Tunable Light-guide Image Processing
Snapshot Spectrometer (TuLIPSS) for Earth
Science Research and Observation

NASA Instrument Incubator Program
NNH16ZDA001N-IIP

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Rice University
Principle of TuLIPSS Technology

- Custom fiber light-guide reformats image to create void spaces to allow spectral cube acquisition in a single – snapshot (cube is acquired instantaneously with no-scanning)

DOI: https://doi.org/10.1364/OE.27.015701.
1. VIS System – 500-900 nm – **Smart Farming** *(Water Stress & Nutrition vs Genotypes)*

2. VIS-SWIR System - 200 nm sub-regions within 500-900 nm and 1100–1700 nm – **Water Stress, Soil Moisture** – feedback to *crop assessment*, (other applications considered - Green House gas sensing)

Referencing low altitude flights (1000-3000 ft) with ground reference and satellite data

Sample reflectance spectra for different plant genotypes subject to different levels of water stress


Field Implementation Progress

02-2020
- Field VIS system integrated
  - Length: 750 mm
  - Width: 220 mm
  - Height: 133 mm
  - Mass: 6.8 kg
  - Spatial image points – 20,000-30,000 (170x170)
  - Spectral Sampling: 31+
- Preparation to flights

04-2021
- Field VIS system optimization
  - Length: 600 mm
  - Width: 220 mm
  - Height: 133 mm
  - Mass: 6.8 kg
  - Spatial image points – approx. 63,000 (250x250)
  - Spectral Sampling: 35
- Field imaging – optimization and validation

Applications flights were not performed yet due to COVID, switched to lab on the ground field experiments
SWIR TuLIPSS Configuration

- Data cube size (mid-static)
  - Spectral: 50-54
  - Spatial: 19,200 (approx. 132x145)
- Tuning Examples:
  - Low Spectral / High Spatial
    - Spectral: 30-32
    - Spatial: 28,400 (approx. 132x214)
  - High Spectral / Low Spatial
    - Spectral: 72-75
    - Spatial: 13,400 (approx. 132x101)

Remote Spectral Imaging 1100-1300 nm

Selected video frame for image composite

VIS-SWIR sensor

Tube lens f: 180 mm

Prism 38°

Objective f: 144 mm

Filter wheel

SWIR bundle

Input: 66x69 blocks

Output: 22x200 blocks

Spacers: 750 um

1220nm

1140nm 1148nm 1166nm

1164nm 1172nm 1180nm

1198nm 1196nm 1204nm

1212nm 1220nm 1228nm

1236nm 1244nm 1252nm

1264nm 1292nm 1300nm

1180nm

1204nm

1228nm

1252nm

1280nm
VIS TULIPSS OPERATIONAL FEATURES
1. Extracted Spectrum from location and average for representative spectrum (for example: red roof tiles).

2. Characteristics of the spectrum is used to group similar spectra across whole scene.

3. Applied spectral grouping across entire mosaic.

Components Unmixed:
- Roof tiles
- Construction bricks
- Tree leaves cover
Acquisition vs Object’s (Flight’s) speed

Intensity Profile samples

100µs  500µs  1ms

White line is location of intensity profile of transition from window to vehicle body.

Slope at transition point showcases image blur.

Examples of acquisition times for various flight conditions

<table>
<thead>
<tr>
<th>Objective [mm]</th>
<th>Altitude [feet]</th>
<th>Width/pixel [ft]</th>
<th>Integration for pixel shift at 100 Knot, 168.8 f/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3,000</td>
<td>0.6</td>
<td>3.50 ms</td>
</tr>
<tr>
<td>50</td>
<td>10,000</td>
<td>6.0</td>
<td>35.5 ms</td>
</tr>
<tr>
<td>100</td>
<td>3,000</td>
<td>0.3</td>
<td>1.75 ms</td>
</tr>
<tr>
<td>100</td>
<td>10,000</td>
<td>3.0</td>
<td>17.5 ms</td>
</tr>
</tbody>
</table>
Augmented Dynamic Range

Images shown at same display brightness and scaling, single exposure images show the limitations of their dynamic range.

Composite of 3 raw images, saturated pixels replaced with shorter integration data. Respective scaling applied. The Procedure allows increased dynamic range.

Imaging sequences through external trigger of the camera with varied, cyclical exposure, such as a repeating pattern of 500µs, 10ms, and 100ms obtain real time augmented dynamic range. In Flight experiments we plan to augment overlapping regions.

Augmented dynamic range avoids saturation of bright area’s while clearly resolving dark areas.
Water Plant Stress Experiment

A Simple Method for Simulating Drought Effects on Plants

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- Modified Snow and Tingey system drought procedure
  - Place potted plants on columns of porous foam. Different water levels produce different soil moisture conditions
  - Start all plants at \( Z = 1 \text{ cm} \) (no drought condition) on December 4th and progressively lower water levels for different drought conditions over two weeks, ending on December 18th
  - After two weeks conditions represent well watered, mid drought, and severe drought groups

- Plant: *Liriope muscari*
  - Type of grass used in drought study that is easily available

Validation of TuLIPSS spectra as compared to Ocean optics. A small illuminated area produces a similar spectrum to ocean optics.

Plant-wide averages from TuLIPSS can be approximated by a weighted averaging of different spectral components found with Ocean optics.
Plant Data: Over Time

Time 1 = Day 0
Time 2 = Day 14
Time 3 = Day 40

Tracking plant spectra over time shows two trends:
1. Medium stress sees a relative decrease in red region
2. Severe drought sees increase in red signal as leaves brown

For each plant, the left image shows the reconstruction and the right image shows in red where fiber cores were sampled for spectra.
Field: Soil conditions

Sorghum in field is planted in either sand or clay, each plot has two plants started at different time points.

Sorghum growing in sandy soil at two time points featured here. Younger is on left.

Spectrum exhibits three peaks at 560nm, 603nm, and 638nm.

Ocean optic signals are readings from green leaves selected from each population. Each group has three leaves which are averaged over the group.

Reference Camera image of young sorghum in sandy field. One plant has leaves with many different colors and this variance will make its way into the TuLIPSS imaging.
TuLIPSS Imaging Results

Distinct peaks at 612nm and 653nm

Split samples into two populations:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Young Ratio</th>
<th>Old Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy</td>
<td>1:2.92</td>
<td>1:12.70</td>
</tr>
<tr>
<td>Clay</td>
<td>1:14.93</td>
<td>1:68.53</td>
</tr>
</tbody>
</table>

Signals are taken from a square in the center of the image. A threshold is set so that areas further into crop mass are not selected (see plant outlines).
Old Sorghum in Clay Soil

Hyperspectral snapshot imaging quickly and easily highlights the few remaining healthy plants.
Summary

- VIS TuLIPSS field imaging ready system was packaged and optimized
- TuLIPSS is capable of rapid snapshot spectral imaging and sub-millisecond integration times, augmented dynamic range and conditioning of overlapping regions.
- VIS Field imaging experiments are ongoing and TuLIPSS is being validated in smart farming application, crop water and nutrition stress
- SWIR system is being tested for field applications
- Radiometric system model was developed and serves as a design and configuration guidance.
  - System model App
    - Allows to Simulate/Predict signal levels for different land covers and system configurations
  - Validated the model
    - based on the absolute irradiance measurements
    - based on surface reflectance and global irradiance against TuLIPSS measurements