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IMPROVEMENTS, CALIBRATION, AND ACCURACY OF THE
FINNISH GEODETIC INSTITUTE FIELD GONIOSPECTROMETER

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<p>This work presents the features of Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO), concentrating on recent improvements, calibrations, and accuracy of the device. Several similar instruments by international research colleagues are introduced and the theories of bidirectional reflectance factor and bidirectional reflectance distribution function are briefly explained. Some data are presented to give an idea of the measurement results.</p> <p>FIGIFIGO is a device for multiangular reflectance factor measurements under field conditions. Some most noteworthy features of the instrument, compared to similar devices, include: fast operation and assembly, high portability, possibility for both laboratory and field measurements, and high degree of automation.</p> <p>The most important improvements to the system include: a sky camera for device orientation, optics with rotatable linear polarizer, and a fine tune mirror for spatial correction of optics footprint. With the addition of these features, FIGIFIGO has become more reliable and accurate, and scientifically more useful.</p> <p>Calibration of the system has increased the reliability of the data, and has provided the operators with information on how to operate the instrument most efficiently and accurately. The utilization of this information translates directly to more reliable and scientifically more important data.</p>		
Keywords: Finnish Geodetic Institute Field Goniometer; FIGIFIGO; Spectrometry; BRF; BRDF; Remote Sensing		

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<p>Tässä diplomityössä esitellään Geodeettisen laitoksen kenttägoniospektrometri, FIGIFIGO, siihen tehdyt kalibraatiot, tarkkuusmittaukset ja parannukset. Työssä esitellään myös muita samankaltaisia laitteita, selitetään mittauksen teoria ja esitellään joitakin saatuja tuloksia.</p> <p>FIGIFIGO on kenttäkäyttöön suunniteltu mittalaite, jolla voidaan määrittää erilaisista pinnoista heijastuneen valon spektri useista eri suunnista. Tätä tietoa voidaan käyttää pintojen heijastavuuden mallintamiseen, satelliiteista saadun datan varmentamiseen ja ilmakuviin tehtäviin korjauksiin.</p> <p>FIGIFIGO on suunniteltu mahdollisimman varmatoimiseksi, nopeaksi ja kevyeksi. Tämän työn kuluessa laitteistoon on lisätty muun muassa kalansilmälinssillä varustettu kamera, jolla määritetään laitteen asento suhteessa aurinkoon, sekä uudet optiikat, joilla voi mitata valon polarisaatiota. Nämä lisäykset ovat mahdollistaneet entistä monipuolisemmat mittaukset ja siten uusien tieteellisten tulosten hankkimisen.</p> <p>Laitteiston kalibraatio on antanut lisää varmuutta saatujen tulosten oikeellisuudesta ja tarkkuustestien perusteella tehdyt muutokset ja parannukset ovat entisestään lisänneet laitteiston mittatarkkuutta ja luotettavuutta.</p>		
Avainsanat: FIGIFIGO, spektrometria, BRF, BRDF, kaukokartoitus		

Preface

I wish to thank my instructor Jouni Peltoniemi for his valuable comments and advices and professor Aarne Halme for supervising this work. I also appreciate the help from my colleagues at Finnish Geodetic Institute. Especially Juha Suomalainen has contributed significantly to this work.

I also thank my family and my friends for their support during this work.

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1 Introduction

Light reflected from a surface can be detected using various methods. Most know to humans is our own eyes. However, our eyes have limited capability to detect colors, since our eyes only have three different kinds of color sensing cells, for three partially overlapping bands of light. Modern spectrometers, devices that measure the intensity of electromagnetic radiation as a function of wavelength, can individually detect the radiation intensity of hundreds of narrow bands of electromagnetic spectrum.

Remote sensing of Earth from space-borne instruments has been a widely studied area of science for decades. The advancements in optical sensor technology have led to availability of multi-angle spectral data. These multi-angle data are taken from satellites having sensors that view Earth from multiple directions along the track of the satellite. When the satellite passes, constantly collecting data, a single area of Earth's surface is measured from several different viewing angles. This setup is used for example in Multi-angle Imaging SpectroRadiometer (MISR), Figure 1. These data can be used to retrieve physical characteristics, such as aerosol type, cloud morphology and height, and land cover [1]. Clouds strongly affect Earth's climate, and thus the uncertainty regarding the effect of the clouds is a problem when modeling climate change. MISR provides additional data for improving these models.

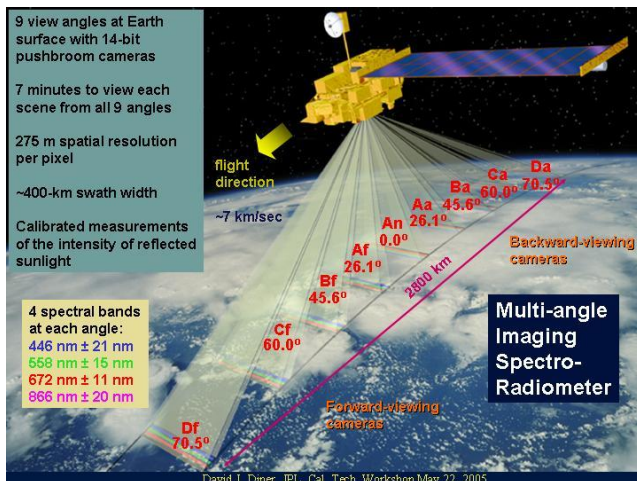


Figure 1: MISR Observing Concept [2]. The picture illustrates the measurement concept of MISR. The satellite has nine similar instruments with different view angles, all viewing along the track of the satellite.

Satellites are suited for global remote sensing purposes and similar measurements from aerial vehicles are suited for local area remote sensing. However, further understanding of the reflectance properties of land cover, a device with smaller footprint is needed. Field

goniospectrometers are designed to gather reflectance data from multiple viewing directions from a small sample. This data can be used for modeling of the reflectance properties of the sample, known as bidirectional reflectance distribution function (BRDF) and verifying existing models. The data can also be used to validate satellite and aerial observations and for better understanding of relationships between biogeophysical parameters and BRDF [3].

For remote sensing applications it is important to separate the spectral signal of the forest understory from the signal of the canopy. This is possible by modeling the various understory vegetation BRDF [4].

Goniospectrometers can also be used inside laboratory with artificial light. This has several advantages and disadvantages when compared to outside measurements; inside the measurement setup can be made heavier and more accurate, changes in atmosphere do not interfere the measurement and the spectral bands, where water vapor in atmosphere absorbs most of the light outside, are available in laboratory. Also the amount of diffuse light can be minimized inside by using dark, nonreflecting surfaces. On the other hand the samples in laboratory measurements cannot be as natural as they would be outside.

This work concentrates on reporting the recent improvements and calibrations done on Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO), designed and constructed in Finnish Geodetic Institute [5]. The device is optimized for fast field measurements under solar illumination conditions. Rapid operation is a key factor when having to rely to Sun for illumination, since the conditions vary rapidly due to water vapor in the atmosphere and the changing direction of solar radiation.

The purpose of this work is to report some of the improvements and calibrations done to the device during years 2007, 2008 and 2009. The purpose of these improvements is to further improve the device to achieve better usability under field conditions. The operator of the device has many tasks during field measurements, and thus the risk for operator error is high. By making some tasks automated, the risk of erroneous operation is reduced. Also if the operator can trust the device to work correctly, the operator can concentrate to more important environment monitoring.

A number of improvements to the existing setup have been implemented and tested. Some experiments to determine the mechanical accuracy of the structures and the optical accuracy of the optical components have been made. Also our laboratory setup is presented, the measurement theory is explained and some example spectral data are displayed.

2 Previous studies

Optical remote sensing is a field of study, which has many applications for groups of various interests. Techniques first used by military are now becoming available also for scientists and even for public. Satellite and aerial images provide huge amount of useful data, and the rise of web based image databases, Google Earth etc., provide the public with access to wide variety of aerial images. As more and more data is produced, the need for more automatic and sophisticated methods for image correction and interpretation and instrument calibration are needed. Some of these methods require knowledge about the reflectance properties of the measured targets.

2.1 Other goniometers

Over the years many different kind of instruments have been built for measuring the reflectance properties of various targets. Some devices are designed to be only used in laboratory and some are to be used in field. In this section some of the most significant devices are presented.

2.1.1 EGO

The European Optical Goniometric Facility (EGO) installed at the Joint Research Center of the European Union has a laboratory goniometer [6] with high angular precision and possibility to use different sensors and light sources. The goniometer is constructed of two horizontal and coaxial circular rails of about 4 m in diameter. The inner rail provides support for a vertical arc, which allows the sensor to be moved over the target. The outer rail supports a semi arc, where the light source is mounted. This design allows the azimuth and zenith angles of both the light and sensor to be selected freely. The massive structure, weighing about 700 kg, can only be used in the laboratory. The total time for a low angular resolution measurement is reported to be over an hour.

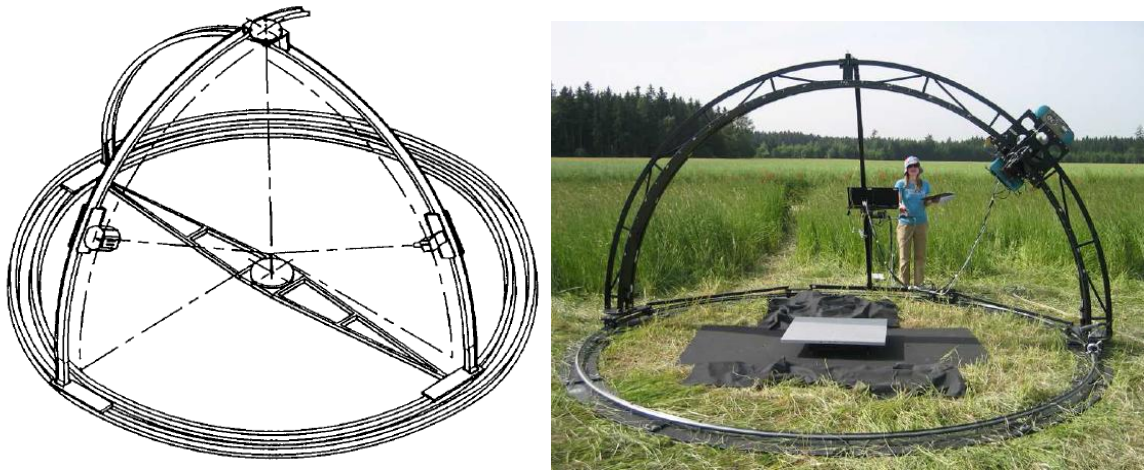


Figure 2: Left: EGO [6], Right: FIGOS [7].

2.1.2 FIGOS

Field-Goniometer System (FIGOS) [8] in Switzerland uses similar design to EGO, but since it is designed for field measurements under solar illumination the light source is not needed. The total weight of the system is 230 kg, making it possible for two persons to set the system up in 90 minutes. The device allows faster measurements than EGO, with a total measurement time of one sample to be 18 minutes. 66 spectra are taken from each sample with azimuth resolution of 30° and zenith resolution of 15° . Recently another spectrometer has been installed to the device [7]. The purpose of the second spectrometer is to make simultaneous measurements of the incident light from the opposite direction to the spectrometer measuring the sample.

2.1.3 PARABOLA

Both of the abovementioned devices measure a constant sample by means of moving the detector around the sample at a constant distance. This allows a small sample to be measured, but requires large and accurate systems for the detector movements. Another design is to have the detector pointing outward and rotated around, while collecting data. This design allows the instrument to remain fairly small and allows large homogenous areas to be measured rapidly. An example of this design is the Portable Apparatus for Rapid Acquisition of Bidirectional Observation of the Land and Atmosphere (PARABOLA). Latest version, PARABOLA III [9] measures at eight spectral channels, and is designed to provide reference data for satellite instruments, such as Multi-angle Imaging SpectroRadiometer (MISR). The device can scan both sky and ground hemispheres in 3.3 minutes, generating 2664 samples at different view angles.

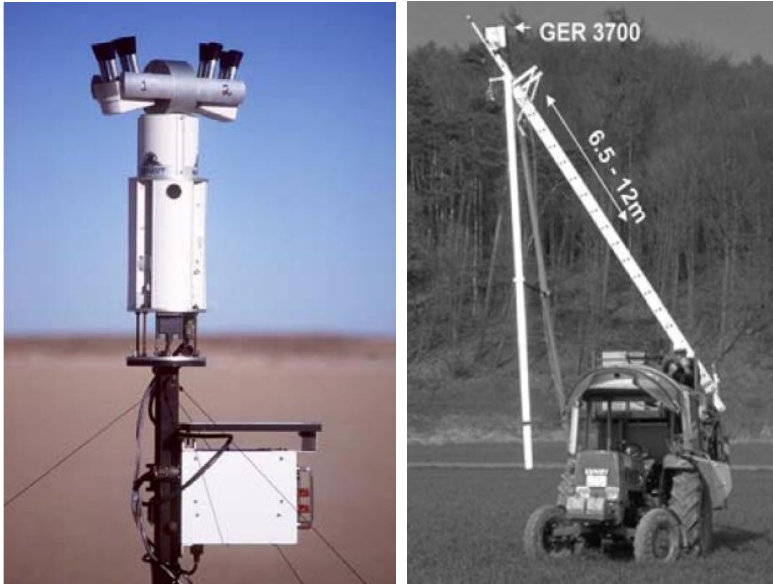


Figure 3: Left PARABOLA III. [9], right MUFSPeM. [10]

2.1.4 MUFSPeM

Mobile Unit for Field Spectroradiometric Measurements (MUFSPeM) [10] and its successor Mobile Goniometer System (MGS) [11] developed at Technische Universität München are large crane like devices, mounted on a 4WD vehicle. The devices are built for monitoring plants growing in a field, and thus the footprint size must be rather large for adequate sample averaging. The devices consist of a 10 meter arm with optics at the tip. The optics and the arm can be tilted to allow spectra to be collected from different view angles. This instrument is suitable for measuring samples at large open areas.

