Short Term Scientific Mission Report COST Action OPTIMISE: ES1309 **Topic:** Usage of small drones for measuring light absorption within a tree canopy - development of the platform and setting experimental protocols

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Period: from 2016-09-05 to 2016-09-18
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1 Purpose of the STSM

Main objective of my STSM was to prepare unmanned aerial vehicle (UAV) platform for of vertical/horizontal profiles of light within canopy and measurement protocol for research carried with this type of platform. Profiles (both vertical and horizontal) of light measured in real conditions within examined canopy are crucial for validation of radiative transfer models (RTM) developed specially for studies of plant-radiation interactions. Together with flying platform measurement protocols are needed, which will allow standardization of spectral measurements within tree canopies. Standardization of measurement protocols helps maintain consistency of acquired data sets between different field campaigns and are necessary for comparison of data collected by different research teams.

Designed platform is defined as a lightweight, versatile drone for carrying light instruments like compact or mirror less RGB/NIR cameras, spectrometers, integrated spectral sensors (NDVI: Normalized Differential Vegetation Index, PRI: Photochemical Reflectance Index, PAR: Photosynthetically Active Radiation). Flight controller of the drone should have capability of internal logging of measured data and integration of this data with internal sensors like accelerometers, baromether, gyroscopes, compass and position from Global Positioning System (GPS). Achieving the greatest possible accuracy of the drone position logging (sensor position) defined as latitude, longitude, altitude above ground level, roll, pitch and yaw, has great importance in validation/comparision of RTMs which solutions are sensitive to changes in measurement setup geometry. For small drones recently available on the market best solutions for positioning base on Real Time Kinematics (RTK) GPS devices.

Preliminary analysis allowed us to choose a set of components which will be used for the drone. Platform will incorporate state of art open source flight controller software stack ArduPilot installed on the newest highly customizable Raspberry Pi 3 microcomputer coupled with Emlid Navio2+ board. Navio2+ board works as a flight computer and as a sensor board with inertial measurement unit and analogue to digital converters. As a RTK system Emlid REACH was selected, because of the very good quality/price ratio according to the customers reviews publicly available on the internet and internet boards dedicated to scientific and geodetic community.

Parameter	Specification
Dimensions	40 mm x 42 mm x 24 mm
Weight	60 grams
Detector	ELIS 1024
Field of View	30^O bare optics
Wavelength range	335 – 824nm (VIS) / 633 – 1123nm (NIR)
Integration time	10 μs – 10 s
Resolution	3.0 nm (optical) 0.47 nm (digital)
Interface	USB

Table 1: Ocean Optics STS specification

Parameter	Specification
Dimensions	24 mm (diameter) x 28 mm (height)
Weight	90 grams
Sensitivity	0.2 mV per $\frac{\mu mol}{m^2 s^1}$
Calibration Factor	5.0 per $\frac{\mu mol}{m^2 s^1}$ per mV
Field of View	180^O
Response time	<1ms
Interface	analog

Table 2: Apogee SQ-110

Combination of described drone and proper measurement protocol will create system for acquiring high accuracy orthomosaics or structure from motion digital surface models and geolocated data from non-imaging sensors. Geolocated data together with high quality DSM allows examination of canopy structure influence on spectral measurements.

2 Description of the work carried out during the STSM

Design of the drone, selection of all parts necessary for flying (motors, electronic speed controllers, propellers, frame and power system) and primary assembly was subject of the different STSM held at the same institution (EUR.AC Bolzano). Our work was to develop (leverage) the drone on all layers (hardware, software and protocols) into a scientific platform for delivering data useful for scientific purposes. Whole work was divided into several stages which were achieved consecutively.

First step was dedicated to determining type of proximity measurements, which will be conducted during the STSM and according to that final selection of sensors. Selection of sensors influence most of the steps, so it was our first task to achieve. After examination of scientific potential, we decided to select two different types of sensors, which will measure different parameters, through different interfaces (one digital and one analogue). This approach allowed us to prepare deeper tests of platform, which included both types of interfaces used in scientific payloads. For high resolution spectral measurements small spectrometers from STS model line specially designed by Ocean Optics for embedded systems or UAV applications were selected. We used two units with different spectral range, one STS-VIS and one STS-NIR (table 1).

