CENTER FOR EMBEDDED NETWORKED SENSING

Estimating Spectral Reflectance of Natural Imagery Using Color Image Features

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Problem Statement

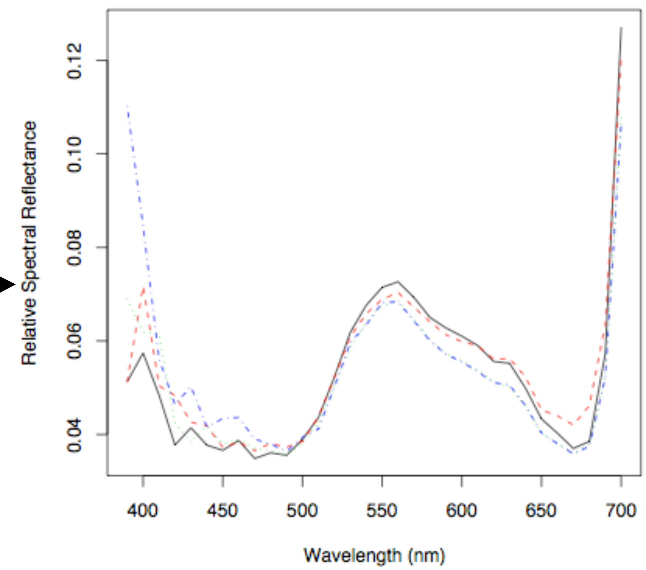
- Some natural phenomena can be measured *directly* without harming the environment:
  - Temperature
  - Rainfall
  - Humidity
- Others, require destructive instrumentation:
  - CO_2 flux from single plant, meadow, or soil

Use *indirect* sensing using an imager

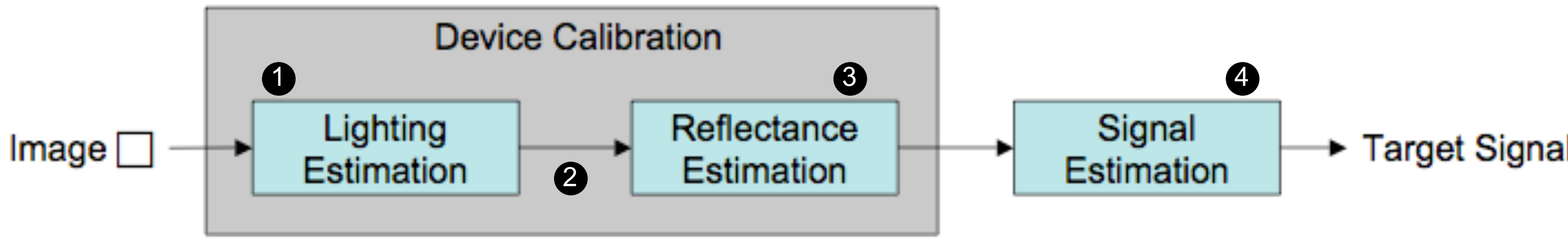
The site at James Reserve where mosscam is located

Problem Statement

- Why Relative Spectral Reflectance (RSR)
  - It is a proxy for various natural phenomena
  - It is illumination invariant
  - It can be easily verified in the field using a spectroradiometer



Process Overview



1. Estimate the incident illumination in the scene
2. Transform the image to be under a reference illuminant
3. Estimate the subject's spectral reflectance using color image features
4. Estimate the target signal

Device Calibration: Physical Model of Image Formation

$$r_k = \int_w E(\lambda)S(\lambda)R_k(\lambda)d\lambda$$

- r_k = response of the kth sensor
- w = bandwidth of device
- $E(\lambda)$ = incident spectral power distribution
- $S(\lambda)$ = subject's relative spectral reflectance
- $R_k(\lambda)$ = the sensitivity of the kth sensor

