# Influence of the partially polarized natural light on the spectral ground truth measurements

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# Abstract

In previous works, it was found that the polarization alters the spectrometers spectral response. Considering that the natural light is always partially polarized (reflection, Rayleigh scattering, etc.), some concerns were raised about the accuracy and variability of the outdoor measurement, particularly for trial ground truth measurements. This report demonstrates that, in some circumstances, the measurement can be affected by the polarization; direct sun reflection and reflection from close objects must be avoided. However, measuring surfaces at right angle (as suggested in usual calibration procedure) minimized the alteration of the spectral response of the sensors. Hence, by respecting rigorously the measurement protocol, the ground truth data is valid. But, ground truth measurements acquired with a slant-path angle are more or less accurate; an important proportion of the signal variability is due to the polarization.

# Significance to defence and security

For the development of hyperspectral sensing technologies, several measurement trials are done for the acquisition of airborne and ground truth data. This data must be accurate as possible because analysis and processing technique are developed using this data. The measured data has always suffer of a high level of variation due by unknown causes: target inhomogeneity, illumination variation due to clouds passage, etc. In this report, the polarization and the sensitivity of the spectrometer to the polarization angle have been identified as one of these cause of variability. Knowing this source of measurement artefacts, we can now 1) define a better acquisition protocol and get better data or 2) at least avoid the measurement conditions that favorise the generation of measurement artefacts. The information presented in this report contributes to the development of the hyperspectral program.

# Résumé

Lors de travaux précédents, on a trouvé que la polarisation altère la réponse spectrale des spectromètres. Considérant que la lumière naturelle est toujours partiellement polarisée (réflexion, diffusion de Rayleigh, etc.), quelques inquiétudes ont été soulevées à propos de la précision et variabilité de mesures faites à l'extérieure, particulièrement pour les données vérités acquises au sol durant les campagnes de mesures. Ce rapport démontre que, dans certaines circonstances, les mesures peuvent être affectées par la polarisation; les réflexions directes du soleil et les réflexions par des objets proches doivent être évitées. Cependant, mesurer les surfaces à angle droit (tel que suggéré dans les procédures de calibration usuelles) minimise l'altération de la réponse spectrale des capteurs. Ainsi, en respectant rigoureusement le protocole de mesure, les données vérités sont valides. Mais les mesures de données vérités acquises à angle sont plus ou moins précises; une proportion importante de la variabilité du signal est dû à la polarisation.


# Importance pour la défense et la sécurité

Pour le développement des technologies de capture hyperspectrale, plusieurs campagnes de mesure sont faites pour acquérir des données aéroportées et des données vérités acquises au sol. Ces données doivent être aussi précises que possible parce-que les analyses et techniques de traitements sont développées en utilisant ces données. Les données mesurées ont toujours souffert d'un haut degré de variation dû à des causes inconnues; cible non-homogène, variation de l'illumination dû au passage des nuages, etc. Dans ce rapport, la polarisation et la sensibilité des spectromètres à l'angle de la polarisation ont été identifiées comme étant une de ces causes de variabilité. Connaissant cette source d'artéfacts de mesure, nous pouvons maintenant 1) définir un meilleur protocole d'acquisition et obtenir de meilleurs données ou 2) au moins éviter les conditions de mesure qui favorisent la génération d'artéfacts de mesure. Les informations présentées dans ce rapport contribuent au développement du programme hyperspectral.

# Table of contents


Abstract . . . . . i
Significance to defence and security . . . . . i
Résumé . . . . . ii
Importance pour la défense et la sécurité . . . . . ii
Table of contents . . . . . iii
List of figures. . . . . . iv
1 Introduction . . . . . 1
1.1 Sources of natural polarization . . . . . 1
1.2 Signal variability . . . . . 1
2 The experiment . . . . . 3
2.1 Hypothesis . . . . . 3
2.2 Experimental setup . . . . . 3
2.3 Instrument stability: tested with an integrating sphere . . . . . 5
2.4 Instrument response: tested with an integrating sphere and a polarizer . . . . . 5
2.5 Optical axis alignment error . . . . . 5
2.6 The target . . . . . 6
2.7 Blue sky . . . . . 6
3 Measurement series . . . . . 7
4 Measurement interpretation . . . . . 9
4.1 Painted plate . . . . . 9
4.2 Blue sky . . . . . 16
5 Conclusion . . . . . 17
References . . . . . 19

