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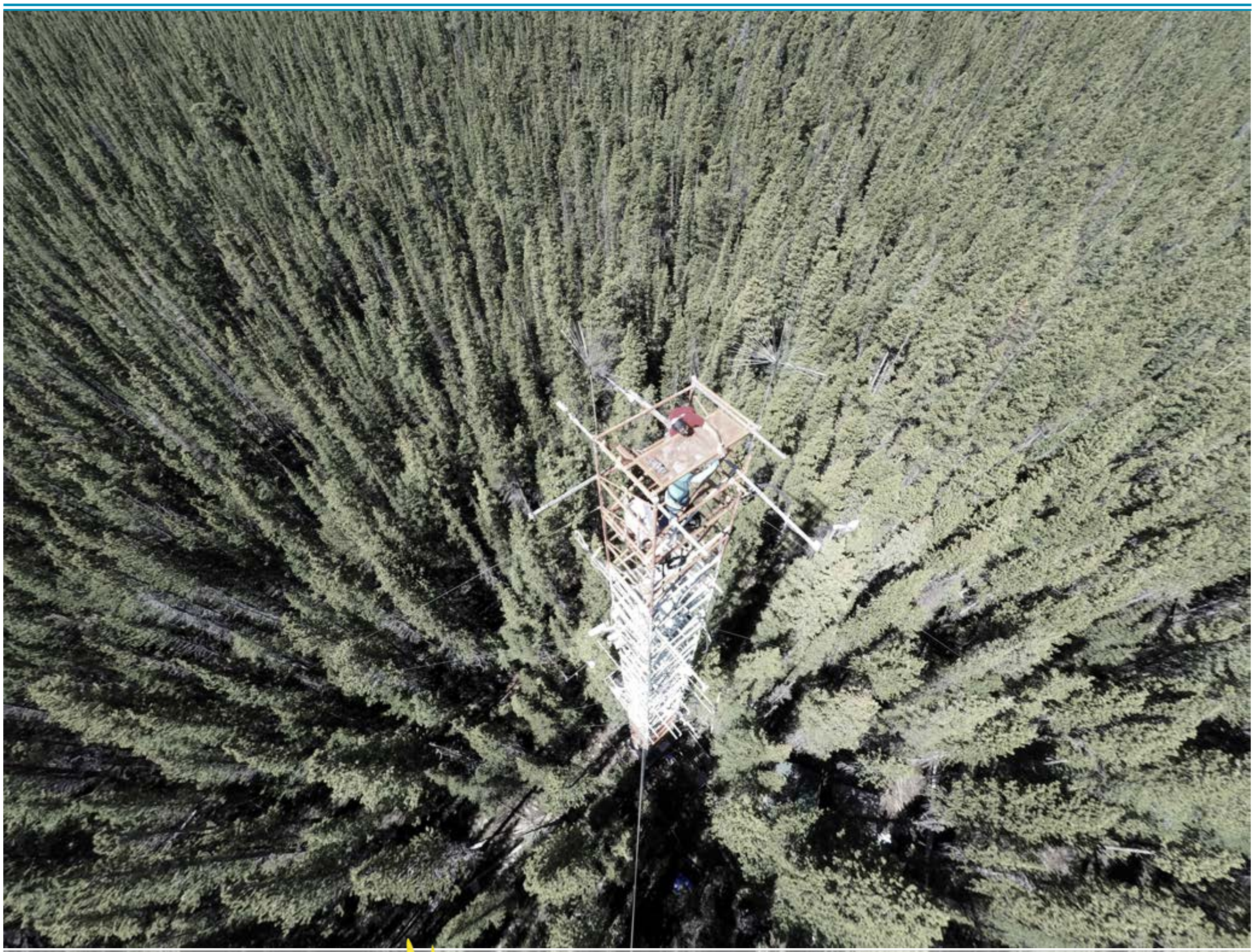

PhotoSpec

MEASURING SOLAR- INDUCED CHLOROPHYLL FLUORESCENCE

PhotoSpec - Comprehensive Ground-Based Studies of Solar-Induced Chlorophyll Fluorescence

From the

New Methods for Measurements of Photosynthesis from Space Study

Technical Development Start date: 9/26/2014
Technical Development End date: 12/31/18
Final Technical Report submission date: April 30, 2018

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I) Technical Development List of Participants

PhotoSpec was a joint collaboration between Caltech, JPL and UCLA as main contributors, with additional collaborators from Carnegie and the University of Michigan:

Christian Frankenberg (Caltech/JPL)	—	Caltech lead
Darren Drewry (JPL)	—	JPL lead
Jochen Stutz (UCLA)	—	UCLA lead, PhotoSpec instrument developer
Ulli Seibt (UCLA)	—	UCLA co-I, Ground-based support
Joseph Berry, Carnegie/Stanford	—	Carnegie, Science advisor and SIF expert
Gretchen Keppel-Aleks, U. of Michigan	—	PhotoSpec user
Stanley Sander, Josh Fisher (JPL)	—	JPL support (analysis, Mt. Wilson)
Katja Grossmann (UCLA)	—	PhotoSpec PostDoc, instrument design
Troy Magney (NASA NPP fellow)	—	PhotoSpec PostDoc, data analysis

II) Executive Summary

Goal of the program

The major goal of the PhotoSpec program was to develop a set of robust ground-based spectrometers that meet the measurement requirements to retrieve solar-induced chlorophyll fluorescence by exploiting solar Fraunhofer lines.

Key Areas of accomplishment

- Hardware: We developed five PhotoSpec systems for measuring SIF in the red (670–732 nm) and far-red (729–784 nm) wavelength range as well as as canopy reflectance (400–900 nm) to calculate vegetation indices (exceeding goals)
- Software: We developed a solid instrument control and data acquisition system, which controls PhotoSpec spectrometers, scanning motors, PAR sensor readout and calibration within a single program continuously.
- We developed a new simple and robust retrieval setup for SIF, which is embedded in the software.
- We deployed the instruments across diverse sites, ranging from agricultural fields in Iowa and alpine needle-leaf forest in Colorado to a wet tropical site in Costa Rica.
- We obtained follow-up funding for using PhotoSpec systems from NASA grants.