Device Calibration: Modeled Image Formation

$$r \approx \hat{E}(\lambda)\hat{S}(\lambda)^T R(\lambda)$$

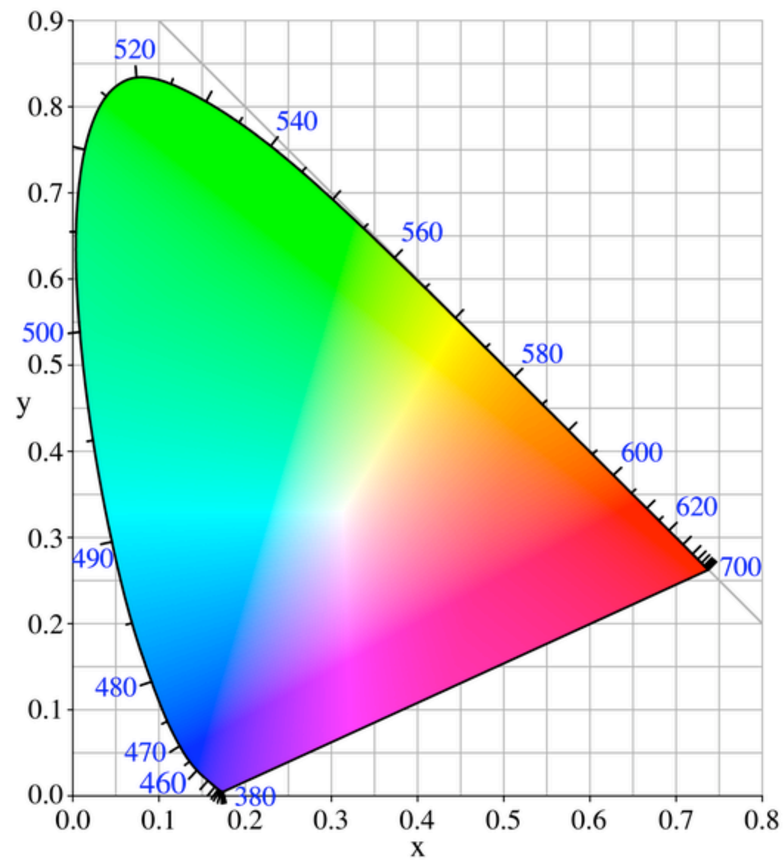
$$r \approx (\mathbf{B_e} w_e)(\mathbf{B_s} w_s)^T \mathbf{R}$$

- Discretize the bandwidth and rewrite in matrix notation
- Model E(λ) and S(λ) using functional PCA
- Results in 6 unknowns (w_e and w_s)

This system is under-constrained.
Estimate the spectra in sequence.

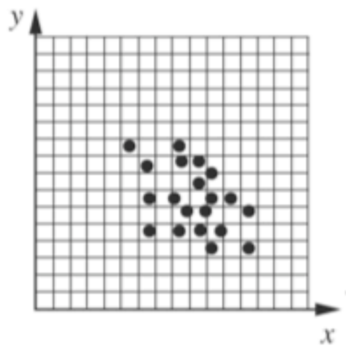
Device Calibration: Compensate for Brightness

- Chromaticity rather than color
  - Plane of uniform brightness in a 3-dimensional color space
  - Helps to compensate for variations in shutter speed and aperture
- Use the *xy* dimensions of the *xyY* color space

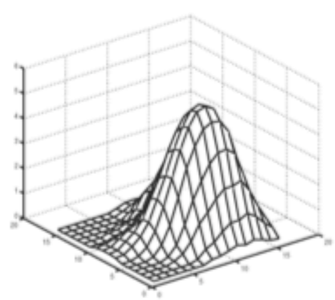


Device Calibration: Estimating Incident Illumination

Color By Correlation (Finlayson et. al.)



