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Commissioning report for Development of micro spectro-gonio radiometer & delivery to TA2

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PU	Public	X
PP	Restricted to other programme participants (including the Commission Service)	
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Abstract:
This delivery report presents the development and the current performances of the new micro spectro-gonio radiometer “SHADOWS” developed for the measurement of reflectance spectra and SBRDF of small and dark samples.

- Section 1 presents the SHADOWS project
- Section 2 presents the concept of the instrument and describe in details the different parts of the instruments and their function.
- Section 3 presents the preliminary calculations and tests designed to estimate the future performances of the new instrument as a function of several measurements parameters and to make the choice of the best scientific compromise.
- Section 4 presents the technical choices for the Near-IR spectral range extension.
- Section 5 presents the tests performed to determine the different spectral and illumination/observation geometry limitations of the system, as well as the constraints imposed on the sample size and texture. And compare them with the expected ones.
- Section 6 first presents the nominal set of acquisition parameters defined for the tests and calibration measurements as well as the samples used for them. The reproducibility of the measurements, the sources and range of non-linearity, the S/N ratio, as well as the photometric accuracy are then presented. Several examples of spectra on typical or challenging samples are then presented.
- Section 7 draws the conclusions
- Section 8 presents the deliverable
- Section 9 presents the proposed future extensions of the capabilities of SHADOWS

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1 Introduction and aims

1.1 The SHADOWS project

This task will further expand the spectral range of a new spectro-gonio radiometer, called SHADOWS (see acronyms below) with a radical new design that will allow far greater sensitivity and the capability to analyse small (sub cm) sample sizes at low temperatures, i.e. samples from space such as meteorites, analogues of cometary and asteroid material and interplanetary dust particles. The task is split into: i) definition of instrument requirements and calibration protocols; ii) development, calibration and validation of the capabilities of the new spectrometer. Currently available instrument setups for studying small samples usually operate only at room temperature and either measure reflectance spectra, but at a single or limited angular geometry (and mostly under biconical geometry), or only photometric curves over a limited set of wavelengths. These limitations greatly hinder the effective interpretation of remote sensing data and there is a vital need to generate hyper-spectral databases in order to fully understand the composition and physical state of planetary surfaces, especially in the context of missions to study icy moons and asteroids/comets. The standard IPAG spectro-gonio radiometer SHINE, which is designed to measure the reflectance spectra of large translucent and coarse grained (up to a few mm) samples e.g. snow, has two fundamental limitations. First, it cannot handle small samples – minimum volume is limited to > 0.5 cm^3 for near-nadir single spectra and > 2 cm^3 for bidirectional reflectance distribution function (BRDF). This limits the use of samples such as space weathered materials and individual rare minerals and organics. Second, the instrument has limited sensitivity (and measurement speed) for low albedo materials due to its wide illumination area (20 cm diameter) and observation area (diameter 2/cos(Θe) cm). The research team (IPAG & IAS-CNRS, IGS-PAS, IAPS-INAF) led by IPAG was developing an innovative micro spectro-gonio radiometer concept designed to operate in the visible and very near IR range (~300-1100 nm) and optimized for very small, dark and/or fine-grained samples. A radical improvement in performance was achieved by reversing the illumination-observation geometry with an illumination area (a few mm^2) smaller than both the sample surface and the observation spot. The pre-study and calculations showed an expected gain in S/N of a factor larger than 25 in the visible, compared to the SHINE instrument. JRA2/WP 8 - task 8.4 was designed to build on this initial investment (€150k) to expand the new instrument capabilities to the NIR-IR (1000-5000 nm) while at the same time performing accurate photometric and spectral calibrations (as defined by the expert team) to greatly improve performance and accuracy. The SHADOWS instrument will allow European scientists to record N-IR spectro-photometric data on rare samples that will lead to radical re-interpretations of data produced in past planetary missions and play leading roles in analysis of data on primitive bodies produced in current and future missions.

Acronyms:

SHADOWS: **S**pectro-photometer with c**H**anging **A**ngles for **D**etection **O**f **W**eak **S**ignals

SHINE: **S**pectro-p**H**otometer with variable **IN**cidence and **E**mergence

SSHADE: **S**olid **S**pectroscopy **H**osting **A**rchitecture of **D**atabases and **E**xpertise

1.2 Aims of the SHADOWS micro spectro-gonio radiometer

As defined in the Europlanet proposal the new SHADOWS instrument should be able to measure BRDF over almost the whole solar spectrum (~300-5000 nm) for samples as small as a few mm^3 and with grain sizes typically < 25-50 μm and with albedo as low as 0.01. The instrument is designed to initially operate at room temperature and in a cold room (-20°C) and also to fit our SERAC cryogenic cell (-40°C – +80°C). Full development, building, testing, calibration and validation in the nominal operating mode should be performed by the research team in 2016-2017 before SHADOWS is made available for access in TA2/WP3 (D8.3, this deliverable). During the validation phase, relevant planetary and analogue samples have been supplied by the expert team to test the spectroscopic and photometric performances of the instrument in term of S/N and photometric accuracy: organic and carbonaceous samples (from CNRS-IAS); micron or sub-micron sized mineral samples e.g. clays, zeolites and silica (from IGS-PAS); analogue materials as proxies of asteroid surfaces and comet nucleus (from IAPS-INAF). Both the new SHADOWS and the current SHINE instruments will be operated together for TA2/CSS (Cold Surface Spectroscopy) in the last 2 years of the EPN2020-RI project. All team members are part of the SSHADE (solid spectroscopy database infrastructure - JRA5/WP11) consortium (20 lab spectroscopy teams from 8 countries - VA2/WP6), about a dozen of which have direct interests in this new experimental capacity on small dark and/or fine grained samples. Many others people are already, or will be, interested by the outstanding performances of this new SHADOWS spectro-goniometric instrument for the measurement of dark and rare samples.

2 Description of the SHADOWS micro spectro-gonio radiometer

Authors	Bernard Schmitt (manager), Pierre Beck, Sandra Potin, Olivier Brissaud,

Abstract: This part presents the concept of the instrument and describe in details the different parts of the instruments and their function.

We describe here the final SHADOWS instrument, as delivered, with its various parts and functions. In many aspects it is similar to our previous SHINE instrument but with one major fundamental change: the relative size of the illumination and observation spots is reversed: $D_{illumination} < D_{observation}$. If all light illuminating the surface in the illumination spot is either absorbed within the sample or exit within the observation spot then all requirements are met to measure the absolute reflectance of an equivalent infinitely wide and deep surface.

A picture of the full SHADOWS instrument is given in Fig. 2.1, as well as a scheme in Fig. 2.2.

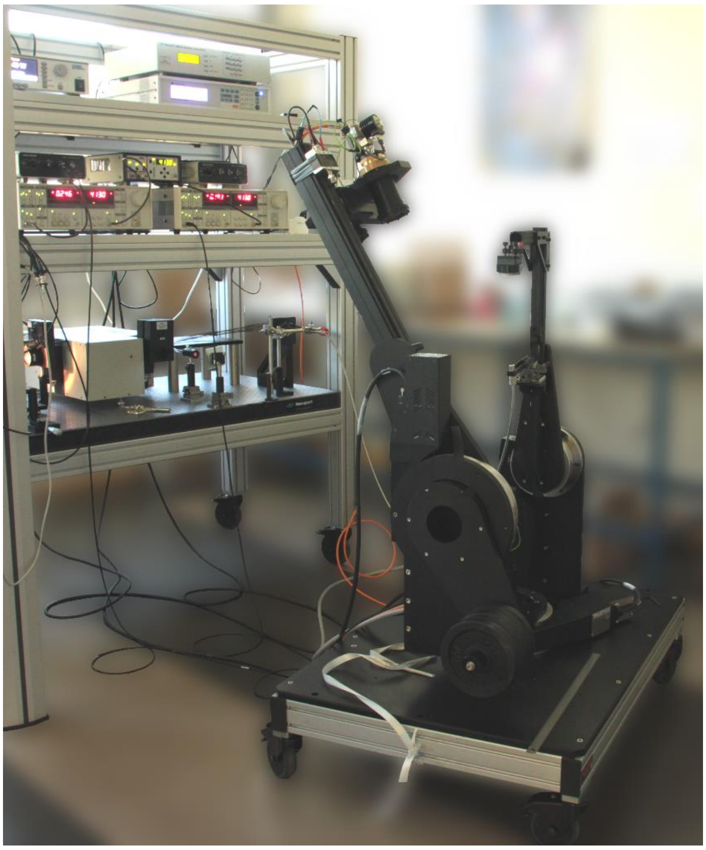

Figure 2.1: Picture of the SHADOWS instrument, showing all instrumentation and goniometer parts.

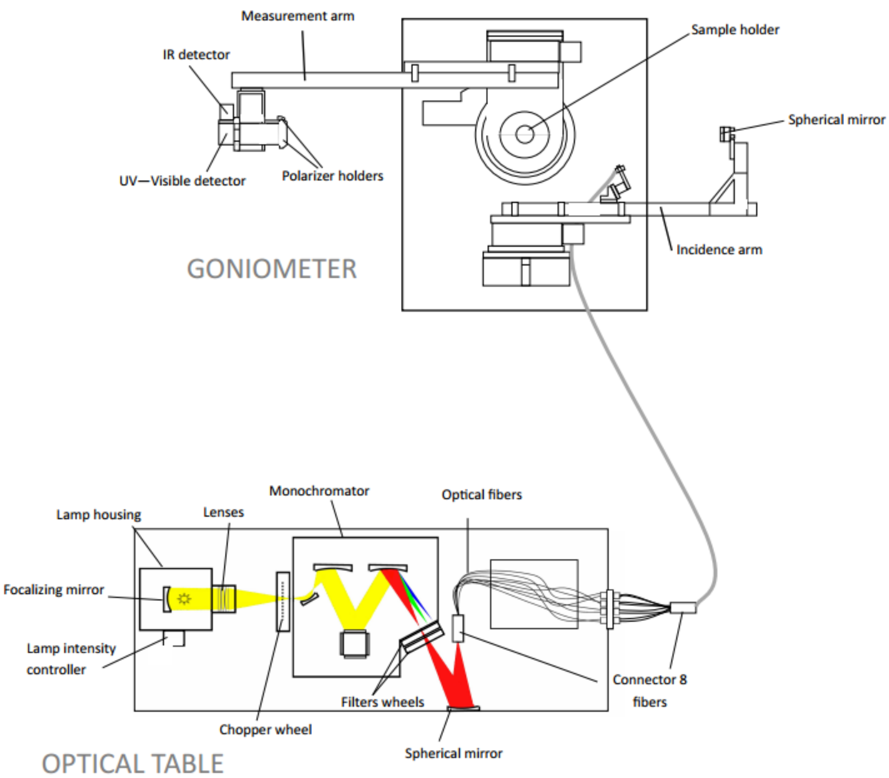

Figure 2.2: Complete instrument scheme showing the optical table (see Fig. 2.3) where the monochromatic light is generated and the goniometer acquiring the spectra (see Fig. 2.1).

2.1 Illumination

Light from a 250-W quartz tungsten halogen lamp, mounted in a lamp housing (ORIEL OPS-Q250), is focalized by a home-made lens assembly directly onto a monochromator motorized input slit (variable width from 4 µm to 2 mm; height: 15 mm. The lamp housing includes a temperature-stabilized photodiode that constantly measures the output of the lamp and adjusts the power-supply setting to compensate for any light-intensity variations. This system provides a highly stable long-term output (light variations < 0.1% peak to peak over 24 h). A chopper wheel (ORIEL Model 75160NF) with an adjustable frequency is placed between the source lens assembly and the monochromator slit to modulate the light beam. This modulation allows the use of synchronous detection measurement to improve the detection limit of the detectors and to remove from the signal all light not originating from the source, especially the thermal IR emission from the sample and some optical parts. The monochromator (ORIEL MS257) has a F# of 3.9. It incorporates a quadruple grating turret (1200, 600, 300, and 150 lines/mm), that covers the spectral range from 220 to 9000 nm, and two filter wheels (after the exit motorized slit) with six long-pass filters to eliminate the higher orders. Two broad UV–visible bandpass filters are added to eliminate most of the stray light disturbing the low signal measurements below 550 nm. At the output of the monochromator, a concave spherical mirror collects the monochromatic flux and forms a about 2.3x-reduced image of the exit slit on a fiber-optic bundle (Le Verre Fluoré). The first 0.76 m-long bundle contains 8 fluoride glass fibers (ZBLAN) with excellent transmittance from 300 to 4700 nm. The fibers are aligned at one end (input) to match the slit image and are separated up to the other end where they are connected individually with another fiber bundle of the same type (2 m long) with its output arranged in a circle (diameter: 2.2 mm) at the other end. The fiber core diameter, 600 µm, determines the maximum output slit width (1.5 mm) and, accordingly, the largest spectral bandpass for each grating. The first fiber bundle allows to depolarize the variably polarized light emerging from the monochromator. The second fiber bundle flexibly carries the light to the focal point of a spherical reflector (diameter: 50.8 mm; f = 152.8 mm) placed on the illumination arm of the goniometer. This mirror illuminates the sample surface at a distance of 500 mm with a small 8-spots beam, 5.2 mm in diameter (Fig 2.5) slightly focused (convergence half angle: 2.9°). This solid angle defines the nominal illumination angular resolution. Unfortunately we completely lost the transmission in one fiber (Fig 2.5, to be investigated if we can recover it) but even without it we exceeded all the expected performances (see §6).