III) Introduction

From the KISS workshop to the technology program

Solar-Induced Chlorophyll Fluorescence (SIF) is an emission of light in the 650 - 850 nm spectral range from the excited state of the chlorophyll-a pigment after absorption of photosynthetically active radiation (PAR). Thus, SIF is a powerful proxy for photosynthetic activity and was found to correlate well with gross primary production (GPP). With the advent of satellite-based measurements of SIF from satellite such as GOSAT, GOME-2 and OCO-2, there has been a strong interest by the carbon cycle as well as vegetation community to use SIF data on the global scale to study photosynthetic dynamics and its impact on carbon fluxes across the globe. This prompted our initial 2012 KISS workshop *New Methods for Measurements of Photosynthesis from Space.*

While the availability of global SIF data provides great opportunities, there are remaining challenges, primarily because I) we don't have reliable SIF data at the scale of typical flux measurements of carbon and water on the ground and II) there are uncertainties in how SIF scales from the leaf to the canopy level. To tackle these challenges, a robust ground-based SIF measurement system is required that can perform measurements like from space but at fine local scales. While there have been spectrometer ground-based systems before, they have not yet matched the requirements for using our SIF retrieval techniques developed for space. Achieving this was the primary goal of our KISS technology program and a logical consequence from our initial KISS workshop in 2012.

Scientific motivation

The primary scientific rationale for the PhotoSpec technology program is the current lack of consistent SIF measurements at spatial sand temporal scales that can be directly related to ground-based carbon flux measurements from so-called fluxtower sites. This is important for various reasons: a) the current satellite based SIF observing system doesn't allow for a direct comparison of satellite SIF with fluxtower GPP because of spatial mismatches due to the large satellite footprint (>10km for GOSAT, GOME-2) or sparse sampling (OCO-2); b) satellite observations are typically at fixed local overpass times, so information on the diurnal time-scale is lost but could be very powerful; c) directional effects of SIF are poorly studied but are expected to be similar to the bidirectional reflectance distribution function (BRDF) of vegetation as it is determined by the fraction of shaded vs. sunlit leaves.

To study all these aspects, a ground-based system that can provide accurate and precise SIF observations at short time-scales is needed and needs to be deployable from fluxtower sites. Ideally, we would also be able to measure the bidirectional distribution function of SIF, which require a 2-dimensional scanning mechanism.

Technical motivation

The technical challenges posed by this project can be summarized as follows:

1) The SIF retrieval based on Fraunhofer lines only relies on changes in the optical depth of Fraunhofer lines on the order of only a few per-mil. This requires a very high signal-to-noise-ratio (SNR) and stability of the instrument, which must still be affordable to enable a small (and growing) network of PhotoSpec systems.

2) We need the ability to look at different parts of the canopy, which requires moving parts to enable a 2-Dimensional scanning mechanism. At the same time, we need to be able to perfectly reproduce the location of the viewing directions and maintain the same instrument performance for all viewing directions.
3) The instrument needs to be perfectly stable and work under field conditions in different climates (large variations in humidity and temperature as well as varying wind conditions) with as little human intervention as possible. This also requires remote access for instrument control as well as automated data transfer.

Fortunately, most of these requirements listed above are similar to those for UV/Vis spectrometers used for atmospheric trace gas retrievals. In both cases, changes in optical depths in the mer-mil range need to be detected, posing strict requirements on the instrument performance. The atmospheric community, in particular Jochen Stutz from UCLA, has worked on optimizing these system for a long time, creating a unique opportunity to bring the atmospheric and SIF community together, leveraging decades of instrument experience. Without this knowledge and experience transfer, a development like PhotoSpec within the timeframe and budgetary constraints of this KISS project would certainly not have been possible.

IV) Outcomes of the technical development program

In the following, we will briefly describe the achievements of the PhotoSpec project, separated by hardware development and initial science results. It should be mentioned that PhotoSpec was a truly collaborative project, with work shared by all three key partners from Caltech, JPL and UCLA. Most of the hardware development was performed at UCLA, with Caltech and JPL involved in the design phase as well as software development.

a. Results — Hardware

Within the PhotoSpec project, a fully operational PhotoSpec system was designed, built and tested. Experiences with our first engineering model as well as long term deployments in humid climates in Costa Rica as well as Iowa revealed other minor issues (water infiltration) that are now being solved in the final system design.
The instrument is field deployable and can run autonomously over extended periods, recording high resolution spectra in the red and far-red SIF range as well as a wider spectral window at moderate resolution with an identical field of view for all three wavelength ranges. SIF and various reflectance indices are obtained using a retrieval algorithm that provides relative and absolute SIF in the red and far-red wavelength range independently and at the same time. The ratio of the two fluorescence peaks can be used for several

applications, e.g., the determination of the chlorophyll content at leaf level or canopy structure.

The purpose of the broad-band spectrometer is to derive vegetation indices (EVI, PRI) as well as the red edge position. The PhotoSpec instrument has the ability to scan in the vertical and horizontal viewing direction using a 2D scanning telescope unit. The 2-axis pointing mechanism can be programmed to sample various viewing observation geometries, which was shown to provide a wealth of information, in particular for the PRI.