(a)



(b)

x1, y1	0.1	0.0	0.7	0.1	0.0	0.0	0.0	0.9
x1, y2	0.2	0.1	0.6	0.2	0.0	0.4	0.1	0.9
x1, y3	0.2	0.1	0.5	0.4	0.0	0.4	0.1	0.7
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
x1, yn	0.6	0.3	0.3	0.9	0.2	0.6	0.1	0.0
x2, y1	0.9	0.3	0.1	0.9	0.4	0.7	0.1	0.0
x2, y2	0.4	0.3	0.1	0.7	0.2	0.5	0.2	0.0
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
	:	:	:	:	:	:	:	:
xn, yn	0.0	0.1	0.0	0.1	0.5	0.1	0.6	0.0
	ill 1	ill 2	ill 3	ill 4	ill 5	ill 6	ill 7	ill 8

(c)

Device Calibration: Lighting Transformation

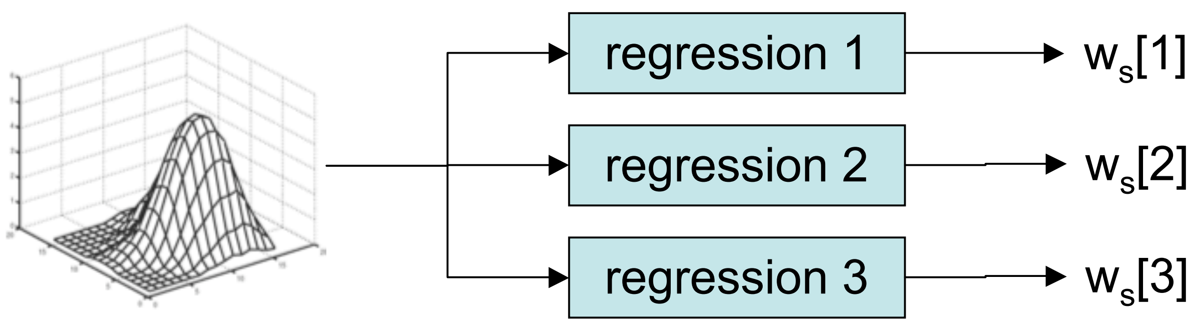
$$\begin{bmatrix} E_1(\lambda_R)S(\lambda_R) \\ E_1(\lambda_G)S(\lambda_G) \\ E_1(\lambda_B)S(\lambda_B) \end{bmatrix} = T_{light} \begin{bmatrix} E_2(\lambda_R)S(\lambda_R) \\ E_2(\lambda_G)S(\lambda_G) \\ E_2(\lambda_B)S(\lambda_B) \end{bmatrix}$$

$$T_{light} = \begin{bmatrix} E_1(\lambda_R)/E_2(\lambda_R) & 0 & 0 \\ 0 & E_1(\lambda_G)/E_2(\lambda_G) & 0 \\ 0 & 0 & E_1(\lambda_B)/E_2(\lambda_B) \end{bmatrix}$$

- Given some $E(\lambda)$ found previously, we can compute T_{light}
- This assumes that $R(\lambda) = \delta_k$ $k = \{R, G, B\}$
- Though unrealistic, this assumption has been shown to hold for cameras presented with “reasonable” light sources (like daylight)

Device Calibration: Estimating Spectral Reflectance

- Unlike lighting estimation, we have less insight into the relationship between the spectral reflectance model and the image's color coordinates.
- Estimate the 3 model parameters using non-linear regression
- Use chromaticity coordinates as input



Application: Measuring Moss Photosynthesis

Ecologists want to determine the effect of short summer rain events on the moss' ability to survive

