BALLOON-BORNE MULTISPECTRAL IMAGING OF VEGETATION
FOR THE MONITORING OF CARBON DIOXIDE LEAKS ORIGINATING
FROM A SIMULATED GEOLOGIC CARBON SEQUESTRATION FACILITY

by

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research committee, senior thesis coordinator, and department chair and has been found to be satisfactory.

<table>
<thead>
<tr>
<th>Date</th>
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<tr>
<td></td>
<td>Todd Lines, Ph. D, Advisor</td>
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The analysis of a proof-of-concept tethered-balloon multispectral imaging system used to indirectly monitor CO$_2$ leaks at a geologic carbon sequestration site. The multispectral imager uses vegetation stress to gauge elevated CO$_2$ levels. Vegetation stress is determined through the collection of both red and near-infrared reflectance. This data is used to calculate the normalized difference vegetation index (NDVI). The tethered balloon imager is compared to a scaffold-mounted multispectral imaging system that was previously established as an accurate gauge of NDVI and CO$_2$ leaks. Both imagers gather reflectance data at a simulated geologic carbon sequestration site during a simulated leak. Additionally the paper shows the characterization of both imager’s transmittance profiles and simulated spectra used to create response profiles that help confirm the reliability of the airborne imager in accurately measuring NDVI.
ACKNOWLEDGMENTS

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Chapter 1

Introduction

1.1 Geologic Carbon Sequestration

Geologic carbon sequestration (GCS) is a form of carbon footprint mitigation being considered for implementation throughout the world. It involves pumping CO\textsubscript{2} back into a porous rock formation in order to offset current emissions. Much still needs to be understood about the effects of high-volume and high-concentration CO\textsubscript{2} on the geography where it might be deposited. Elevated levels of CO\textsubscript{2} can be dangerous to humans, animals, and plants. Systems capable of detecting leaking CO\textsubscript{2} are key to the success of geologic carbon sequestration site. Any proposed sequestration site would require the deployment of an early detection system that could give site operators the ability to locate leaks as they sprout and prevent long term damage to the environment.
1.2 The Detection of Elevated CO₂ Levels Using Multispectral Imaging

The Zero Emissions Research and Technology (ZERT) center at Montana State University in Bozeman, MT focuses its research on the effects of GCS. ZERT has active research in the modeling of CO₂ sequestration, the effects of sequestration sites on the geographic region they inhabit, and the detection and analysis of leaks that develop at the sequestration sites. The Optical Remote Sensor Laboratory (ORSL) of the Montana State University Electrical and Computer Engineering Department is currently researching a multispectral detection system that uses CO₂-driven plant stress as an indirect measure of CO₂ levels. While slightly elevated levels of CO₂ in the atmosphere can lead to increased plant health, elevated levels of CO₂ in the soil can have catastrophic results to the vegetation [1–4]. Therefore, a leaking GCS site is expected to have regions of CO₂-stressed vegetation and that plant stress could be used to pinpoint the location of the leak. By developing the proper method of gauging plant health, regions of elevated CO₂ levels could be identified in order to provide an early leak detection system of leaks at a GCS site.

One such method of gauging vegetation stress stems from multispectral imaging. Chlorophyll absorption in the red portion of the visible spectrum (~600 nm) and leaf structure reflectance in the near infrared (NIR) spectrum (~700 nm) produce a vegetation reflectance spectrum that is low in the red and high in the NIR. This difference provides a contrast against which plant health can be observed [1–4]. As CO₂ levels in the soil rise above 20 percent, a stress on the vegetation is observed [4]. As a plant begins to die, its reflectance in the red wavelengths rises due to decreases in chlorophyll production and NIR reflectance drops due to the degrading leaf structure; this results in large wavelength-dependent changes in reflectance at approximately
1.2 The Detection of Elevated CO₂ Levels Using Multispectral Imaging

685-700nm. The sharp rate of change in reflectance in this range can be exploited to provide a measure of plant stress. A reliable measure of plant health that uses these parameters is called the Normalized Difference vegetation Index (NDVI).

\[ NDVI = \frac{\rho_{\text{NIR}} - \rho_{\text{R}}}{\rho_{\text{NIR}} + \rho_{\text{R}}} \]

Red and near-infrared reflectance are represented by \( \rho_R \) and \( \rho_{\text{NIR}} \), respectively. NDVI values range from 1 to -1. Healthy vegetation values range from about 0.6 to 0.4 while unhealthy vegetation is found to have an NDVI values of 0.3 and below. Positive numbers below 0.1 usually indicate soil or dead vegetation, while many man-made structures have negative NDVI values. In past research, ORSL has shown that NDVI can be used to accurately locate CO₂ leaks at a GCS site [5–10].