For analogue measurements Apogee SQ-110 Sun Calibration Quantum Sensor was selected, which was dedicated to measurement photosynthetic photon flux density $\frac{\mu mol}{m^2 s^1}$ which is in linear way scaled to voltage. We decided to use two units, one in nadir to the ground and one looking into the zenith. Both sensors were attached to the Navio2+ 6 channel ADC.

After selection of the sensors we started preparing initial integration of them with the flying platform, especially with the on-board computer. Flight controller Emlid Navio2+

is in fact external board (often caller hat) mounted on top of Raspberry Pi computer with installed Raspbian Linux-based operating system. During the STSM third version of the Raspberry Pi was the newest one supported by the Emlid. Thanks to usage of small microcomputer with many general purpose input/output ports capable of running fully featured linux system process of integration of sensors is simplified to installation or compilation of device drivers (kernel modules) and libraries. Thanks to the special distribution of the Raspbian linux delivered as an disk image by Emlid all drivers for sensors on Navio2+ were already installed. One of this sensors was 6ch Texas Instruments Analog-to-Digital converter ADS1115 which was used for reading voltage from two Apogee sensors. For STS spectrometers special USB drivers and libraries called Seabreeze were necessary. Their source codes and documentation are publicly available on github.com. After common compilation procedure of kernel modules we were able to read in the operating system raw data from all sensors: Ocean Optics STSs, Apogees, integrated 9 degrees of freedom circuit with 3 x accelerometer, 3 x gyroscope, 3 x compass.

Most important part of the integration of sensors with the platform was preparing dedicated software for data logging, which will combine data from all sensors into one dataset easily processed by different scientific software suites. At this moment we decided to use python as a lead programming language, because of available scientific libraries (for example: NumPy Matplotlib), very fast prototyping and already prepared python sketches for Emlid Navio2+. Thanks to the choice of Python (scripting language) improvements and changes in code were very easy and instant without need for compilation. We decided to synchronize all data with internal clock of the Raspberry Pi, aided by GPS time. Measurements were logged with 1 second time resolution and every measurement was timestamped. In the case of spectrometers time resolution was influenced by integration time, which could be longer than 1 second. In such case time resolution for spectral measurements with spectrometers was equal to the integration time ($+\epsilon$ for saving a spectra). Especially important task was to process and save data from sensors simultaneously. Measurements done at almost the same moment are necessary when sensors are mounted on a moving device (drone), because every movement (turbulence, wind gust) changes angles between target, sun and sensor what in straight way changes results of measured light. Created set of python scripts (available as a github repository) addressed all of our requirements related with designed measurement protocol.

Together with software integration RTK modules were configured. Emlid REACH RTK is build on Intel Edison microcomputer what makes them standalone. In our case we had to configure base and rover according to the manual delivered by manufacturer and decide what channel of communication we will use for transfer of corrections between devices. REACH supports WIFI, Blue-tooth, USB and serial modems. Primarily we thought about 3DR serial telemetry radios, but due to problems with delivery as abackup we decided to use WIFI. Both units where connected to the laptop with external wireless network card configured as an access point. With active telemetry radio it is possible to connect REACH directly to the drone flight controller, but in our case, where WIFI was used we set both RTK to internal logging mode, which creates special files for post-processing with library Tomoji Takasu's RTKLIB.

Final step in preparations of hardware was related with physical integration of sensors with the drone. We had to prepare mounts which will hold sensors during the flight in secure and solid way. At first mounts are created to secure the device before falling down (what could be dangerous for people and the device). Second purpose is maintain right location and position of the device during measurements in the relation of other sensor and the drone. In our design we had to mount 6 separate devices (STS x 2, Apogee x 2, Navio2+, REACH). Thanks to the Techno Innovation South Tyrol KAG we were able to use Ultimaker 2 3D printer and Trotec Speedy 400 laser cutter in the process of mounts preparation. Special suspension system for the Navio2+ was already designed by makers community, so we only downloaded the design from thingiverse.com and sent it straight to ABS 3D printing. In the meanwhile we designed in Solidworks 3D CAD mounts for STS and Apogee. STS modules are delivered without any mounts or holes, so for 2 spectrometers special box with holes for 4 screws was drawn. The box minimized distance between two devices and were easy to mount on a drone with plastic straps. For this part 3D printing was selected, despite quite long over printing time (around 8 hours). Apogee sensors are already equipped with a hole with screw thread, what makes design of mount much easier. We decided to use simple 2D board with a hole for screwing the sensor and two additional holes for locking the board to the drone. Two similar boards were cut with laser cutter and mounted on the drone with screws. One board was on the top of an arm looking into zenith and the second below an arm looking into nadir. As usual in field research last level of security was added by duct tape.