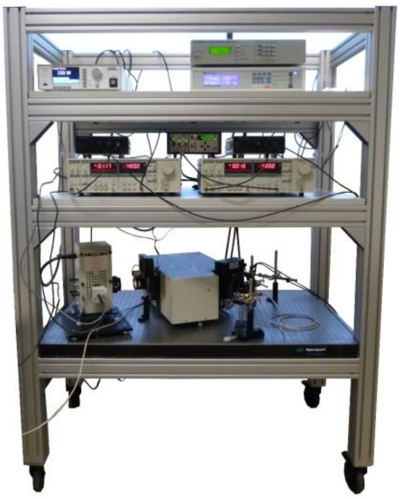

Figure 2.3: Picture of the source bench (bottom and top left), the control electronics of the goniometer (top right) and the detection system (middle)

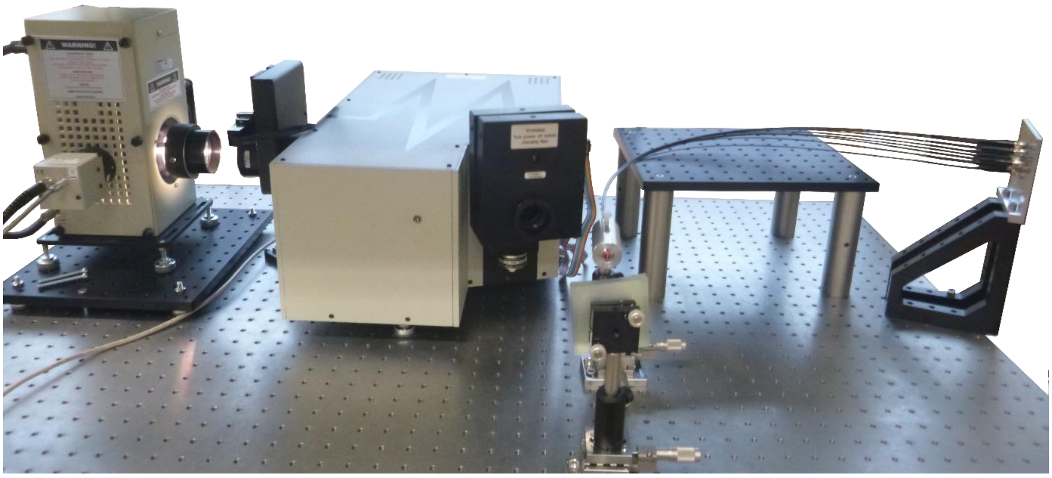

Figure 2.4: Detail of the optical table, where the monochromatic light is generated. The picture shows, left to right, the lamp housing and its stabilization detector, the chopper wheel, the monochromator and its filters wheels, the injection mirror and the first part of the optical fibers.

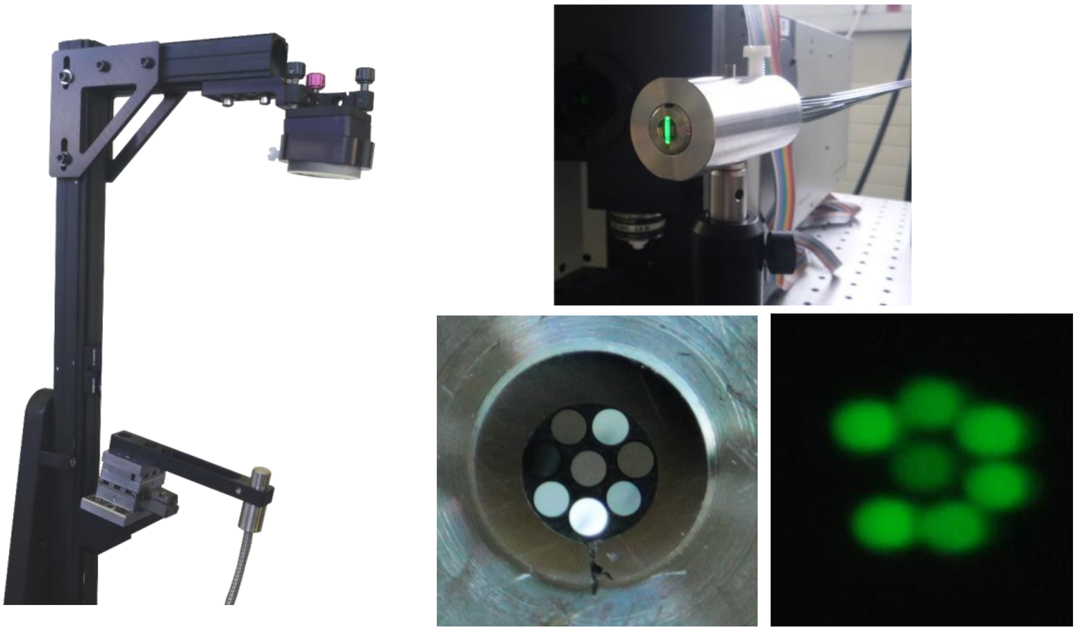

Figure 2.5: Detail of the illumination arm (left): the end of the optical fiber bundle and the spherical mirror illuminating the sample. The input (top right) and output (bottom center) of the fiber bundle show the organization of the fibers to fit the monochromator slit and provide a circular 8-spots pattern on the sample (bottom right). Note the missing fiber.

2.2 Observation

The radiance of the sample is measured by two detectors: a silicon photodiode with a spectral response from 185 to 1200 nm and an InSb photovoltaic detector covering the spectral range from 800 to 5200 nm (Fig. 2.6). The IR detector is cooled to 80 K by a Stirling micro-cooler (Infrared Associates K508), and a cold diaphragm is used to restrict the field of view of the thermal background radiation to improve the S/N ratio. The modulated signals are amplified by current-to-voltage preamplifiers and measured by lock-in amplifiers (SR 810). Each detector is fitted with a three-element achromatic condenser to collect the radiance of a small sample area (20 mm in diameter) within a narrow solid angle (FWHM of 4.1°). This solid angle defines the nominal observation angular resolution. When necessary, one can achieve better angular resolutions by inserting a diaphragm in front of the detector optics, but to the detriment of the S/N ratio. The two detector assemblies are fixed to the observation arm of the goniometer and are separated by 10° in the principal plane. Their distance to the sample is 700 mm.

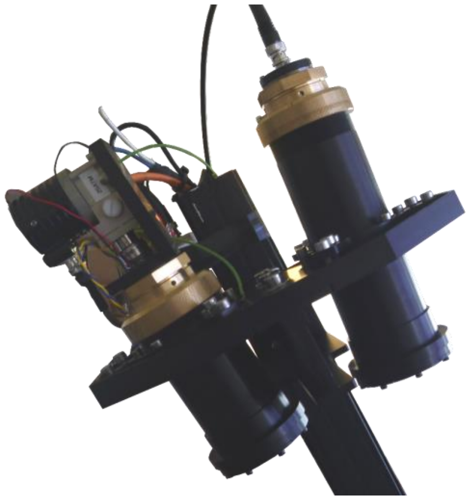

Figure 2.6: Detail of the observation arm holding the two detectors and their optics: infrared with its micro cryo-cooler (left) and visible (right). The two detectors are separated by 10°

2.3 Goniometer

The goniometer is designed and constructed from three rotation stages (Micro-contrôle RV160PE & RV240PE, with ESP301 3-axis motion controller/driver) allowing rotation of the illumination arm from 0° to 90° incidence (Θi) and of the observation arm from 0° to 90° for the zenithal emergence angle (Θe) and from 0° to 180° for the azimuth (Θaz) (Fig. 2.7). All axes are driven by stepper motors with 0.001° increments. The position repeatability is 0.002°, and the rotation speed has been fixed at 2° s^{-1}. A counterweight is used for each arm to reduce the rotation torque. The structure and the different sample holders of the goniometer are anodized black to minimize the effects of stray light in the visible. The center of the sample surface is placed at the intersection point of the three rotation axes.

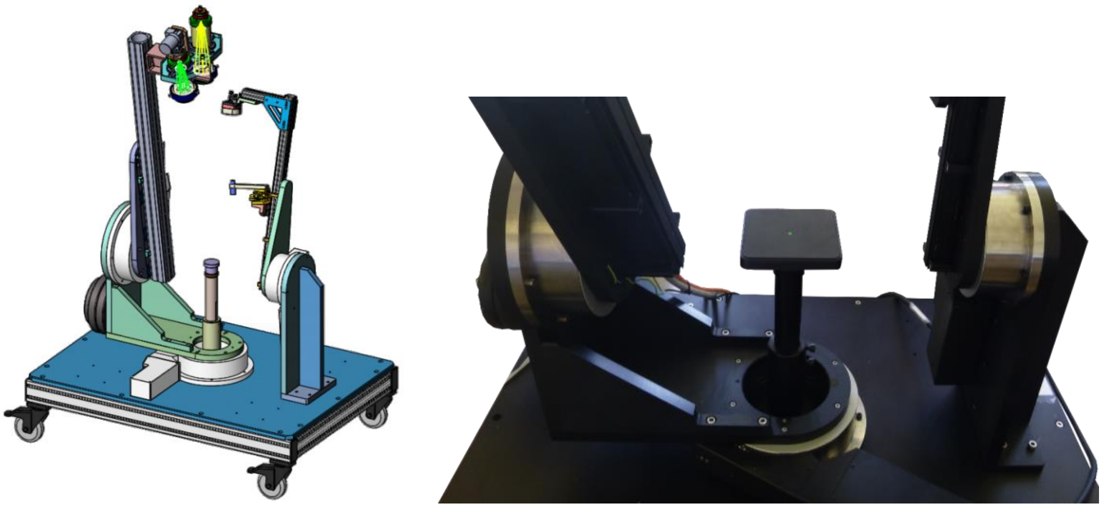

Figure 2.7: Scheme of the goniometer (left) and detail of the sample holder situated between the two arms and holding a Spectralon© 5% reflectance reference target. The tiny illumination spot (5mm diameter) can be seen in the middle of the sample (green light).

2.4 Software

A special instrumentation software based on LabVIEW (National Instruments) with a general-purpose interface bus board has been developed to fully drive the SHADOWS spectro-gonio radiometer, to define all the acquisition parameters (Fig. 2.8), and to record, display and calibrate the data (Fig. 2.9) through interactive front panel user interfaces. The program drives the monochromator (gratings, slits, filter wheels), the goniometer (three stepper motors), and the two lock-in amplifiers. The acquisition parameters (spectral range, resolution and sampling (or individual wavelengths), angular ranges and sampling (or individual geometries), amplifier gain, integration time constant, averaging time, calibration steps, etc.) can be flexibly defined and optimized, allowing different types of experiment to be specified (single wavelength–full angular configurations, fixed geometry–full spectrum, spectra at fixed phase angle, etc.). The program defines the optimum sequential ordering of the geometrical configurations within the allowed angular ranges (see §5.1) and records the detector signals as well as several environmental parameters (time, detector temperatures, sample temperature, lamp flux, etc.) for all spectro–angular configurations.
The program also reduce and calibrate the data using pre-measured reference standards and the measured sample reflectance is automatically calculated and displayed in real time during the acquisition. All information about acquisition parameters, sample environment and calibration parameters are registered in a text file, along the spectral data.

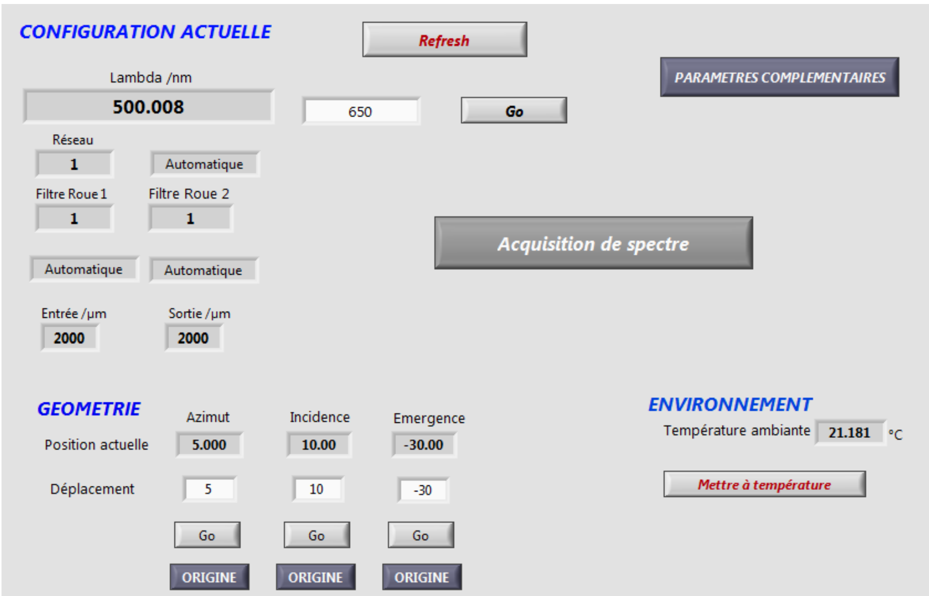

Figure 2.8: Screenshot of the starting window, enabling the operator to set the positions of the goniometer arms, the wavelength and spectral resolution, and start a spectral acquisition.