### 1.2.1 Tethered-Balloon multispectral Imager

Although recent research has shown the reliability of various multispectral imagers in the detection of elevated levels of CO₂ gas, these systems are all fixed to a scaffold and monitor a region measuring about 3m x 3m. Such a field of view (FOV) is inadequate to the demands of monitoring a GCS site that might span hectares of land. An imager that could monitor much larger areas than a fixed platform-based imager is needed. This thesis describes one approach to meeting this need, namely using a compact, low-cost multispectral imaging system mounted on a tethered balloon to image a significantly larger region.
Chapter 2

Experiment Design

2.1 ZERT Site

In order to simulate a GCS CO$_2$ leak, the ZERT field site contains a pressurized horizontal pipe just under the field surface [10]. A stainless steel well casing measuring 98 m in length and 10.16 cm in diameter was used to simulate the carbon well. The last fifteen and twelve meters of pipe on the respective ends are solid. The other 70 m consists of a 20-slot interior pattern with an open area of .55%. The pipe was partitioned into six sections in order to improve even flow and CO$_2$ distribution along the length of the well as well as to increase the flexibility of the system. The six partitioned zones (five 12 m long zones and one 9 m zone) are separated by an inflated rubber packer system. Each zone is plumbed separately and controlled independently to allow individual flow rates to the six zones. Perforations in each section of the tube allow for the simulation of a leak. Regions along the pipe characterized by exceptionally elevated CO$_2$ concentrations are referred to as “hotspots”.
2.2 Equipment

During the summer of 2012, as part of a controlled CO$_2$ release experiment conducted at the ZERT site, two multispectral imaging systems were deployed to study the feasibility of using a tethered-balloon-borne imager to detect gas leaks. The first of the two systems was a low-cost multispectral imaging system designed and built at Montana State University for outreach and education projects conducted from a tethered balloon [11]. This balloon-borne imager had never before been used at the ZERT site. The second of the two systems was a two-channel (red and NIR) imaging system designed and built at Montana State University for continual operation on a scaffold at the ZERT site [5-7]. This section outlines the design and operation methodologies for both of these imaging systems. Details related to the processing of the tethered-balloon system’s images is treated in Appendix B).
As part of an outreach program, ORSL developed a low-cost imager for the Montana Space Grant Consortium (MSGC). The multispectral imager is mounted on a tethered-balloon that elevates the imager to approximately 50m. It uses three low-cost complementary metal oxide semiconductor (CMOS) cameras that capture reflectance data across the blue, red and NIR wavelengths [11]. These channels are created by the use of low-cost optical filters placed directly in front of the CMOS cameras. Given the approximate height of the imager, the 65 × 50 deg viewing angle of the lens, and a resolution of 640 × 480 pixels, the cameras are capable of resolving a 64 x 46 m area at about 13 cm² per pixel. To aid the operator in capturing useful data, the
imager broadcasts realtime video telemetry of a selectable color channel. This can be viewed on a portable video monitor by operators on the ground. It uses a ZigBee relay to trigger image acquisition during flight. It was originally intended for educational purposes but initial data indicates that the imager could be utilized in commercial or scientific applications. This imager acquires both red and NIR signals and is perfectly adapted to measure NDVI over a wide FOV.

2.2.2 Scaffold-Mounted Multispectral Imager

Figure 2.3: Scaffold-Mounted imager is large, two-port box on top of scaffold. Tripod on bottom right corner holds spectralon reflectance calibration panel.

(Photo courtesy of Dr. J. Shaw)
Past research has shown multispectral imaging can be used to detect elevated CO$_2$ levels in a vegetated area [5–7,12,13]. The imager used during the CO$_2$ release of 2011 was used again during 2012 in order to provide a benchmark for the tethered-balloon imager. The scaffold imager sits roughly 3 meters above the ground pointed downward at 45° below horizontal. It uses a megapixel CMOS camera with a resolution of 1280 x 1024 [7]. At an elevation of 3m above ground, its FOV is approximately 100 m$^2$, giving it a pixel density of roughly 1 pixel per cm$^2$. A Thorlabs FW102B six-position rotating filter wheel populated with Thorlabs FB650-40 and FB800-40 bandpass filters capture the needed spectra to calculate NDVI. The area of interest captured by the imager was a region immediately surrounding the hotspot as well as two separate control regions.