Goal of the STSM was related with experimental protocol for measurement of light absorption inside trees canopy. We discussed different measurement schemes, which will be the best to cover all scientific issues having in mind common problems with UAV operations like batteries capacity, amount of battery sets, telemetry range and desired spatial resolution. We concluded that first part of measurements should be dedicated to the acquisition of high accuracy, high resolution digital elevation model (DEM). Model could be created from RGB/NIR images taken by digital camera and then processed in surface from motion algorithm for orthomosaic and 3D models. High quality DEM will be used to describe structure of canopies and position of non-imaging measurements in relation to analysed canopies. Second part of measurements should be dedicated to the main scientific topic like light absorption within tree canopy. We decided to flight along transects on different altitudes and then simulate random walk on different altitudes. Our scheme was prepared to upload into flight plan and flight computer.

For safety reasons and easier operation we decided to select test site with sparse canopies, where trees heights are above 10 meters and almost flat surface. Sparse canopy gives larger error margin for a drone operation and potential GPS glitches. Flat surface make flight at defined altitude much easier to plan. Our desired range of altitudes was between 2 and 20 meters. In such case slope on the test site could heavily interfere with measurements. Primarily we decided to use site near eddy-covariance tower at Renon, but after infield inspection and consultation with local forestry service we decided to look for a different site. At slopes of Renon canopies are dense and then very quickly trees disappear at the higher altitudes, transition zone is very narrow and usually quite step. Upper, flat parts of the Renon are covered by grass or bushes without any trees which could be useful for the experiment. Thanks to a suggestions from local forestry service we found almost perfect test site 10 kilometres north from Bolzano in Jenesien (1450 m. ASL). We found there quite flat pastures covered with low grass and with sparse groups of tries like in the english type park.

Preflight site assessment revealed that biggest threat for our operation was from the side of farm animals – cows (mostly) and horses. This area was far enough from inhabited places and only solid structures in the perimeter were small wooden storage buildings. Near to the eastern border of the area there was a hiking trail but we seen only a few tourists. In both cases (animals and tourists) we decided to observe them during the flight and inform operator in case of potential danger. During flights minimum distance between the drone position and nearest man or live stock was always larger than 100 meters.

Unfortunately problems with supply of important parts for the new platform (telemetry, RC receiver with PPM/SBUS) for real field test we decided to use a backup drone – large multi-purpose platform from EUR.AC manufactured by Soleon Germany. Thanks to prepared universal mounts we were able to easily attach sensors, RTK and Navio2+ board with Raspberry Pi on top of the Soleon drone. All sensors were connected to the Raspberry Pi, which was powered from 5V power bank. Raspberry Pi was set as an access point and operation was controlled by SSH connection. Flight controller responsible for the drone flight and planning of flights was Mikrokopter. RTK module was mounted on one drone's arm, powered from USB and connected with the base/ground station through WIFI. We captured RGB images with the Ricoh camera mounted on a gimbal and then made spectral measurements. For better accuracy and validation ground control points were used. During flights with STS spectrometers, on ground measurements of radiation with integrating sphere were acquired by Spectra Vista HR-1024i spectrometer.

After tests pictures from Ricoh camera were processed in Pix4D software to create orthophotomosaic and DEM. Data from sensors operated by Raspberry Pi was merged into one dataset and interpolated to the same timestamps (microsecond resolution, then averaged to one second). Data from RTK was downloaded and post-processed with the dedicated software. Relation of data points with canopy structure was made with DEM and positions from GPS/RTK.