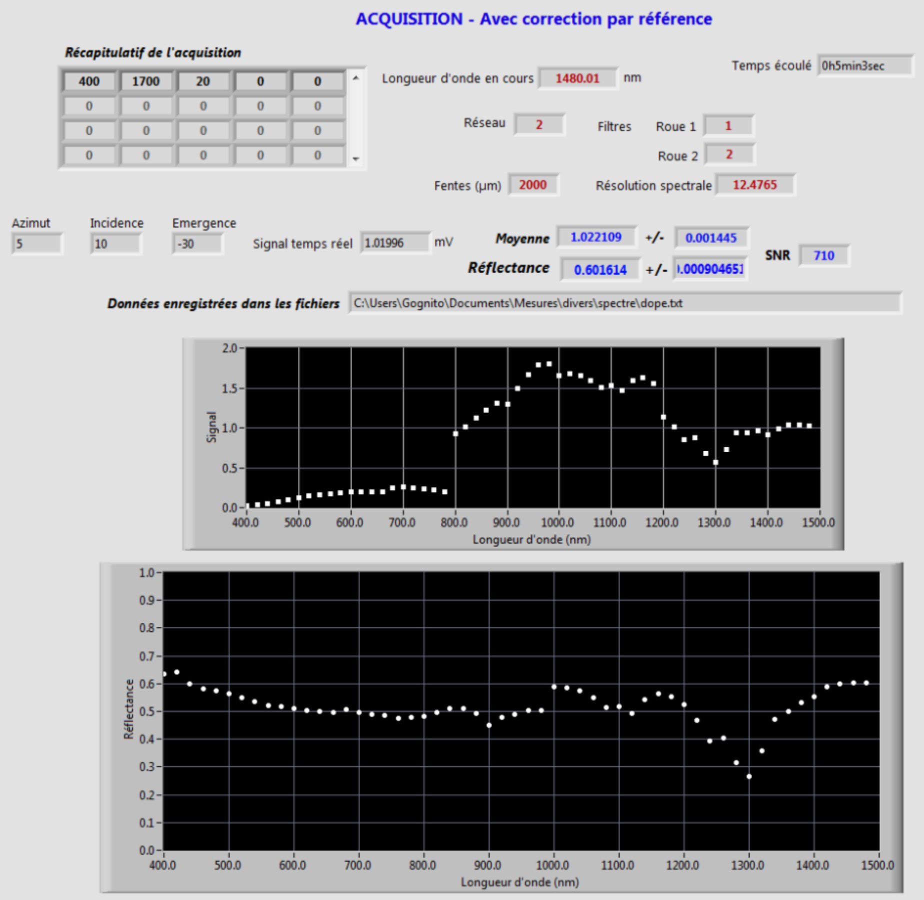

Figure 2.9: Screenshot of the acquisition window. The spectrum is automatically corrected by the references Spectralon and Infragold, and the reflectance spectrum is drawn in real time during the acquisition.

Note: The English version of the software interface is under finalization.

2.5 Nominal performances

The table below summarize the nominal performances of the system as it is delivered for TA2. Further improvements of some of these characteristics are expected with more sophisticated calibrations and addition of options.

Spectral range : 400 – 4700 nm (300-400 & 4700-5000 nm: lower S/N)
(4200-4300 nm: atm. CO_2 limited)

Spectral resolution : variable
- mini : < 0.1 nm (but S/N limited)
- maxi : 6.4 nm (200 - 1400 nm), 12.8 nm (600 - 2500 nm), 25.8 nm (1100 - 3400 nm), 51.3 nm (> 2500 nm)

Bidirectional Reflectance
- Incidence angle : 0° to 75° (60° for bright samples)
  resolution: ± 2.9°
  minimum sampling: 0.1°
- Emergence angle: 0° to 85°
  resolution: ± 2.05° (options: 0.8°, 1.25°, 1.65° but lower S/N)
  min. sampling: 0.1°

- Azimuth angle : 0° to 180° (more than half an hemisphere)
  resolution: ± 2.05° (options: 0.8°, 1.25°, 1.65° but lower S/N)
  min. sampling: 0.1°
- Phase angle : 5° to 160°
  for bright samples: ~8 to 140°

- Illumination diameter (nadir) : 5.2 mm
- Observation diameter (nadir) : 20 mm

Samples

- Type : minerals, fine grained ice, organics, meteorites …
- Albedo < 0.0003 to 1
- Texture : fine to very fine grained granular or compact
- Grain size : < 500 µm grain/crystal diameter
  < 150 µm with a single fibre
- Size mini: D > 5.7 mm (for illumination at nadir)
  D > 2 mm with a single fibre
  L x l > 20.5 mm x 5.7 mm (for illumination up to 75°)
- Temperature : room temperature or heated
  down to -20°C (in cold room)
  down to -40°C (in SERAC environmental cell)

Photometry :

- Absolute: 400-2500 nm: < 1% over all configurations (relative to Spectralon© 99% reference panel)
  2500-4700 nm: better than 2% over all configurations (relative to Infragold© reference panel)
- relative: better than 0.5% (400-4700 nm)

Acquisition time : single spectrum: 70 min over the 400-4700 nm range @ 10 nm sampling (431 spectral channels)
BRDF: 24h for 50 wavelengths and 180 geometries

3 Definition of SHADOWS performances requirements

Authors	Development: Bernard Schmitt (manager), Pierre Beck, Olivier Brissaud, Sandra Potin + expert team (IGS-PAS, CNRS-IAS, IAPS-INAF)

Abstract: This part presents the preliminary calculations and tests designed to estimate the future performances of the new instrument as a function of several measurements parameters and to make the choice of the best scientific compromise.

3.1 Calculations and tests of preliminary design in the NIR

Illumination optical calculations in the NIR have been performed with the current new design developed for the visible range in order to verify that this design is also adapted to the NIR range and to optimize the NIR optical transfer of the whole system from the source to the spectrometer. The main result was that a minimum gain in S/N ratio of 25 should be obtained in the NIR while keeping the other performances nominal. And that there may be a few ways to further improve this number.

3.2 Experimental determination of the S/N improvement.

The prototype of the core of the new illumination design has been inserted in our current instrument in order to test (at minimum cost and risk) the expected NIR performances of the NIR extension of the new instrument.
With this setup we ran a number of tests on various samples and dark reference surfaces in order to determine the ability of the new design to measure dark (reflectance < 10%) to very dark (reflectance < 2%) surfaces and to estimate its current improvement in S/N in the NIR relative to our currently operating spectro-gonio radiometer.
We demonstrated that for dark surfaces the gain in S/N overpass largely the minimum factor of 25 expected from the preliminary calculations: in the current test configuration we reached a factor 50-60 while measuring at a slightly higher spectral resolution.

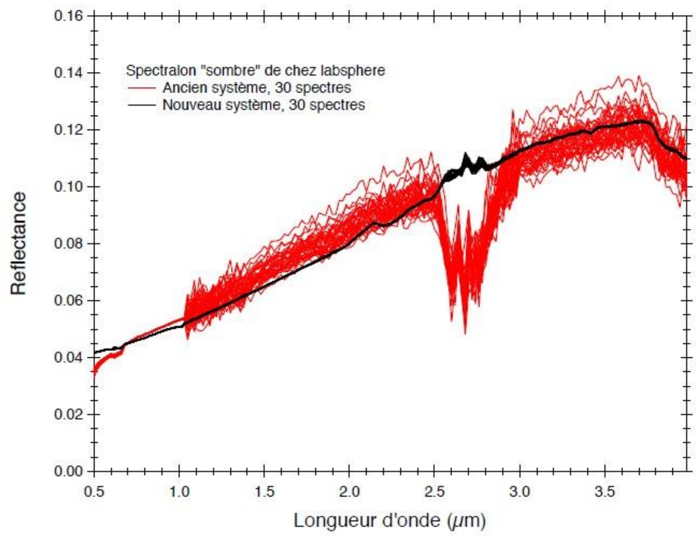

Figure 1:
Comparison of the noise and reproducibility of the Vis-NIR spectra (30 individual spectra) of a dark Spectralon© 5% (LabSphere) reference surface between our current setup (red) and a prototype of the new design (black).

3.3 First tests on reference and challenging surfaces

In order to test the performances of the instrument and its components we selected a set of 4 dark materials that we used during the whole process of development:
Two dark synthetic reference surfaces

- Dark spectralon 5% (LabSphere)
- Metal velvet (Acktar)

A very challenging material with a reflectance given to be less than 0.05% in the visible and less than 0.5% over the whole NIR, that is currently the darkest material known on Earth!:

- VANTABLACK sample (VBS1004)

In order to cover most of the range of albedos of dark materials we used a CM carbonaceous chondrite (ALH83100) with spectral reflectance varying between 0.05 and 0.3.

Their spectra are reported in Figure 3. From these results it is possible to confirm that the new design is able to measure samples with reflectance as low as 0.03% in the visible and NIR (< 2000 nm) and 0.2% in the MIR (at least 4500 nm).

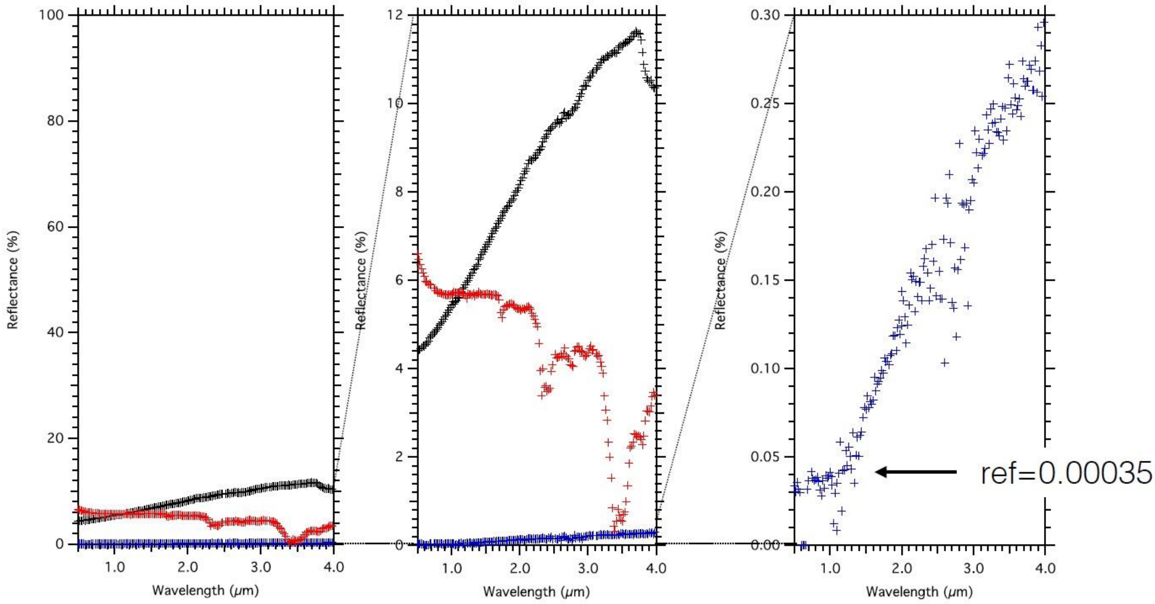

Figure 2: Measurements (with proto) of three dark spectralon 5%, black), very dark (Black MetalVelvet, red) and extremely dark samples (VANTABLACK, blue) at 3 different reflectance scales. It show the ability of the design to measure reflectance as low as 0.00035!

First tests on a CM chondrite showed the ability of the new concept to perform BRDF measurements over a wide spectral range, high spectral resolution, wide angular range and high angular resolution with high S/N ratio in a reasonable time. We thus measured it over 150 different geometries for a total time of 30 hours (one day and 2 nights) (Figure 4). The gain in time is here a factor of a few thousands! (with the same measurement parameters a single spectrum with about 10 times worst S/N takes half a day with our current system…). And the results at 3800 nm are still very good (almost no noise seen in the BRDF curves).