2.1.5 ASG

Automated spectro-goniometer (ASG) [12] is a fully automated goniometer, using another approach to the problem of moving the sensor. The goniometer consists of a frame supporting a two part measurement arm above the target. The arm has two degrees of freedom; upper one rotating about the vertical axis, while the other is at an angle of 45° relative to the vertical. This setup makes any combination of azimuth and zenith angles available. The device has measurement distance of 65 cm to the target, measurement time of under 6 minutes for 10° zenith and azimuth resolution for a half hemisphere and weighs 50 kg.

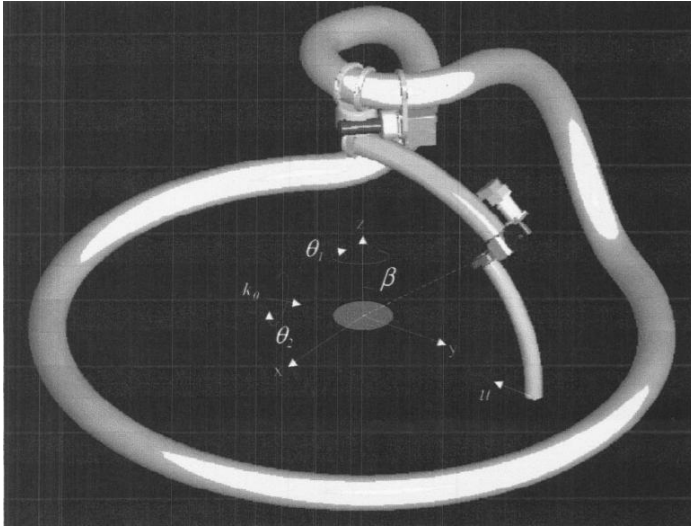


Figure 4: Concept drawing of Automated Spectro-Goniometer (ASG) [12]. A two-part measurement arm is moved over the sample, allowing any measurement zenith and azimuth angle.

2.2 FIGIFIGO and its predecessors

Finnish Geodetic Institute has been involved to the goniometric measurements of reflectance factor since early nineties. Early models were done with low budget, e.g. model 1 was made of pieces of an abandoned bookshelf, but the experience achieved by using those models made it possible to construct more elaborate designs.

Model 3 was similar in design to the FIGOS system, using a large rotating ring with tilting frame for the detector. This version was still operated manually, which caused the measurement to be long and prone to errors. Also the instrument was heavy making it impossible to transport to remote locations.

The fourth version of the goniometer was constructed using similar design to the current version, but was still operated manually. This version was really lightweight, making it possible to use even at most remote locations. This laid the foundation for model 5, which had an automatic tilting arm and control software. Current model, Finnish Geodetic Institute Field Goniospectrometer, FIGIFIGO, is still based on this design, but automation and improvements have been developed.

Prior to this work FIGIFIGO has had a long development history, with lessons learned from encountered problems and improvements constantly being developed. The work done by Jouni Peltoniemi and Jyri Näränen with the early models has laid foundation for the model reported by Juha Suomalainen [5]. This model, FIGIFIGO, was the starting point of the

device reported in this work. The model was already operational, but was in need of improvements for more reliable operation. Also the calibration of the device was not yet complete and there were issues with electronics, software, accuracy, etc. During preparation of this work numerous reliability issues have been solved, calibrations have been done, measurement accuracy and the overall usability have improved.



Figure 5: Top left: Goniometer model 1 at Sjökulla test field. Top right: Goniometer model 3 at Finnish Geodetic Institute roof. Bottom left: Goniometer model 4 at Hintereisferner, Austria, measuring glacier. Bottom middle: Goniometer model 5 at Finnish Geodetic Institute backyard, measuring forest understory sample. Bottom right: FIGIFIGO 2007, at Abisko Sweden.

2.3 Journal articles about FIGIFIGO

FIGIFIGO and its previous versions have been used during several field and laboratory campaigns, with reflectance properties of over 200 samples measured. Several scientific articles have also been written about these data, including the ones presented in following paragraphs, and the data have been stored to a library format for further studies.

A study by Peltoniemi et al. [13] was carried out using second version of the goniospectrometer. The study is about characteristics of snow, which can be observed from the reflectance spectrum. This study suggests that there are features observable from the data between different snow types. Grain size and shape of the snow, wetness, density, and microtopographic roughness are suggested to give distinct features.

Another study by Peltoniemi et al. [4] presents measurements of several samples of forest understory vegetation. The measurements were done in Suonenjoki Finland using third version of the goniospectrometer. The study suggests that characteristic features for species of understory vegetation are observable.

Finnish Geodetic Institute has an aerial photography test field at Sjökkulla, Kirkkonummi. The sight consists of several targets made of different types of gravel, arranged in large flat targets for aerial camera radiometry calibration. Several versions of FIGIFIGO have been used to measure the reflectance characteristics of the test field. A study by Peltoniemi et al. [14] reports the measurement results taken using first, third and fifth versions of the goniospectrometer. During summer 2008 the gravels at the test field were replaced, and the current version of FIGIFIGO was used to measure the new gravels.

2.4 Personal contributions

Prior to this work Juha Suomalainen has constructed most of the device [5]. Preparation of this work began at summer 2007. During this work many of the operational parts have been replaced to achieve better reliability, several new components have been added, and accuracy has been verified. The addition of sky camera to detect the goniometer orientation, fine tune mirror to adjust the footprint position, more robust design of the measurement arm, replacement all of the wiring and electric components with more reliable ones, and verifying the measurement accuracy have been the most laborious tasks. Also many changes to the software have been made in collaboration with Juha Suomalainen. New optics have been constructed and tested, and overall usability has been improved.

Since summer 2007 several natural and artificial samples have been measured on field and in laboratory in collaboration with Jouni Peltoniemi, Juha Suomalainen, and Eetu Puttonen. These samples include: forest understory measurements at Sodankylä, Finland, summer 2007; asphalt measurements at Masala, Finland, summer 2007; snow measurements at Sodankylä, Finland, spring 2008; Sjäkulla gravels, Sjäkulla, Finland, summer 2008; and snow measurements during spring 2009.

2.5 Theory

In this chapter the basics of the physical quantities and equations are presented. The terminology used here is based on work by Nicodemus, et al. [15], later also used by Shaepman-Strub [16].

First the physical quantities for directional and hemispherical cases need to be described. The value describing the directional intensity of light is called radiance. It is defined as the incident flux to a surface element through an element of solid angle. If the radiance is integrated over whole hemisphere the value is called irradiance. Unit dimension for radiance is $[\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}]$ and for irradiance $[\text{W}\cdot\text{m}^{-2}]$.

In optical remote sensing, spectrum defines the intensity of radiance or irradiance as function of wavelength. The intensity of irradiance varies depending on various factors, including the temperature and chemical composition of the emitting source, and absorptions in atmosphere.

As stated by [15] there are three basic types of illumination: directional, conical and hemispherical. In directional case the illumination of a surface element is from one source only and the solid angle of illumination is small. In conical case the illumination of a surface element is coming from a solid angle that is significant in size. In hemispherical case the illumination comes from whole hemisphere above the surface element. This is the most common case when doing measurements in the field, since sunlight is reflected from the atmosphere and the surroundings to the surface element.

As for illumination the three abovementioned cases apply also for measurement. If the sensor collects the light reflected by the surface element only from a small solid angle, the measurement can be called directional. If the size of the collecting solid angle is significant the measurement is called conical. If the measurement is done over full hemisphere, the measurement is called hemispherical.

When combining the illumination and the measurement cases, a total of nine different geometries can be achieved. The nomenclature used by [15] describes these by combining the words describing the illumination and the observation geometries. For example: directional-conical and bidirectional (Figure 6).

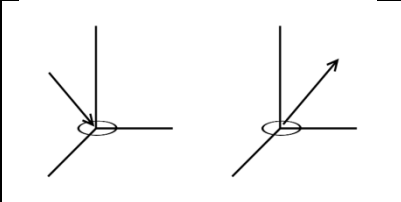
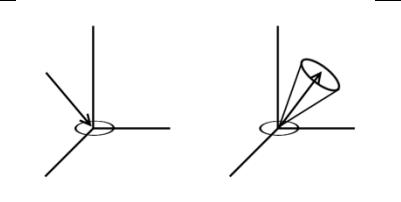
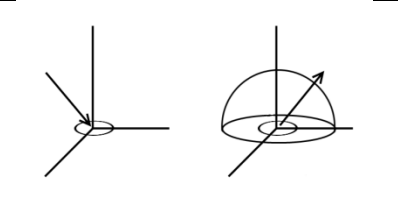
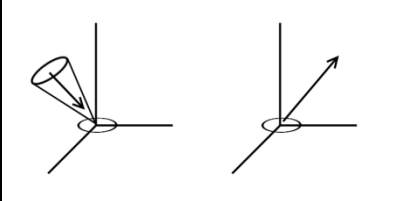
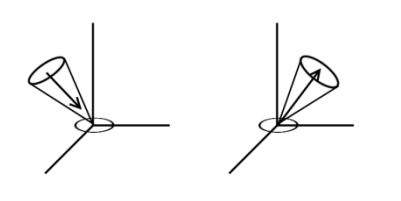
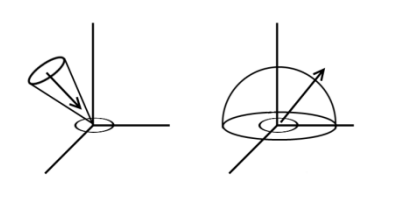
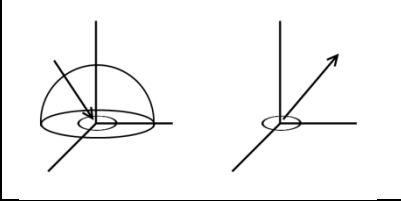
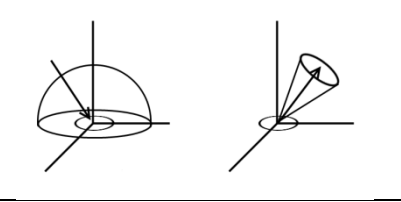
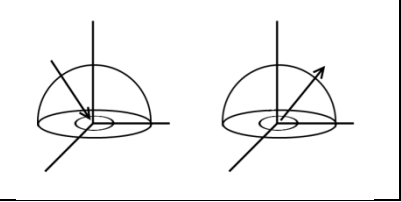
Bidirectional	Directional-conical	Directional-hemispherical
		
Conical-directional	Biconical	Conical-hemispherical
		
Hemispherical-directional	Hemispherical-conical	Bihemispherical
		

Figure 6: Different illumination and reflected light cases. Directional light or measurement is considered to be over an infinitesimally small solid angle, conical light or measurement is over a significant solid angle, and hemispherical is over whole hemisphere.

For simplicity the measurement setup discussed in this work is considered directional, as the aperture of the collecting optics is small compared to the measurement distance. This causes small uncertainty to the actual direction of the reflected light.

Also the solid angle of the Sun is 0.5° when viewed from the Earth, causing the solar illumination to be conical. However this effect is neglected in this work and sunlight is considered directional.

2.5.1 Bidirectional Reflectance Distribution Function

The bidirectional reflectance distribution function (BRDF) describes the scattering of a parallel beam of incident light from one direction in the hemisphere into another direction in the hemisphere. [16]

$$BRDF = f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} \quad (1)$$

Where θ_i is the zenith angle and ϕ_i is the azimuth angle of the illumination, respective to the sample surface. θ_r and ϕ_r are the zenith and azimuth angles of the observation as expressed in Figure 7.

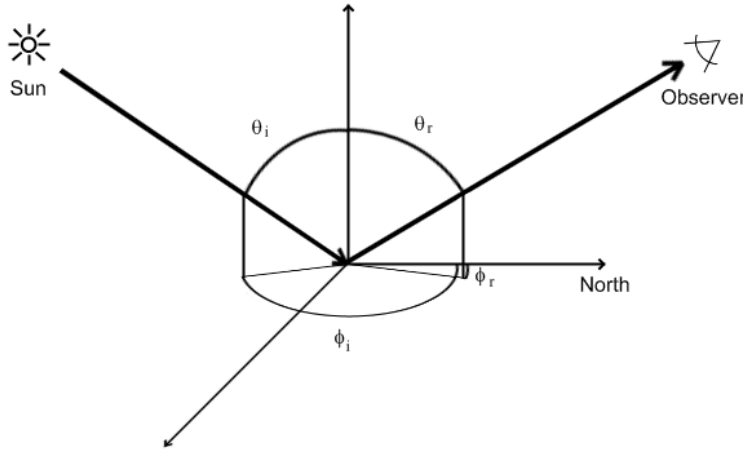


Figure 7: Illumination and observation geometries.