2.2.3 Calibration Panels

Figure 2.4

Figure 2.4: In order to calculate absolute reflectance, the spectralon panel (left) was used in the scaffold-mounted system while canvas tarp (right) were used to calibrate the tethered-balloon system.

[Photo courtesy of Dr. J. Shaw]
To obtain quantitative reflectance values in any given frame, it was necessary for a calibration target of well-known reflectance to be present in every image captured by the camera. An 12 in. square panel of spectralon was used with the platform-based imager. However, the tethered-balloon imager would not sufficiently resolve the small panel from the elevation at which it operates. Therefore, a canvas tarp painted black and white measuring 1m x 2m was placed in the FOV of each image. The MATLAB routines used to process the images include calibration data relevant to the tarp or spectralon. These data were used to calibrate the quantitative reflectances for the remainder of pixels in the image.

2.3 The Release of CO₂

Figure 2.5

Figure 2.5: Tethered-balloon shown in the field next to the scaffold

[Photo courtesy of Dr. J. Shaw]
2.3 The Release of CO₂

The goal of the summer 2012 research at ZERT carried out by ORSL was to prove that the tethered-balloon imager could feasibly be used as a CO₂ leak detection system at a GCS. To gauge its usefulness in this task, data acquired through the tethered-balloon imager were compared with the data from the scaffold-mounted system.

During the summer of 2012 a controlled release was conducted, with CO₂ flow starting at 6 pm on July 10, 2012 with a flow rate of 0.15 tonne/day. A lightning event cut power and the gas stopped flowing at 16:15 Mountain Daylight Time on July 11, 2012. CO₂ flow was restored (0.15 tonne/day) at 17:15 MDT on July 15, 2012. Power outages occurred at the site from 6-9 pm on July 25 & 26, 2012 (flow was interrupted). On July 30, 2012 the CO₂ flow rate increased to 0.3 tonne/day at 8 am. CO₂ flow was ended permanently on August 13, 2012.

Every ten minutes between 8am and 4pm during the release, the scaffold-based imager captured images of a roped-off vegetation test area. The images were processed by isolating a region on the edge of the hotspot and two control regions where low CO₂ flux was expected. The scaffold imager had both horizontal and vertical control spots for the purposes of a separate research program. The vertical control region was used solely for analysis. Images were processed to provide a reliable timeseries of NDVI snapshots throughout the release. On four separate days spread throughout the release, the tethered-balloon system was flown and used to gauge the vegetation health of the same regions (control and hotspot). The results of the two imagers were compared to assess the capability of the tethered-balloon imager in detecting elevated levels of CO₂.
2.4 Image Processing

Images acquired by the tethered-balloon imager were processed using a MATLAB routine in which the two images (red and NIR) were visually superimposed and the calibration tarp’s light and dark regions identified. NDVI values were then computed by MATLAB routines, pixel by pixel and represented in a color-coded map. Hotspot and control regions were selected manually since image orientation differed from picture to picture. For a complete treatment on the imaging processing procedure, see Appendix B.
2.5 Obtaining Meaningful Results

To compare the results of the two imagers, a characterization detailing their filter transmittance data and simulated reflectance values for healthy, unhealthy and soil signatures was created. Transmittance characterizations of the filters used in both imaging systems are readily available and well-documented. To compare the response of the two imagers, a sample reflectance spectrum was multiplied by a normalized set of transmittance values unique to properties of the optical filters used in the imaging system. These data were used to calculate a difference in signal response of the individual imagers.

At this time an analysis of absolute uncertainty in data acquisition and processing has not been completed. Therefore, the percent difference in NDVI values between the two simulated signals was used as a baseline for uncertainty in the data acquired by the tethered-balloon imaging system.

In order to ensure that accurate data were collected both remotely and on site. During the CO$_2$ release, daily monitoring of the scaffold-mounted imager was performed both on-site and remotely to ensure that accurate data were collected. The tethered-balloon system was launched by MSGC students and the supervision of the deployment of the imager, acquisition of images and the analysis of data resulting from these launches fell under my responsibility.
Chapter 3

Results and Discussion

3.1 Results

This chapter outlines optical simulations performed, their results, image processing, and a comparison and analysis of the results of the two systems.