# List of figures


Figure 1: Fixation of the optical fiber inside the cylinder. . . . . . . . . . . . . . . 4

Figure 2: Rotating barrel allowing the rotation of the spectrometer on its optical axis. Here the barrel is facing the sun, i.e., $\phi_i$=180°. . . . . . . . . . . . . . 4

Figure 3: The measured surface is a 4x8 feet flat panel painted with gray-green flat paint. The panel is large enough to fill the spectrometer footprint at every viewing angle. . . . . . . . . . . . . . . . . . . . . . . . . . . 6

Figure 4: Geometry of measurement setups. . . . . . . . . . . . . . . . . . . . . . 7

Figure 5: Example of spectral measurements for two rotation angles. At the beginning, the spectrum is flat (a white reference is done). When the cylinder rotates on its axis, the spectrum changes. This is this change $I(\delta,\lambda)/I_0(\lambda)$, versus the cylinder rotation 'δ', that is reported in the following figures for various wavelengths. . . . . . . . . . . . . . . . . . . . . . . . . . 8

Figure 6: Signal variation caused by the rotation 'δ' of the spectrometer on the optical axis for nadir observation. The sun incident angle is $\theta_I$ = 50°, the nadir observation angle is $\theta_r$ = 0° and the azimuth is $\phi_r$ = 180° (face to the sun). . . . 10

Figure 7: Signal variation with rotation in forward direction (in the principal plane). . . 12

Figure 8: Signal variation with rotation in direction perpendicular to the incidence plane. Line 'A' (1334 nm) is insensitive to polarization (360° cycle). Line 'E' is extremely sensitive to the polarization and line 'D' has a polarization shift of 90° relatively to line 'E'. . . . . . . . . . . . . . . . . . . . . . . . 13

Figure 9: Polarization sensitivity of the ASD spectrometers. The red line is the mean spectra that will be registered by the ASD spectrometer if it was not sensitive to the polarization. Dash lines indicate the wavelengths which are used for presenting the results of the described experiment. Green and blue plots are the spectrometer responses for various polarization angles. . . . . . . . . . . 14

Figure 10: Characteristic features of the polarization: 180° cycle and, the inverse behavior of the signals for the SWIR wavelengths smaller than 1334 nm (i.e., 1085 nm, 1300 nm) to those with higher wavelength (i.e., 1500 nm, 1700 nm, 2100 nm, 2150 nm). . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

Figure 11: Raw spectrum of the blue sky. . . . . . . . . . . . . . . . . . . . . . 16

# 1 Introduction

Recent experiments [1] demonstrated that the spectrometers are very sensitive to the polarization. The measurements, done with the ASD FieldSpec spectrometer, can change by as much as 50% in SWIR2 (by changing the polarization angle). Also, in presence of the polarized light, bending the optical fiber produces unpredictable changes of the spectral response [1]. This spectrometer sensitivity to the light polarisation is not specific to the ASD spectrometer we used. In fact, all spectrometers use gratings, beam splitters or refractive components, which are sensitive to the polarization.

In natural environment, the light is always partially polarized. We have a tendency to ignore it, considering that this does not affect our measurement. But, knowing this, and knowing the spectrometer sensitivity to the polarized light, this raise the question: **How accurate are the ground truth measurements done in trials?**

## 1.1 Sources of natural polarization

The ground truth measurements are taken under natural irradiation conditions (‘illumination’ is used for the visible band only. The natural irradiation is already partially polarized. Furthermore, the measured surface, if not adequately manipulated, can also generate polarization when it is measured at tilt angles (particularly close to the Brewster’s angle).