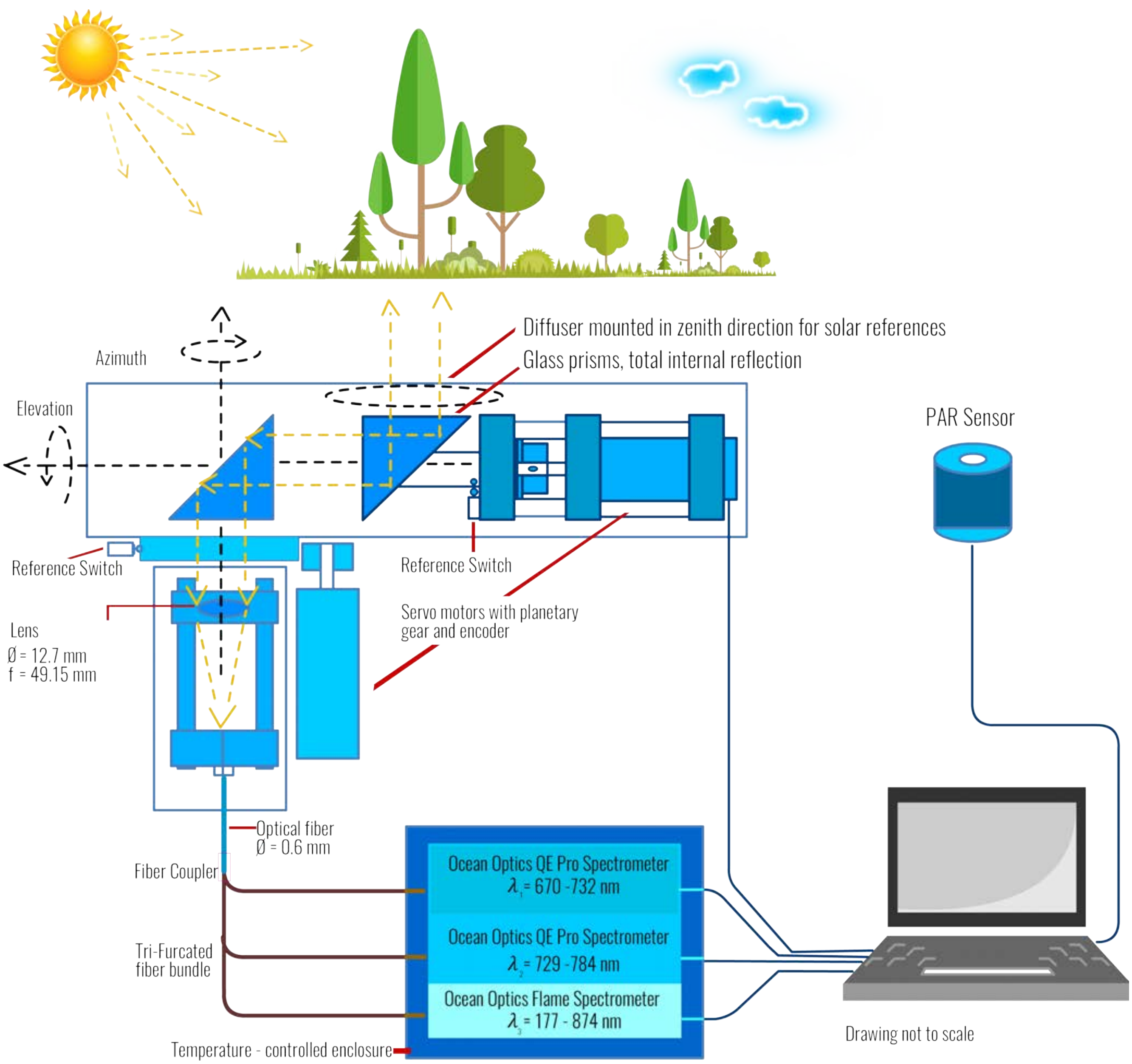

Figure 1: Conceptual PhotoSpec design, including the 2D telescope unit, feeding light into a single fiber, which trifurcates feeds into three different spectrometers with an identical field of view (FOV).

In the following, we briefly explain the solutions to the major engineering tasks for achieving the aforementioned capabilities:

2D scanning mechanism The 2D scanning telescope unit consists of two parts that can be rotated by high precision servo motors (see Figures 1 and 2): A rotating prism scans in elevation direction from zenith to nadir (right prism in Figure 1, left prism in Figure 2). This second prism (left in Figure 1, right in Figure 2) is mounted in a channel that rotates in the azimuth direction about the telescope vertical axis.

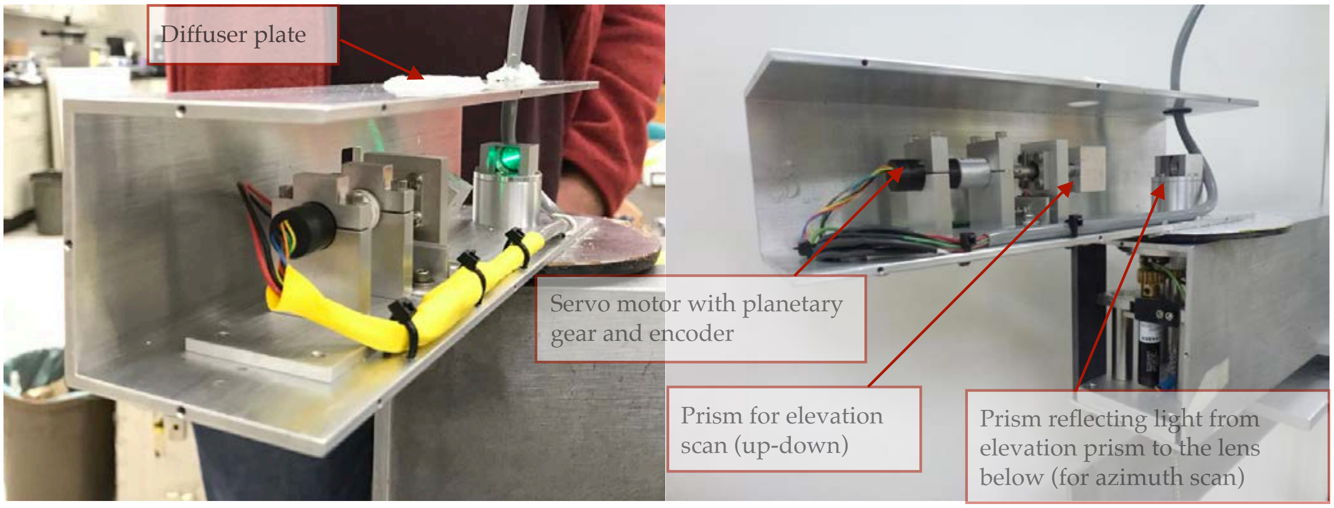

Figure 2: Telescope unit in the UCLA laboratory. The 2 axis scanning mechanisms using 2 prisms and servo motors can be clearly seen. The green light in the left picture is from a light source being fed backwards into the scanning system, which is being used to identify where the telescope is pointing at exactly (which can be

The azimuth channel can in principle rotate by 360° degrees. The optical path through the telescope starts with sunlight entering through the first rotating elevation prism (12.5mm uncoated N-BK7 total internal reflection prisms), reflects the light to a secondary, identical prism mounted at the telescope vertical axis. This prism reflects the light into the telescope, which consists of an uncoated, plano-convex lens (diameter d = 12.7mm, focal length f = 49.15mm) that focuses the light onto a single glass fiber of 0.6mm diameter. The telescope is focused to infinity and thus has a FOV of 0.7° (full angle). The advantage of this optical setup is that the scanner/telescope throughput is independent of the pointing direction, as all optical elements are passed through the same angle for all viewing directions. In addition, the optical fiber will never move, which enhances lifetime and stability.

The scanner unit collects light at user selectable azimuth and elevation angles using two small servo motors with planetary gears and a Hall encoder (Faulhaber 1266 S O12 B K1855). The elevation and azimuth scanning unit each include a limit switch, which serves as an absolute angle reference. Laboratory tests show that we can determine the angular position of each motor to better than 0.1°.