The spectral dependency can be accounted for by defining BRDF as a function of wavelength λ .

$$BRDF_\lambda = f_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)}{dE_i(\theta_i, \phi_i; \lambda)} \quad (2)$$

2.5.2 Bidirectional Reflectance Factor

Since BRDF uses infinitesimally small surface elements and angles, and requires direct measurement of the illumination, another concept is introduced. Bidirectional reflectance factor (BRF) describes the ratio of the reflected radiant flux from the sample to the ratio of reflected flux from a lossless and diffuse (Lambertian) surface in same illumination conditions and reflected beam geometry.

$$BRF = R(\theta_i, \phi_i; \theta_r, \phi_r) = \pi f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L_r(\theta_i, \phi_i; \theta_r, \phi_r)}{L_r^{id}(\theta_i, \phi_i)} \quad (3)$$

Where L_r^{id} is the BRDF of an ideal Lambertian surface. Since it reflects equally to all directions in hemisphere, its BRDF is $1/\pi$.

When utilizing this function the measurement setup can be considerably simplified, since the radiometric calibration of the spectrometer does not need to be absolute, and the atmosphere does not need to be taken into account. Only requirement is that conditions and measurement equipment remain stable during the measurement.

Nearly lossless and nearly Lambertian reflecting reference targets are available on the market, making it possible to make direct measurements required for BRDF. When utilizing the assumption of the Lambertian reference surface, only one reference measurement need to be done for several direct measurements for the sample, assuming that the illumination conditions remain constant. This saves a lot of time and effort during the actual measurements.

2.5.3 Polarization

Most of the radiation sources produce radiation that has equal distribution of polarization states, and thus the light is said to be unpolarized. When the radiation passes through media and scatters, there are many mechanisms that tend to polarize the scattered radiation. Such mechanisms are for example Rayleigh scattering, and Fresnel reflection.

To measure degree of linear polarization of a sample, a measurement is needed for at least two polarization directions. Measurements are taken changing the polarizer direction between the measurements. From the acquired data a degree of polarization for the reflectance spectrum can be calculated. Some example data is presented in chapter 5.

3 FIGIFIGO instrument description

Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO) is a device for multi-angular spectral measurements under field conditions. The instrument has been designed to be lightweight and robust to withstand the harsh conditions during field measurements, and to be as transportable as possible. Some of the measurement sights can be inaccessible by car, and thus the device must be carried over relatively long distances. As for all field equipment, reliability is critical to avoid losing valuable field measurement time because of device malfunctions. The device must also be easy to use, and not to have tedious measurement process with numerous details to be remembered, since some things are easily forgotten when the measurements are done in a tight schedule.

The heterogeneity of the samples must also be considered in the instrument design. To achieve adequate sample size, without compromising the assumption of directional measurement, the measurement distance must be long enough. To achieve sample size of over 10 cm in diameter measurement distance of 2 m is decided to be adequate. This means that the solid angle of the measured radiance is lower than 3° .

When operating at field and measuring at direct sunlight, time is always a critical factor as water vapor in atmosphere can cause rapid fluctuations in solar irradiation and the position of the sun is constantly changing. Using FIGIFIGO measurements can be made at rapid pace which minimizes the risk of changes in illumination between different measurement points.

3.1 Technical details

Current construction of FIGIFIGO consists of an arm of variable length which can be tilted 90 degrees from vertical to both directions by a motor housed inside goniometer body (Figure 8). The body also contains electronics and an ASD FieldSpec pro FR spectroradiometer. The body acts also as a base that supports the movements of the arm. The high end of the arm has a horizontal optical rail where custom made optics set is connected. At the tip of the rail is a fine tune mirror that guides the light reflected from a sample area in front of the body to the optics. This allows the optics to be placed close to the arm, leaving only the lightweight fine tune mirror far from the supporting arm. The mirror can be turned about two axis using two servomotors. This allows the footprint of the optics to be moved in two directions. A sky camera is used to detect the goniometer orientation, Panasonic Toughbook CF-18 is running the control software, and a pyranometer monitors the illumination conditions.

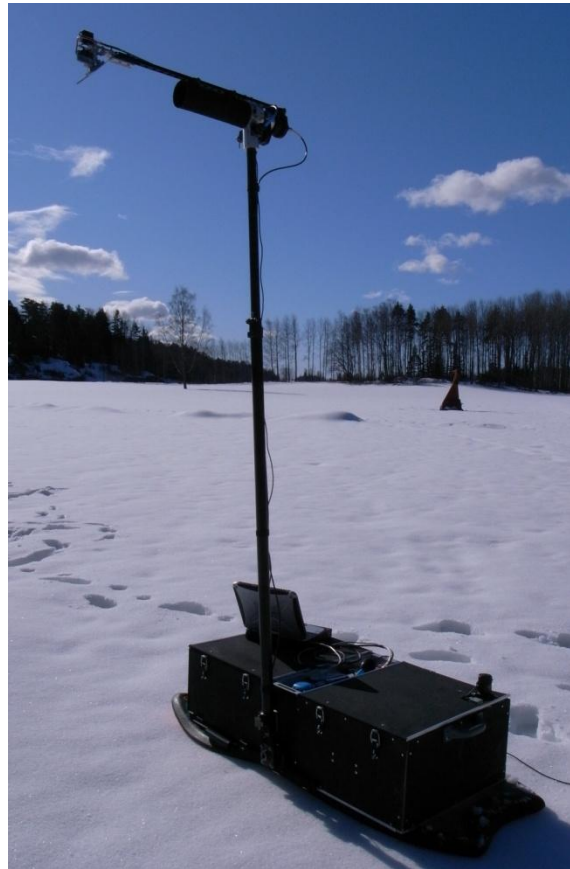
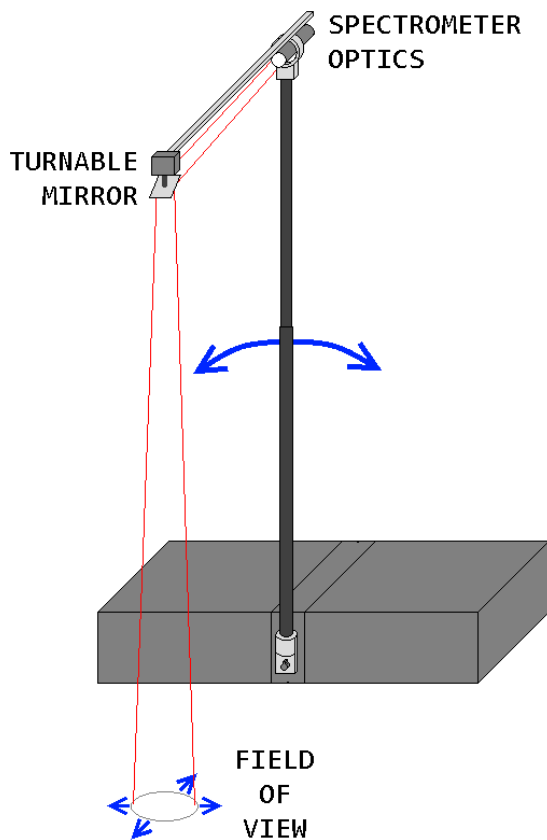


Figure 8: Overview of FIGIFIGO. Left: The Goniometer concept drawing. The arm can be tilted both ways, while the optics view a sample in front of the goniometer body. Two laser pointers are used to make the footprint visible to the users (drawing by Juha Suomalainen). Right: A photograph of FIGIFIGO during snow measurement on field at Masala, Finland, spring 2009.

3.1.1 ASD FieldSpec pro FR

The primary measurement instrument of FIGIFIGO is ASD FieldSpec pro FR spectroradiometer (Analytical Spectral Devises, Inc., Boulder CO, USA). The instrument has spectral resolution, know as Full Width at Half Maximum (FWHM) of 3 nm at 350-1000 nm band and 10 nm at 1000-2500 nm band [17]. FieldSpec pro FR has three different sensors for different wavelength bands. The first one uses a 512 element photodiode line array to where the light is dispersed by a static holographic reflective grating. This sensor is called VNIR (Visible and Near InfraRed). The second sensor, SWIR1 (Short Wave InfraRed), uses a scanning holographic grating, which disperses the light to a single fixed InGaAs detector. The third sensor, SWIR2, works similarly to the second one, but is optimized for longer wavelengths.

3.1.2 The goniometer body

The goniometer body is made of plywood with an aluminum profile frame. Dimensions of the body are 103x51x27 cm (length x width x height), length measured to the direction of measurement plane. The body is separated into two sections; one housing the ASD FieldSpec pro and the second all other electronics. The body is equipped with two hatches that provide quick access to the electronics and the spectrometer. On top of the body is a switch table where all the relevant power switches are positioned. The switch table also has two cables connecting to the controlling computer, one providing 12 volt to extend the operation time beyond what the batteries of the computer could supply. The other one is a USB cable for data connection.

In the middle of the long side of the goniometer body is situated a motor that drives a carbon fiber measurement arm. The arm is connected to the motor axle with a machined aluminum connection block that provides support for the arm and includes an inclinometer for accurate arm zenith angle measurement. The driving motor is a high torque geared brushless DC servomotor with encoder feedback and a compact computer-controlled driver.

The electronics of FIGIFIGO include a LabJack U3 data acquisition and control device that is used to measure the voltage output of various sensors of FIGIFIGO. LabJack turns these voltages to digital values using a 12-bit analog-to-digital converter and sends them to the controlling computer via USB connection. LabJack also reads the output of an optical encoder that is used during laboratory operation to measure the azimuth angle of FIGIFIGO relative to the light source.

3.1.3 The arm

FIGIFIGO is equipped with a motor-driven carbon fiber arm of adjustable length between 1.5 and 2.6 meters. The purpose of the arm is to house optics placed at the high end of the arm and allow movement over an arc above a sample. A fiber optic cable is run from the optics down to the goniometer body, ending at the spectrometer. The optics are placed right on top of the arm to prevent torsion caused by an unbalanced load. The optics are connected to an optical rail that is placed perpendicular to the arm itself, see Figure 9. This rail is connected to a machined aluminum block, which connects the rail and the arm. At the other end of the rail is a fine-tune mirror at an angle of 45° to the optical rail. The mirror is computer-controlled and can be tilted about two axes by about $\pm 10^\circ$, providing the system the possibility to correct misalignments, caused by placement of the sample above or below the axle of the arm. The black tube, which can be seen in Figure 9, is a lightweight cardboard tube coated with black fabric. The purpose of the tube is to prevent stray light from the surroundings from entering the optics.

When measurement is initiated the arm is tilted by the motor to a predefined starting angle and then driven at constant angular velocity over the measurement sequence. With standard optics set the measurement sequence starts by first tilting the arm to the maximum measurement angle, and driving the arm at constant velocity to same angle at the other side of the arc, while the spectrometer is constantly collecting spectra. Angles over 80° are possible but not practical, as the arm could hit the ground, and the elongation of the field of view would cause the spectra to be collected from outside the target area.

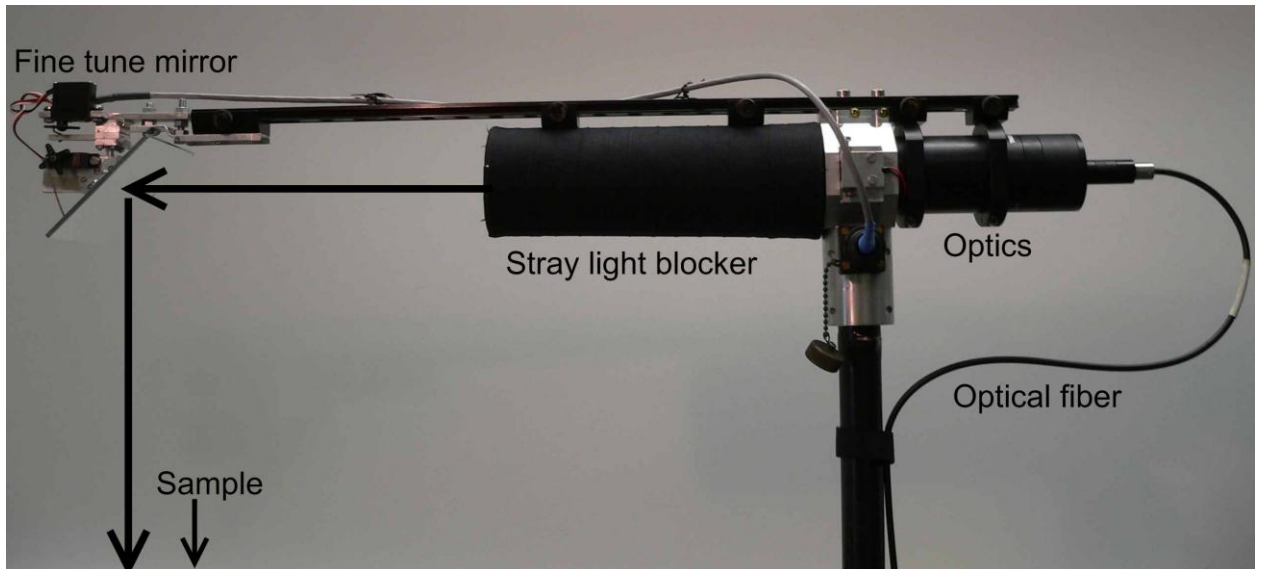


Figure 9: Top of the measurement arm. All the parts are attached to a horizontal optical rail, which allows easy attachment and detachment of the components and assures correct alignment. The optical fiber runs from the end of the optics to the spectroradiometer, the fine tune mirror corrects the parallax error caused by different heights of the sample and the arm axis. Stray light blocker reduces the stray light from the surroundings from entering the optics.