3.1.1 Optical Simulations

Since both imagers incorporate differing CMOS chips and optical filters, a comparison of imager response was needed to determine if the tethered-balloon imager was in fact capturing reliable data. Filter conditions and silicon response and the optical spectral transmittance of the balloon imager’s translucent case were accounted for in the model. The imager profiles were used to simulate imager responses to both healthy and unhealthy vegetation and soil. Sample spectra of actual vegetation at the site were used. A simple Matlab routine calculates the simulated response spectra by multiplying the sample signal with the normalized sum of the transmissivity of the red and infrared filters multiplied by the silicon response.
A transmittance profile was created by superimposing transmittance profiles of the FB650-40 and FB800-40 bandpass filters and multiplying the resultant transmittance profile with the predicted spectra of healthy, unhealthy, and soil conditions.
Transmittance values by the silicon response (of the CMOS chip). Transmittance values are normalized to the maximum value in the spectrum. A quasi-collimating lens system is used to avoid spectral shifts in the imager response due to light incident at off-axis angles; therefore an angle-dependent filter profile is not required.
Tethered-Balloon Imager Simulated Spectra

Figure 3.2

Figure 3.2: (top) Transmittance profile of the tethered-balloon imager shown for an incident angle of zero degrees

(bottom) Predicted healthy, unhealthy, and soil spectra are displayed

The transmittance profile of the tethered-balloon imager is angle dependent and undergoes a significant spectral shift due to off-axis incident light. This shift
is not expected to significantly affect the NDVI measurements because the spectral shift does not cross the ‘red-edge’ region near 700 nm, where the vegetation reflectance changes most rapidly with wavelength. The simulations account for the transmittance of the filter with both on and off-axis incident rays.

**Figure 3.3**

![Tethered Balloon Imager Simulated Reflectance Spectra](image)

*Figure 3.3: The dotted lines represent the sample spectra shown with a potential interaction between on and off axis signal sources.*

**Predicted Deviation of Signals**

After an examination of the results of the optical simulations, predicted NDVI values were calculated for both imaging systems and compared by calculating the percent difference between the two largest variations in signal between the two imaging systems. This usually meant dividing the simulated tethered-balloon signal at 40° by the scaffold imager’s corresponding value. These tests showed that a ten percent differ-
ence in NDVI value should be expected between the two systems while their response to a soil signal may differ by as much as 33 percent.

Table 3.1 Simulated NDVI Values for both Scaold Imager and Tethered-Balloon Imager

<table>
<thead>
<tr>
<th>Signal</th>
<th>Scaold NDVI (Scaold)</th>
<th>Predicted NDVI 0°</th>
<th>Predicted NDVI 40°</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Health y Vegetation</td>
<td>.6968</td>
<td>.6965</td>
<td>.6374</td>
<td>10%</td>
</tr>
<tr>
<td>Unhealth y Vegetation</td>
<td>.3303</td>
<td>.3295</td>
<td>.3586</td>
<td>10%</td>
</tr>
<tr>
<td>Soil</td>
<td>.0413</td>
<td>.0393</td>
<td>.0590</td>
<td>33%</td>
</tr>
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</table>

Above: percent difference between the two systems

Table 3.2

<table>
<thead>
<tr>
<th>Signal</th>
<th>Scaffold Imager</th>
<th>Tethered-Balloon Imager (max/min)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy Vegetation</td>
<td>.6968</td>
<td>.6374</td>
<td>10%</td>
</tr>
<tr>
<td>Unhealthy Vegetation</td>
<td>.3303</td>
<td>.0393</td>
<td>10%</td>
</tr>
<tr>
<td>Soil</td>
<td>.0413</td>
<td>.3295</td>
<td>33%</td>
</tr>
</tbody>
</table>

3.1.2 Comparison of Processed Data

The following sections contain a discussion of the observed results of the two separate imaging systems.
3.1 Results

Scaold Imager

Figure 3.4

Figure 3.4: NDVI plotted vs. time for the one-month 2012 controlled CO\(_2\) release experiment. Data represent daily averages collected by the scaffold-mounted imager. It acquired data from 9 am to 4 pm everyday during the experiment. Blue circles are the control region and the red circles are the hotspot.

Solid vertical lines correspond to the flow of CO\(_2\). Dotted line refers to an interruption to the flow of CO\(_2\). The green solid line indicates an increase in the CO\(_2\) flow rate.