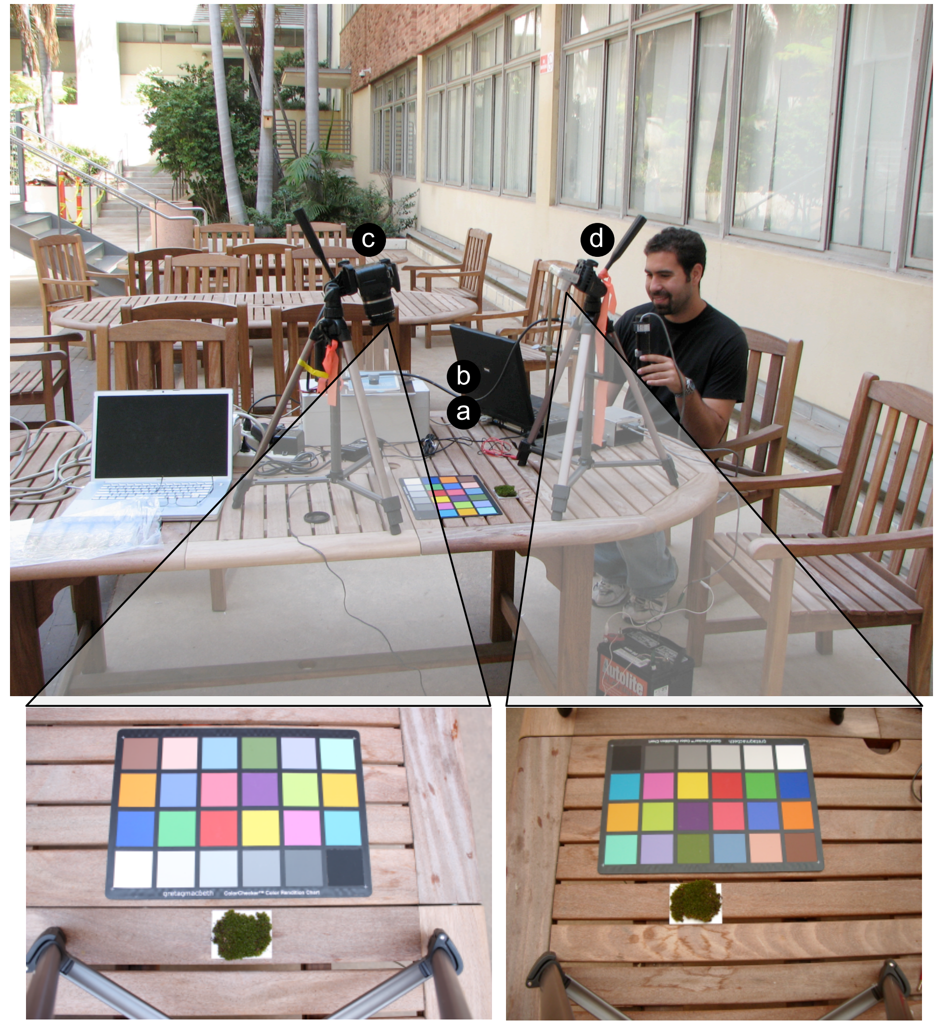
- There are no available sensors
- Methods suggested by previously ecological studies have insufficient temporal resolution

Tortula princeps

Photosynthesis begins to occur
5 minutes after being hydrated

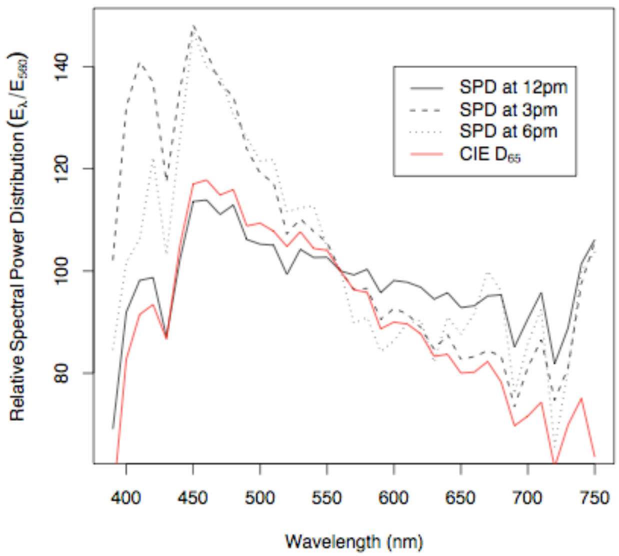
Evaluation: Experimental Setup

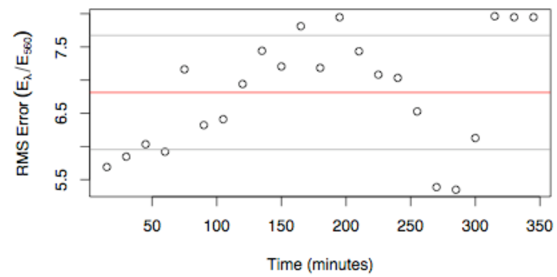
1. Collect moss from JR
2. Hydrate moss and allow to dry over time
3. Collect samples:
   a. illumination
   b. spectral reflectance
   c. high-quality images
   d. low-quality images