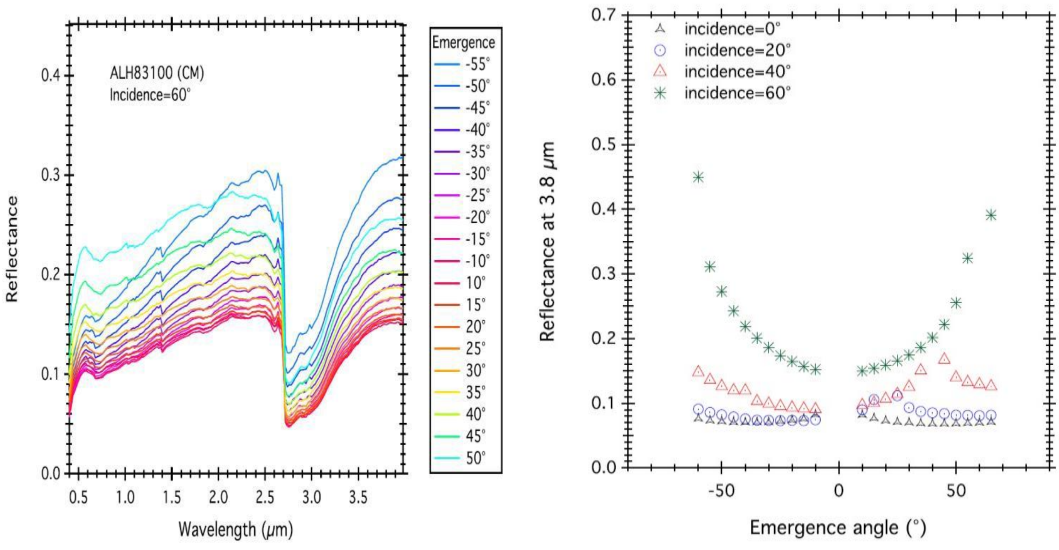

Figure 3: Left: Part of the measurements of a spectral BRDF of a CM carbonaceous chondrite (150 spectra in 0.4-4µm range in 30 hours). Right: BRDF at 3.8µm for 4 of the incidence angles and 22 emergence anglesFrom these very positive results it was possible to study the best compromise between illumination and observation angular resolution and maximum ranges, illumination spot size on the sample (i.e. minimum sample mass) and S/N ratio.

Now, after favoring a compromise (#1 in Table 1) that will decrease the size of the sample to 8 mm and extend the maximum illumination angle to 70-76° a **minimum gain of 54** is expected in the S/N, at 20% better resolution (and 67 at same spectral resolution).

3.4 Specifications of the instrument and expected minimum performances

Table 3.1: Instrument specifications and expected performances

	TEST system	**Compromise #1** (adopted)	Compromise #2
ILLUMINATION			
Mirror diameter (useful)/(real)	50.8mm / 65mm	50.8mm / 65mm	50.8mm / 65mm
Distance Mirror/fibre	219.2mm	219.2mm	219.2mm
Distance Mirror/sample	500mm	500mm	500mm
Illumination spot diameter (mm)	5.93 (theoretical) 7.5 (measure)	4.8 (theoretical) 6.1 (estimated)	4.1 (theoretical) 5.2 (estimated)
Eclairement divergence (resolution)	±2.9°	±2.9°	±2.9°
Maximum angle	72.7° (theoretical) 60° (measured)	76.1° (theoretical) 70° (estimated)	78.2° (theoretical) 73° (estimated)
Fibers optics (µm)	9 fibers 750/800	8 fibers 600/650	8 fibers 500/550
Fiber optics bundle diameter	2.6mm	2.1mm	1.8mm
O.N fibers/mirror (useful angle) *(current Gonio ±7.6°)*	±6.6°	±6.6°	±6.6°
OBSERVATION			
Detector diameter	2mm	2mm	2mm
First lens diameter	52mm	52mm	52mm
Number of lenses	4	3	3
Distance 1rst lens/sample	700mm	700mm	700mm
Observation spot diameter	20mm	20mm	20mm
Observation divergence (resolution)	±2°	±2°	±2°
Angle maxi	80°	80°	80°
PHASE ANGLE			
Minimum phase angle	<6°	<6°	<6°
SAMPLE			
Nominal diameter	25mm	25mm	25mm
Minimum diameter	9mm	8mm	7mm

	TEST system	**Compromise #1** (adopted)	Compromise #2
SIGNAL/NOISE			
Gain S/N (InSb @77K, 1-5 µm) (relative to current instrument)	Calculation : 75 Measured : 50 - 60 Slits: A=B=1500	**54** (with 2 lens) Slits: A=B=1200 (max)	38 (with 2 lens) Slits: A=B=1000 (max)

4 Optimization of the spectral range extension

Authors	Development: Olivier Brissaud, Bernard Schmitt (manager), Pierre Beck, Sandra Potin

Abstract: This part presents the technical choices for the Near-IR spectral range extension.

4.1 Selection of the NIR spectral range

The question of the NIR-IR spectral range is a critical one as it imply a trade-off between the scientific objectives only achievable at high wavelengths (typically in the 3500-5000 nm range), the S/N of the measurements over the remaining range and cost & complexity of the system.

The main interest to reduce the maximum wavelength is to reduce the thermal infrared contribution in the background signal and thus the noise of the detector with, as a result, an increase of the S/N over the remaining spectral NIR range of the detector.

Such an increase could be done by different ways that have been evaluated:

1) Placing a cooled (80K) low pass filter inside the closed cycle cryostat of the detector.
2) Choosing a single detector with a lower cutoff wavelength and thus a higher sensitivity.
3) Splitting the NIR range in two parts, one low wavelength / high sensitivity in a first step, and a second with higher cut-off but lower sensitivity to be added in a second step.

The last solution, while optimizing the S/N in the NIR, was rapidly eliminated because of its higher cost and complexity: need 2 cooled detectors (NIR + IR), and thus with the visible range: 3 supports, 3 optics and 3 synchronous detections + many additional constraints on observation angles, weight, cost …

When analyzing the different new major scientific subjects of study that will be accessible with the micro spectro-gonio radiometer it appeared that cutting the wavelength range below about 4300 nm will have very significant impact on the science that can be achieved. In particular the study of minerals, water in minerals and organics and that of the organics themselves will be limited, in particular due to:

- The water of hydration band may have a high wavelength wing extending up to 4200 nm and thus part of the continuum above is necessary to correctly assess its integrated intensity.
- Some organics have very interesting bands around 4400-4700 nm (CN functions, see Fig. 5.1)
- Strong carbonate bands around 4600-4800 nm, as on Ceres.

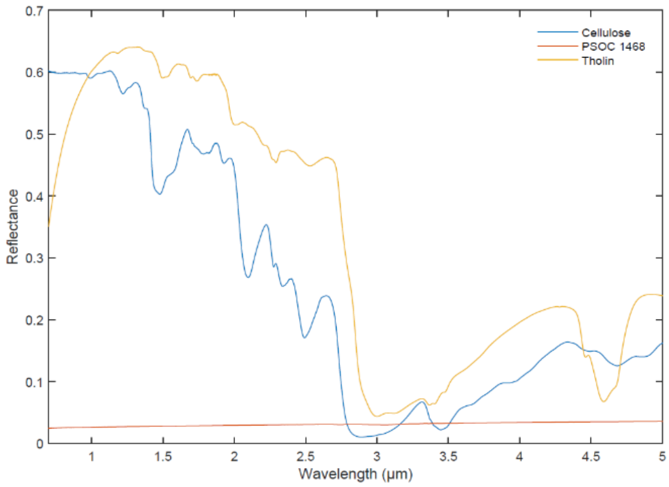

Figure 5.1: Measurements of organics over the 1-5 µm range

With such a high cutoff wavelength the calculations showed that the remaining gain in S/N was no more significant enough and partly compensated by the additional cold low pass filter.
It should be noted also that our whole system is placed in a chamber that can be cooled and that at -20°C the total amount of thermal radiation is already reduced by a factor 1.8 compared to room temperature, but by a larger factor when integrated over the detector sensitivity range.

We finally decided to keep the widest spectral range as possible, i.e., up to at least 4800 nm as for our current goniometer. However with the expected minimum gain in S/N ratio of 25 in the NIR we expect to be able to reach 5000 nm with still good S/N using a classical InSb cryocooled detector.

4.2 Selection of the materials for the NIR

To insure a good S/N up to 5000 nm we have thus selected the materials all along the optical chain to allow an optimized NIR+IR throughput up to the detector.

- ***Lamp + optics***

A QTH Quartz-Halogen lamp with a back reflector has been chosen to improve the collection efficiency of its NIR radiation relative to our previous system. It was thus necessary to design a focalization optics with CaF2 lenses, with good efficiency and achromaticity, to let all wavelengths up to 5µm$^+$ to be focalized on the entrance slit of the monochromator.

- ***Monochromator***

The monochromator has already been chosen and delivered with a grating #4 allowing to go well above 5000 nm (similar to the one of our current spectro-goniometer).

- ***Optical fiber bundle:***

A specially made Fluoride glass infrared fiber optic bundle has been designed and ordered to be manufactured by ‘Le Verre Fluoré’ company. It has an excellent throughput up to 4800 nm and still a good one up to 5000 nm.

- ***Cooled Near-infrared detector and its optics:***

Our choice was finally on an InSb detector with good detectivity value and cooled at 80K with a mini Stirling cryocooler and without long wavelength filter but with a cooled field stop to reduce the solid angle of thermal radiation to the focalization optics. A special collection optics with MgF2 coated Sapphire and CaF2 lenses has been designed.

A test of S/N in the NIR up to 5000 nm was performed on a dark calibration target (Spectralon 5% reflectance) with the prototype system installed on our current spectro-gonio radiometer. It allowed expecting a good S/N up to at least 4700-4800 nm in nominal conditions. The deviation of the reflectance above 4800 nm (at very low signal) has been studied during the photometric calibration procedure.

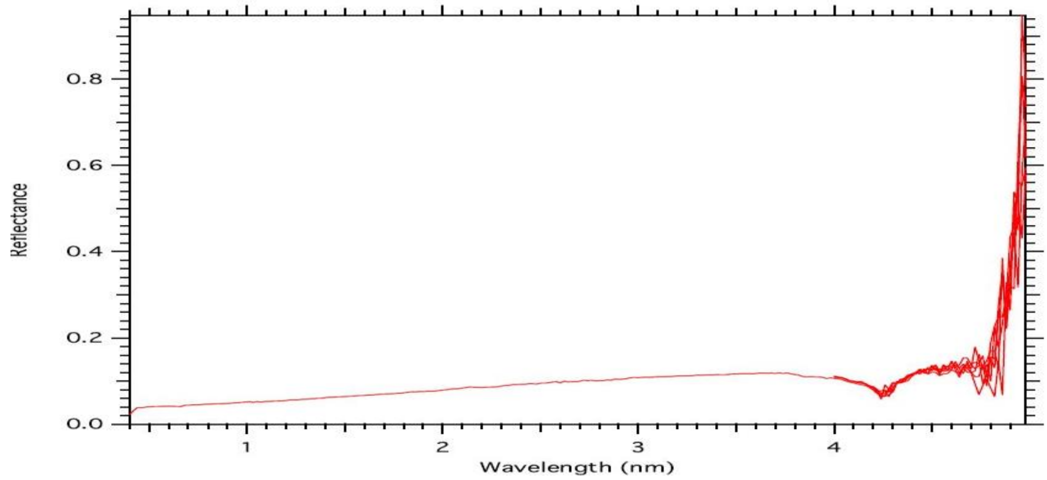

Figure 3: Measurements (with prototype system on current goniometer) of the dark Spectralon 5%, over the whole 0.4-5 µm range. Six individual measurements are displayed above 4 µm.

All the materials have been tested individually and added to the system before starting the final verification and calibration phases of the whole system. These results are reported in §5.

5 Limitations of the system

Authors	Sandra Potin, Olivier Brissaud, Pierre Beck, Bernard Schmitt (manager) (CNRS – IPAG, F)

Abstract: This part presents the tests performed to determine the different spectral and illumination/observation geometry limitations of the system, as well as the constraints imposed on the sample size and texture. And compare them with the expected ones.

5.1 Available geometries

For maximum angular performance the illumination and detection arms need to cover most of the different possible geometries to have BRDF measurements as complete as possible.

Geometrical configurations

Due to the instrument design, some geometrical configurations may not be possible. Figure 1 represents the polar diagram of the geometries in which the detectors can move.

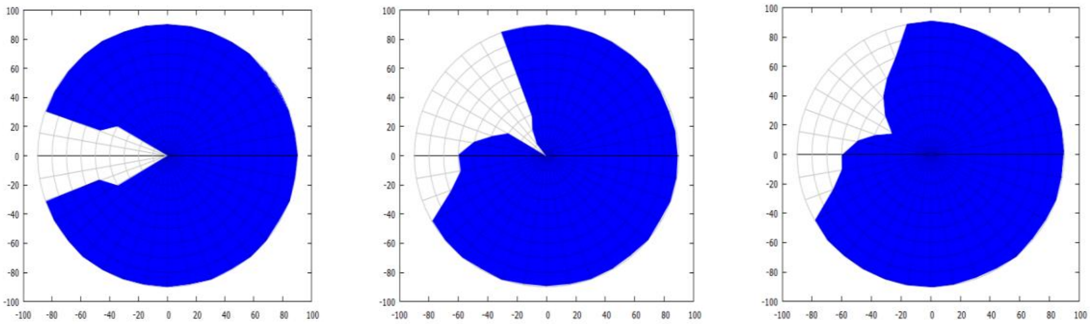

Fig. 1: reachable geometries (polar plot of observation and azimuth angles) depending on the incidence angle (from left to right : incidence 0°, 40° and 80°). The available geometries are in blue.