The data from the scaffold imager reflect the dry summer season experienced in Bozeman, MT in 2012. A drier than normal summer resulted in an accelerated decrease in plant health in both controls and the hotspot. Generally, the hotspot region itself was already visually slightly stressed at the beginning of the release. It
is believed that the continued seasonal release of CO$_2$ at the ZERT site has led to semi-permanent damage in the field around the hotspot region.

The first occurrence that merits discussion is CO$_2$ flow interruption due to a lightning strike on the afternoon of the July 11th. NDVI data show a slight increase in NDVI across all regions on the 11th and 12th and a continued increase in NDVI in both the horizontal control and the hotspot until the 14th while the vertical control region returned to a downward trend on the 13th. It is important to also note that the weather station located at the ZERT field site registered over 8mm of rain on the 10th and 11th. Heavy rainfall usually translates to an increase in NDVI the following two days [5–9]. The continued increase in vegetation health around the hotspot on the 3rd and 4th days following the rains could possibly be connected to the slightly increased levels of CO$_2$ resulting from the first day of the release followed by the five day flow outage due to a lightning strike. Heavy rains saturate the soil, which causes the CO$_2$ from the leak to 'bubble' out of the ground fast. Elevated CO$_2$ levels in the soil asphyxiate the roots while increases in CO$_2$ concentration in the air tend to 'fertilize' the vegetation.

The restoration of CO$_2$ flow on the 15th of July corresponds to quasi-immediate drops in NDVI in all regions. An accelerated degradation in NDVI is observed in the hotspot region. Also, there were a pair of brief outages on the 25th and 26th that must have affected CO$_2$ flow. The scaffold imager shows fluctuations in NDVI around the 25th and 26th that correspond to brief power outages as well as slight rainfall, the combination of which could explain the erratic behavior around this time period. The next slight increase in NDVI corresponds with additional heavy rainfall on the 27th of July. On the 30th of July the CO$_2$ flow rate was doubled, which effectively poisoned all three regions and corresponds with the convergence of the three signals in the beginning of August. By the tenth of August, the test region was heavily
3.1 Results

stressed by the dry weather and extra-heavy CO₂ flow rate.

**Tethered-Balloon Imager**

![Figure 3.5](image)

Figure 3.5: NDVI v. Date for the data collected using the tethered balloon imaging system. Circular data points represent the vertical control and the x's represent the hotspot region.

The tethered-balloon imager registered NDVI values systematically lower than the scaffold-mounted imager throughout the release in both its control and hotspot regions. However, even with the downward bias of NDVI, the tethered-balloon imager data do correspond very well with observed conditions. The systematically lower NDVI readings of the tethered-balloon imager very likely could be a result of the imager viewing the vegetation with angles centered on normal incidence to the ground, whereas the scaffold-mounted imager viewed the same vegetation from angles centered...
on approximately 45 degrees. In the normal-incidence view it is expected to see more soil between individual plants than in the 45-degree view, and the increased fraction of soil observed by the balloon imager would therefore result in lower NDVI values.

Figure 3.6

Figure 3.6: NDVI calculations from August 10th, 2012 show extreme levels of stress in the field. Images taken from the top of the scaffold confirm trends in NDVI image.
3.2 Conclusions and Future Research

Figure 3.7

Through the deployment of two multispectral imaging systems, one balloon-borne and the other scaffold-mounted, a profile of their efficacy in monitoring elevated CO₂ levels at a GCS has been created. This experimentation included the deployment of the two systems, monitoring the tethered-balloon launches, the collection of two imagers’ data sets, computer modeling of their response functions using realistic vegetation and soil reflectance spectra, laboratory-measurement of calibration panel reflectance as a function of angle, and image processing of the tethered-balloon system’s data.

When the tethered-balloon imager’s NDVI data were compared to that of the scaffold imager, a general agreement in the downward and upward trends are observed.

Note that scaffold-imager error is confined within the circular data points.
Chapter 3 Results and Discussion

Considering a thorough accounting of imaging signals including optical simulations and the inclusion of on and off-axis source signals, a likely explanation for observed differences between the two imaging systems sources has been proposed. Future work at ORSL will include a comparison of the tethered-balloon and scaffold-mounted imagers’ responses to identical signal sources measured at normal and 45° incidence. These tests will be conducted under late-summer conditions to simulate the conditions of the 2012 gas release.