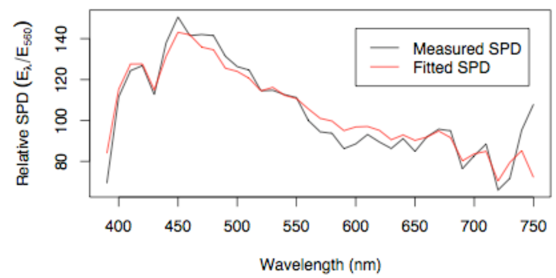


Samples acquired every 15 min for ~6 hrs (23 samples total)

Evaluation: Incident Illumination Modeling



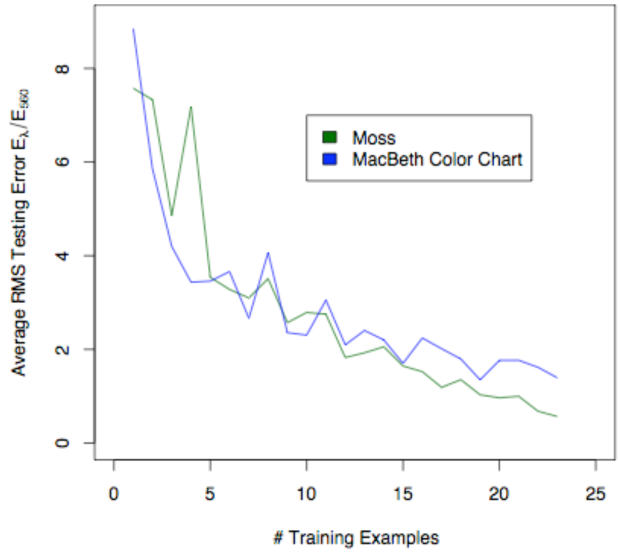


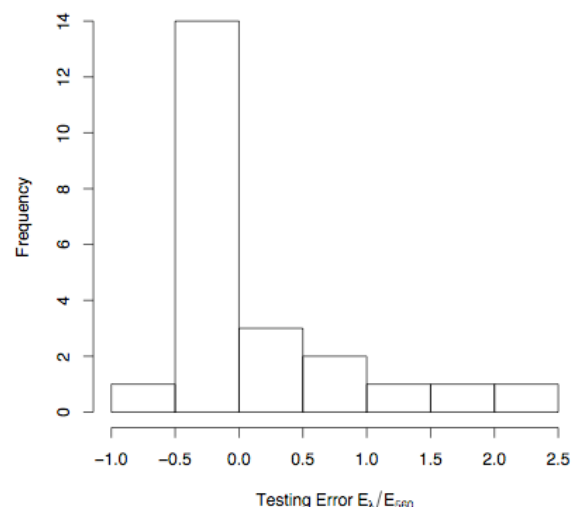


- Measured illumination (left) is similar to D_{65} although it is slightly bluer
- Model (by Judd et. al.) fits well (right top), with a slight temporal component to the error
- Even the worse error has minimal error and correct characteristic shape (right bottom)

Evaluation: Estimating Incident Illumination

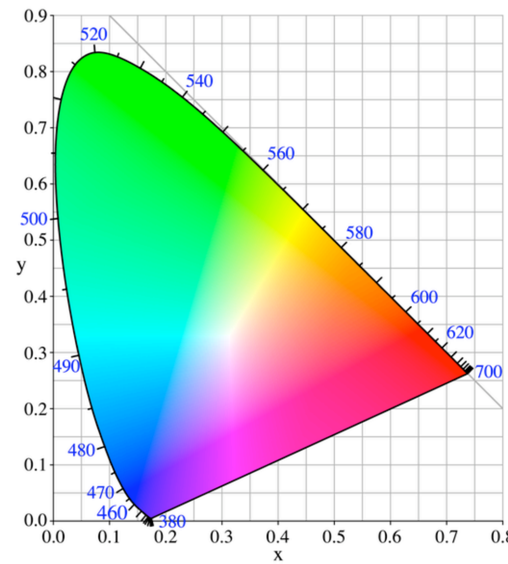
- Accuracy of the Color by Correlation algorithm becomes reasonable (top) once enough training examples are used
- With 12 training examples, we find that error (bottom) clusters near zero
- Interestingly, performance was comparable with and without JPEG compression