For every incidence angle, more than two thirds of all the geometries are available to the detection arm. Considering the symmetry relative to the principal plane, the azimuth angle has only to span 180° to cover the equivalent of half a hemisphere around the sample. So, with our goniometer every configuration needed for a BRDF is available. The only limitation is at combinations of high observation angles (> 60°) and large azimuth angles (> 150-160°)

5.2 Maximum incidence angle

This angle is determined by the size of the illumination spots relative to the observation spot. The minimum value of the maximum angle of incidence (worst case) is determined when observation is at nadir or when azimuth is 90° (minimum size of the observation spot). With a illumination spot size of 5.2 mm at nadir and an observation spot size of 20 mm at nadir, this angle is 75°.

At higher observation angles (and azimuths lower than 90°) this maximum angle of incidence increase. For example it is 82.5° for observation at 60° emergence and 0° azimuth.

The illumination angle is also limited by the size of the sample, a smaller sample implying a smaller maximum illumination angle.

We can further increase this maximum incidence angle to 85° (at nadir observation) by keeping only the central fiber optics (masking the 7 surrounding fibres, with a spot size of 1.5 mm, but in the detriment of the illumination flux and thus S/N ratio (roughly decreased by a factor 8).

5.3 Maximum emergence angle

There is no really limitation in emergence angle up to 90°. Even when the observation spot cover part of the sample holder it should introduce no artefact as the modulated illumination is strictly restricted on the sample.

5.4 Minimum phase angle

The main geometric limitation of the system is the phase angle. Reflectance measurements are strongly perturbed at small phase angles because the illumination mirror enters the field of view of the detectors as the phase angle decreases. Different apertures can be installed in front of the detectors to modify the solid angle of detection. A baffle is installed to avoid light to go directly from the fibres to the detectors without being reflected on the mirror. For each of these apertures, the minimum phase angle is measured and represented on figure 2.

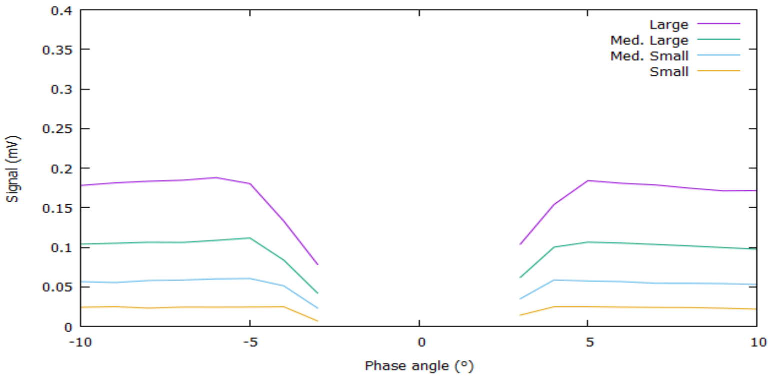

Fig 2: Signal measurement by the detectors passing above the mirror, for the 4 types of apertures

Spectra can be acquired to small phase angles, down to 5° (and 4° with the smallest aperture). For comparison, the previous goniometer SHINE allows spectra down to 8° phase angle for bright samples and 4° for dark samples.

5.5 Sample texture

The SHADOWS spectro-gonio radiometer has been designed with the aim to be able to measure sub-cm samples with small grain sizes.
Grain size is limited by the number of grains illuminated that should be statistically relevant, i.e. typically > 100, in order to probe a wide variety of incidence angles on their facets (if any) exposed at the surface and thus, in particular, average the specular contribution (first external reflection).
With a total illumination spots size of 5.2 mm in diameter the maximum grain size should be about 500 µm and preferably lower for well crystallized samples. When only a single illumination fibre is used (spot size: 1.5 mm) this maximum size is reduced to 150 µm.

5.6 Sample size

The size of the sample is constrained by the size of the spots, the maximum incidence angle measured as well as the grain size and the reflectance of the sample.
For dark samples, typically with REFF < 0.2 over all the measured spectral range, the lateral size of the sample should be just slightly larger (0.5-5 mm depending on grain size) than the size of the illumination spots to account to the limited lateral internal scattering of the light. For such dark samples the thickness should be no more than 10 grain diameters to avoid any photometric contribution of the sample holder to the reflected signal (at level < 0.1%).

Nadir illumination
For nadir illumination the sample size is minimum. As an example, a dark sample with grain size < 25 µm and 50% porosity can have a minimum diameter of 5.7 mm and 0.25 mm in thickness implying a sample volume of only 6.5 mm^3.
Much smaller samples can be measured by keeping only the central fibre optics, thus reducing the nominal sample diameter to 2 mm at nadir illumination, and thus its

volume to 0.8 mm^3, i.e. of the order of a milligram of material. For micron-sized granular samples this amount can be further reduced to less than 0.1 mm^3, i.e. ~ 100 µg, while keeping the photometric accuracy.

Measurements in the principal plane
Measurements of BRDF in the principal plane (i.e. with azimuth angle = 0°) with varying illumination angles require that only the size of the sample along the principal axis should be adapted to the maximum incidence angle measured. It thus require a larger sample volume by a coefficient $1/\cos(\Theta i_{max})$.
For example for a maximum illumination angle of 60° a dark sample with 25 µm grain size should be contained in a sample holder at least 5.7x11 mm wide and 0.25 mm deep (~16 mm^3).

Full BRDF measurements
Measurements with varying illumination and azimuth currently require both dimensions to be increased by $1/\cos(\Theta i_{max})$ and thus a sample volume increased by $1/\cos^2(\Theta i_{max})$. However a future option will allow to fix the position of the sample relative to the illumination, instead to the observation, and will thus allow to have similar sample constraints as for measurements in the principal plane.
For a dark sample with 25 µm grain size the sample holder should be at least 5.7x20.5 mm wide and 0.25 mm deep (~30 mm^3).

Case of bright samples
Due to the longer path length of the light inside the sample (multiple diffusion), brighter samples require more lateral margin (typically 100 x grain size for REFF > 0.7) around the spot and thicker samples (typically 100 x grain size), as for our current spectro-gonio radiometer SHINE designed for large bright samples, in order to satisfy the photometric constraints. The grain size limitation and maximum illumination angles are thus much stronger for such samples, but SHINE can easily measure them if in enough amount.
For example for a maximum illumination angle of 60° a bright sample with 25 µm grain size should be contained in a sample holder 10.2x15.5 mm wide and 2.5 mm deep (~400 mm^3).

6 Calibration & Verification

Authors	Sandra Potin, Olivier Brissaud, Pierre Beck, Bernard Schmitt (manager) (CNRS – IPAG, F) Joanna Gurgurewicz, Arkadiusz Derkowski, Luigi Castaldo (IGS-PAS, PL) Rosario Brunetto, Emmanuel Dartois (CNRS-IAS, F) Cristina de Sanctis, Fabrizio Capaccioni (IAPS, I)

Abstract: This part first presents the nominal set of acquisition parameters defined for the tests and calibration measurements as well as the samples used for them. The reproducibility of the measurements, the sources and range of non-linearity, the S/N ratio, as well as the photometric accuracy are then presented. Several examples of spectra on typical or challenging samples are then presented.

6.1 Definition of a nominal set of acquisition parameters

For the definition of the performance of the system a set of nominal acquisition parameters have been defined. In particular the spectral resolution is set to 10 nm or better (when the worst achievable resolution is < 10 nm) over the whole spectral range as it is a typical value of the recent spectro-imagers onboard space missions or still under development. Performance with different parameters can be calculated from this nominal cases.

Temperature	room
Spectral range	400-4700 nm
gratings	1: 400-680 nm 2: 680-1600 nm 3: 1600-2840 nm 4: 2840-4700 nm
Spectral sampling	10 nm
Spectral resolution	1: 6.4 mm 2: 10 mm 3: 10 mm 4: 10 mm
Slit width	1: 2000 µm 2: 1600 µm 3: 780 µm 4: 380 µm
Angular configuration	Incidence: 0° Emergence: -30° Azimut: 0°
Diameter of illuminated spot	5.2 mm (8 fibers)
Time constant	300 ms
Averaging	10 measurements
Acquisition time	70 minutes

Table 6.1: Nominal measurement conditions

Our nominal sample is: Spectralon reference @ 5% albedo

A modified nominal condition has been also defined with all parameters the same but with a fixed monochromator slit width (1500 µm) and thus with a variable spectral resolution, increasing by factor 2 at each grating (4.8, 9.6, 19.2, 38.4 nm).

The total acquisition time of a single spectrum depends on the spectral range covered, spectral sampling, acquisition time constant and averaging and can be estimated from the acquisition time of a spectrum in nominal conditions. Acquisition time constant and measurement averaging are adapted to the average reflectance of the sample to optimize the total time for a requested spectral resolution and S/N ratio.

Example:

Spectral sampling (nm)	Time constant (ms)	Acquisition time (min)
10	300	70
20	300	35
20	1000	90

Table 6.2: Examples of total measurement time as function of acquisition parameters

Some elements or parameters of the system can be easily changed from the nominal configuration for special needs, such as very small samples (using only 1 or 3 fibers by masking, instead of 8), or higher angular resolution (using) but they generally imply lower S/N and thus compromises on the other parameters.

6.2 Selection of typical and challenging samples

In addition to the reference and challenging samples selected in §3.3 each member of the expert team (CNRS - IPAG, IGS-PAS, CNRS-IAS, IAPS) preselected a set of typical and challenging samples. These samples were presented a partner meeting held in Grenoble in July 2017. A subset of a dozen of the most interesting of them has been selected to test the performances of the instrument over its expected range of operation and sometimes beyond, or to illustrate the quality of the spectra in terms of spectral range and resolution, S/N, …

These samples are:

Natural samples:

- Calcite (CaCO3)
- Basalts (from Udokan and Ogade)
- Lava (San Bartolo, Montiferru/Bonarcado)
- Chondrite meteorite (type CM)
- Irradiated Allende meteorite (with 40 keV He+ and Ar+ ions)
- Clays: Ca-SCa-3 and TMA-SCa-3 (Clay Mineral Database)
- Limestone (Mt Ernici)

Artificial samples:

- Dark Spectralon© 5% calibrated reference (LabSphere™)
- Metal Velvet© (Acktar™)
- Spectral Black© (Acktar™)
- VANTABLACK© aligned carbon nanotubes (VBS1004)
- Aeroglaze© paint Z306 & Z307

6.3 Reproducibility of signal

To characterize signal variations, a series of 20 consecutive spectra was registered on Spectral Black. Figure 6.1 shows all the spectra, as well as the calculated standard deviation.