An improved error calculation should be performed to increase the degree of certainty of what the tethered-balloon imager data represent. Also, current image processing routines require a majority of the time and effort spent manually aligning images for analysis. A script that could handle the superposition and orientation processes would be of great value as well. The tethered-balloon system seems like a good candidate for CO₂ leak monitoring at a GCS site due to its low-cost to implement and relatively simple operation procedures. However, a definative analysis of the relationship between imager angle and the field of interest needs to be studied to provide a clear analysis of its ability to be used in real-world situations.

Due to the balloon-bourne system’s low-cost design, ease of operation, and the plethora of optical principles demonstrated by the system, it is recommended that the department investigate acquiring or building a similar system for undergraduate use at Brigham Young University - Idaho. A tethered-balloon imaging system could be used for optics-related research and as a teaching example of many basic principles of optics.
Appendix A

Optical Simulations

A.1 Sample Spectra

The optical simulations aimed to reproduce accurate signal response that each imager might read and use the results to create a correction factor between the two imagers. A sample spectrum from the ZERT field was used for healthy and stressed vegetation signals. A standard spectra was selected for the soil signal.

Figure A.1

(left) Sample vegetation spectra from the ZERT site field measure by ORSL
(right) The sample soil signal for this figure was used in the simulations
A.2 Matlab Code

The following Matlab routine was used to generate filter profiles and signal responses. Code included was for the simulation of the scaffold imager. A variation using a different set of filter profiles was used for the tethered-balloon imager simulations.

```matlab
% Load reflectance data for healthy and unhealthy vegetation and vegetation
VegUnhealthy = load_reflectance_data('Unhealthy New.txt');
VegHealthy = load_reflectance_data('Healthy New.txt');
Soil_Data = load_reflectance_data('Soil.txt');

% Create filter profiles
FB650 = load_filter_data('FB650-40.txt');
FB800 = load_filter_data('FB800-40.txt');

% Create silicon response profile
Silicon_resp = load_silicon_response('silicon response_N.txt');

% Concatenate spectrum boundaries
spectrum = cat(1, FB650.wavelength, FB800.wavelength);

% Interpolate values of reflectance for wavelengths that match the data points given in the filter transmission value data set

% Interpolation of reflectance values for healthy vegetation by wavelength
veg_red = interp1(VegHealthy.wavelength, VegHealthy.reflectance, FB650.wavelength);
veg_nir = interp1(VegHealthy.wavelength, VegHealthy.reflectance, FB800.wavelength);

% Interpolation of reflectance values for unhealthy vegetation by wavelength
uh_veg_red = interp1(VegUnhealthy.wavelength, VegUnhealthy.reflectance, FB650.wavelength);
uh_veg_nir = interp1(VegUnhealthy.wavelength, VegUnhealthy.reflectance, FB800.wavelength);

% Interpolate Soil Reflectance Values
soil_red = interp1(Soil_Data.wavelength, Soil_Data.reflectance, FB650.wavelength);
soil_nir = interp1(Soil_Data.wavelength, Soil_Data.reflectance, FB800.wavelength);

% Interpolate Silicon Response values
SR_red = interp1(Silicon_resp.wavelength, Silicon_resp.response, FB650.wavelength);
SR_nir = interp1(Silicon_resp.wavelength, Silicon_resp.response, FB800.wavelength);

% Multiply filter transmission by silicon response
red_tx = (FB650.transmission).*(SR_red);
ir_tx = (FB800.transmission).*(SR_nir);
```
A.2 Matlab Code

```matlab
% Find a normalization transmission constant for the red and NIR reflectances (%data is not
% normalized to 100%)
mFB650 = max(red_tx); mFB800 = max(nir_tx);

% Normalize transmission values
norm650tx = (red_tx)./mFB650; norm800tx = (nir_tx)./mFB800;

% Create a transmission profile
tx = cat(1,norm650tx,norm800tx);

% Give reflectance values over the spectrum for healthy and unhealthy vegetation and soil
soil_ref = cat(1,((norm650tx).*(soil_red)),((norm800tx).*(soil_nir))).*100;
hveg_ref = cat(1,((norm650tx).*(veg_red)),((norm800tx).*(veg_nir))).*100;
uh_veg_ref = cat(1,((norm650tx).*(uh_veg_red)),((norm800tx).*(uh_veg_nir))).*100;

% Calculate NDVI
% Calculate healthy reflectances and NDVI
href_red = sum((norm650tx).*(veg_red))/(sum(norm650tx));
href_nir = sum((norm800tx).*(veg_nir))/(sum(norm800tx));
healthy_NDVI = (href_nir-href_red)/(href_nir+href_red);

% Calculate unhealthy reflectances and NDVI
uhref_red = sum((norm650tx).*(uh_veg_red))/(sum(norm650tx));
uhref_nir = sum((norm800tx).*(uh_veg_nir))/(sum(norm800tx));
unhealthy_NDVI = (uhref_nir-uhref_red)/(uhref_nir+uhref_red);

% Calculate healthy reflectances and NDVI
soilr_red = sum((norm650tx).*(soil_red))/(sum(norm650tx));
soilr_nir = sum((norm800tx).*(soil_nir))/(sum(norm800tx));
soilr_NDVI = (soilr_nir-soilr_red)/(soilr_nir+soilr_red);

% Concatenate red and nir reflectance values for healthy and unhealthy vegetation
Y(:,3) = soil_ref; Y(:,2) = uh_veg_ref; Y(:,1) = hveg_ref;

% Plot Imager Response
createfigure(spectrum,Y); % createfigure is just a script to create figures with the same bounds
and information
transmittance(spectrum,tx.*100) % similar to createfigure, but make transmittance profiles, not
reflectance
```
A.3 Simulation Results