The downwelling irradiance is the sum of the direct sun light and a diffuse component. The direct sun irradiance is unpolarized but the diffuse component is polarized. Actually, the diffused component of the downwelling irradiance (blue sky) is generated by scattering of the incident sunlight by atmospheric constituents (gas molecules (Rayleigh-scattering), aerosol (Mie-scattering)). To this downwelling component, the backscattering of the upwelling radiation reflected from the ground can also be considered. These interactions induce a polarized component. Other sources of polarized light are the ambient irradiation, i.e., the parasitic reflections from near surfaces (e.g., smooth water surfaces, building walls, shiny objects).

## 1.2 Signal variability

During field campaigns, the measured target is under natural irradiation conditions. It is known that the measurement variability is quite high because of several factors: atmospheric conditions, wind, proximity of the operator, clouds, etc. With a good measurement protocol, most of these artefacts can be nullified. This is why measurements are always done relatively to a calibrated surface of reference; the Spectralon. By measuring the Spectralon and the target surface in exactly the same conditions, the surface comparison provides the exact surface reflectance.

However, to these factors, we must now add the interaction between the polarization and the spectrometer;

- the incident irradiation on the target can be polarized,
- the reflection on the target (at tilt angles) polarizes the light,

– the polarizations caused by the reflection on the target and on the Spectralon are not the same, and
– the spectrometer is sensitive to the polarization axis of the light that enters into the spectrometer entrance.

This brings an additional signal variability that can appear between the calibration step (Spectralon measurement) and the target measurement (change of detector position, optical fiber bending, tilted target, etc.).

This raises other important questions concerning the optimal conditions of spectra acquisition in order to minimize the effect of the instrument polarization sensitivity:

1. Is the measurement protocol adequate?

2. How much variation is produced by the ‘uncontrolled’ polarization?

Taking into account the polarization sensitivity of the ASD FieldSpec spectrometer, several experiments were made in order to test its potential impact on the field measurement accuracy.

# 2 The experiment

The goal of the experiments was the evaluation of the measurement variability due to ASD FieldSpec spectrometer's sensitivity to polarization.

As it was demonstrated in previous study [1], the ASD FieldSpec spectrometer's spectral response, as all other spectrometer using gratings, scan mirrors or beam splitters, is affected by the light polarization. In other words, the spectrometer has a privileged polarization axis where it is more sensitive. Moreover, the bending of the optical fiber (with the ASD spectrometer) also changes the spectral response by rotating the polarization axis at the exit of the optical fiber.

Therefore, the experiment consist in measuring signal variability 1) by rotating the instrument on the optical axis while it is measuring a uniform signal that may be partially polarized and 2) by fixing the optical fiber relative to the instrument in order to prevent the unpredictable changes of probed spectra due to its displacements during measurements.

## 2.1 Hypothesis

When the instrument is rotated on its optical axis, the signal measurement changes. After completing a 360° rotation, the measurement must be again similar to the starting measurement. With the rotation, the signal should show a sinusoidal pattern variation. Two patterns can be measured:

1. the signal change over a 180° cycle: This means that polarization is involved; rotating a polarizer over a 180° cycle has the same effect.

2. the signal change over a 360° cycle: This means an error in optical axis alignment or instrument mechanics sensitive to the instrument rotation. An axis alignment error will produce a FOV (Field of view) variation, sensing not exactly the same part of the target.

## 2.2 Experimental setup

Taking into account the instrument polarization sensitivity and the polarization of the natural irradiation, a simple experimental setup was prepared with the following arrangements:

1. The optical fiber was toughly fixed to the spectrometer body. Bending (or changing the bending) the optical fiber causes an unpredictable rotation of the polarization axis, thus, this changes of the spectral response of the instrument [1]. The fixing of the optical fiber prevent this behaviour.

2. The spectrometer was put into a cylinder which could be rotated around its longitude axis. The setup is shown in the Fig. 2.

3. Optical fiber input was positioned on the cylinder axis, assuring that the FOV axis isn't off-axis, minimizing footprint variations on the target (when rotating the cylinder).