3.1.4 Fine tune mirror

FIGIFIGO is equipped with a fine tune mirror, which is used to fine tune the position of the footprint of the optics. The main purpose of the mirror is to correct parallax errors in footprint position. The errors are caused by the fact that the axis of rotation of the arm is 5 cm above the ground level, and because the sample area often has height structure.

The mechanical structure of the fine tune mirror is constructed of 5 mm aluminum plate, and is held together by screws. A Thorlabs snap-on rail carrier is used to connect the mirror to the optical rail at the top of the arm. Two small servomotors are used to control the rotation of the mirror. Same type of servos are generally used in model aircrafts and therefore are perfectly suited for this purpose, as the requirements for model aircrafts and

this application are the same; light weight, speed, robustness and accuracy. The mirror itself is a 10 by 10 cm piece of front surface mirror, measured to be large enough to just cover the full field of view of both custom made sets of optics. The mirror should not be too large, since when measuring from direct backscattering direction, the mirror will cast a shadow over the sample area. Many of the interesting scattering features are found from this direction, so the shadowing area must be kept at minimum. This is also why the mechanics of the mirror are situated behind the mirror.

The mirror is controlled using a controller board [18]. The board uses a PIC16F84A microcontroller and can control up to four servomotors and four general purpose on/off outputs. The board is connected to controlling computer using standard serial port, and a simple set of commands is used in communication with the microcontroller. The resolution of the board is limited to 8 bits, so only 256 steps are available when turning the mirror. This still translates to resolution of better than 1 cm, when the arm is set to 2 meters and is at upright position.

The goniometer control program uses the reading of the inclinometer to calculate correct orientation of the mirror. This is achieved when a number of parameters are known; the length of the arm, the desired height of the footprint and the translation for each step of the controller to the resulting angles where the center line of the field of view of the optics is pointing. This calculation is done in real time and is found to be fast enough to correct the parallax error during the measurement.

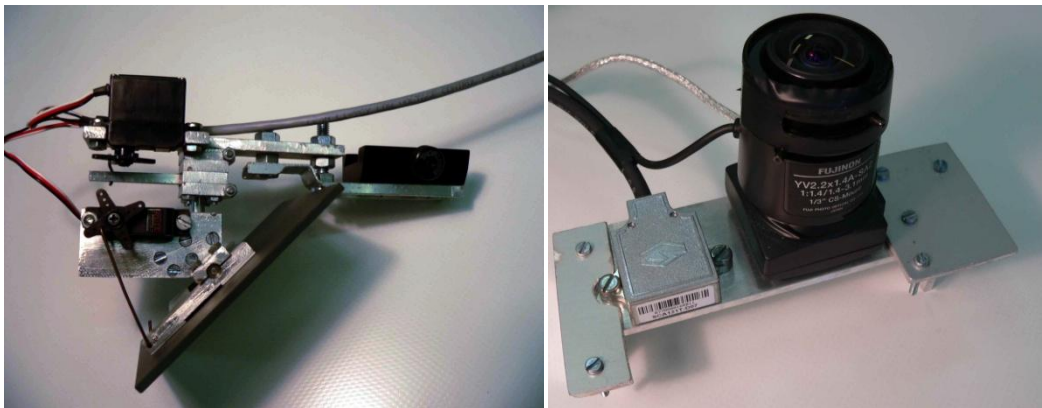


Figure 10: Left: The fine tune mirror. The movements of the mirror are controlled by two servomotors. Right: The sky camera. The camera is attached to an aluminum plate, which attaches to the goniometer frame by three screws.

3.1.5 Sky Camera

The electronic compass used to determine FIGIFIGO azimuth angle was found to be a source of error, when the measurements needed to be made at a location with metal objects nearby. This is often the case at urban environments, car parks, stadiums, etc. where metal piping, power cables, or structural metal can be buried right under the surface. Since many of these locations are interesting measurement sights, a new way for measuring the azimuth angle needed to be created.

As the measurements cannot be conducted during cloudy weather the Sun is always visible during measurement. If the position of the Sun can be measured relative to FIGIFIGO, the azimuth angle can be determined. For this purpose an USB camera with a fisheye lens was purchased. The USB camera is an IDS Imaging Development Systems GmbH uEye UI-1645LE-C-HQ USB industrial camera, 1280x1024 pixels, with standard CS optics mount. The optics used with the camera have 180° field of view. When a picture of the sky is taken, the pixels representing the position of the Sun can be easily found. To prevent errors from reflections or possible shadowing of the camera, software makes two tests to validate the result. First the area of the pixels representing the Sun is calculated and if the area is over an empirically determined threshold, error can be assumed. Second test is to calculate the standard deviation of the position of the pixels assumed to represent the Sun. This is done to counter errors caused by reflections. If the standard deviation is over a predetermined threshold, an error can be assumed. These methods are found to be adequate to validate the result.

Because the FIGIFIGO body is placed directly on the ground, perfect leveling of the body cannot be guaranteed. Since the sky camera is mounted directly to the goniometer body, the orientation of the center line of the sky camera lens does not necessarily point directly to zenith direction. If not accounted for, this would cause error to the final azimuth angle reading. Thus a two axis inclinometer has been installed rigidly to the sky camera mount, which is then fixed to the goniometer body. The inclinometer measures the inclination of the camera, and thus also the inclination of the goniometer body, at the same moment the picture is taken. From this inclination data, rotation matrixes for the camera can be calculated and used to correct the orientation error.

Other purpose for the sky camera is to take color pictures of the sky, to be used during the preprocessing stage and data analysis stage for determining the weather conditions during the measurement. This information is crucial for determining the quality of the data, and is a more methodical way for to log cloud cover than just visual observations during the measurement.

3.1.6 Polarizing optics

A recent addition to FIGIFIGO is a custom made set of polarizing optics. The construction has a calcite Glan Thompson linear polarizer mounted to a motorized rotator. The rotator can rotate 360° in resolution of 1°, so any desired orientation can be achieved. The construction also has some lenses to guide the light through the optics, and a depolarizer to scramble the polarization of the light before it enters the optical fiber. This is needed since the ASD FieldSpec Pro was found to be sensitive to polarization, which is unwanted.

The polarizing optics are currently used to measure the target at two or four different polarizer orientations. Also the reference spectralon panel is measured at the same polarizer orientations. The procedure is to turn the arm a whole arc over the sample while measuring spectra at one polarization. For one polarization direction this means one arc, two arcs for two polarizations, etc. This causes the measurement time to increase respectively.

3.1.7 Data connections

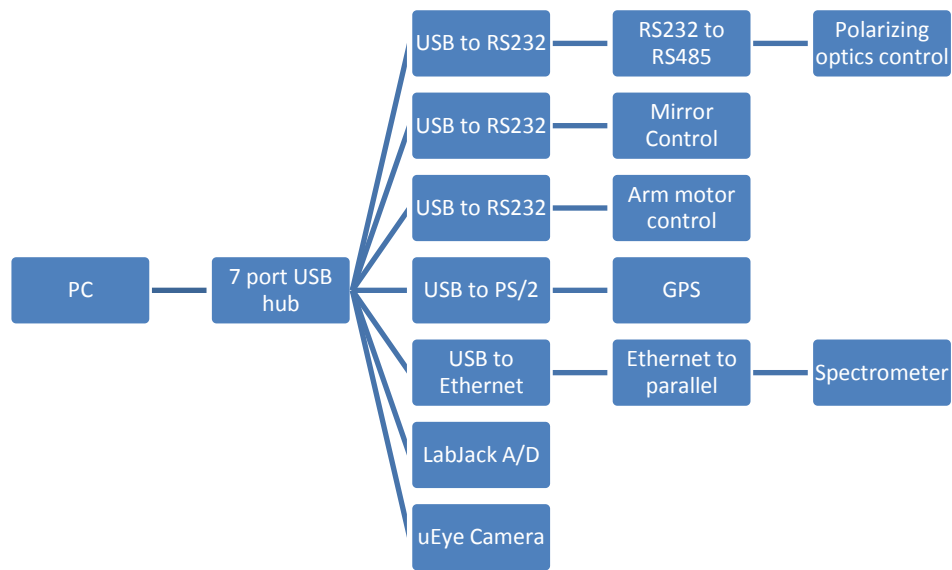


Figure 11: Data connection diagram. The picture illustrates the various data protocols needed in order to communicate with the instruments.

Figure 11 shows how the various components are connected to the controlling computer. The primary data bus is USB. A single USB cable connects the computer to a 7 port USB hub which in turn connects all the various devices together. Some components do not use USB natively and thus converters are needed.

3.2 Laboratory instrumentation

FIGIFIGO can also be used at laboratory with artificial illumination. During laboratory measurements FIGIFIGO is placed on a ring, 2 meters in diameter, which allows rotation around azimuth angle, while constantly having the optics footprint at the center of the ring. The ring is equipped with an optical encoder that allows the rotation of the ring to be recorded at accuracy better than one degree.

Since sunlight is not available in laboratory conditions, an artificial light source must be used. Good laboratory lighting must be stable, collimated, unpolarized, homogenous, and have good signal on all measured wavelengths. Currently we are using stabilized light source that keeps the intensity of the illumination at constant within one percent. Also the shape of the spectrum of the lamp radiation is as close as possible to the spectrum of the sunlight.

During outside measurements, when the Sun is used as an illumination source, the solid angle of the Sun viewed from Earth is about 0.5° , meaning that the collimation of the incident light is within 0.5° . To achieve such collimation of the light at laboratory conditions with a point source, the lamp should be placed far away (over four meters) from the sample. This would cause the intensity of the light to attenuate due to the $1/r^2$ effect of the distance, and thus deteriorate the signal to noise ratio of the measurement. To overcome this, light needs to be collimated using other means.

With previous versions of laboratory equipment a 7 cm in diameter lens was placed in front of the light source to collimate the light. This provided some collimation, but placing lenses in the path of the light causes spectral effects. This is because lenses have slightly different focal lengths at different wavelengths. Also the intensity of the light changed significantly when measured across the collimated beam.

At spring 2007 an off axis parabolic mirror was introduced as a solution for the collimation problem. The mirror is milled from a disk of solid aluminum using a CNC machine and polished by a company specializing in polishing metal objects. A perfect mirror finish was not pursued to keep the costs acceptable. The mirror itself is about 5 cm thick from thickest point and 53.8 cm in diameter, weighing about 11 kilograms. The focal length of the parabola is 47 cm above the surface, with off axis angle of 45° . This is the distance where the filament of the lamp should be to achieve optimal results. An off axis parabola shape was chosen to allow the lamp to be placed as close to the mirror as possible and still not directly in the path of the collimated light beam. Because of the heavy weight of the mirror and lamp it is not convenient to use the collimated beam directly from the off axis parabolic

mirror, but a regular flat back surface mirror is used to direct the collimated beam to the sample. The flat mirror is mounted to a telescopic pole and the height can be adjusted between 1.5 and 4 meters. The mirror is hinged to allow rotation about one axis. A long string and a pulley are used to manually adjust the angle of the mirror when the telescopic pole is extended.

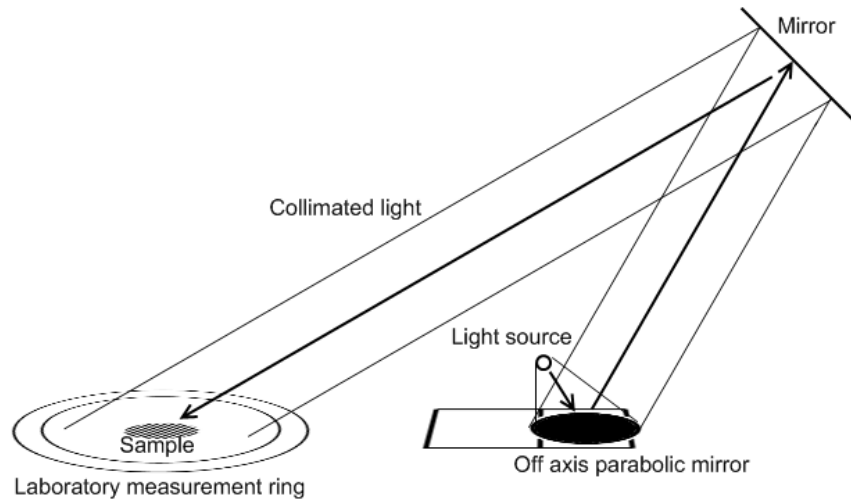


Figure 12: The laboratory lighting setup. The light source and the off axis parabolic mirror are mounted in same frame to keep the geometry constant. A large flat mirror is placed on a heavy tripod, and is used to reflect the light to the sample.

3.3 Software

The FIGIFIGO control program, GonioControl 4, is designed to be an interface between all the FIGIFIGO instruments and the user. GonioControl 4 is written in National Instruments LabVIEW graphical programming language, which allows high modularity, fast and easy programming, and many instruments already have preprogrammed interfaces in LabVIEW. GonioControl 4 allows high level of automation during the field measurements, and thus the measurements can be carried on at rapid pace, with minimal possibility for user based errors. The software takes care of logging the data in predefined raw data format, reducing the amount of work needed during post processing of the data. The data is saved in

multipurpose HDF5 data format [19] that allows the data to be easily opened in various programs, including Matlab.