During analysis of results were reviewed mostly from the site of experimental protocol. Approach in which spectral results were analyzed together with canopy structure has potential to create simplified statistic models. We proposed model which base on a relation (distance, direction) between measurement points and nearest tries. We collected a lot of data (spectral and flight related), which could be interesting for other UAV/remote sensing related projects.

3 Description of the main results obtained

STSM presented in this report in dedicated to the development of the platform and experimental protocol so I decided to present most important achievements of platform development and results from field test in the results section.

We spent plenty of time preparing and improving software solutions designed for the platform to be sure that everything works as desired. To achieve best results we decided to write software which will full fill the following requirements:

- simultaneous operation of separate processes for different sensor (threads)
- every sensor should has its own part script which could be selectively turn on/off
- data is saved in to ASCII format for quick infield review
- data is saved in defined interval into separate files for lowering risk of data loss
- every data line is time stamped with microsecond resolution
- final data could be merged into time resolved consistent data set

We wrote all of the software in Python scripting language with the following libraries: threading, time, sys, Queue, navio, seabreeze, spidev and numpy. All scripts were added to a github repository so they could be improved and reused by other scientific teams interested in this solution.

Data from every sensor was saved with the highest possible time resolution presented in table 3, every line represents one data file.

All of the scripts were combined in one work flow triggered by one BASH script. For data processing special script for merging the data into one dataset was prepared. As presented in the table above time resolutions were different so there two different options for interpolation. One interpolate all data based on time to the lowest time resolution. Second interpolate data to the highest resolution. Of course different interpolation scenarios could be used. At the beginning the easiest linear interpolation was selected.

Sensor	Time resolution [s]	Rows per file	Data columns
Apogee UP/DOWN	0.1	600	3 (time, UP, DOWN)
Compass x 3 Gyroscope x 3 Accelerometer x 3	0.1	600	10
GPS	1	60	5 (time,GPStime,Lat,Lon,Alt)
STS NIR	integration time	100	1025 (time, 1:1024 bands)
STS VIS	integration time	100	1025 (time, 1:1024 bands)

Table 3: Data logging structure

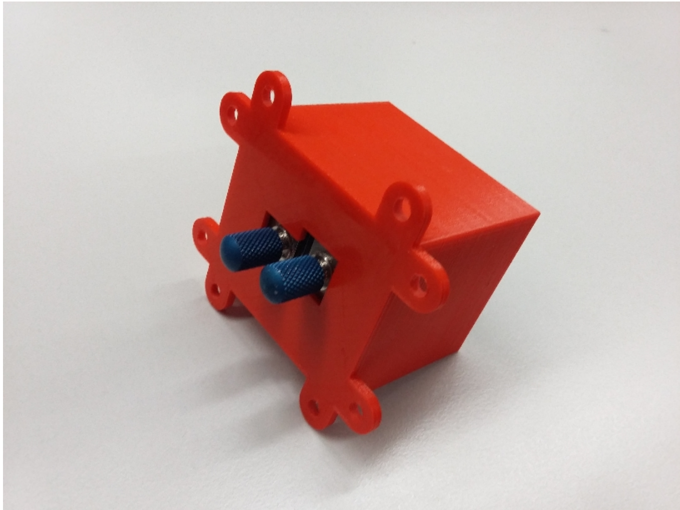

Figure 1: 3D printed mount for two STS spectrometers

STS spectrometers do not have internal shutter so script had to be prepared to follow 4 important parts of spectral measurements: integration time optimisation, white target measurement, black current measurement. After start of the script whole process was signalized by RGB LED integrated into Navio2+. Colour coded commands with defined intervals tell what should be done. After selecting integration time (70% of sensor saturation) 10 white/black spectra were save into separate file with proper file name. When calibration went right, LED blinking green signalized that all sensors are ready for flight. Data from spectral sensors could be normalized by different radiance and size of ground support related with altitude of flight (GPS) and exact orientation of a sensor (Compass, Gyroscope and Accelerometer).

During field operation Raspberry Pi which was used as a main data collecting computer was set as an access point for WIFI network. Thanks to this solution I was able to connect to the computer with SSH client on a laptop or smart phone to start measurements, check debug output or examine some results. It was especially useful for checking integration times of spectrometers, which we used for decision process of selecting flight time.