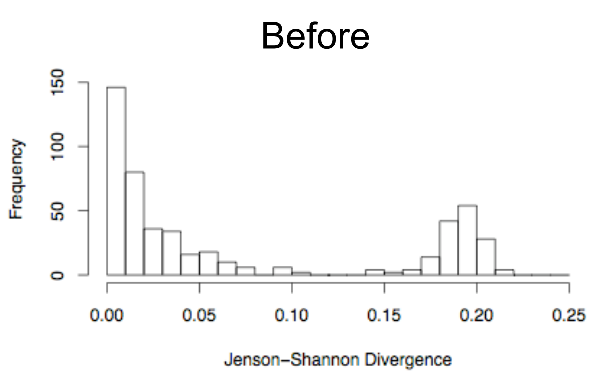


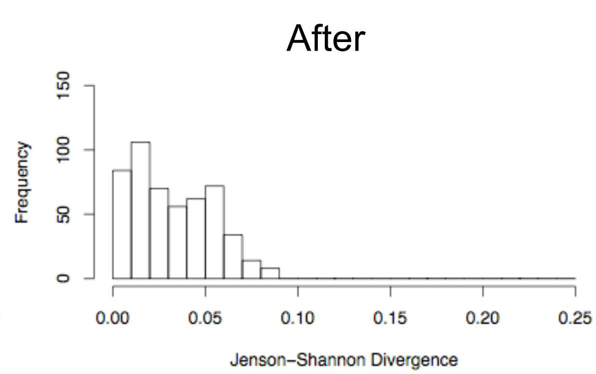


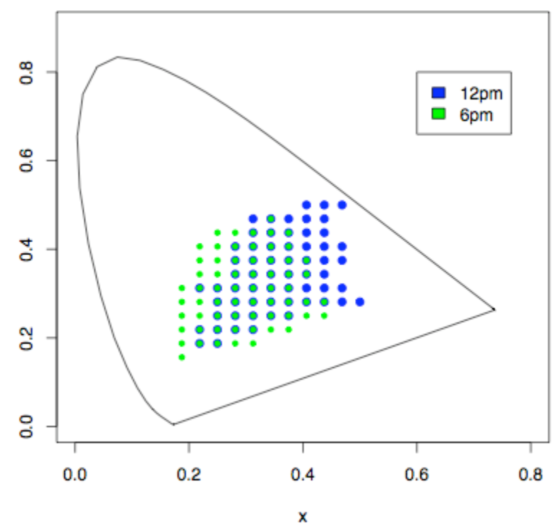
Evaluation: Lighting Transformation

- Images of a reference object (MacBeth color chart) shift over the course of the day
- We visualized this change using the 2D Jenson-Shannon divergences of all pairs of images