Depending on the needs in the field, the single fiber has a length of 5 - 100m and is connected to a tri-furcated distributor fiber bundle (2m length) via a fiber coupler. Our maximal single fiber length used to far is 60m. The distributor bundle has a single circular end on one side and splits into three ends with 15 fibers each (0.06mm diameter) on the other side. The 15 single optical fibers are arranged linearly in a column and serve as the entrance slit of the three spectrometers, with a height of 0.9mm and a width of 0.06mm. This fiber arrangement ensures that all three spectrometers simultaneously observe the same target in the canopy.
A diffuser plate (ground glass or Teflon coated glass) is mounted on top of the elevation channel (zenith direction) to allow regular measurements of solar reference spectra (diffuser spectra). In order to allow regular measurements of the spectrometer dark current and offset, a black target is located inside the elevation channel.
The 2D scanning telescope unit has a size of approximately (33 x 11 x 42) cm and can be mounted on observation towers above a canopy. The narrow field of view of 0.7°, (12.2 mrad) yields an observed footprint of the 2D scanning telescope unit of approximately 12cm diameter from a height above the canopy of 10m (spot size in cm = 1.22*distance in m). This footprint is sufficient to target single trees individually, gaps in canopies, or sunlit and shaded areas over the entire canopy.

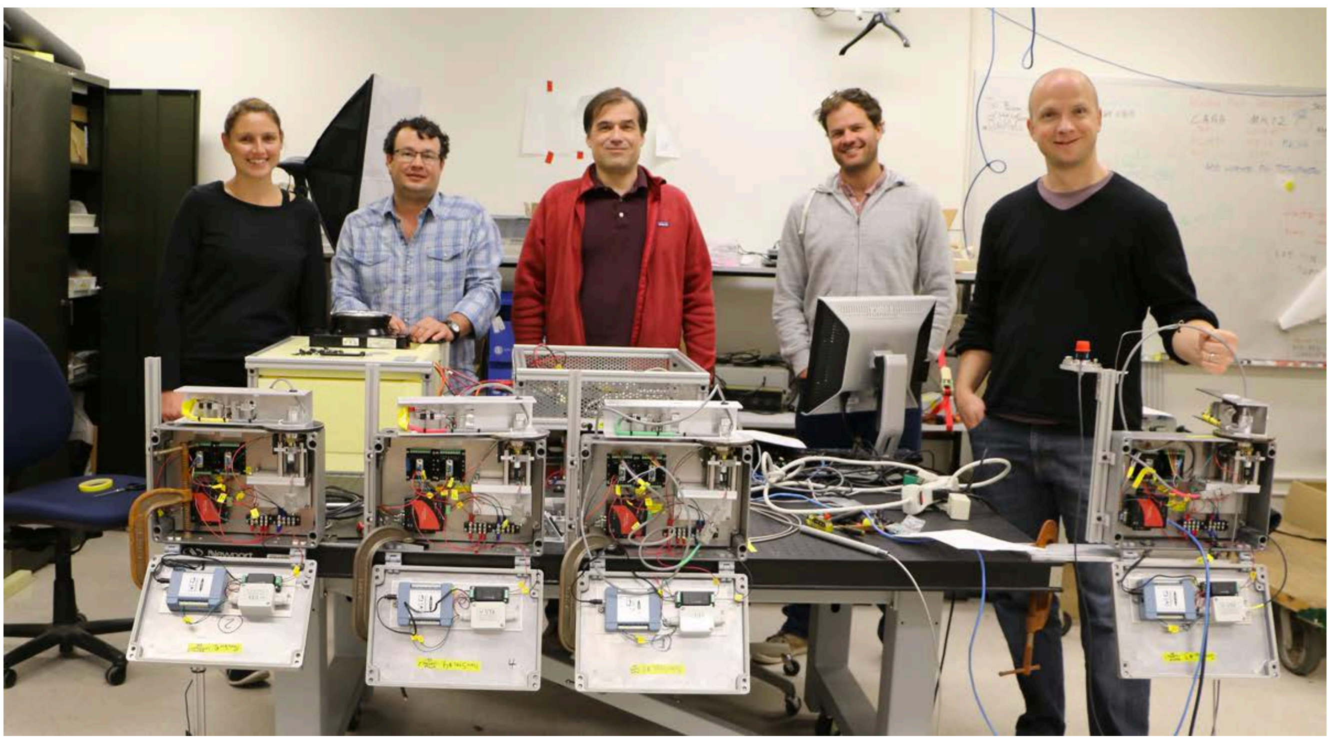

Figure 3: PhotoSpec team photo in front of 4 finished telescope units at UCLA (control electronics inside the box). From let to right: Katja Grossmann (UCLA), Darren Drewry (JPL), Jochen Stutz (UCLA), Troy Magney (NPP fellow) and Christian Frankenberg.

Instrument stability The linear ends of the tri-furcated fiber bundle serve as entrance slits for three thermally-stabilized commercial spectrometers from Ocean Optics, Inc., Florida, USA (two QEPro spectrometers, one vis-NIR Flame spectrometer).

The two QEPro spectrometers (henceforth referred to as 'red' and 'far-red') cover a SIF retrieval wavelength range at high spectral resolution (red: 650 -712nm, FWHM = 0.3nm; Far-red: 729 - 784nm, FWHM = 0.3nm), which encompass the two fluorescence emission peaks around 685 and 740nm. The Flame spectrometer of the PhotoSpec prototype provides moderate resolution spectra (339 - 1022nm, 1.2nm} FWHM) in order to retrieve vegetation indices (Figure 4).

The arrangement of the optical bench of the spectrometers is based on the crossed Czerny-Turner principle and the spectrum is measured by a CCD detector. The QEPro spectrometers are equipped with a 2400 groove/mm grating and a back-thinned Hamamatsu S7031-1006 detector with 1044 pixels, whereas the Flame spectrometer has a 600 groove/mm grating and a Sony ILX511B linear silicon CCD array with 2048 pixel. The detectors in the QEPro spectrometers are typically kept at -10° C to minimize dark current (but we encountered condensation at the detector at times, requiring de-humidifiers or constant flushing of the housing with dry air).