This setup allows observing the same sample area under the same irradiation and observation conditions, but for different orientation of the privileged polarization axis of the instrument. It is supposed that in the case where the probed light is polarized, this polarization will interact with the instrument polarization axis and a double cycle (over a 360° rotation) will be observed in the variation of the measured signal.


Optical fiber entrance on the cylinder axis

Optical fiber fixed to the spectrometer

***Figure 1:*** *Fixation of the optical fiber inside the cylinder.*

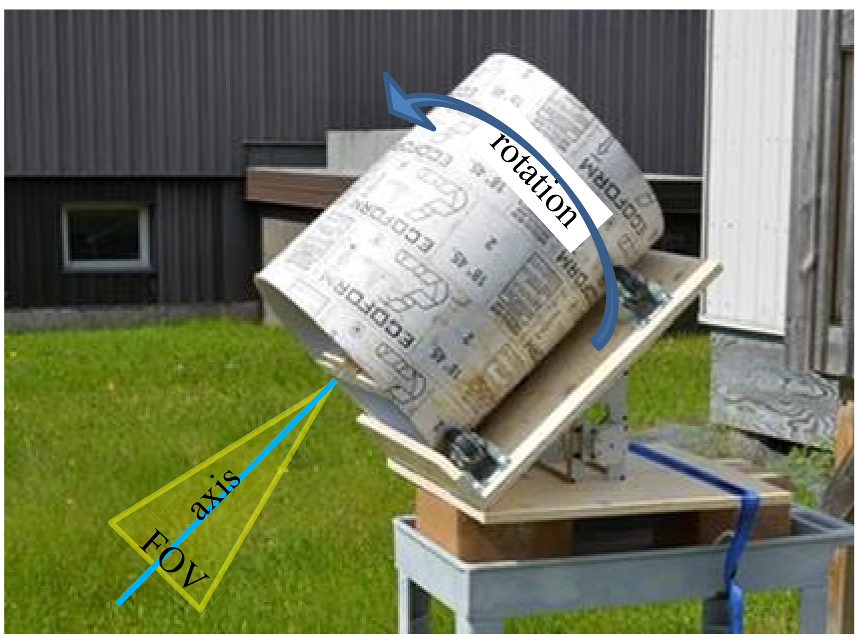



***Figure 2:*** *Rotating barrel allowing the rotation of the spectrometer on its optical axis. Here the barrel is facing the sun, i.e., $\phi_i$=180°.*

## 2.3 Instrument stability: tested with an integrating sphere

We first tested the instrument with an integrating sphere, which is an unpolarised light source. This was to be sure that the instrument is stable when it is rotated, i.e., there is no signal variations caused by mechanical parts (like the oscillating gratings) that could be affected by their orientations. Rotating the instrument in front of this light source did not provoke any change in the measured signal.

## 2.4 Instrument response: tested with an integrating sphere and a polarizer

We also tested the effect of the instrument rotation in the presence of the completely polarized light, i.e., a polarizer was put between the instrument and the integrating sphere. The result was equivalent to those obtained with rotating polarizer in front of the fixed spectrometer [1]. The change of spectral response is shown in Fig. 9.

## 2.5 Optical axis alignment error

This is a low cost experimental setup. The wooden setup was judge accurate enough for the experiment. But the first measurement showed that the misalignment between the optical axis and the barrel axis could be a major source of measurement variations. The wooden setup was adjusted to minimize this alignment error. The final misalignment error is estimated to be less than one degree.

From Ref. 2, we know that the optical fiber has a measured total FOV of 26° (from null sensitivity from the left side to the null sensitivity on the right side). But the sensitivity profile has a Gaussian shape. Hence, the real effective FOV is about 12°, i.e., from the left to the right side at half maximum of sensitivity. This central 12° of FOV is responsible for 85% of the detected signal. The remaining FOV (between 12° and 26°) has only a marginal sensitivity.