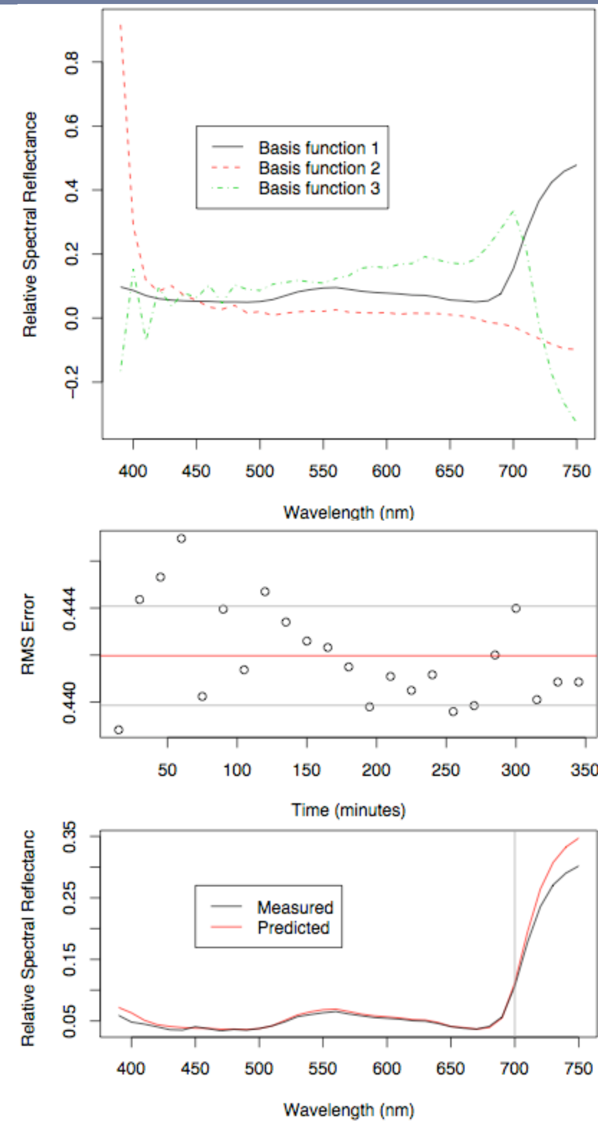






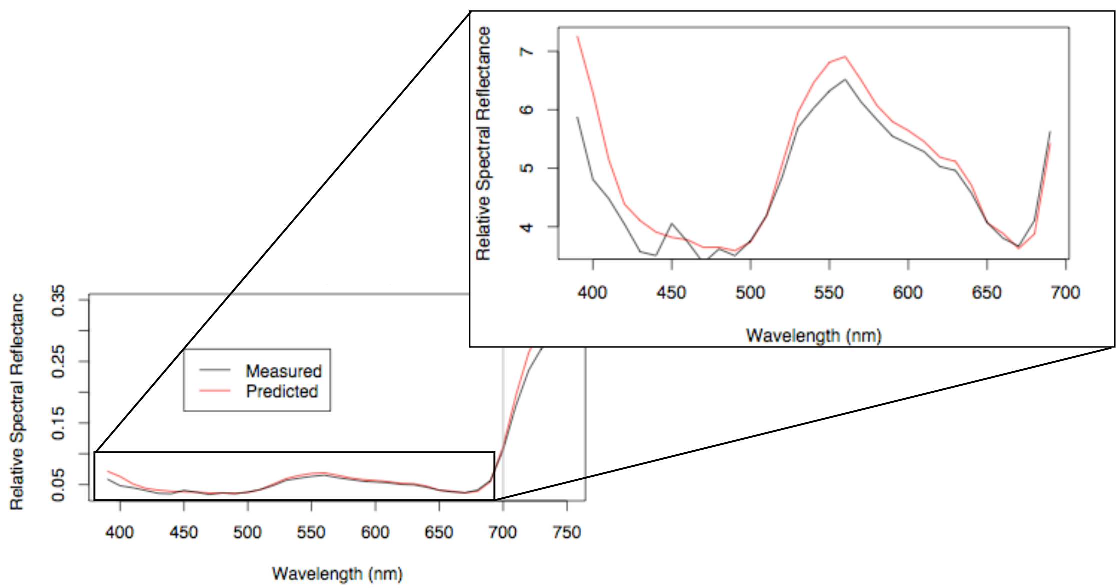
Evaluation: Estimating Spectral Reflectance

