The faint red glow of photosynthesis

The chlorophyll fluorescence of a leaf of Macodes petola, made visible by a special camera system.

200 years ago

When Joseph von Fraunhofer in the year 1814 pointed one of the first ancient spectrometers towards the sun, he discovered spectral lines, later known as Fraunhofer lines. In these narrow lines, the atmosphere absorbs all light and they appear dark. Fraunhofer could not have known that 200 years later his discoveries would enable outstanding insights into the machinery of plants photosynthesis itself. Using cutting edge devices, extremely accurate calibration and measurement methods, biologists drive Ocean Optics spectrometers to their very limits to catch the faint red glow of chlorophyll fluorescence inside the Fraunhofer lines.

Chlorophyll fluorescence

All plants are green. But invisible to the human eye, plants emit a tiny red light, whenever they do photosynthesis. This chlorophyll fluorescence is directly correlated to the plants activity and therefore health and carbon uptake. In other words accurate measurements of chlorophyll fluorescence [F] are the holy grail of ecosystem biologists.

But F remains hidden in the white sunlight, which is several orders of magnitude stronger. To give an example, on a good blue sky day the sun irradiance can reach up to 1 $W/m^2*nm*sr$. The fluorescence emitted from a healthy plant is at the same time just 0.002 $W/m^2*nm*sr$. It is a needle in the haystack.

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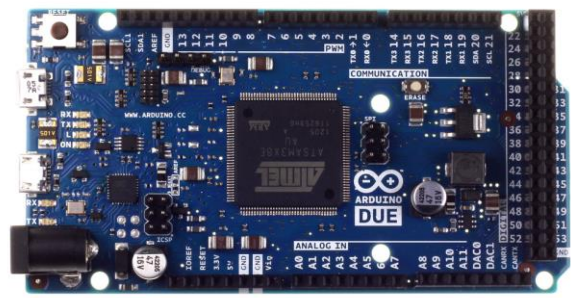
Methods and System

To catch F signal-to-noise is everything. Thus we use Ocean Optics QE and STS spectrometer which both show an extreme performance in signal-to-noise. Using the internal TEC cooling as well as the built in temperature sensors, the spectrometers are driven in a feedback loop temperature controlled housing. This way dark current and signal-to-noise are increased to a stable and extraordinary good level.

But cooling costs electrical power and power is limited at remotely sites in the wilderness, where high quality measurements of F are needed. This is why we employed cheap low power open source microcontrollers from the Arduino world to drive scientific grade spectrometers. Combining both worlds in an intelligent power control system we finally reached a fully solar driven system.

Just like a plant.

External parts of the cooling system



Arduino DUE open source micro-controller, operating spectrometer, cooling system and environmental sensors

Discriminating signal from background

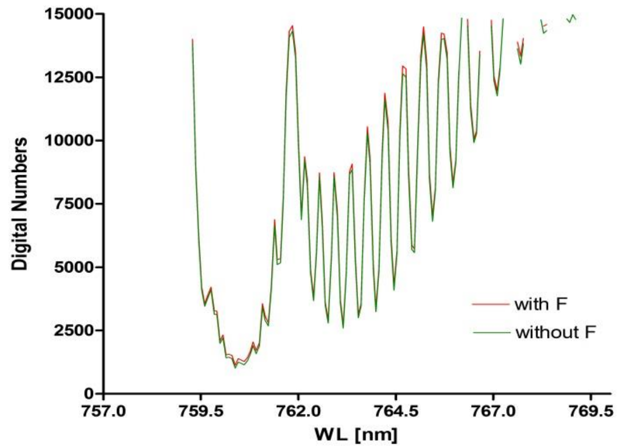
Even though we have pushed the spectrometers to their limits the faint red glow of F still needs to be decoupled from the overwhelming background light. This is when the Fraunhofer lines come into the game. A high resolution spectrometer with a very narrow full width half maximum can accurately measure the Fraunhofer lines. That means inside a Fraunhofer line it does measure almost zero. The fluorescence of plants however shifts light from blue and green wavelengths into the red and thus fills up the dark Fraunhofer lines. On other words, measuring inside and outside the Fraunhofer lines over plants, gives us a measure of the plants fluorescence.

Prototype of the autonomous fluorescence measurement system during a test run over pasture in Italy.

The Fraunhofer Line Discrimination (FLD) method is a mathematical approach to retrieve the tiny signal of F from the hyperspectral measurements inside and outside of the the Fraunhofer Lines.

I = irradiance
L = reflectance
(at wavelength λ inside/outside the Fraunhofer line)

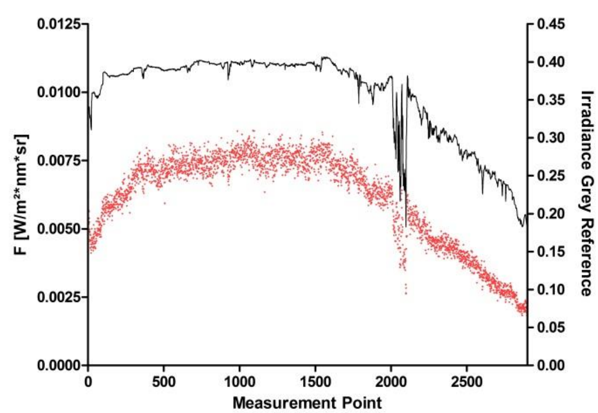
$$F = \frac{(L(\lambda_{in}) \cdot I(\lambda_{out}) - L(\lambda_{out}) \cdot I(\lambda_{in})}{(I(\lambda_{out}) - I(\lambda_{in}))}$$



O_2A Fraunhofer line at 760 nm, measured with an Ocean Optics QE spectrometer. The red line shows the signal with and the green without fluorescence.

Reinventing our understanding of plants

But this is not the end of the story, and this is where the science begins. Deploying multiple of the described hyperspectral devices all over the world over different kinds of vegetation is a plan for the future. As the spectrometers do not only measure F but also cover information in the VIS and NIR, multiple plant parameters can be derived to get a comprehensive understanding of every stage in plant development. This data measured over the day and year bears invaluable information to the biologist and the farmer and could finally reinvent the way we look directly into the plants and their current needs.



Looking into plants in a novel way - On the right, a preliminary daycourse of F(red dots) measured by the prototype is shown for vegetation. The black line represents the sun irradiance. Note how F drops with an incoming cloud.

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