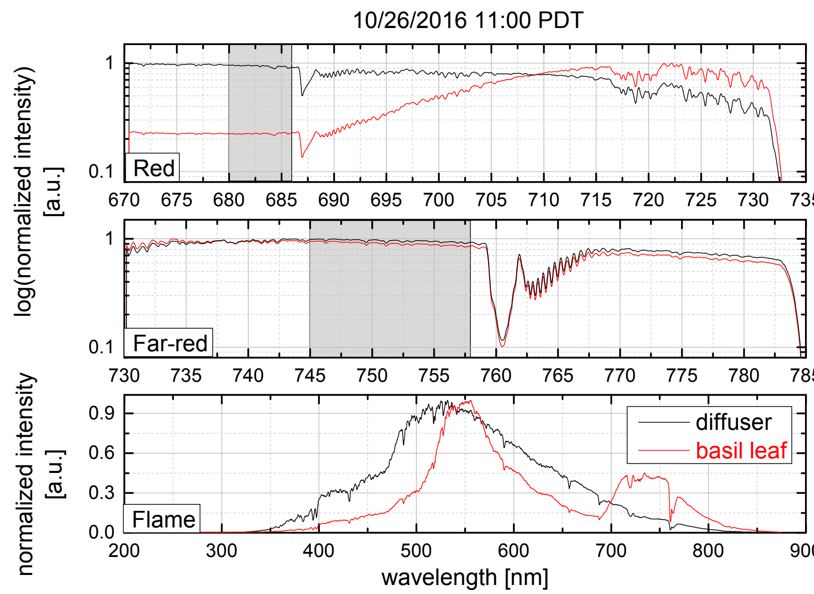

Figure 4: Top: 3 Spectrometers located in the PhotoSpec thermally controlled housing: 2 QE Pro (center, stacked on top) and one smaller Flame (on the right side). Spectrometers are heated with Kapton® Insulated Flexible Heaters. Bottom: Example spectra obtained via the diffuser (black) and pointed to a basil leaf (red) for all three PhotoSpec spectrometer system. Our baseline SIF fitting windows are shown in grey, with additional windows being tested for their information content.

The QEPro spectrometers are equipped with a 0.2mm entrance slit and an OG590 or RG695 optical long-pass filter, and the Flame spectrometer with a 0.025mm entrance slit and an order sorting filter at the detector.

In order to ensure that the spectrometers are optically stable, i.e., do not show changes in their spectroscopic or electronic dark current and linearity and performance, we use a two-stage temperature stabilization design. The three spectrometers are mounted inside a thermally-stabilized enclosure. The air inside of the enclosure is cooled to 18° C using a Peltier cooler (TE Technology Peltier module + TC-48-20 controller) with a temperature stability of approximately 0.1° C for the spectrometer environment, while slightly heating the spectrometers to 25° C with a temperature stability of better than 0.05K (Omega Polyimide Film insulated flexible heaters and a 585-05-12 TECPak thermal controller from Arroyo Instruments).

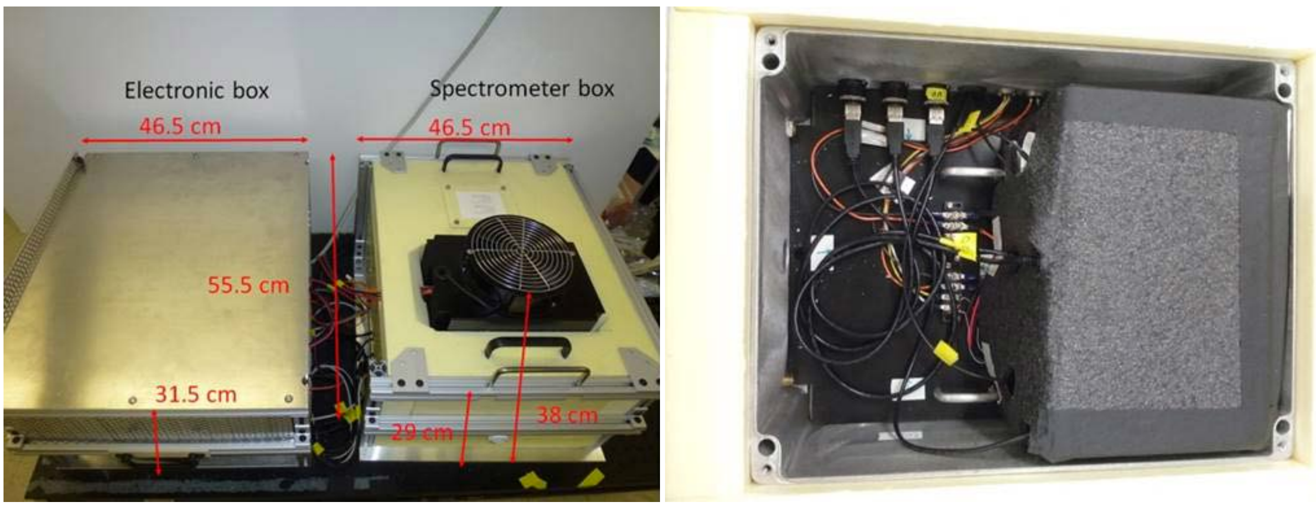

Figure 5: Left: Spectrometer System. Thermally stable Spectrometer box with the Peltier cooler sticking out , next to the electronic box (computer, etc). Right: opened Spectrometer Box on the right panel (2 QE Pro + 1 Flame spectrometer located under the black insulation).

Field Deployments The initial testing of the PhotoSpec prototype was performed in Stunt Ranch (Santa Monica mountains) due to its proximity to UCLA, which facilitated testing under realistic conditions without prohibitive travel distance (but admittedly a much drier climate than elsewhere). At the moment, we have 4 primary PhotoSpec sites, where measurements have been performed in 2017 and will continue in 2018 with the support of external grants for the 2 sites in Iowa in Corn and Soy fields. These locations span a wide range of interesting biomes and climates, including alpine evergreen needleleaf forests (Niwot Ridge, Colorado), agricultural fields around Ames, Iowa (collaboration with USDA) as well as tropical rainforest in Costa Rica at the La Selva biological station. At each of the key sites (excluding Stunt Ranch), there are eddy covariance flux measurements at each site, which will allow us to fully study the correlations of SIF with gross carbon exchange (GPP) as