The alignment of the optical-fiber bundle FOV was measured in laboratory. First, the barrel axis was pointed toward a specific target. The alignment was mechanically verified with a carpenter's square. Then, a laser point source was displaced in the optical fiber bundle FOV and the extreme positions were noted and measured with a ruler. Then the barrel was rotated by 180°, alignment verified and the extreme positions were measured again. From these measurements, we deduced two pointing errors:

1. approximately one degree off axis error between the alignment of the optical fiber bundle and the rotating barrel axis,

2. approximately one degree off axis error between the optical fiber FOV axis and the physical axis of the optical fiber bundle.

## 2.6 The target

As test sample we used a painted metal plate (Kaki) put horizontally on the ground. The reflected incident beam from the smooth flat surface will be partially linearly polarized with the dominant electric vector perpendicular (polarization 'S') to the plane of incidence.

***Figure 3:*** *The measured surface is a 4x8 feet flat panel painted with gray-green flat paint. The panel is large enough to fill the spectrometer footprint at every viewing angle.*

## 2.7 Blue sky

The direct sun irradiance is unpolarised. However, the sun light scattered (Rayleigh scattering) by the atmosphere's constituents become polarized. The plane of polarization of scattered light is perpendicular to the plane containing the incident and the scattered ray [7]. In the spectral band covered by ASD spectrometers (350 nm to 2500 nm), Rayleigh scattering is a strong source of polarization [5]. The scattering creates a band of maximum polarization at angles 90° away to the Sun. For a very clear sky, the degree of linear polarization in this band can reach at least 90%, but it typically is lower due to molecular anisotropy [4] [6]. Away from the 90° arc of maximum polarization, the degree of polarization decreases smoothly, reaching 0% near the Sun or in the opposite direction [4]. Unpolarised incident light scattered in forward direction continues to be unpolarised [7]. The sky polarization pattern will move across the sky with the change of the Sun position [6].

Using this known sky polarization pattern, we tested the responsivity of our instrument to the sky polarization in two directions: in the principal plane (azimuth: $\phi_r = 0°$, sun behind the sensor) and in orthogonal direction ($\phi_r = 90°$, sensor perpendicular to the sun) and with an angle to zenith of 60°. The Sun zenith angle was also near 40°.

# 3 Measurement series

The measurements made for the painted plate were taken for two instrument orientations (Fig. 4):

- Instrument acquire the forward reflection (facing the sun, $\phi = 180°$) from the sample (instrument is in the principal plane)
- Instrument put in 90° to the principal plane (side position)