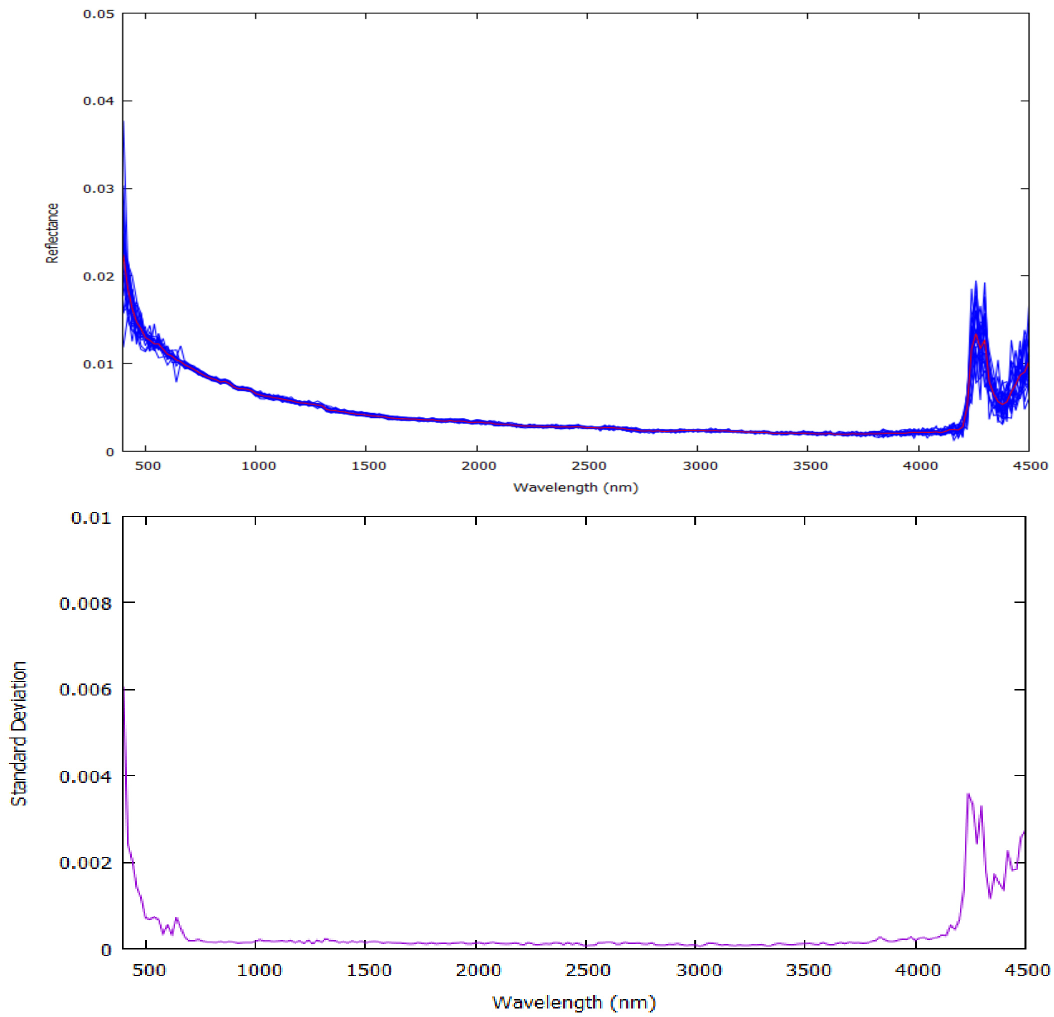

Figure 6.1: 20 spectra of Spectral Black and associated standard deviation. The standard deviation is typically 0.0001 between 650 and 4000 nm. Ambient CO2 fluctuations produce the 'band' around 4250 nm.

The SHADOWS micro spectro-gonio radiometer shows a very good reproducibility over the 400-4500 nm range, and in particular in the 650-4200 nm range where the standard deviation is as low as 0.0001 reflectance unit, even on very dark surfaces (<< 1%). Measurements are possible below 400 nm and above 4500 nm but for somewhat brighter surfaces (> 5-10%).

6.4 S/N ratio

The S/N ratio was measured at two reflectance levels, 1 and 0.05-0.1, in both the nominal conditions with spectral resolution fixed at 10 nm (see 8.1), and in the modified nominal conditions with a time constant of 1s and a fixed monochromator slit width (1500 µm) and thus with a variable spectral resolution, increasing by factor 2 at each grating.

The S/N ratio determined in modified nominal conditions (and with a 1s time constant) with 25 spectra of the Spectralon 5% reference panel, displaying a reflectance increasing from 4% à 500 nm to about 10% at 3700 nm (Fig 6.2), varies between 100 and 9000 in the 450-4650 nm range and drops to about 5 at 350 nm and 15 at 5000 nm (Fig. 6.3).

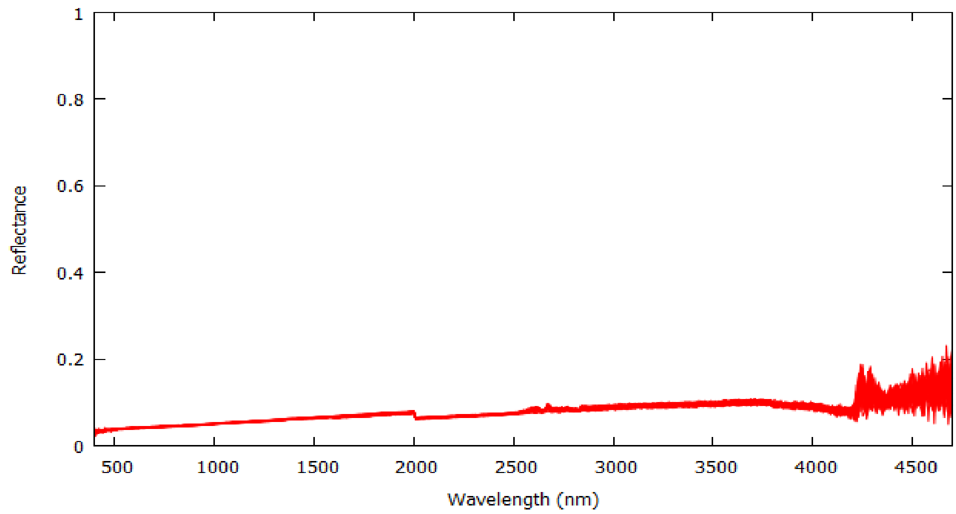

Figure 6.2: Series of 30 spectra of the reference Spectralon© 5%, in nominal conditions (with a fixed spectral resolution of 10 nm).

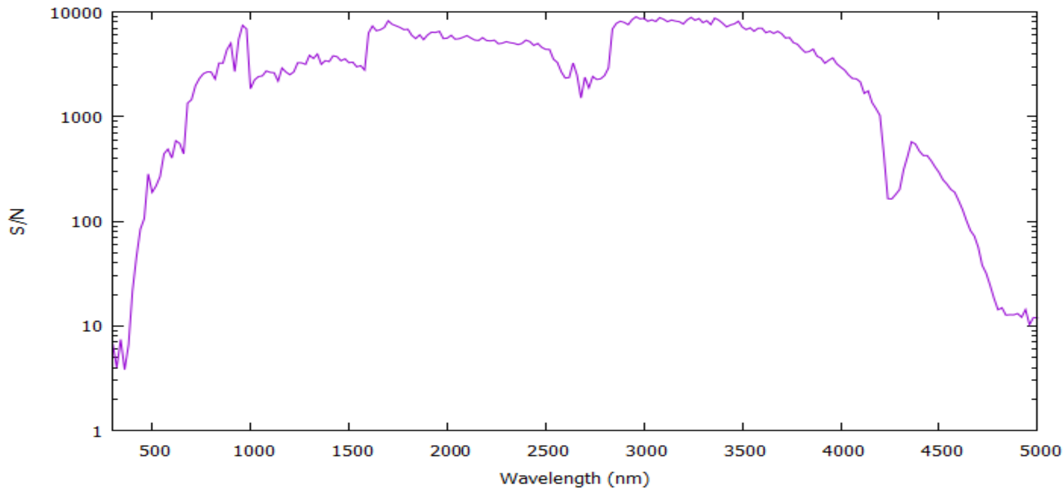

Figure 6.3: Signal-to-Noise ratio in the 350-5000 nm range measured with the Spectralon© 5% target (reflectance 5-10%) in modified nominal conditions with a time constant of 1 s. The decreases around 1700 nm and 4250 nm are due to the stability of H_2O and CO_2 respectively in the ambient air.

The S/N ratio of SHADOWS has been increased very strongly compared to the SHINE spectro-gonio radiometer when scaled to identical measurement conditions and S/N definition (Brissaud et al. 2004, Fig 4), especially in the near-infrared. For example at 1000 nm the S/N is about 60 times higher but at 4000 nm the S/N increased by a factor 250.
If we succeed to recover the missing fibre (to be investigated) we can expect to further increase these values by about 15% (i.e. x70 @ 1000nm and x290 @ 4000 nm).
Additional increases in S/N will be obtained when the instrument will be installed in the dark cold room (-20°C) as this will eliminate all ambient light and all parasite light coming from the source/instrument bench (located outside) and also reduce the thermal emission of the sample (by about a factor 2-2.5).

6.5 Detectors linearity and stray light

As we want to be able to measure very dark materials it was necessary to carefully test and calibrate the detectors at low flux. Low signal measurements can reach the non-linear response zone of the detectors. Added to the possibility of having stray light coming from the monochromator and thermal contribution in the infrared, this can add a non negligible error on the spectra at very low fluxes. It is essential to accurately measure this stray light and to determine the non linearity of the two detectors. Fig. 6.4 represents low signal measurements for the two detectors, along with some signal ranges measured for some dark to very dark surfaces.

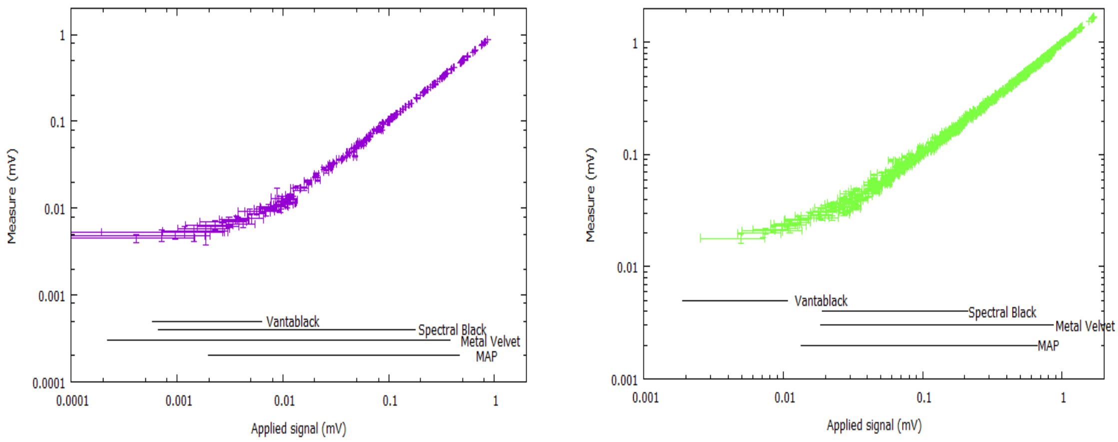

Fig. 6.4: Low signal measurements for the two detectors as a function of input signal (visible: left, purple curve, IR: right, green curve)

The response of the detector shows a very linear behaviour over most of its range but the curve bending at very low fluxes (mostly corresponding to < 1% reflectance) shows a combination of non-linearity from the detectors and an offset from stray light (+ thermal background in the IR) or from electronics. The amount of stray light passing through the monochromator can depend on the high-pass filter used. The amount of thermal contribution depends on wavelength and on the temperature of the room and of the sample. A series of measurements will be performed to determine with high accuracy this offset and non-linearity in order to extend to very low fluxes (outside nominal performances) the high photometric accuracy of the spectra obtained in the nominal conditions.

6.6 Photometric calibration

Comparison with calibrated surfaces

The Spectralon© 5% has a 'calibrated' reflectance (400-2500 nm) provided by Labsphere™ and can be used as a reference target. Figure 6.5 shows the calibrated Spectralon© 5% directional-hemispheric reflectance spectrum together with the one acquired with the SHADOWS micro spectro-gonio radiometer and calibrated using our Spectralon© 99% reference panel (home-made full BRDF calibrated). The relative difference of about 4% (absolute reflectance difference < 0.003) between the two spectra is due to the different illumination-observation geometries and measurement techniques as we measured this reflectance at 0° incidence and 30° emergence while Labsphere™ measured the directional-hemispheric reflectance at 5° incidence. From an absolute calibration of the Spectralon© 99% 'reference' panel performed with SHINE by integrating a full BRDF of this material we already demonstrated that the Spectralon© 99% 'reference' panel has a reflectance departing from lambertian behaviour and a directional-hemispheric albedo most probably overestimated by 2-3% (Bonnefoy 2000, thesis) due to the measurement inside an integrating sphere. This seems also the case for the Spectralon© 5% panel. So we expect a similar 'overestimation' of the reflectance of the Spectralon© 5% 'reference target'. A full calibration of the BRDF of this target will be needed to warrant an 'absolute' calibration better than 1%.

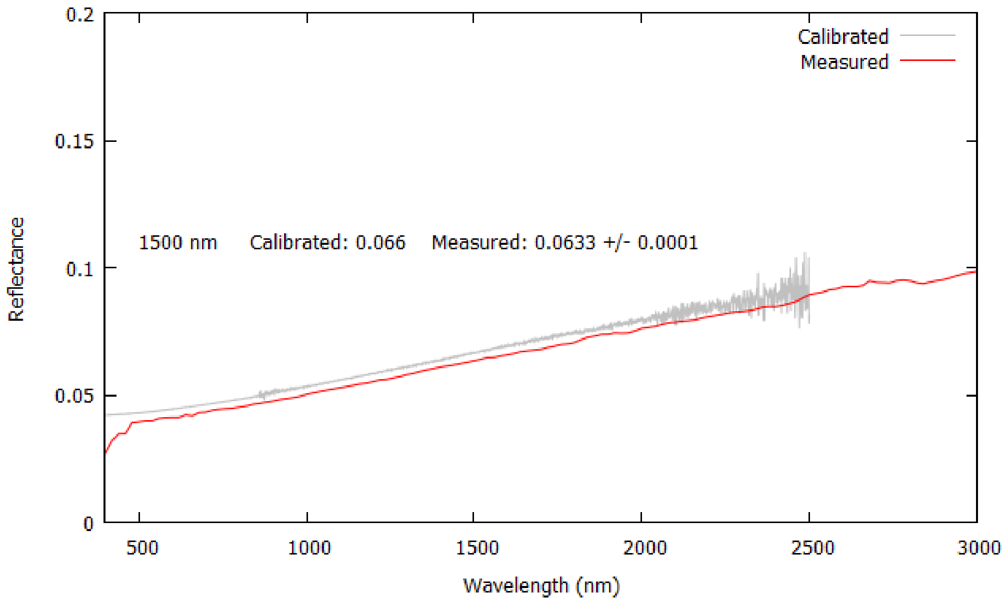

Figure 6.5: Comparison between the directional-hemispheric reflectance spectrum of a Spectralon 5% reference panel, as provided by Labsphere™, and a bidirectional reflectance spectrum of the same panel measured with SHADOWS in nominal conditions (Θi=0, Θe=30°). The relative difference of about 4% between the two measurements is due to the different geometries and to a probable overestimation by Labsphere™ of the reflectance of the target.