During this work the main structure of the software has remained unchanged, but numerous modifications have been made. New servers have been added for the new physical components; sky camera, polarizing optics rotator, and fine tune mirror. Numerous bug fixes have been made, timings of the operations have been verified, the raw data format has been modified, and the user interface has been reworked.

3.3.1 General Structure

GonioControl 4 follows the real world instrumentation by having a module, called virtual instrument or server, for each of the FIGIFIGO major component. The modules are controlled by a main program, graphical user interface (GUI), that takes care of initialization, the execution order of commands, and acts as an user interface. The modules are running independently at the background, receiving data from the instrument and commands from the main program. So even if one of the modules malfunction due to software error or technical failure the main program is still operational and the data logging can continue from other modules (Figure 13).

The acquired data is tagged with a timer value and stored to global arrays, which are saved to the HDF5 file after a command from the main program. The status of the servers is displayed in another set of global variables. This set of global variables is also used to transfer sensor data to the user interface. The commands are given out as events that are predefined structure in LabVIEW. The commands are given out by the GUI, which reads them from a command list and sends out global events. The events are listened by the modules. If a module needs respond after that command, the status of the module is changed from “ready” to “not ready” at global variables, the operations are executed, and the status is set to “ready” again. After each command the GUI waits until all of the modules are ready for the next command. The command list for each type of measurement is stored in a separate text file, and can be easily changed for another kind of measurement.

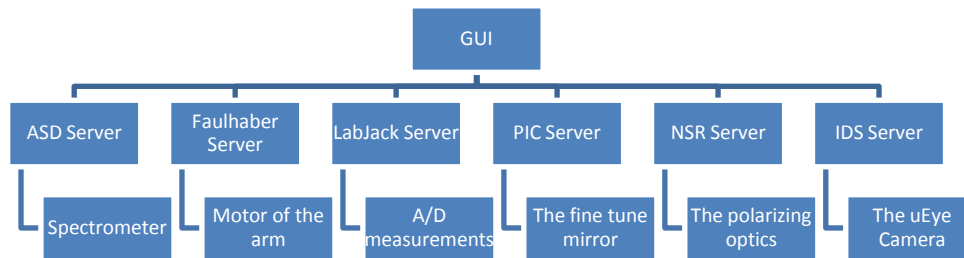


Figure 13: Software hierarchy. All servers run in parallel, independent of each other. The GUI controls the flow of the program.

Figure 13 displays the current structure of the program. The modules are named after the devices that they are controlling. GUI is the main program and user interface, ASD server manages the Analytical Spectral Devices FieldSpec Pro FR spectroradiometer, Faulhaber server manages motion control of the measurement arm, PIC server connects to the PIC16F84 microcontroller controlling the fine tune mirror, NSR server connects to the Newport Serial Rotator controlling the polarization direction, and IDS server connects to the Imaging Development Systems camera.

3.3.2 Data logging

Since FIGIFIGO provides many kinds of data, a reliable and easily approachable data format was needed. HDF5 (Hierarchical Data Format) [19] by National Center for Supercomputing Applications (NCSA) was chosen, because of its versatility and support for Matlab, LabVIEW, and IDL.

While the measurement is running, the data is gathered from the modules, labeled with timer value, and stored to arrays at global variables. Each module uses its own array and adds the new data to the end of that array. When one measurement arc is complete the data are saved from the arrays to the HDF5 file, and the arrays are cleared.

3.3.3 User interface

Figure 14 shows the main user interface of FIGIFIGO. The UI is designed to be operated from a touch screen ruggedized laptop under field conditions. At the upper left corner are displayed the relevant angles for light - and measurement directions, the reset button resets the laboratory azimuth ring encoder value and the button is replaced by “Update” button if the sky camera is used. Top middle are displayed some operation status flags, used mostly for debugging. The “STOP” button can be used to stop all actions to prevent damage to personnel and instrumentation during an unexpected situation. Middle and bottom left buttons are used to operate the instrument. The upper of the right side graphs shows the

latest measured spectrum, and the lower one shows the pyranometer value over time, which is used to verify the measurement conditions.

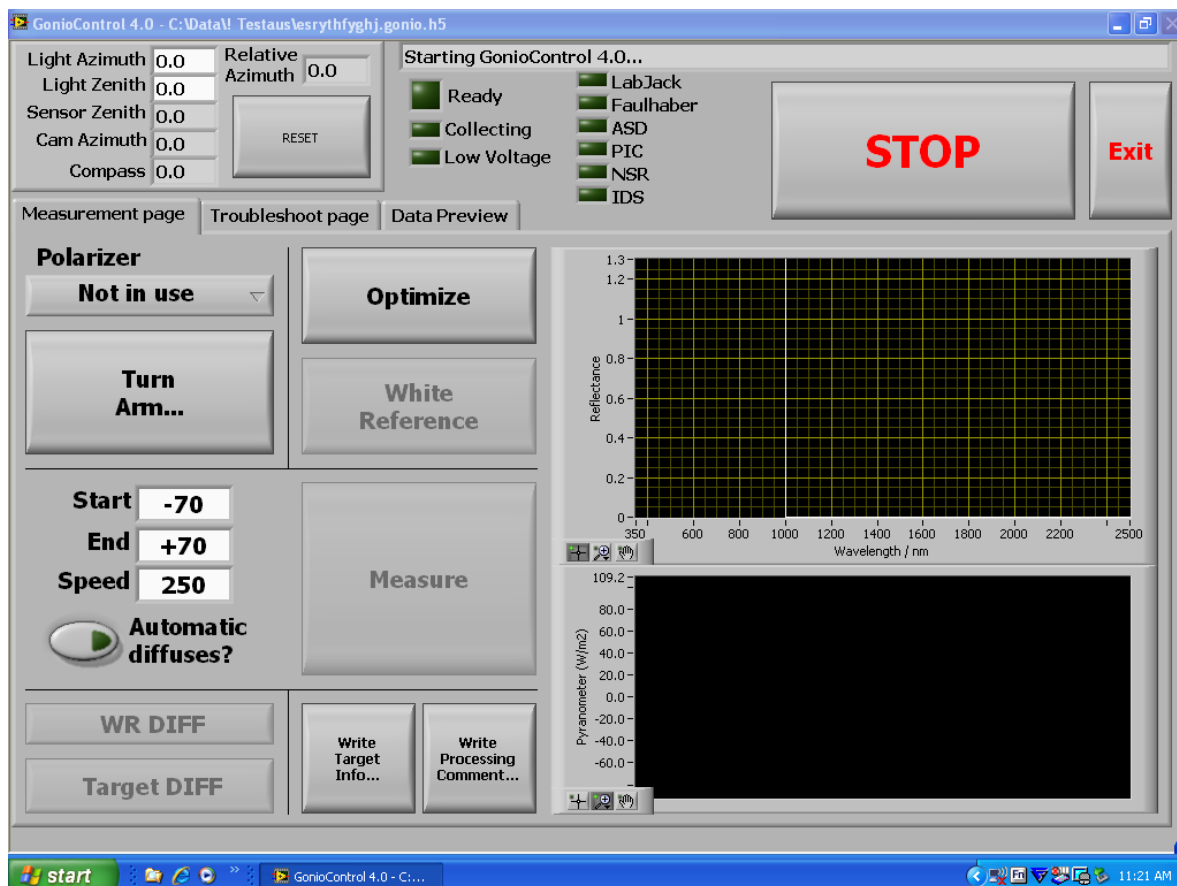


Figure 14: The user interface of FIGIFIGO. The software is starting and no data is available to be displayed. The various buttons are used to control the operation, and the numeric fields display or change angular variables.

3.4 Using FIGIFIGO

The measurement starts by selecting suitable target that is both homogenous and representative sample of the surface being measured. Depending of the field of view of optics and the length of the arm the sample needs to be circular with diameter of 30 to 50 cm. If the sample has significant height variations, the sample area may need to be even larger. Also the $1/\cos \theta$ elongation of the field of view at lower viewing angles must be considered. The elongation is caused when the diameter of the field of view is unchanged, but the viewing angle is not straight from above (Figure 15).

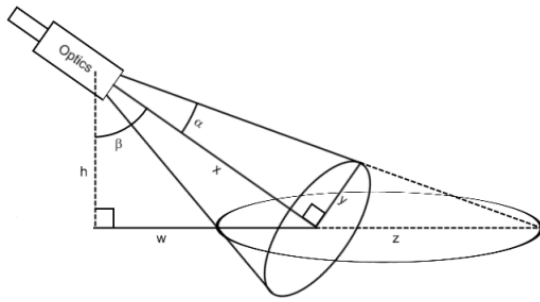


Figure 15: Elongation of the footprint at lower viewing angles, which is major limiting factor to the maximum view angle.

The measurement arm is turned at constant angular velocity from a starting zenith angle to ending zenith angle, up to $\pm 90^\circ$ possible, while the spectrometer constantly measuring spectra. After one turn the azimuth angle is changed by turning the goniometer body around the sample ensuring that the field of view does not move on the ground. Usually azimuth angles of 0, 10, 20, 40, 60 and 80 degrees from principal plane (direction of the incident light) are measured (Figure 16).

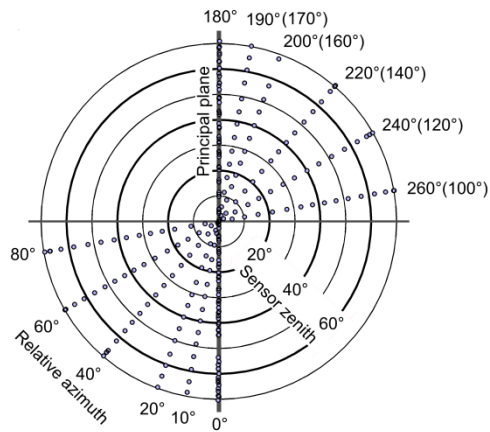


Figure 16: The azimuth angles to which the goniometer body is turned during the measurement. The dots represent the actual measurement points (figure by Juha Suomalainen).

4 Error analysis and calibrations

In this section some measurements, done on some most critical components, are described. The purpose of these measurements is to give some estimate of the possible errors and their sources. For some cases implemented improvements and their impacts are also presented.

In first subchapter the most important test equipments are presented; the Newport two axis rotation stage, and the spectralon reference panel. Second subchapter shows results from two tests done on spectrometer fore optics. Third subchapter is about the quality of the laboratory illumination, fourth and fifth subchapters are about two mechanical accuracy tests: One for the laboratory measurement ring azimuth accuracy, and one for the measurement arm zenith accuracy.

4.1 Test equipment

4.1.1 Newport rotation stage

For most of the tests a two axis rotation stage was used. The stage consists of URS100 and URS75 rotation stages, manufactured by Newport Corporation. The rotators are DC motor driven, equipped with high precision encoders, and homing function. The absolute accuracy of the rotators is guaranteed to be within 0.023° and resolution is 0.0005° . The stage can be operated either manually using remote controls or by computer over serial interface.

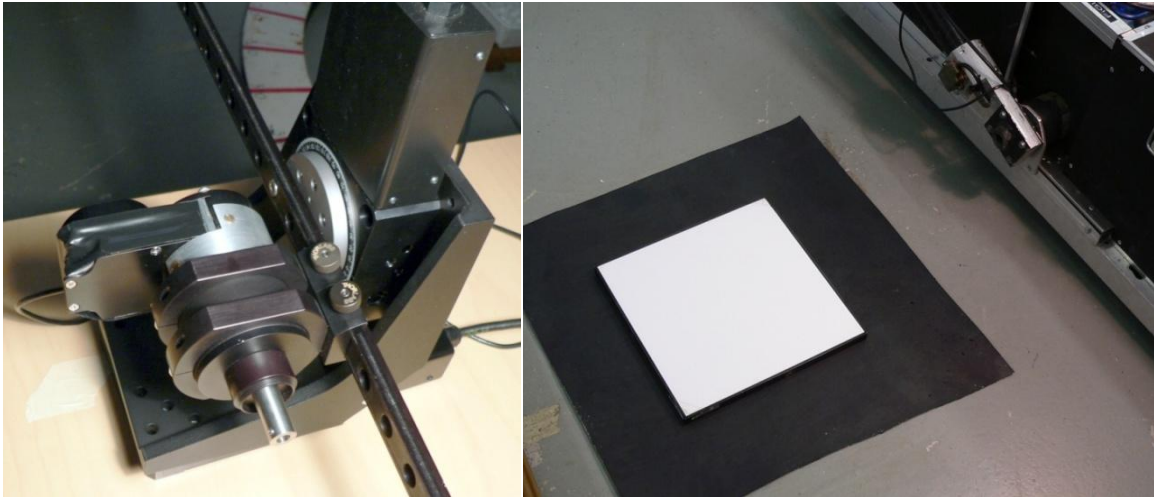


Figure 17: Left: Newport Rotation stage with the polarizing optics. Right: Spectralon reference panel on laboratory floor in front of FIGIFIGO.