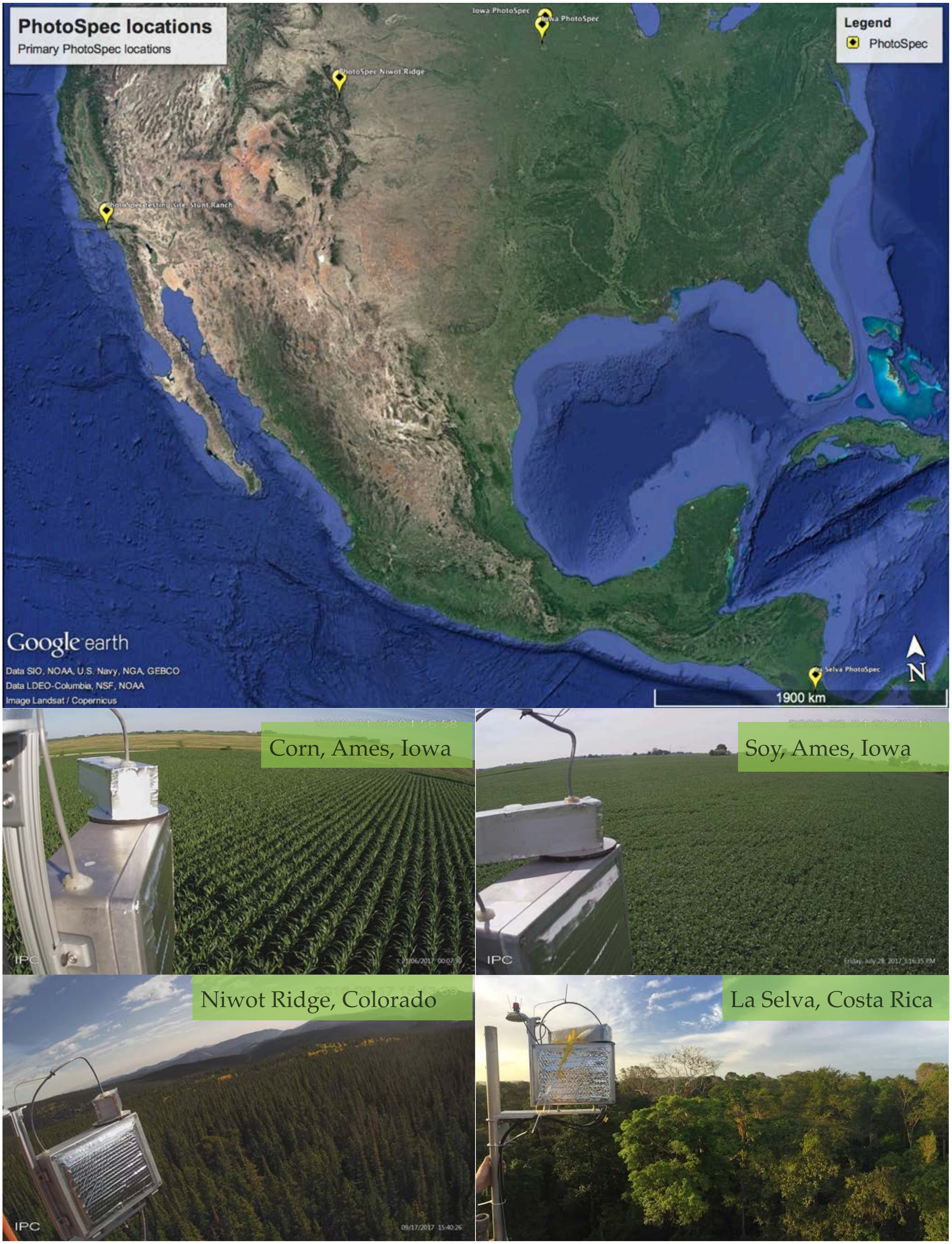

Figure 6: PhotoSpec locations in 2017/2018; Top: map. Bottom: Location pictures taken from the webcam, which is part of every PhotoSpec system and can be remotely accessed.

well as other environmental variables such as PAR, temperature, vapor pressure deficit or soil moisture.

Retrieval and Software: We implemented the overall PhotoSpec retrieval algorithms into the same overall data acquisition software used for instrument control. An example of a spectral fit using the red spectral range with PhotoSpec is shown in Figure 7. As can be seen in the top plot, we only rely on the optical depths of Fraunhofer lines, avoiding atmospheric absorption features by O_2. This has key advantages, as we won't have to account for re-absorption of SIF in the atmosphere and can also ignore changes in the photon path distribution function (PPDF) of incoming light, which would alter the depth of atmospheric absorption features. Figure 8 shows an example of a full diurnal cycle of SIF even in challenging condition with frequently changing cloud cover (as indicated by rapid changes in PAR, the photosynthetically active radiation from the sun). Currently, results from all sites are under study by teams at UCLA, Caltech and JPL, with several scientific publications in preparation or planned.

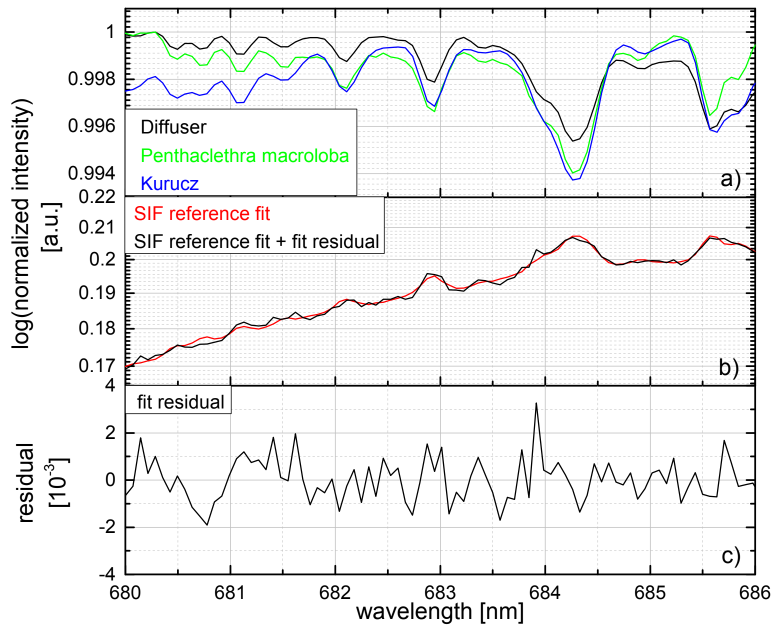

Figure 7: Spectral fit of red fluorescence using the red spectral band recorded by one of the Ocean Optics QE pro spectrometers. Fit residuals are only on the order of 1per-mil.