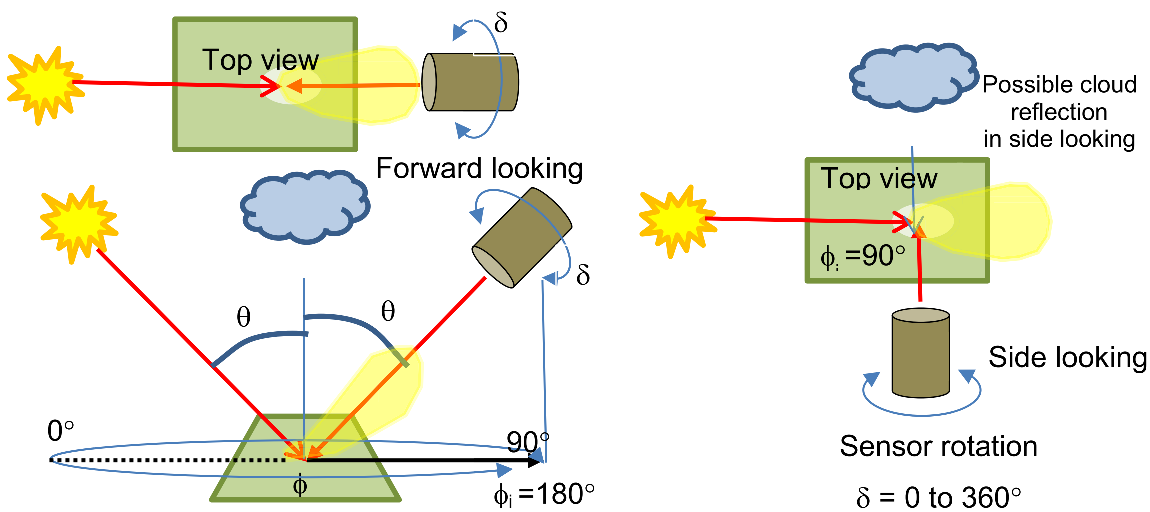



***Figure 4:** Geometry of measurement setups.*

The spectra were taken for nine positions of instrument orientation around its optical axis varying from $\delta = 0°$ to 360° with increment of 45°, and for different pointing nadir angles, i.e., for $\theta_r = 0°$(nadir), 31°, 45° and 56°. The sun nadir incident angle is approximatively 50°, its exact elevation is indicated in the graphs off Figs, 6, 7 and 8.

When starting a measurement series, the spectrometer stares at the scene and a white reference is set is acquired ($\delta$=0,t=0). This means the first spectrum is recorded as the spectrum of reference and all following measurements are divided by this first spectrum. The first spectrum of reference is divided by itself, so the displayed spectrum has a unit value (the white reference). The following displayed spectra (acquired in white reference mode) show only the variation of the spectral response, respectively to the spectrum of reference.

Hence the recorded spectra are the ratio: I ($\delta$(t)) / I($\delta$=0,t=0) (simply noted $I/I_0$). Examples are given in Fig. 5 for two different cylinder rotation angles. One may note that some wavebands are very noisy. This is caused by atmospheric absorption. These bands are ignored in the following analysis. But the global shape (slope) of the curves is clearly different for the two rotation angles. This indicates a polarization or an off-axis FOV effect. This is the 180° or 360° cycle pattern that will identify the cause of the variation. Note that after the acquisition of the white reference, the continuous spectrometer reading is always changing. The raison is that the blue sky is not a perfect blue sky: there are tinny clouds that cause illumination variations. This contributes to add variability in the measurements. We had to wait that the signal stabilized before starting a measurement series (better sky conditions), which was done in a very short period of time (less than a minute). Atmospheric conditions contribute to create signal variation, but these variations are not correlated with the cylinder rotation (180° or 360° cycle).

Spectral variation as a function of the rotation angle

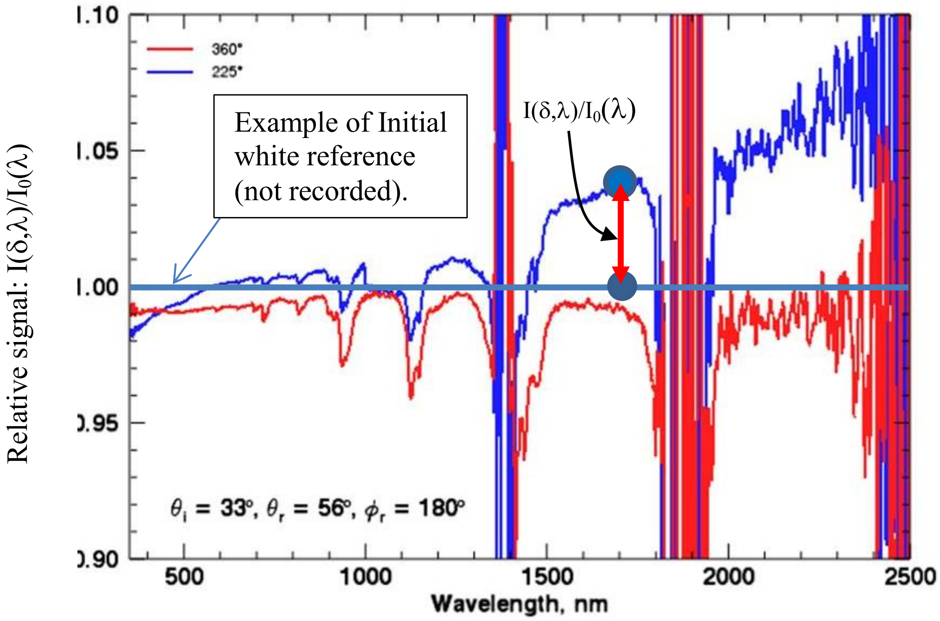



***Figure 5:*** *Example of spectral measurements for two rotation angles. At the beginning, the spectrum is flat (a white reference is done). When the cylinder rotates on its axis, the spectrum changes. This is this change $I(\delta,\lambda)/I_0(\lambda)$, versus the cylinder rotation 'δ', that is reported in the following figures for various wavelengths.*