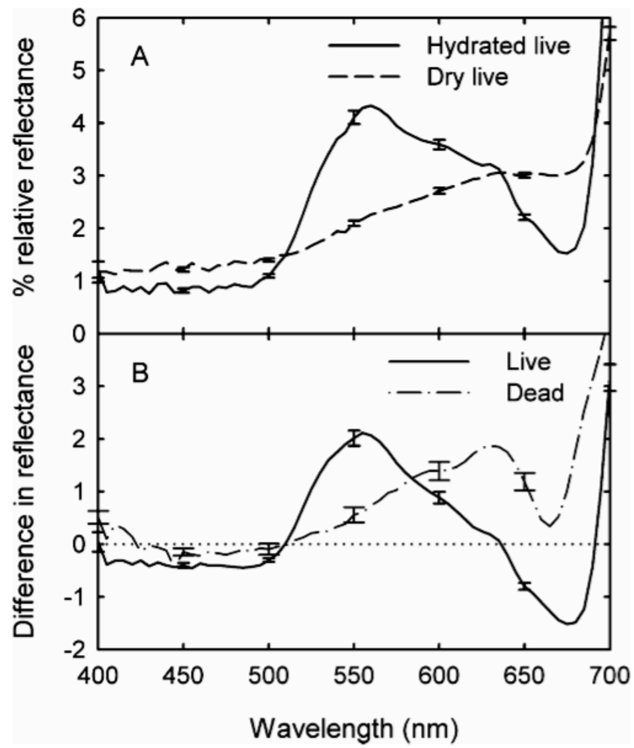
- We use only 3 basis functions: they contain 99.96% of the data
- The variation in the second and third basis functions (top) is expected:
  - variation low and high in the spectra caused by the sensor
  - variation in the middle caused by changes in the moss



Evaluation: Estimating Spectral Reflectance

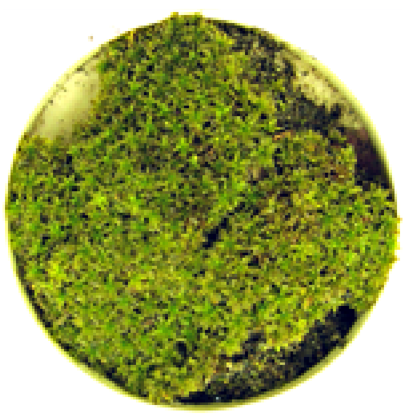
- Predicted reflectance curve is quite good
- Quite similar to a hydrated moss sample (significantly different from dry/dead moss sample)

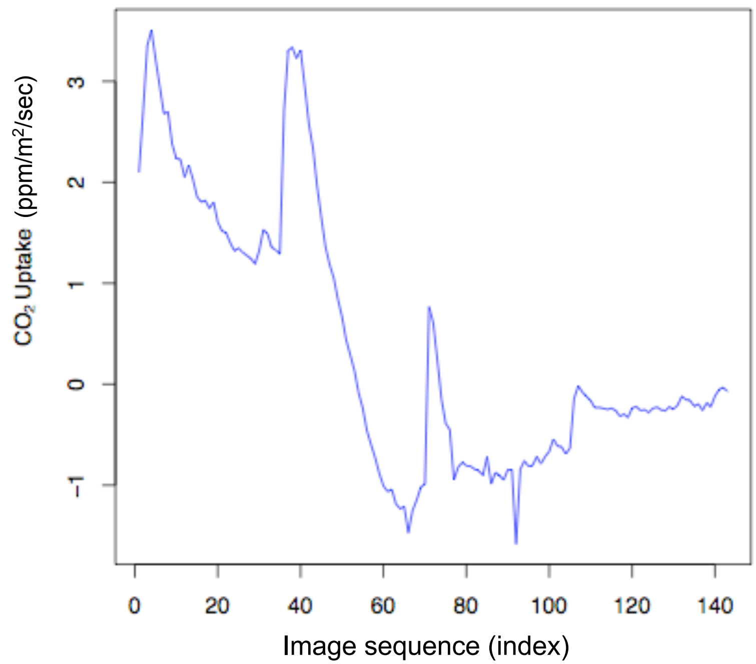




Future Work

- End-to-end measurement of target phenomena
- Analyze error contribution of each modeling step
- Define minimum imager requirements





Questions?

Related work

- Illumination Modeling: Judd et. al.
- Illumination Estimation: Finlayson et. al.
- Lighting Transform: Forsynth et. al.