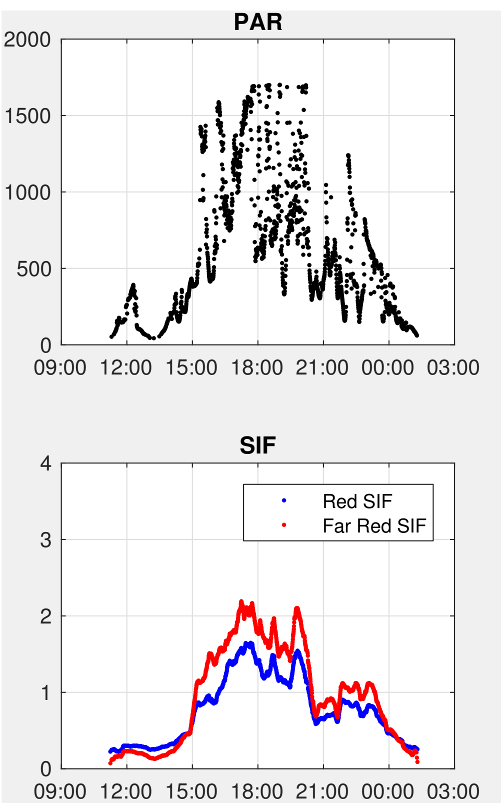

Figure 8: Diurnal Cycle of SIF and incoming light in Iowa (Corn).

Each site has its own uniqueness. The agricultural sites cover both C3 (soy) and C4 (corn) crops, which have very different photosynthetic pathways as photorespiration in C4 plants is largely suppressed, which should result in a different slope between SIF and GPP. Niwot ridge is unique as it maintains greenness in winter while shutting down photosynthesis. This is a unique opportunity for studying photosynthetic down-regulation and the impact on SIF, which is now studied with collaborators from Utah and Colorado.

b. Results — Papers/presentations

The key PhotoSpec overview paper is currently under re-review with Remote Sensing of the Environment:

Grossmann, Frankenberg, Magney, Hurlock, Seibt, and Stutz, 2018. PhotoSpec: A New Instrument to Measure Spatially Distributed Red and Far-Red Solar Induced Chlorophyll Fluorescence, Remote Sensing of the Environment, under re-review

Other papers

Troy S. Magney, Christian Frankenberg, Philipp Köhler, Gretchen North, Katja Grossmann, Jochen Stutz, Joshua B. Fisher, Alexis Harrington, Thomas S. Davis5 Ying Sun, Albert Porcar-Castell. In revisions. "Controls on the shape of the Chlorophyll fluorescence spectrum from the leaf to the canopy". Nature Plants.

Frankenberg, C., Drewry, D., Geier, S., Verma, M., Lawson, P., Stutz, J. and Grossmann, K., 2016, July. Remote sensing of solar induced Chlorophyll Fluorescence from satellites, airplanes and ground-based stations. In Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International (pp. 1707-1710). IEEE.

Presentations:

Grossmann, K., Magney, T.S., Frankenberg, C., Seibt, U., Pivovaroff, A.L., Hurlock, S.C. and Stutz, J., 2016, February. PhotoSpec-Ground-based Remote Sensing of Solar-Induced Chlorophyll Fluorescence: First Results. In AGU Fall Meeting Abstracts.

K. Grossmann, C. Frankenberg, U. Seibt, S. Hurlock, Pivovaroff, J. Stutz 2015, PhotoSpec -- Ground-based Remote Sensing of Solar-Induced Chlorophyll Fluorescence, AGU Fall Meeting Abstracts.

Grossmann, K., Magney, T.S., Frankenberg, C., Seibt, U., Pivovaroff, A.L., Hurlock, S.C. and Stutz, J., 2017, PhotoSpec - Ground-based Remote Sensing of Red and Far-Red Solar-Induced Chlorophyll Fluorescence , FLEX fluorescence workshop: REMOTE SENSING OF FLUORESCENCE, PHOTOSYNTHESIS AND VEGETATION STATUS, Frascati Italy

Frankenberg et al, 2017, Solar Induced Chlorophyll Fluorescence from the Leaf Through the Global Scale, FLEX fluorescence workshop: REMOTE SENSING OF FLUORESCENCE, PHOTOSYNTHESIS AND VEGETATION STATUS, Frascati Italy

Frankenberg, C., Stutz, J., Grossmann, K., Drewry, D., Geier, S., Verma, M., Sun, Y. and Magney, T.S., 2016, February. Solar Induced Chlorophyll Fluorescence from the leaf through the global scale. In AGU Fall Meeting Abstracts.

Magney et al., "PhotoSpec: Tower-based SIF and reflectance observations." OCO-2 Science Team Meeting. March 21, 2018. Pasadena, CA. Presentation

Stutz, J., K. Grossmann, U. Seibt, D. Dierick, T. S. Magney, and C. Frankenberg. "Red and Far-Red Solar-Induced Chlorophyll Fluorescence Observations in the Tropical Rain Forest of Costa Rica." In AGU Fall Meeting Abstracts. 2017.

Magney et al., "Drivers and variability of the Chl fluorescence emission spectrum from the leaf through the canopy." American Geophysical Union Fall Meeting. San Francisco, CA. Dec. 14, 2017. Presentation

Magney et al., "Making sense of SIF from the leaf through the aircraft." OCO-2 Science Team Meeting. Boulder, CO. Oct. 2017. Presentation

Magney et al., "Scaling chlorophyll fluorescence from the leaf to the satellite." JPL Postdoc Research Day. Pasadena, CA. Aug. 2017. Poster

Magney et al., "Biology, chemistry, and physics from the chloroplast to the satellite." Evergreen State University undergraduate Biology seminar. May 19, 2017. Olympia, WA. Presentation

Magney et al., "Beyond greenness: measuring the pulse of the biosphere from leaf to satellite." Colorado State University, Department of Forest and Rangeland Stewardship Research Seminar. Fort Collins, CO. May 8, 2017. Presentation

Magney et al., "Mechanistic interpretation of SIF." OCO-2 Science Team Meeting. California Institute of Technology. Pasadena, CA. Mar. 22, 2017. Presentation

Magney et al., "Can we see plant photosynthesis from space? Insights across leaf, tower, airborne, and satellite scales" Occidental College Biology Department Seminar. Los Angeles, CA. Feb. 28, 2017. Presentation

Magney et al., "Scaling plant fluorescence from the leaf to the satellite: Towards global mapping of terrestrial photosynthesis?" Environmental Science and Engineering Department Seminar. California Institute of Technology. Pasadena, CA. Nov. 30, 2016. Presentation

Magney et al., "The complicated relationship between fluorescence and photosynthesis: from the leaf to the satellite." JPL Carbon Club Seminar. Pasadena, CA. Nov. 4, 2016. Presentation

Magney et al., "Carbon cycle science from space." California Polytechnic Institute – Pomona. Graduate level geophysics course. Pomona, CA. May 31, 2016. Presentation

Magney et al., "Scaling chlorophyll fluorescence from the leaf to the satellite." California Polytechnic Institute – San Luis Obispo. Upper-level ecology course. San Luis Obispo, CA. May 13, 2016. Presentation

Bowling, D. R., P. Blanken, S. P. Burns, C. Frankenberg, K. Grossman, J. C. Lin, B. A. Logan et al. "Seasonality of photosynthesis of a Rocky Mountain subalpine forest: implications for SIF as a metric for GPP." In AGU Fall Meeting Abstracts. 2017.

c. External funding opportunities

We have already successfully obtained several NASA funding sources, which are either fully based on PhotoSpec, will build new spectrometer systems or use existing PhotoSpec data for scientific analysis. We have build an excellent collaborative team between Caltech, UCLA and Caltech, which had its inception with this KISS project.