# 4 Measurement interpretation

The graphs presented in this chapter show how the spectrometer reacts when it is rotated on its optical axis by the angle ‘δ’. In an acquisition sequence, the rotation starts with $\delta(t=0) = 0$. The following rotation steps are done by increment of 45°, but the rotation angles are noted $\delta(t)$ because the measurement are done at different time, where the scene illumination can possibly change because of the presence of clouds. For specific wavelengths, the left-side graphs present the signal variations:

$$dI = \frac{I(\delta(t))}{I(\delta(t=0))}$$

(which is simply noted $I(\delta)/I_0$ in the graphs) caused by the cylinder rotation. Also, in the right-side graph, an evaluation of the extreme spectral variation is done by calculating the relative range (in %) between the maximum and minimum signal obtained at a different rotation angles. This variation should have been normalized by the mean signal ( $(I_{max}-I_{min}) / ((I_{max}+I_{min})/2)$ ), but the signal is already in relative mode and is already normalized to one.

## 4.1 Painted plate

Figures 6–8 present the results of this experiment for the painted plate. For detector in nadir ($\theta_r = 0$, Fig. 6), the signals (for different wavelengths) show sinusoidal variation which is about 2% in VNIR (350 to 970 nm) and SWIR1 (971 to 1411 nm) and rise up to 3–4% in SWIR2 (1412 to 2500 nm). The sinusoidal variation cycle is 360°, there is no sign of polarization in this measurement. This pattern could result of the combination of the slight alignment error and small inhomogeneity of the observed panel in the IFOV.

**Signal variation caused by the spectrometer rotation**

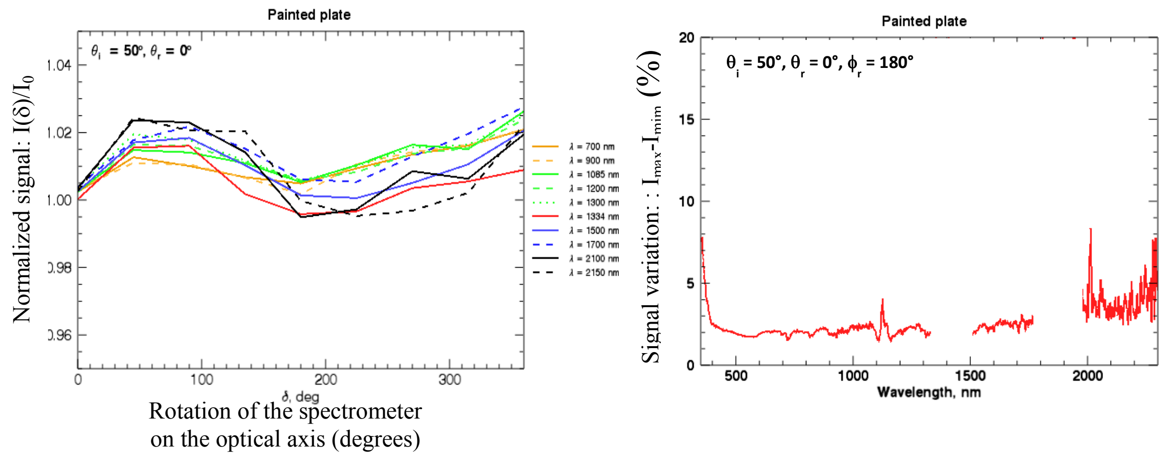



***Figure 6:*** *Signal variation caused by the rotation 'δ' of the spectrometer on the optical axis for nadir observation. The sun incident angle is $\theta_I = 50°$, the nadir observation angle is $\theta_r = 0°$ and the azimuth is $\phi_r = 180°$ (face to the sun).*

In forward direction, for viewing angle $\theta_r = 31°$ (Fig. 7A), the observed pattern is very similar as that for nadir observation. The variation of the signal with rotation is less than 2% for VNIR and SWIR1 and rise up to 5% in SWIR2. The polarization effect is not evident. We can barely see a double cycle (due to the polarization) overlapping the 360° rotation cycle.