Comparison with original spectro-gonio radiometer

In order to have an independent look at the photometry accuracy of the SHADOWS micro spectro-gonio radiometer we compared various measurements made in identical conditions both with SHADOWS and with the well calibrated original SHINE spectro-gonio radiometer.

Figure 6.6 shows two spectra of an Aeroglaze© Z307 paint (normal reflectance ~3-4%), one measured with SHINE and the other with SHADOWS. The SHADOWS micro spectro-gonio radiometer shows a very good photometric accuracy, better than 0.002 in reflectance, and much less noise (pic-to-peak noise < 0.001) than the original spectro-gonio radiometer on dark surfaces (pic-to-peak noise ~ 0.01)

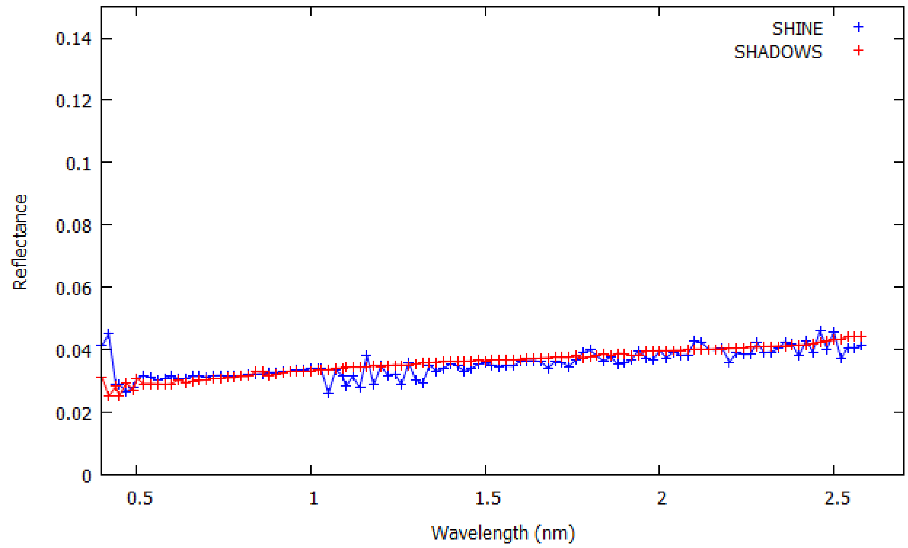

Fig. 6.6: Comparison of spectra of the same dark surface (Aeroglaze© Z307 paint) acquired with SHINE (blue) and the new SHADOWS spectro-gonio radiometer (red) in the modified nominal conditions.

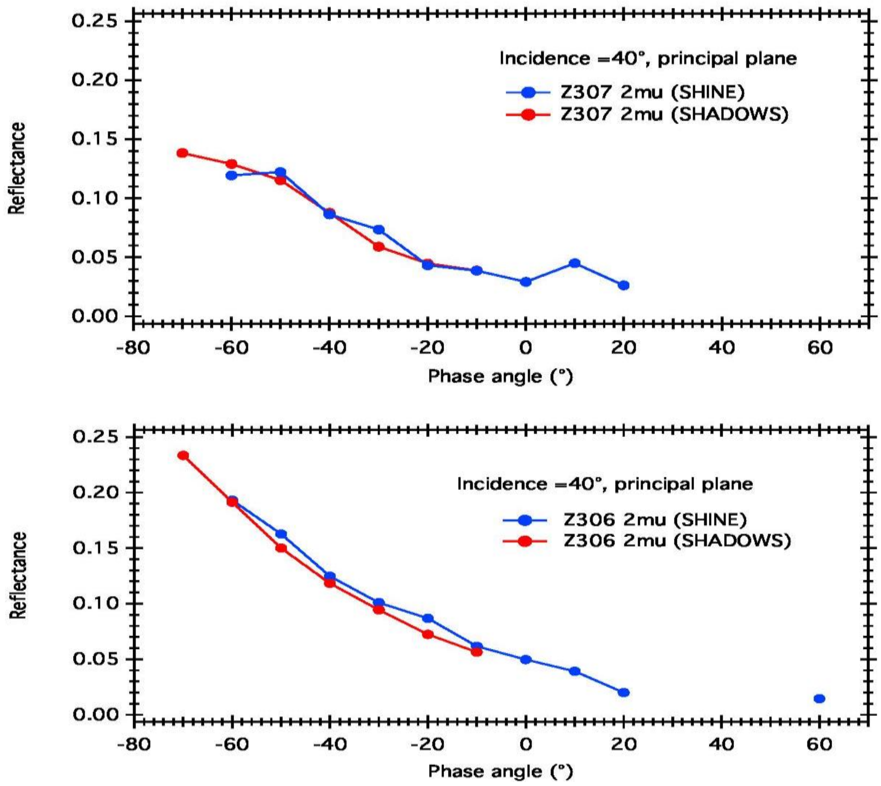

Fig. 6.7: Comparison of the BRDF at 2000 nm for Θi=40° of the same dark surface (top: Aeroglaze© Z307 paint, bottom: Aeroglaze© Z306 paint) acquired with SHINE (blue) and SHADOWS (red)

Bidirectional measurements on this Aeroglaze© paint (Z307) and a similar one (Z306) clearly confirm that the photometric calibration of SHADOWS is excellent with departure from SHINE within the noise level of the SHINE reference instrument (~ 0.01) (Fig. 6.7). The BRDF curves obtained with SHADOWS are extremely smooth confirming the high S/N. But the main limitation to cross calibrate the two instruments at such low reflectance level is the low S/N of the SHINE instrument despite its boosted (and very long) acquisition parameters (time constant, total time, …).

We are thus confident that SHADOWS has already an absolute photometric accuracy better than 1% and a relative photometric accuracy, from wavelength to wavelength and between various geometries, better than 0.5%.

6.7 Examples of measurements on typical and challenging samples

In this section we show a series of spectra of the selected samples to illustrate the quality of the spectra in terms of spectral range and resolution, S/N and photometric accuracy, … for a variety of typical to very challenging samples.

All spectra are recorded in the modified nominal conditions (see § 6.1).

Challenging dark samples

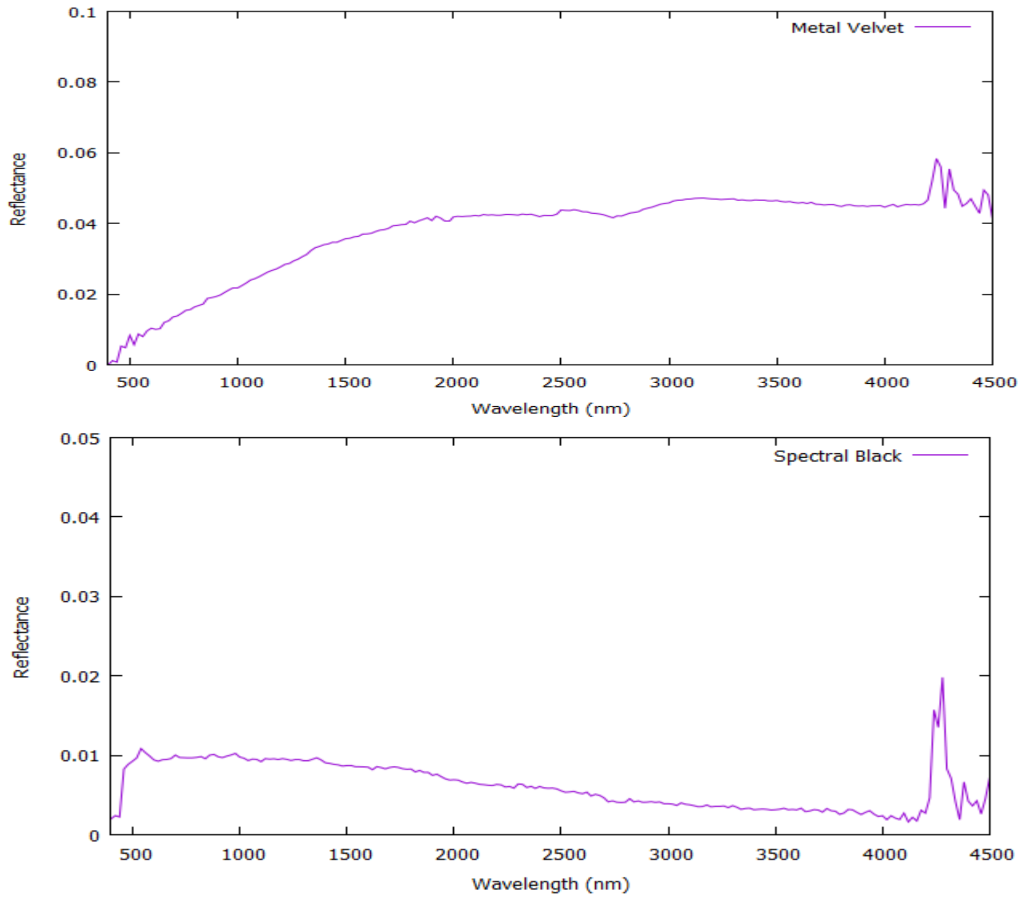

Figure 6.8a: Measurements of two dark (Black MetalVelvet,©, top) and very dark samples (Spectral Black©, bottom) in nominal conditions. Most weak spectral variations are noise (except between 1800 and 3000 nm for Metal Velvet).

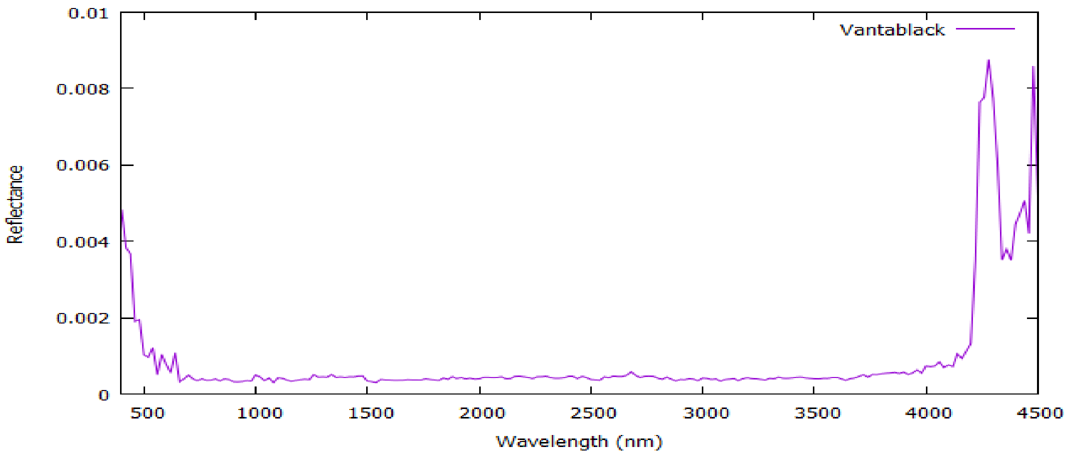

Figure 6.8b: Measurements of an extremely dark sample (VANTABLACK©) in nominal conditions (except we used a 1s time constant). It confirms that peak-to-peak noise is less than ±0.00005 in reflectance, except below 650 nm and above 4200 nm where it increases progressively together with an increase of the reflectance due to still uncorrected non-linearity at very very low signal. It also confirms the ability of SHADOWS to measure reflectance as low as 0.00035 with still acceptable S/N !