We had an opportunity to fully control process of physical integration of sensors on the drone. We started from measurements of devices, then design in CAD/3D modelling software and finally print/cut mounts for STS spectrometers and Apogee sensors. This work was done with SolidWorks 3D CAD suite. Designed mounts were separate, but it was possible to plan one larger mount for all of sensors. We decided that it will be more universal to prepare separate solution, but of course it is important to write down spatial distances between sensors mounted on a drone. Additionally with separate mount it is easier to introduce differences in view angles, but it is easier to attach sensors to a drone. Below is presented picture of printed 3D part.

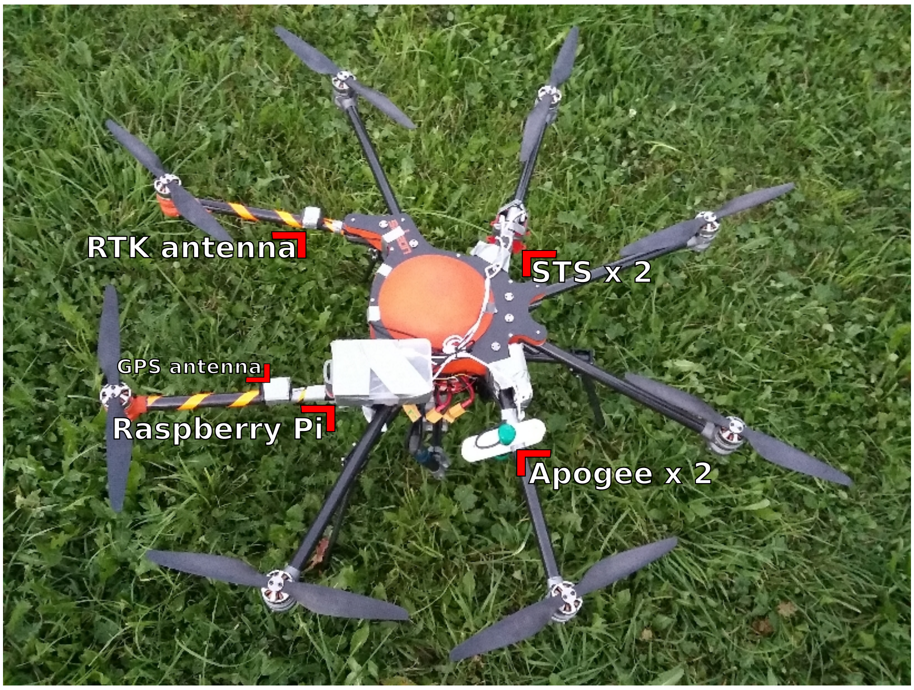

Figure 2: EUR.AC drone with sensors mounted

When all mounts were prepared we mounted them on the drone with screws, plastics straps and duct tape. It was important to check all cables, data connection, location GPS/RTK antenna and obstacles in sensors field of view. All of the sensors together with the Raspberry Pi were separated from the drone power supply and plugged to a 5V power bank with enough capacity for several hours of operation (6000mAh).

For measurement protocol we defined three main areas which should be taken in mind during planing and execution of field campaigns. Those areas are: set of sensors, set of necessary data for logging and flight patterns. For set of sensors we recommend utilizing, aside main sensors for proximity sensing like spectrometers or PPFD:

- inertial measurement unit with one accelerometer, gyroscope and compass for every axis (X,Y,Z) which will deliver roll, pitch and yaw information which should be used for corrections of radiation measurements
- real time kinematics GPS or DGPS for centimetre scale accuracy of orthophotomosaics and DEM
- data is saved in to ASCII format for quick infield review
- spectrometer with integrating sphere for measurement of incoming solar radiation

All of logged point data should be timestamped with sub-second resolution. Timestamps are crucial for merging a data from different sensors into one consistent data set with GMT time for all data line (from GPS time), yaw, pitch, roll in degrees (from IMU calibrated with exact position of sensors on a drone) and latitude, longitude, altitude (from RTK/DGPS in degrees/meters). For the examined areas should be created a DEM with pictures georeferenced with RTK GPS or DGPS.

