchy of spatial

- scales. Finally, thermal infrared measurements can be combined with hyperspectral measurements to further investigate vegetation status (e.g. Carlson et al., 1995).
- Evaluation of scaling algorithms. The SWAMI can be raised and lowered to various altitudes for studying the spatial scaling relationships of surface radiometry over homogeneous or heterogeneous canopies along a continuum of GIFOV sizes.
- Aquatic remote sensing. Phytoplankton or sediment loading in rivers or oceans may be quantified spectrally at multiple scales through deployment of the SWAMI on a barge or boat.
- Remote sensing education. The SWAMI is an ideal platform for involving students of all ages in the excitement of remote sensing. The ability for a student to steer an airborne imaging device in real time, at a familiar site, provides a rich context for learning in a hands-on setting. Future efforts may include student competitions to engineer and build environmental sampling devices for flight on the SWAMI platform after the model established by the NASA Student Involvement Program. The SWAMI has been used in field education experiences for Native American students and pre-service teachers.
- Expanded measurement capabilities. The modular design of the SWAMI allows for the addition and/or substitution of additional sensors, such as thermal, multispectral, or hyperspectral imaging devices, on the platform. Further advances in platform stabilization techniques may allow for deployment of sun photometers or compact laser instruments for future applications. Conversely, aspects of the platform such as remote spectrometer control can be easily removed from the SWAMI and utilized in alternate platforms (e.g. trams, UAVs, cable-mounted systems, light aircraft, helicopter) to investigate questions that require such approaches.

## 6. Conclusion

The Short Wave Aerostat-Mounted Imager (SWAMI) has been developed to study a range of remote sensing questions. The unique sampling opportunities made possible by the tethered balloon sampling platform allow for novel methods to be employed for model validation, evaluation of existing spectral analysis techniques, and spatial scaling of terrestrial processes that are linked to surface radiometric variability. The development of the SWAMI is consistent with recent calls in the remote sensing community to develop affordable, novel sampling protocols at intermediate scales to better link spectral measurements and vegetation ecophysiological change (e.g. Gamon et al., 2004). Our hope is that the remote sensing and trace gas flux communities will view the SWAMI as a facility that can be used in stand-alone applications or in conjunction with additional remote sensing devices or flux measurements to enable interdisciplinary collaborative research.

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