Selected proposals:
Title: Ground-based remote sensing of Solar-Induced Chlorophyll Fluorescence of evergreen and drought- deciduous plants at Stunt Ranch Santa Monica Mountains Reserve, California (http://stuntranch.ucnrs.org//) **2016**
PI: K. Grossmann
PhotoSpec involvement: PhotoSpec system deployment at Stunt Ranch (infrastructure grant).

Title: Ground-based remote sensing of Solar-Induced Chlorophyll Fluorescence (SIF) at La Selva Biological Station, Costa Rica (http://education.tropicalstudies.org/en/emergingchallenges- in-tropical-science/ects-research-fellowships-ects-r.html//) **2017**
PI: K. Grossmann
PhotoSpec involvement: PhotoSpec system deployment at La Selva, Costa Rica).

Title: Evaluating crop productivity using Solar Induced Chlorophyll Fluorescence measured from ground and space
Solicitation Announcement: NASA NNH16ZDA001N-CARBON:Carbon Cycle Science — **2016**
PI; co-I: Christian Frankenberg (Caltech); Jochen Stutz (UCLA), G. Keppel-Aleks (Michigan)
PhotoSpec involvement: PhotoSpec systems form the basis for this proposal, performing measurements in agricultural fields for 2 year near Ames, Iowa.

Title: Chlorophyll Fluorescence and Soil Moisture Observations to Characterize Terrestrial Vegetation Photosynthesis and Biosphere Carbon Uptake in North America

Solicitation Announcement: NNH16ZDA001N-IDS:Interdisciplinary Science — **2016**
PI; co-I: Nicholas Parazoo (JPL); Jochen Stutz (UCLA), Christian Frankenberg (Caltech)
PhotoSpec involvement: New PhotoSpec system being built, will be deployed in Canada. Niwot Ridge will be used in analysis.

Using PhotoSpec data for science:
Title: Multi-decadal time series of vegetation chlorophyll fluorescence and derived gross primary production
Solicitation Announcement: NASA NNH17ZDA001N-MEASURES:Making Earth System Data Records for Use in Research Environments — **2017**
PI; co-I: Nicholas Parazoo (JPL); Jochen Stutz (UCLA), Christian Frankenberg (Caltech), Troy Magney (Caltech/JPL), G. Keppel-Aleks (Michigan)
PhotoSpec involvement: Existing PhotoSpec results will be used in satellite validation efforts

V) Future Work

As shown above, we have already secured substantial funding to not only maintain but also extend our current set of PhotoSpec spectrometers. In addition, the system is part of larger NASA proposals, such as the Earth Venture Suborbital (EVS-3) call, in which PhotoSpec is part of at least two submissions.
Most of the work so far has ben focused on acquiring data and maintaining the ground-based operations in the field. In terms of future work, we will switch more to science analysis, data interpretation and paper writing. This is now the ideal time as PhotoSpec system have now collected enough data to allow these scientific investigations on the basis of at least a full growing season for each site. One exciting new collaboration already emerged through our PhotoSpec system at Niwot Ridge, CO, where we work with colleagues from the University of Utah (David Bowling, John Lin) and other Universities to study the transition periods from the dormant season to the photosynthetically active period in a unique alpine evergreen needleleaf forest. This will be a very fruitful collaboration as a lot of independent measurements will be brought to the table by different research groups, which will greatly help the interpretation of PhotoSpec data, which provides unique constraints for SIF as well as pigment changes.

VI) How team will continue to move work forward

The team has developed a very good working relationship, which is now further strengthened by the stronger involvement of Nicholas Parazoo from JPL. We see this Caltech/UCLA/JPL collaboration as one that will be long-lasting and providing exciting science opportunities for at least the next 3-5 years. We have ongoing funded research among the team as well as more proposals either submitted, in writing or planned (mostly NASA but

also NSF). Our longer term vision is to work towards a more organized SIF ground-based network, including some partners who are working on similar systems.
In the meantime, we will closely collaborate on exploiting the scientific potential of our current PhotoSpec data.

VII) Conclusions

Our project *PhotoSpec - Comprehensive Ground-Based Studies of Solar-Induced Chlorophyll Fluorescence* has been instrumental to not only put Caltech and JPL on the international map for ground-based fluorescence research but also for evolving the measurement paradigm towards methods only used from space so far. The team developed a robust and high-performing instrument system that allows us to not only measure red and far-red fluorescence separately but also to obtain the full reflectance spectrum, which will provide greatly help interpret PhotoSpec fluorescence data interpretation.
We have presented the PhotoSpec systems at various national and international conferences and worked as a team to deploy the systems across the US and even in Costa Rica. However, the *real scientific* work has just started and we are confident that PhotoSpec will be the basis for various PhD theses and scientific publications for years to come. In summary, the hard work has been accomplished successfully and now we can reap the scientific benefits from all the hardware and logistical work that went into developing PhotoSpec.

VIII) Acknowledgments

First and foremost, we thank the W.M. Keck Institute for Space Studies and internal funds from the Jet Propulsion Laboratory for generously supporting our initial KISS workshop and the follow-on technical development study. Without this support, none of the work presented here would have been possible. Our special thanks goes to Michele Judd, who greatly helped build our fluorescence research community with her commitment to the KISS workshops, as well as her enthusiasm and constant support for the PhotoSpec project.
The research project at La Selva Biological Station, Costa Rica, is supported by the NSF Career 1077 award (grant # 1455381) and the ECTS-R (Emerging Challenges in Tropical Science-Research) research fellowship provided by the Organization for Tropical Studies (OTS). The authors would like to thank the OTS staff at La Selva, especially D. Dierick, for their continuous help and support with the PhotoSpec installation and maintenance.
We thank USDA, in particular Jerry Hatfield, for his incredible support in setting up the PhotoSpec systems around Ames, Iowa.
We thank the flux tower team at Niwot Ridge, in particular Sean Burns and Peter Blanken, for their continuous help and support with the PhotoSpec installation and maintenance.