4.1.2 Spectralon reference panel

For the polarizer test a stable reference target is needed. Spectralon is a material manufactured by Labsphere Inc., and is made of pressed PTFE. The material has high reflectance, good stability and homogeneity, and is close to a Lambertian surface. This material is widely used as a reference target for optical spectrometry applications. The size of our panel is 25 x 25 cm².

4.2 Calibration of fore optics

Fore optics are used to collect the light scattered from the sample being measured to the optical fiber. If the optics are not working properly they may cause systematic errors that are impossible to detect during the measurement. The optics determine the field of view (FOV) of the spectrometer by focusing the incoming beams to the end of the spectrometer fiber. Depending on the distance of the end of the optical fiber to the focal point of the lens, FOV can be some degrees wide.

For the purpose of large spectral band goniospectrometric measurements the optics have some requirements. The optics need to be able to collect light from the target and guide the light to the optical fiber bundle. The optics must not dampen any spectral band at the measurement range and ideally the footprint should stay constant for entire spectral range.

In following two subchapters two tests are described to provide some understanding about the quality of the FIGIFIGO optics. The polarizing optics are rebuilt and tested for signal quality improvement, and the data for the field of view deviation between different sensors is presented for basic optics.

4.2.1 Polarizing optics signal quality

The polarizing optics were constructed during spring 2008 and used during several measurement campaigns. Although the optics worked, the signal quality was poor when compared to signal received from bare fiber, which gives the best possible intensity.

Any optical component placed in the path of the light causes attenuation of the intensity of measured signal and low signal causes poor signal to noise ratio. In theory the Glan Thompson polarizer reduces the measured signal by 50%, since the light that passes the component has only one polarization direction left. On top of this attenuation each optical component in the path of light causes a few percent more of attenuation through surface reflections and absorptions in material. According to Thorlabs, the manufacturer of the

components, the transmission of 1 mm thick sample of uncoated BK7, the glass used in the lenses, is about 93%.

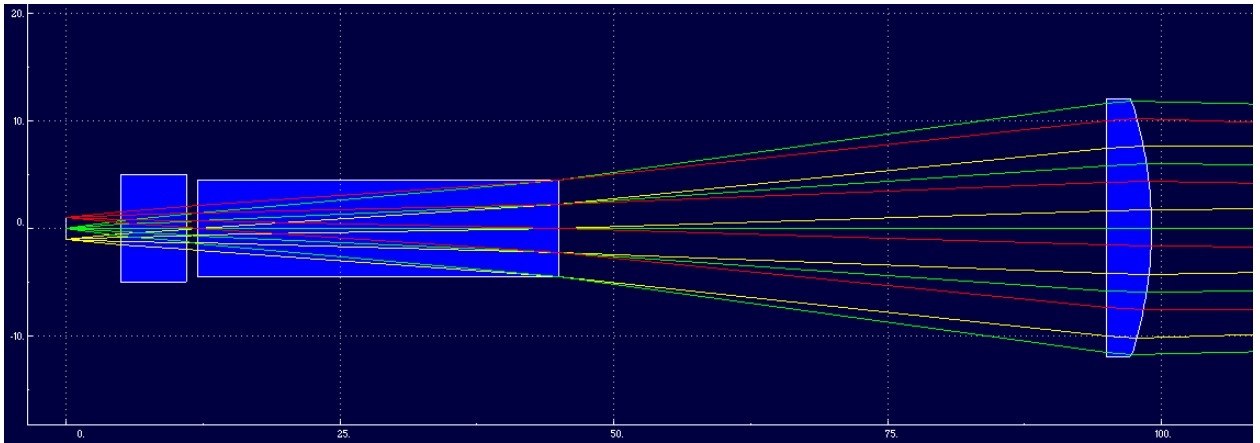


Figure 18: The optical construct of the old polarizing optics. The leftmost is the surface of the optical fiber, next is depolarizer, polarizer and f 75 mm D 25.4 mm lens. The units of the axis are in millimeters. Different colored lines represent beams hitting different areas of the fiber optic bundle.

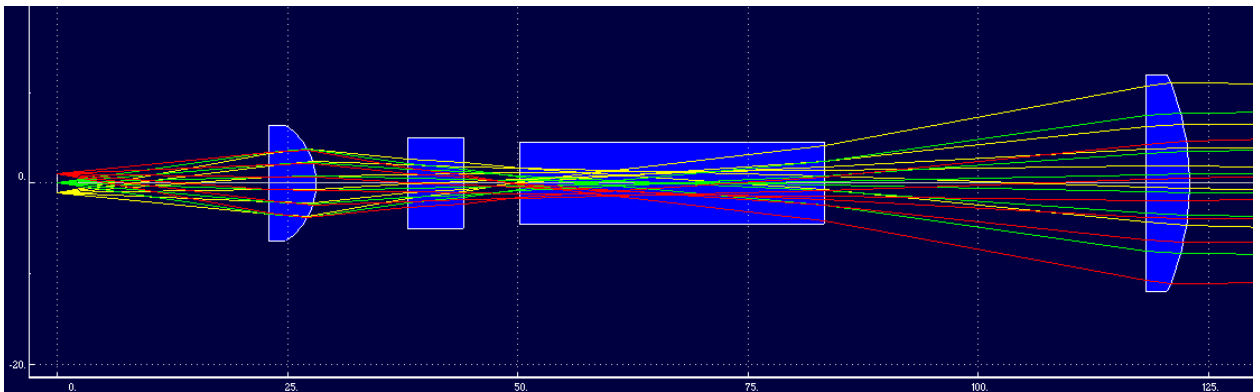


Figure 19: The optical construct of the new polarizing optics. The leftmost is the optical fiber, next is f 15mm D 12.7 mm lens, depolarizer, polarizer and f 60 mm D 25.4 mm lens. The units of the axis are in millimeters. Different colored lines represent beams hitting different areas of the fiber optic bundle.

The construct of the old polarizing optics, presented in Figure 18, has three optical components including the polarizer. If 7% loss of signal is assumed for each component and the loss of one polarizing direction, the measured signal intensity through the old polarizing optics compared to the signal measured from bare fiber should be

$$0.93^3 * 0.5 = 0.4022$$

And for the new polarizing optics, where four optical components are used

$$0.93^4 * 0.5 = 0.3740$$

The actual measurement results are presented in Figure 20. From the graphs it can be seen that the new optics perform as expected, while the old optics do not. The cause for the poor performance of the old optics is in the opening angle of the optical fiber. The fiber of the spectrometer can accept light from angle of 25° . With the old optics the angle from where the light entered the fiber was less than that, while the new optics are designed to allow light from wider opening angle to the fiber. This translates to better coupling of the optics to the fiber, and thus better optical signal.

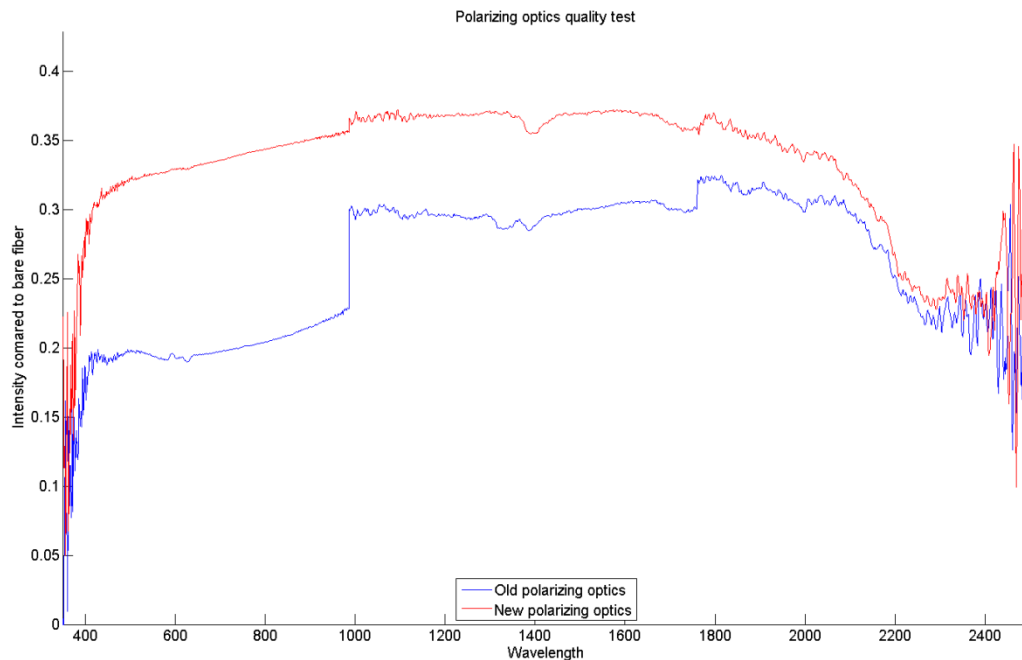


Figure 20: Attenuation of light intensity for old and new polarizing optics. The graph is the signal measured through each optics set divided by the signal from bare fiber. The signal is dropping around 2200 nm because the Glan Thompson polarizer has transmission range of only 350 - 2300 nm. The signal to noise ratio of the detector is poor at the very ends of the measurement range, and thus the data there is mostly noise. The clearly visible steps at sensor borders might be because of the different locations of the fibers in the fiber bundle leading to different sensors.

4.2.2 Optics field of view test

The three sensors of ASD all use different fibers in the fiber bundle and that may cause differences between the footprints of the sensors. A test was conducted for the optics to determine the true field of view and to detect possible differences between different sensors.

The test was conducted by cutting a circular hole of 1 cm in diameter to an opaque black plastic screen and placing a laboratory light source behind it. The optics were placed in front of the screen to a distance of 197 cm from the hole. The hole was covered from the side of the lamp using a regular A3 sized white office paper sheet to diffuse the transmitted light and to prevent excessive heating of the black screen. The optics were mounted to a two axis rotation stage, presented earlier, that was used to control the direction where the optics pointed. The optics were rotated four degrees about one axis at resolution of 0.1 to 0.2 degrees depending on the assumed field of view of the optics. After each rotation a spectrum was collected.

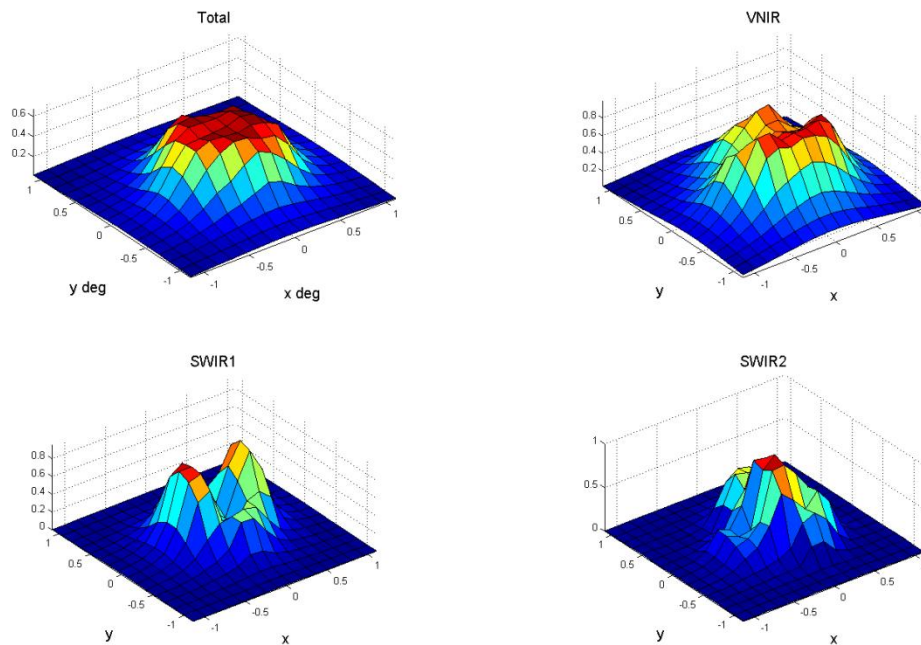


Figure 21: The field of view test results for nonpolarizing optics. The x and y axes display the displacement of each axes in degrees from the center. Z axis represents the normalized intensity values in that direction. The plot is for each individual sensor and total is the combination of all of the sensors.

In Figure 21 the measurement results are presented for the primary optics of FIGIFIGO, called FGI_3deg_2008a. The approximated value for field of view of these optics is 3° , but as can be seen from the figure the actual field of view stays within 2° . Also it can be clearly seen from the image that the sensors have different footprints. This may cause errors to the measurement results if the measured sample is not spatially homogenous, and thus the different sensors would not view the same sample.

To prevent this little can be done. A small angle diffuser inside the optics would help to make the spot for the sensors more uniform, but at the same time it would widen the FOV and cause some loss of signal intensity. As signal already is major concern, the addition of the diffuser is not justified.

If the distance from the sample to the optics is 2.5 m 2° FOV would mean about 9 cm diameter footprint size. When adding here the elongation of the footprint at measurement angle of 70° (practical maximum), as presented in Figure 15, the sample must be homogenous at diameter of 25 cm.

4.3 Testing the quality of illumination

The inhomogeneity of the light spot is a major source of error because the elongation of the spectrometer footprint at different sensor zenith angles, and because of some errors in pointing accuracy. Because of the elongation, only the center of the footprint is constantly at the same position on the sample. The inhomogeneity of the illumination causes errors even if the surface of the sample being measured is homogenous.