The following figures were generated by applying the different optical filter solutions to the Matlab code shown above. All conditions relative to the experiment were modeled.

A.3.1 Scaffold Imager Profile

Figure A.2

Figure A.2: (left) Scaffold image transmittance profile
(right) Scaffold imager predicted signals
A.3.2 Tethered-Balloon Imager at Zero Degrees

Figure A.3 Tethered-Balloon Imager Profile - Zero Degrees Incident Angle

Figure A.3: (left) Predicted transmittance profile for incoming rays with incident rays at a zero degree incident angle to the imager lens.

(right) Predicted reflectance profile for three vegetation signals with incident rays at a zero degree incident angle to the imager lens.
A.3.3 Tethered-Balloon Imager at Ten Degrees

Figure A.4 Tethered-Balloon Imager Profile - Ten Degrees Incident Angle

Figure A.4: (left) Predicted transmittance profile for incoming rays with incident rays at a ten degree incident angle to the imager lens.

(right) Predicted reflectance profile for three vegetation signals with incident rays at a ten degree incident angle to the imager lens.
A.3.4 Tethered-Balloon Imager at Twenty Degrees

Figure A.5: (left) Predicted transmittance profile for incoming rays with incident rays at a twenty degree incident angle to the imager lens.

(right) Predicted reflectance profile for three vegetation signals with incident rays at a twenty degree incident angle to the imager lens.
A.3.5 Tethered-Balloon Imager at Thirty Degrees

**Figure A.6** Tethered-Balloon Imager Profile - Thirty Degrees Incident Angle

![Transmittance vs Wavelength](image1)

![Percent Reflectance vs Wavelength](image2)

Figure A.6: (left) Predicted transmittance profile for incoming rays with incident rays at a thirty degree incident angle to the imager lens.

(right) Predicted reflectance profile for three vegetation signals with incident rays at a thirty degree incident angle to the imager lens.
A.3 Simulation Results

A.3.6 Tethered-Balloon Imager at Forty Degrees

Figure A.7 Tethered-Balloon Imager Profile - Forty Degrees Incident Angle

- (left) Predicted transmittance profile for incoming rays with incident rays at a forty degree incident angle to the imager lens.
- (right) Predicted reflectance profile for three vegetation signals with incident rays at a forty degree incident angle to the imager lens.
Appendix B

Experiment Data

B.1 Processed Images

Image processing begins with loading images into the Matlab routine.
Once the red and nir images are loaded, they must be aligned with one another (using the alignment options in the bottom left of the window). The program’s edge detection algorithm does a good job of giving the operator an idea of where the calibration tarp lies in both images. Although they almost never perfectly align (resolution angle is dependent on wavelength), a ’best fit’ can be obtained fairly quickly.

Once the images are superimposed a white and dark region must be sected under the >>Process>>Select white region and >>Process>>Select dark region menu options. By enclosing a polygon using the program of the two regions, NDVI is automatically calculated and read to be displayed.
B.1 Processed Images

B.1.1 FOV NDVI Images

The following images were processed from all possible images collected during flights on each of the four balloon flights.
Figure B.1

Figure B.1: (left) The yellow line in the middle of the FOV is the balloon tether. It appears in many images.

In both images the stressed vegetation around the hot spot can be observed.