We propose to incorporate 3 flight patterns into the flight missions. Two flights should be dedicated to spectral measurements and one to capture DEM. We assume that flight with a camera is only dedicated to DEM, so we do not need to wait for perfect sun conditions for spectral measurements, so this flight could be done as first or last. On some UAV it will be possible to flight together with camera and spectral payload in such cases of course we need to check light conditions. Our suggested flight patterns:

- traditional linear flight pattern characteristic for taking orthophotomosaics at fixed altitude (for example 50 meters)
- traditional linear flight pattern inside area covered by DEM done in separate layers with different fixed altitude (for example 2, 5, 10, 15, 25, 40 meters)
- pseudo random-walk flight pattern with random locations and altitudes in rage of area covered by DEM. This flight could be done manually or set of coordinates could be drawn by a computer (but we need to manually verify their location and connecting path in relation to the trees in measurements site)

We tested proposed experimental protocol during infield test carried during the STSM. Test flights were done in Jeniesen area 1200 meters above Bolzano on the hill which is northern boarder of the city. Test site location is depicted on the figure 3.

Figure 3: Location of the test site

We conducted flights based on a programmed mission and pseudo random flights with manual control. Programmed flight was dedicated for acquiring high resolution pictures for generation DEM and was done in normal line pattern (green line on map). Sample “random walk” flight is depicted with pink on the map below. Pictures with digital were captured from constant altitude of 50 meters with output resolution of around 1.5 centimeters per pixel. For “random walk” different altitudes were tested.

Figure 4: View of the test site area

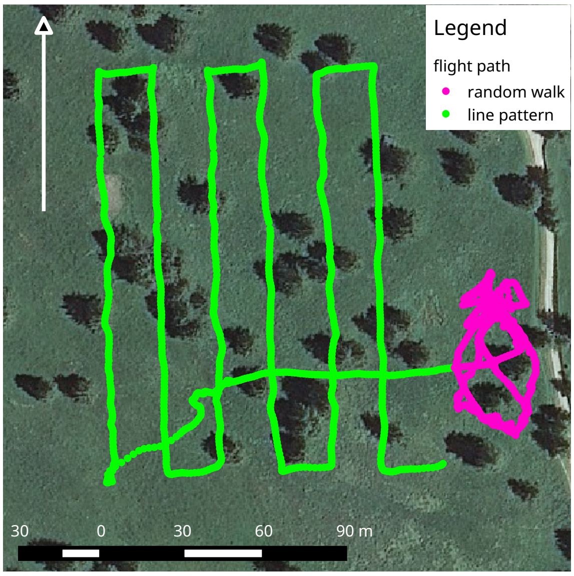

Figure 5: Flight patterns for linear (green) and random walk flight (pink)

Thanks to the known location of trees we defined canopy structure as distance between measurement point and every tree inside radius of influence (arbitrary defined parameter which should be further investigate). For the primary tests influence radius of double tree height was used. For points without any trees inside radius of influence maximum distance was assumed. Cumulated distance for every point together with spectral results like NDVI could be used for calculation of simplified statistical models which could help us investigate influence of canopy structure for light absorption.

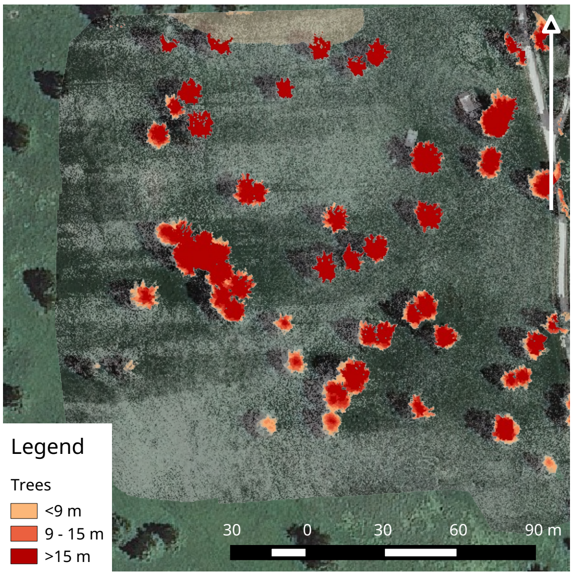

Figure 6: DEM processed by Pix4D allowed us to do automatic height-based trees extraction

As a sample product created from collected and processed data set NDVI (calculated from STS NIR spectrometer 690 / 740 nm) results along linear transect are presented. Altitude of the flight was 50 meters with 8 meters of support diameter. Data was interpolated to spatial extent with triangular interpolation.