At autumn 2008, a test was conducted to determine the quality of the achieved illumination of setup presented in Figure 12. The test was done using similar methods to the optics test described earlier. This time the Newport rotation stage was mounted with the ASD one degree optics, because of the narrow field of view they produce. The collimating mirror and the flat mirror were used to create a spot of collimated light to a 1x1 meter white PTFE plate. The plate is made of similar material to the Spectralon that is used as a reference target. The plate was at distance of 6 meters from the light source and the rotator with the optics was at distance of 5 meters. Spectra were collected from the entire surface at angular resolution of 0.25 degrees. Figure 22 displays the measurement results. As can be seen the spot does not have a large flat surface as is desired, but has a large peak. The position of the off axis parabolic mirror relative to the light source causes major differences in the achieved spot illumination. To improve the quality of the spot, the mirror and the lamp were mounted to a rigid structure, which does not allow the relative position of the components to change. However, the calibration of the position is still to be done, and no measurement data is available.

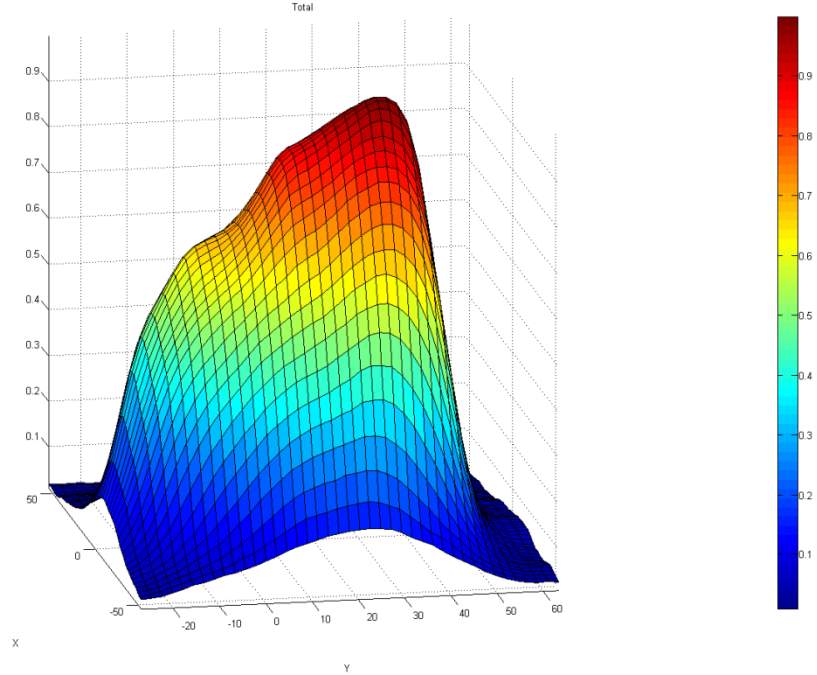


Figure 22: The spatial difference of light intensity over the area of illuminated light spot. X and y are in cm, intensity normalized between 0 and 1. The plot clearly shows a large peak instead of a flat surface.

4.4 Accuracy of the laboratory measurement ring

The laboratory ring is used to turn the goniometer around the sample during laboratory measurements. When the optical encoder was added to the ring at autumn 2008 the accuracy was found to be better than one degree. Due to limitations with the measurement setup better estimate for the accuracy was unachievable at that time. At spring 2009 a second measurement with improved measurement setup was carried out to achieve better error limits.

The measurement setup at spring 2009 consisted of the Newport two axis rotation stage, which was placed to the center of rotation of the laboratory ring. A red laser pointer was mounted to the rotator and a target was attached to the ring to a distance of 101 cm from the center of the rotation. The laser was pointed to the center of the target and both the rotator and the encoder reading was set to zero at this point. After this the ring was turned to positions 10° , 20° , 40° , 60° and 80° and back to 0° according to the encoder. At each position the Newport rotator was turned to a corresponding position according to the

Newport encoder that has accuracy of 0.023° . At each point the spot of the laser was marked to the target.

Table 1: Results of the error measurement of the laboratory ring. The value shows the difference between the Newport rotation stage reading and the encoder value. The last value labelled 0° is when the ring is turned back to 0° according to the encoder. After second measurement the encoder was calibrated, and third measurement shows results after calibration.

	10°	20°	40°	60°	80°	0°
1st measurement	0.11°	0.23°	0.45°	0.62°	0.74°	0.51°
2nd measurement	0.11°	0.17°	0.45°	0.68°	0.85°	0.62°
Calibrated result	0.11°	0.11°	0.06°	0.06°	0°	0.51°

The measurement results are listed in Table 1. As can be seen the maximum difference is 0.85° . So the original assumption of accuracy being better than 1° is valid. After the second measurement the value for encoder counts per degree was recalculated and updated to the software. Third measurement shows that the value stays within the measurement limits of this setup, limited by the 2 mm diameter of the laser spot and inaccuracies when marking the spot position. This means that the accuracy can be said to stay within $\pm 0.2^\circ$ when turning to one direction.

When the laboratory ring was turned from 80° back to 0° a hysteresis of approximately 0.5° was noticed. The calibration did not affect this, and it may be caused by some mechanical imperfections of the system. However the value of the hysteresis still remains small, and when combined with the good accuracy of the one directional turn, the accuracy of the laboratory ring is adequate.

4.5 Accuracy of the measurement arm angle

The accuracy of the measurement arm has great impact to the angular accuracy of the whole system, thus knowing the error limits for the arm is important. The angle of the arm is measured by an inclinometer mounted directly to the low end of the arm, and so the actual inclination of the arm relative to the Earth gravity vector is measured. This leaves out backlash error and poor leveling of the goniometer body from the actual measured value. The inclinometer measures the inclination in two dimensions with 90° difference. The inclinometer is set so that both of the measurement directions rotate with the measurement arm, and the actual angle is calculated using atan2 –function. This function utilizes both x and y directions and works in all four quadrants of the unit circle without the need for extra sign determination.

The mechanical connection of the inclinometer to the arm adds some error to the measured value, because of minor misalignment of the sensor. However, this error is easily compensated by the software just by adding a constant bias value to the measured value. Unfortunately this is not the only possible error in the measurement. The inclinometer output for both of the axis is a voltage signal within 0-5 volt range, while the A/D converter only accepts voltage range of 0-2.5 volts. The measured voltage is brought to measurement range by using simple voltage divider, made of two resistors of equal value. Because of imperfect components, the voltage read by the A/D converter must also be calibrated by software to take into account the imperfect components.

The accuracy of the measurement arm was calibrated during summer 2007 using mechanical angle gauge with unknown accuracy. To achieve better accuracy the measurement arm was recalibrated during spring 2009 using the Newport two axis rotator. The measurement setup was to place the rotator so that the center of rotation of the rotator is on the axis of rotation of the measurement arm. A laser was mounted to the rotator and a target was placed to the high end of the arm. The laser was calibrated to point to mark in the target when both the arm and the rotator were pointing directly up (0°). This position of the measurement arm has been calibrated by adding a bias of 2° to the angle and was found to be accurate within the measurement accuracy. The measurement was then carried out by turning the arm to different angles and then adjusting the Newport rotator to point to the mark in the target. Both the inclinometer reading and the Newport rotator value were then recorded.

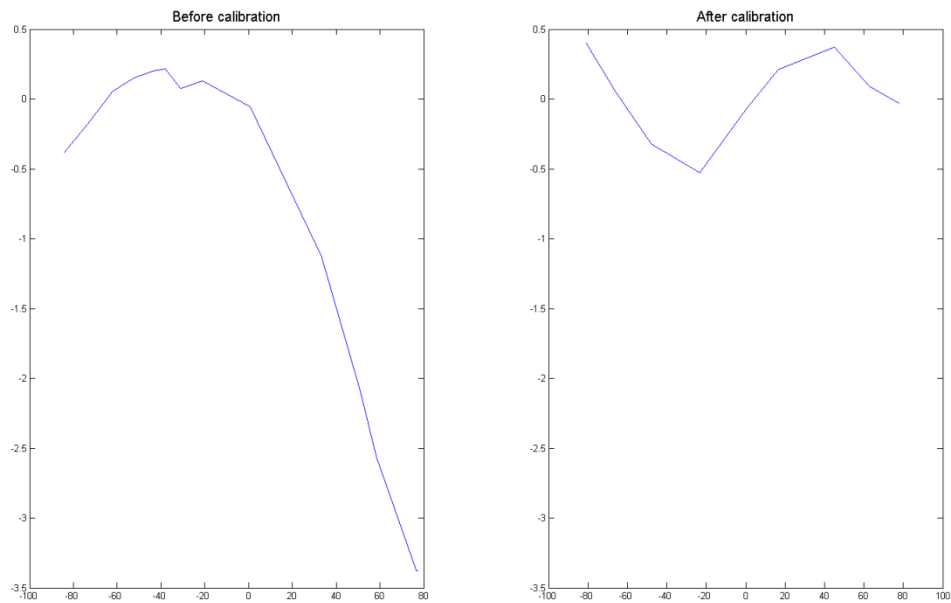


Figure 23: The goniometer arm calibration. x axis is the rotator azimuth value and y is the difference between rotator and inclinometer. Left graph is before calibration and right is after calibration.

Figure 23 shows the measurement results before and after calibration was done. The graph shows the difference between rotator and inclinometer as a function of rotator azimuth angle. From the left graph maximum error of over 3° is visible. By replacing the bias of 2° , mentioned earlier, with two parameters representing the voltage dividers the error is brought to $\pm 0.5^\circ$. Further calibration was found possible, but unnecessary.

5 Recent BRF measurement results using FIGIFIGO

Latest articles considering FIGIFIGO are about polarization data, produced by newly constructed polarizing optics. Puttonen et al. [20] reports the usability of asphalt surfaces as reference targets for aerial photography. Suomalainen et al. [21] report the results of polarized measurements of various vegetation and debris covered land surfaces. Peltoniemi et al. [22] reports the results of polarized measurements from samples of soil, stones and snow.

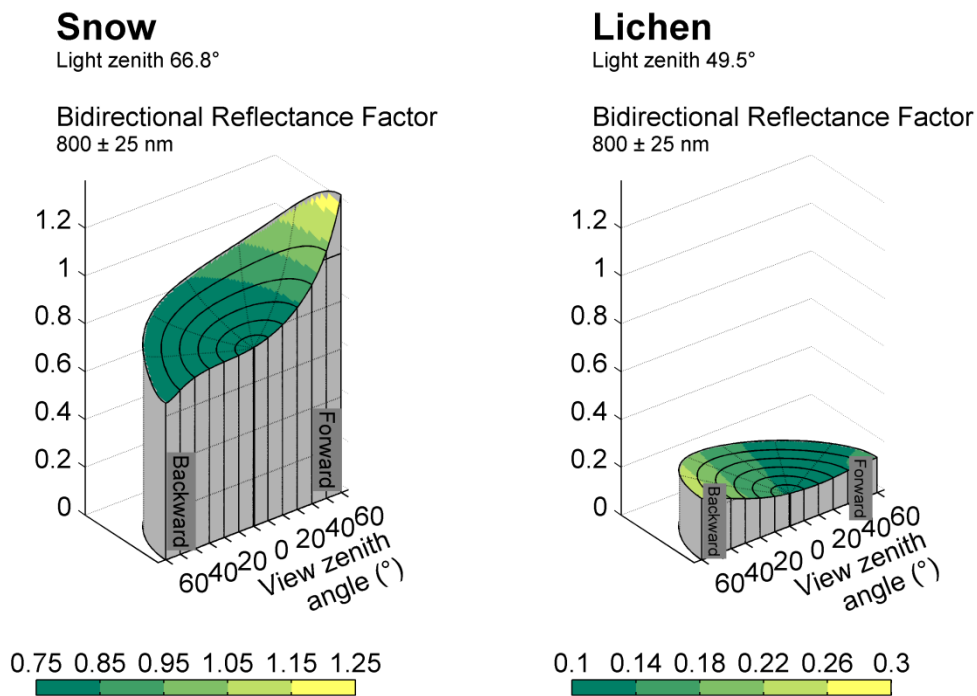


Figure 24: Left: a Bidirectional Reflectance Factor plot of old icy snow. Right: BRF of Lichen. Note the significant difference in overall brightness and the difference in the shape of the surface. Snow scatters forward, lichen backward.

Two example data are presented in Figure 24. The plots express the measured reflection intensity as a function of viewing zenith and azimuth angles. The snow was old and icy, and thus had strong specular reflection. The overall reflectance is high at wavelength of 800 nm. The lichen has significant 3D structure, which leads to more light being reflected back towards the light source. This is caused by the shadowing of the 3D structure of the sample; when viewed from the direction of the light, most of the shadows are hidden behind the

objects, and when viewed towards the specular reflection direction, most of the shadows are visible.

The recent addition of the polarizing optics has made polarized measurements possible. Several measurements of various samples have already been made. During spring 2008 several samples of old and new snow were measured at Sodankylä, northern Finland, new gravels of Sjökkulla test field at Kirkkonummi, Finland were measured at Finnish Geodetic Institute laboratory, and recently snow sample was measured also at the laboratory. All these measurements were taken using the new polarizing optics. Figure 25 shows an example data of degree of linear polarization of a sample of red gravel. Also BRF, reflectance spectrums at three view angles, and a picture of the sample are presented.