July 17th, 2012

Figure B.2

Figure B.2: (right) Note the blue spot on the bottom right on the image. That region of the image is black half of the calibration panel. Through a reflectance test it was determined that the black side of the calibration tarp displayed non-Lambertian scattering (it exhibited non-isotropic scattering in the visible spectrum). It was determined that reliable results could be obtained by discounting the black side of the calibration tarp and only using the white reflector for calibration purposes.
July 25, 2012

Figure B.3: The slight increases in vegetation health observed in NDVI averages for the 25th of July correlate with weather data taken from the ZERT weather station.

August 10, 2012

Figure B.4
### B.2 Weather Data

**Figure B.5**

<table>
<thead>
<tr>
<th>Date of Rainfall</th>
<th>Amount of Rain (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 25</td>
<td>1.8</td>
</tr>
<tr>
<td>June 27</td>
<td>1.2</td>
</tr>
<tr>
<td>July 3</td>
<td>0.4</td>
</tr>
<tr>
<td>July 10</td>
<td>3.8</td>
</tr>
<tr>
<td>July 11</td>
<td>4.6</td>
</tr>
<tr>
<td>July 13</td>
<td>0.4</td>
</tr>
<tr>
<td>July 15</td>
<td>7.2</td>
</tr>
<tr>
<td>July 16</td>
<td>0.4</td>
</tr>
<tr>
<td>July 26</td>
<td>0.6</td>
</tr>
<tr>
<td>July 27</td>
<td>3.2</td>
</tr>
<tr>
<td>Aug 9</td>
<td>0.4</td>
</tr>
<tr>
<td>Aug 10</td>
<td>2.4</td>
</tr>
<tr>
<td>Aug 11</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Figure B.5: Rain data as recorded by the ZERT field weather station during the period measured by the scaffold based imager.

### B.3 Error Estimates

The following script was used to estimate our uncertainty in the tethered-balloon imager signal. The uncertainty in the scaffold-mounted camera is assumed to 2.5% from the previous experimentation.
B.3 Error Estimates

% NDVI from the simulations for the blimp camera
NDVI_Values = [.6968,.3303,.0413];
% NDVI from tethered-balloon image
control_days = datenum(['5-jul-12','dd-mmm-yyyy'],datenum('17-jul-12','dd-mmm-yyyy'),datenum('25-jul-12','dd-mmm-yyyy'),datenum('10-aug-12','dd-mmm-yyyy'));
control.NDVI = [.5326,.3786,.4066,.0215];
hotspot.days = datenum(['5-jul-12','dd-mmm-yyyy'],datenum('17-jul-12','dd-mmm-yyyy'),datenum('25-jul-12','dd-mmm-yyyy'),datenum('10-aug-12','dd-mmm-yyyy'));
hotspot.NDVI = [.3764,.2386,.2760,.0067];
% fractional difference between the blimp and scaffold camera as found from the simulations
Error_Vales = [0.09,0.08,0.5];
% documented error of the scaffold camera estimated to 2.5%
sca_error = 0.025;
% estimated error for the tethered-balloon image ~10% due to spectrum shifts due to off-axis incident light
blimp_error = 0.1;
% define a range of days start = datenum('20-jun-12', 'dd-mmm-yyyy');
finish = datenum('19-aug-12', 'dd-mmm-yyyy');
days = start:finish;
% interpolate error for specific NDVI values
  c_Reading_errors = interp1(NDVI_Values,Error_Vales,control.NDVI,lin, 'extrap');
  hs_Reading_errors = interp1(NDVI_Values,Error_Vales,hotspot.NDVI,lin, 'extrap');
% create the full combined error for the system. I have assumed that all the errors are independent and thus can be added in
quadrature.
  c_NDVI_errors = (c_Reading_errors.^2+sca_error.^2+blimp_error.^2).^0.5;
  hs_NDVI_errors = (hs_Reading_errors.^2+sca_error.^2+blimp_error.^2).^0.5;
% plot the data and errors. our data are a fractional difference so the error at any given value is value*(associated fractional
difference)
hold on errorbar(control.days,control.NDVI,control.NDVI.*c_NDVI_errors,'o')
errorbar(hotspot.days,hotspot.NDVI,hotspot.NDVI.*hs_NDVI_errors,'x')
dateformat('mmm-dd') xlabel('Day of Experiment','Fontsize',16); ylabel('NDVI and Error','Fontsize',16); hold off
Bibliography