We can conclude that our goal was achieved. We developed full concept of small UAV platform from hardware, through software to the level of experimental protocol. We

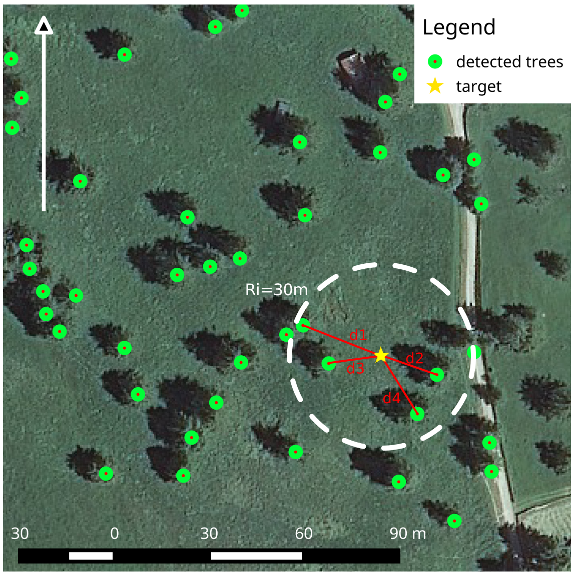

Figure 7: Concept of statistical model for canopy structure influence investigation based on influence radius and distances between trees inside radius of influence

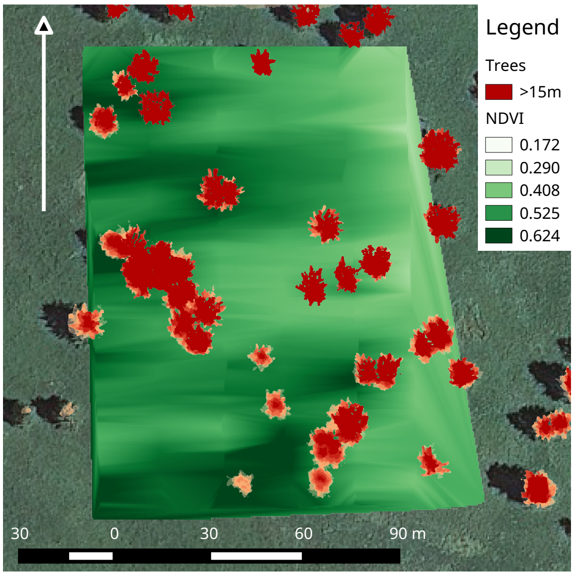

Figure 8: Interpolated and corrected NDVI results from STS spectrometers

tested our concept in the field with he backup drone, but all measurements were done as planned. Collected data has potential for further analysis, especially all of the spectral data taken with STS spectrometers. Source codes of all scripts and 3D designs of all parts are available in public repositories for everyone interested in following the project:
source codes - https://github.com/Myszka/optimise-raspi
3D parts - https://www.thingiverse.com/thing:1834082

4 Future collaboration with the host institution (if applicable)

Concepts created during the STSM will be utilized during already scheduled "Challenges of UAV spatial sampling" workshop which will be organized in Bolzano in October. We will utilize prepared software, mounts and measurement schemes. Together with Enrico we could investigate ideas of statistical models for spectral data in relation to canopy structure. This concept will primary tested on already acquired data set and after investigation of results we will decide on next steps. Together with statistical model I think about process of clusterization and comparison of spectra to determine areas of different spectral features in whole spectrum range. The STSM was a great way to start deeper cooperation, which could result in interesting joint projects in the future.

5 Foreseen publications/articles resulting from the STSM

In the case when we will receive interesting results from the idea of statistical model we will try to prepare publication for one the journals related with proximity sensing/UAV/remote sensing.

6 Confirmation by the host institution of the successful execution of the STSM

attached