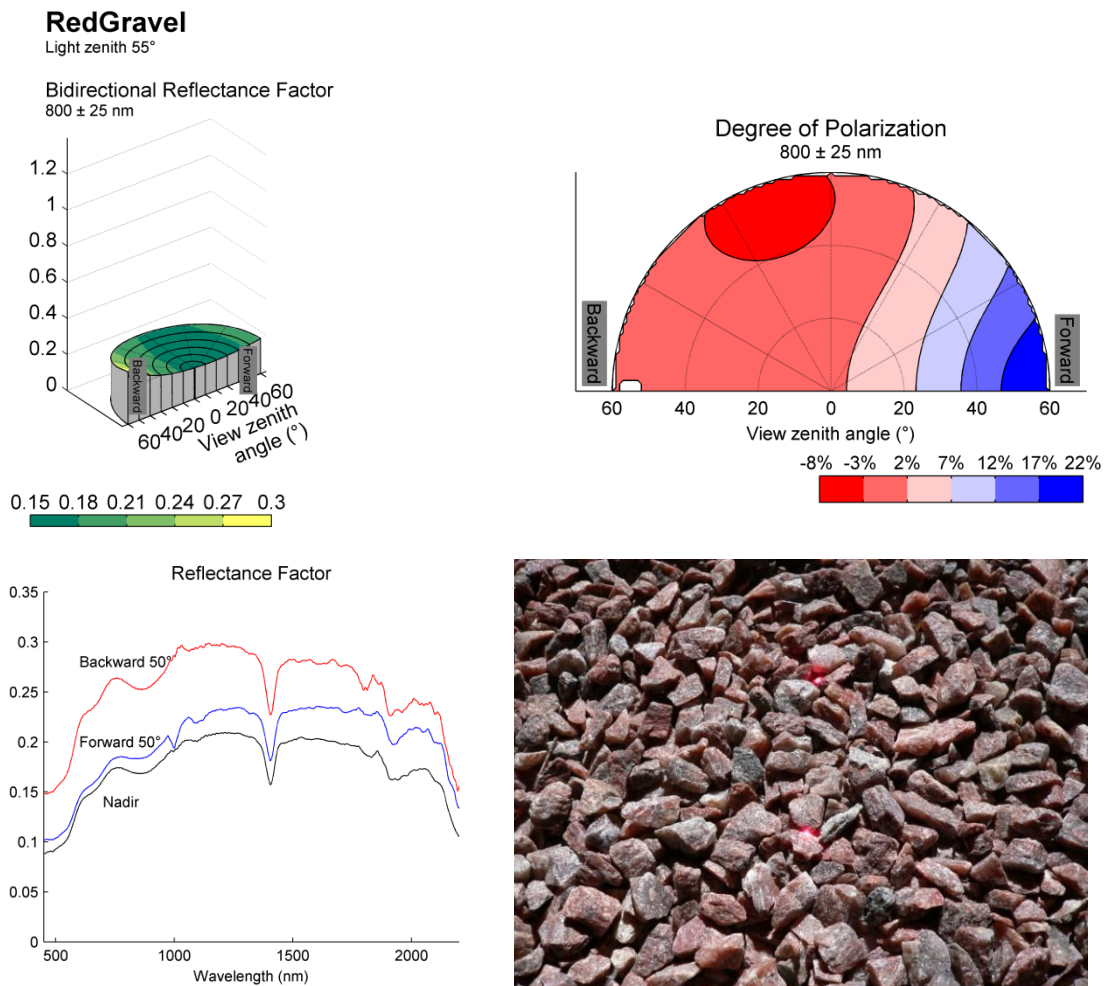


Figure 25: Various plots of a sample of red gravel from Sjökkulla test field. The sample was measured at FGI lad during autumn 2008. Top left: BRF plot of the sample. Top right: Degree of linear polarization of red gravel at 800 nm. Bottom left: Reflectance factor at three different view angles. Bottom right: A picture of the sample.

6 Conclusions

In this work recent developments on Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO) are described. The device has been developed by Finnish Geodetic Institute over several years and there have been several versions of the device. Current version, described in this work, is found to be fast, reliable, man portable, and accurate device for multiangular spectral measurements. The device and its predecessors have been used in numerous measurement campaigns, and the data gathered from these measurements is the foundation for a bidirectional reflectance distribution function (BRDF) database. Numerous scientific articles, based on the device itself or the measured data, have been published

Several improvements, calibrations and additions have been implemented to the system since work by Juha Suomalainen [5]. Most significant of these changes are reported here, while large number of minor improvements, mostly on reliability, remain unreported. However, all these changes contribute to the improved overall usability, reliability and scientific usefulness of the FIGIFIGO.

Bidirectional reflectance factor measurements provide the scientific community with essential data for better understanding of the behavior of light scattering. This understanding is utilized when interpreting the data acquired from various scientific instruments, including satellites and aerial photography. For the general public the data acquired by FIGIFIGO and similar instruments remain mostly invisible, however the data forms the foundation for better aerial and satellite photography, seen for example in Google Earth and similar applications. Also valuable data is gathered for modeling of the climate change and other ongoing natural phenomena.

6.1 Improvements to Finnish Geodetic Institute Field Goniospectrometer

Before the addition of the sky camera to orient the device relative to the Sun, an electronic compass was used during field measurements. The compass works well enough if the surroundings of the measurement sight is clear from metal objects and power lines. Unfortunately the metal objects cannot always be detected or avoided. The addition of the sky camera solved these problems and now the only requirement for accurate azimuth angle measurement is direct sunlight. As direct sunlight is also required for the actual bidirectional reflectance factor measurement (BRF), the sky camera works under all measurement situations.

Addition of the polarizing optics has been a success, and already has provided data for three scientific articles [20], [21], and [22]. These articles state that the polarization data is useful, and contains strong enough signal at low illumination angles and when target is viewed from far forward angles. At this case the signal is strong enough to gain additional data of the parameters of the measured target. Also the studies suggest that the polarization is weak in nadir direction and thus can be safely ignored when conducting near nadir measurements.

The fine tune mirror has made measurements more accurate and easy, because the targets no longer need to be positioned at the exact height of the arm axis. This reduces the preparation time of the samples in the laboratory, and on field it reduces the parallax errors caused by the misalignment, since the height of the sample cannot be adjusted on field.

Calibration of the major components has increased measurement accuracy, and now FIGIFIGO data is more reliable than ever before. Errors of up to 3% were found in angle accuracy, which is now corrected to be within $\pm 0.5^\circ$. The optics were tested, and additional information is now available of the footprint of the optics.

The reliability of FIGIFIGO has increased to a point where malfunctions only rarely occur. Some minor problems still remain, but the overall functionality of the device is now at a level where it is expected to be. The minor issues include problems with the USB connection to the computer; FIGIFIGO must be powered on before connecting the USB cable to the computer. Otherwise the USB tries to draw excessive current and the computer shuts down the USB port. This could be avoided by using isolated USB hub, or two USB cables to the computer. Another problem is the power consumption. When operational the motor draws current of 6 A, the spectrometer 2 A, and the laptop 2 A. The power is drawn from a single 30 Ah lead acid battery, which only lasts about four hours during measurement. However, since batteries are cheap many replacement batteries can be used when operating at a location accessible by car. Suomalainen tested the possibility of using a hydrogen fuel cell to power the system [5], but later that solution was found to be unreliable.

Testing of the laboratory illumination showed that work still remains with the optimal positioning and testing of the illumination homogeneity. As stated in this work the illumination causes major problems and uncertainties to the laboratory measurement results. As can be seen from Figure 22, the lighting intensity changes easily over 10% even at most homogenous regions of size of 20 cm in diameter. However, while testing the setup a possibility for improvement was clearly seen, and for further work remains finding the optimal position for the off axis parabolic mirror. Figure 22

6.2 The effects of this work

This work has made Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO) more reliable instrument, and thus the data gathered by the device can be widely used by scientific community for any application on research field of remote sensing. The reader of this document should get an overview of FIGIFIGO, and by reading this should understand the basic concepts of Bidirectional Reflectance Factor measurement, and Bidirectional Reflectance Distribution Function. Also several other goniometers are briefly presented.

7 References

- [1] Diner, David J., et al. "New directions in earth observing : Scientific applications of multiangle remote sensing." *Bulletin of the American Meteorological Society* 80, no. 11 (1999): 2209-2228.
- [2] NASA. *MISR Observing Concept*.
<http://eosweb.larc.nasa.gov/PRODOCS/misr/concept.html> (accessed March 30, 2009).
- [3] Sandmeier, Stefan R. "Acquisition of Bidirectional Reflectance Factor Data with Field Goniometers." *Remote Sensing of Environment* 73 (2000): 257–269.
- [4] Peltoniemi, Jouni I, et al. "BRDF measurement of understory vegetation in pine forests: dwarf shrubs, lichen, and moss." *Remote Sensing of Environment* (Elsevier) 94, no. 3 (2005): 343-354.
- [5] Suomalainen, Juha. "Multiangular spectrometry and optical properties of debris covered surfaces." *Master's thesis* (University of Helsinki), 2006.
- [6] Koechler, C., et al. "The European Optical Goniometric Facility: Technical Description and First Experiments on Spectral Unmixing." *Proc. IGARSS'94*, 1994: 2375-2377.
- [7] Schopfer, Jürg, Stefan Dangel, Mathias Kneubühler, and Klaus I Itten. "The Improved Dual-view Field Goniometer System FIGOS." *Sensors* 8, no. 8 (2008): 5120-5140.
- [8] Sandmeier, Stefan R., and Klaus I. Itten. "A Field Goniometer System (FIGOS) for Acquisition of Hyperspectral BRDF Data." *IEEE Transactions on Geoscience and Remote Sensing* 37, no. 2 (March 1999): 978-986.
- [9] Bruegge, Carol J., Mark C. Helmlinger, James E. Conel, Barbara J. Gaitley, and Wedad A. Abduo. "PARABOLA III: a sphere-scanning radiometer for field determination of surface anisotropic reflectance functions." *Remote Sensing Reviews*, 2000.

- [10] Schneider, Thomas, Stefan Zimmermann, and Ioannis Manakos. "Field goniometer system for accompanying directional measurements." *Proc. of the 2nd CHRIS/Proba Workshop*, 2004.
- [11] Schneider, T., W.A. Dorigo, K. Huber, and W. Schneider. "Field goniometer measurements for biophysical parameter retrieval in support of CHRIS data evaluations." *Proc. of the 4th ESA Proba/CHRIS workshop*, 2006.
- [12] Painter, Thomas H., Brad Paden, and Jeff Dozier. "Automated spectro-goniometer: A spherical robot for the field measurement of the directional reflectance of snow." *Review of Scientific Instruments* (American Institute of Physics) 74, no. 12 (2003).
- [13] Peltoniemi, Jouni I., Sanna Kaasalainen, Jyri Näränen, Leena Matikainen, and Jukka Piironen. "Measurement of Directional and Spectral Signatures of Light Reflectance by Snow." (*IEEE Transactions on Geoscience and Remote Sensing*) 43, no. 10 (2005).
- [14] Peltoniemi, Jouni I., et al. "Bidirectional reflectance spectrometry of gravel at the Sjökkulla test field." *ISPRS Journal on Photogrammetry & Remote Sensing* (Elsevier) 62 (2007).
- [15] Nicodemus, F.E., J.C. Richmond, J.J. Hsia, I.W. Ginsberg, and T. Limperis. "Geometrical Considerations and Nomenclature for Reflectance." *National Bureau of Standards*, October 1977.
- [16] Shaepman-Strub, G, M.E Shaepman, T.H Painter, S Dangel, and J.V Martonchik. "Reflectance quantities in optical remote sensing - definitions and case studies." *Remote Sensing of Environment* (Elsevier) 103, no. 1 (2006): 27-42.
- [17] Analytical Spectral Devices, Inc. "Technical Guide." *ASD Technical Guide 3rd Ed.* Boulder, CO: Analytical Spectral Devices, Inc, 1999.
- [18] Roll, Ashley. 9 2000. <http://www.digitalnemesis.com/info/projects/picservo/article.aspx> (accessed October 15, 2008).
- [19] HDF Group. <http://www.hdfgroup.org/> (accessed February 23, 2009).

- [20] Puttonen, Eetu, Juha Suomalainen, Teemu Hakala, and Jouni Peltoniemi. "Measurement of Reflectance Properties of Asphalt Surfaces and Their Usability as Reference Targets for Aerial Photos." *IEEE Transactions on Geoscience and Remote Sensing*, *IN PRESS*, 2009.
- [21] Suomalainen, Juha, Teemu Hakala, Eetu Puttonen, and Jouni Peltoniemi. "Polarised bidirectional reflectance factor measurements from vegetated land surfaces." *Journal of Quantative Spectroscopy & Radiative Transfer*, *IN PRESS* (Elsevier), 2009.
- [22] Peltoniemi, Jouni, Teemu Hakala, Juha Suomalainen, and Eetu Puttonen. "Polarised bidirectional reflectance factor measurements from soil, stones, and snow." *Journal of Quantitative Spectroscopy and Radiative Transfer*, *IN PRESS*, 2009.
- [23] Schönermark, Maria, Bernhard Geiger, and Hens Peter Röser. *Reflection Properties of Vegetation and Soil*. Berlin: Wissenschaft und Technik Verlag, 2004.