Typical samples

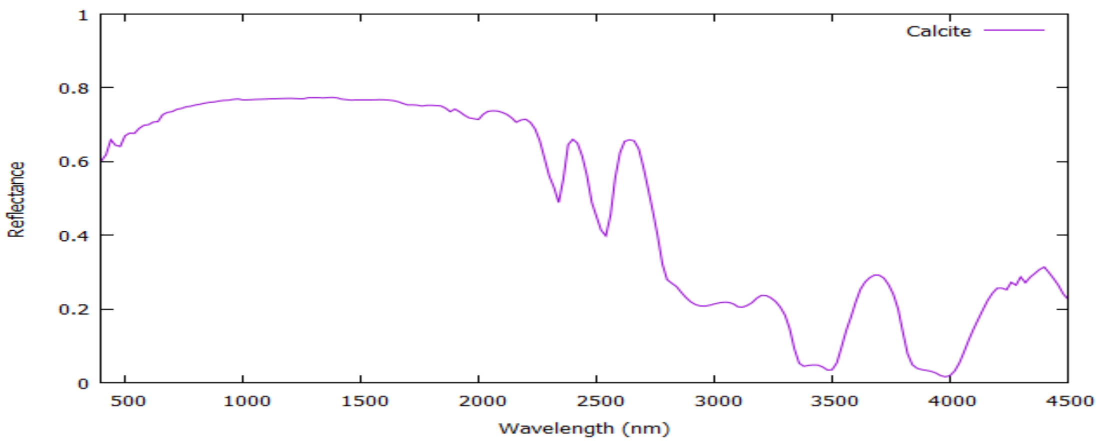

Fig. 6.9: Spectrum of polycrystalline Calcite (CaCO3) in the 400-4500 nm range. All small spectral variations are real except around 4200 nm (atm CO2 variations) and possibly below 650 nm, showing the ability of SHADOWS to detect very weak spectral features.

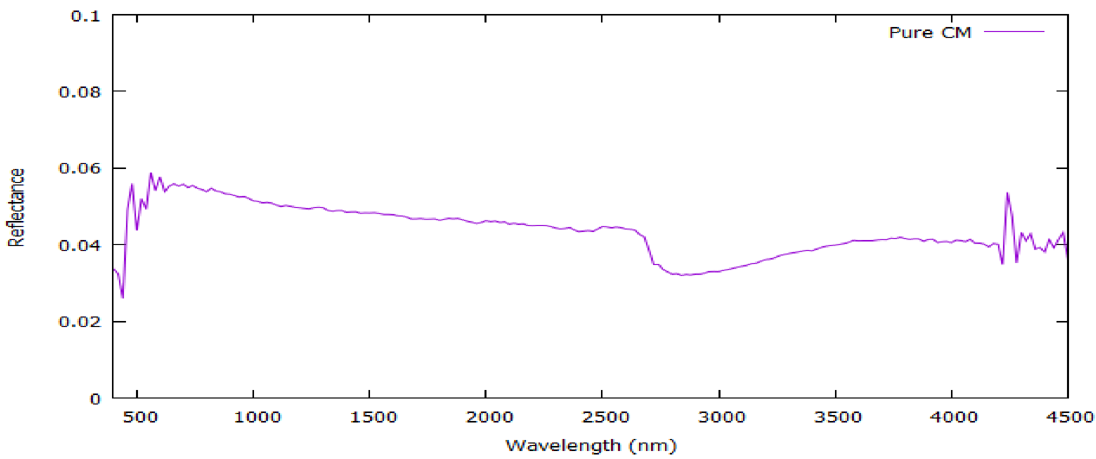

Fig. 6.10: Spectrum of a CM carbonaceous chondrite in the 400-4500 nm range. Most small spectral variations are real, except around 4200 nm (atm CO2 variations) and below 650 nm, showing the ability of SHADOWS to provide high S/N measurements of very dark (3-6%) samples over an extended spectral range.

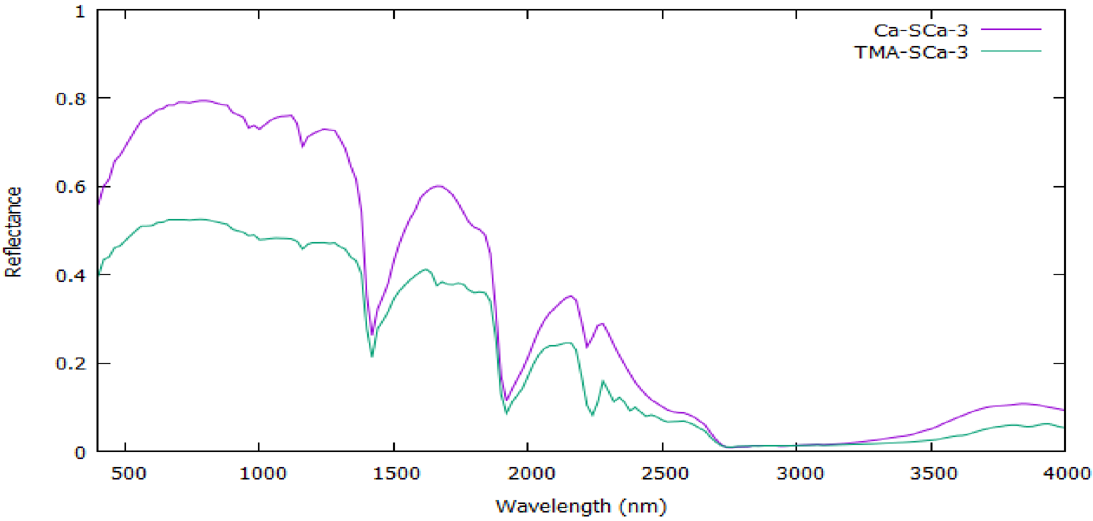

Fig. 6.11: Spectrum of two clays as sub-micronic powder in the 400-4000 nm range. All small spectral variations are real showing the ability of SHADOWS to detect very weak and narrow spectral features.

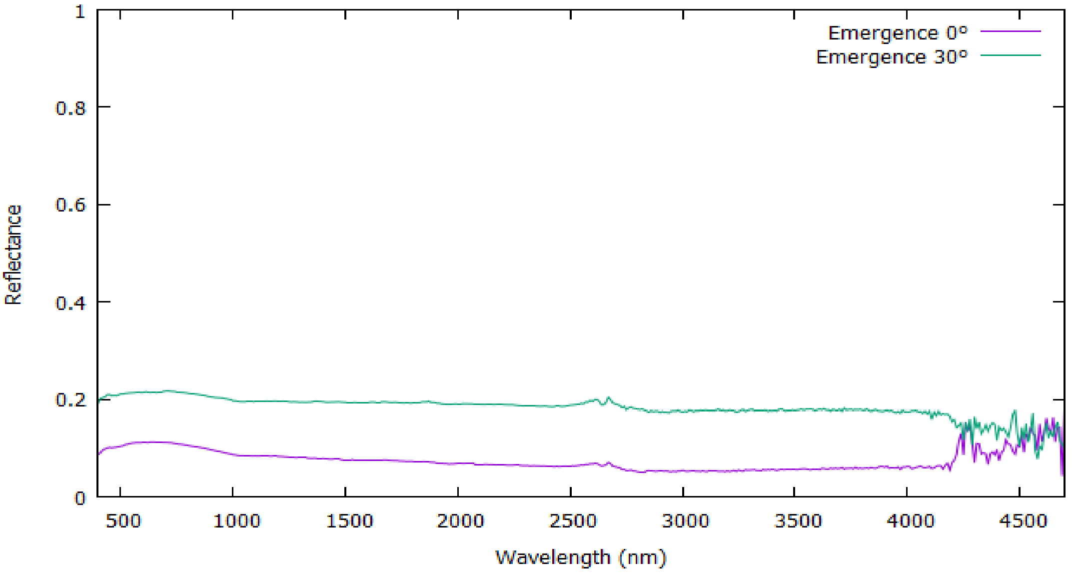

Fig 6.12: Spectra between 400 and 4700 nm of a compact basalt slide sample at incidence 30° and emergence 0° (purple) and 30° (green). The configuration incidence 30° - emergence 30° corresponds to the specular reflection leading to an increased reflectance as can be seen on the next figure (right).

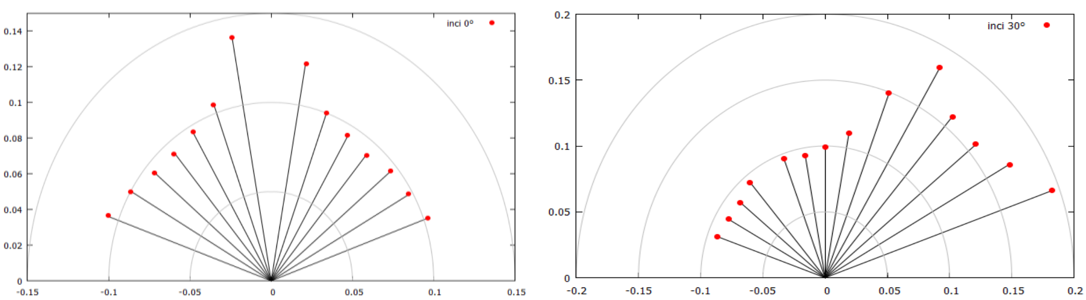

Fig 6.13: BRDF at 1200 nm and in the principal plane of a compact basalt slide sample, at incidence Θi=0° (left) and 30° (right) and emergence angles between -70° and 70°. These figures shows in particular the strong effect of specular reflection coupled to a strong forward scattering.

7 Conclusion

The whole expected performances of the system in terms of spectral range, illumination/observation geometries, Signal-to-Noise and photometric accuracy are met in the nominal conditions and in several cases clearly exceeded our expectations (S/N in the NIR, lowest detectable reflectance, …).

In particular the main improvements relative to our current SHINE spectro-gonio radiometer are:

- **Minimum measurable reflectance:** **< 0.0003**
target was: < 0.01
SHINE: > 0.2 or much longer time below

- **Gain in S/N by a factor:** **> 60 in visible, > 250 in NIR**
target was: > 25
relative to SHINE

- **Minimum volume of sample:** **< 1 mm^3**
target was: < a few mm^3
SHINE: > 0.5 cm^3

- **Control/acquisition software:** **much improved versatility** of the modes of acquisition, parameter choices and results display

Absolute photometric accuracy is met down to 1% reflectance. For lower reflectance of the surface a proper calibration of some non-linearity and offset will be needed.
Given the very high S/N ratio in the nominal conditions (up to 10000 and > 200 over the 400-4200 nm range) even for samples with albedo as low as 5-10% it will be possible to optimize the measurement parameters in some wavelength ranges, depending on the spectral properties of the sample, in order to reduce by a large factor (> 3, up to 10?) the acquisition time and thus further increase the number of wavelengths or geometries that can be measured within one day for a spectral BRDF 4D-cube.

We are thus ready to deliver the whole SHADOWS instrument, tested and calibrated in its nominal operating mode.

8 Deliverable

The SHADOWS micro spectro-gonio radiometer will be available in its nominal mode and a few extended/special modes for Trans-National Access (TA2/CSS) at the next TA call #4 in November 2017. However we are currently analysing which of the already selected proposals of TA call #3 (March 2017) on SHINE may already benefit partly or fully of the improved performance of the SHADOWS instrument. These TA sessions are planned between October 2017 and March 2018.

- The public description of the SHADOWS micro spectro-gonio radiometer is released at the Cold Surfaces Spectroscopy web site: https://cold-spectro.sshade.eu/micro-spectro-gonio-radiometer/
- A first presentation of the SHADOWS micro spectro-gonio radiometer (http://meetingorganizer.copernicus.org/EPSC2017/EPSC2017-243.pdf) and of its use within the Cold Surface Spectroscopy Facility at IPAG (http://meetingorganizer.copernicus.org/EPSC2017/EPSC2017-468.pdf) will be done at the EPSC 2017 conference.

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9 Future extensions of the capabilities of SHADOWS

We propose to continue or undertake in the coming years the following main developments of extensions or improvements beyond the nominal SHADOWS instrument, also depending on specific user requests. These extensions will be partly done in the frame of an IDEX - Initiatives de Recherche Stratégiques (IRS) project of the University of Grenoble Alpes (formerly UJF) including a PhD fellowship (Sandra Potin).

9.1 Future instrument developments

- Integration of the instrument in the cold chamber (-20°C)
- Further reduction of the polarization of the illumination beam
- Addition of several options of masking the fibers
- Development of a set of specialized and optimized micro-sample holders (depending on user requirements)
- Addition of an option to fix the position of the sample relative to the illumination or to the observation azimuth
- Development of polarization measurement option
- Development of an option to measure at small phase angles
- Development of an environmental cell cooled with a very low T cryostat (down to 77K or less)

9.2 Future measurement configurations developments

- Tests and improvement of extended ranges (< 400 nm & > 4700 nm)
- Polarization measurement option
- Small angle measurement option
- Goniometric transmission measurement option

9.3 Future calibration developments

- Absolute BRDF calibration of the Spectralon© 5% reference panel

- Correction of non-linearity and offset for reflectance < 1%
- Determination of the evolution of the S/N for a set of specific, non-nominal, configurations
- Tests and calibrations in the cold chamber at -20°C

9.4 Future software developments

- Addition of an automatic optimization of the electronic gain, time constant and integration time for each wavelength
- Software to estimate the measurement time as a function of an user requirement in term of spectral range, sampling, resolution, number of geometries, sample albedo and expected S/N (mostly to help for TA users)
- The SHADOWS control/acquisition software will be duplicated and adapted to the 'old' SHINE instrument to improve its versatility