With increasing view angle ($\theta_r = 45°$, forward direction; Fig. 7B), the signal pattern becomes more complex as polarization effect become stronger. The double polarization cycle becomes more evident, especially for SWIR2 band where the instrument polarization sensitivity is very high. However, the signal variation remains very small (about 1% for $\lambda < 1350$ nm) and is less than 5% for higher wavelengths.

Close to the Brewster's angle ($\theta_r = 56°$, forward direction; Fig. 7C), the polarization dominates over alignment error in signal variation with rotation. Here, double cycle appear for wavelengths in SWIR1 and SWIR2 bands. Also, the wavelength identified by the letters 'D' end 'E' (in Figs. 7C, 9) shows the typical phase opposition caused by the variation of the sensor spectral response versus the polarization angle (as discussed in relation with Fig. 9). The combined error for $\lambda > 1350$ nm is higher than 5% and increase with wavelength up to 10% (more 7–8% on Fig. 7C).

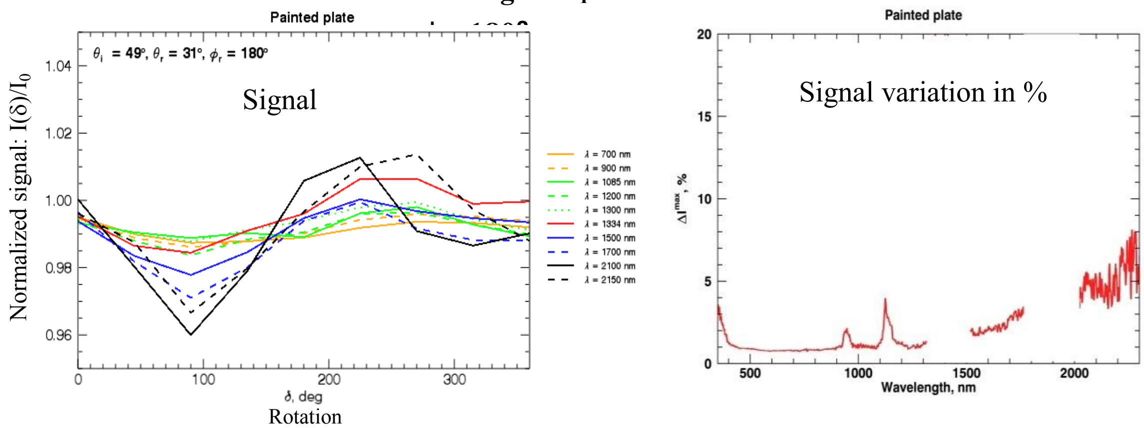
For the observation in direction perpendicular to the incidence plane ($\phi_r = 90°$), the pattern is more complex. The signal intensity is lower but the relative signal variation is higher. The signal variation increases with the wavelength and raise up to 20% for view angle $\theta_r = 31°$ and $\theta_r = 45°$ (Fig. 8A and Fig. 8B). However, for $\theta_r = 56°$ (Fig. 8C) the signal variation is very similar to those observed for $\theta_r = 56°$ in the forward direction (Fig. 7C).

In this situation (side looking), the effect of the direct sun light reflected (and polarized) by the plate is less visible. Note that, even with a flat paint, the BRDF (Bidirectional reflectance distribution function) is far from being Lambertian; it is partially glossy (and probably glossier in the IR than in the visible), even if it appears flat to the naked eye. The sun has a major reflection lobe in the direction of the specular reflection ($\theta_r = -\theta_i$). The major polarization effect appears close to the specular reflection angle and it is maximal at the Brewster angle. In side looking, the sensor is far from this position. Hence, at $\theta_r = 31°$ and $\theta_r = 45°$ there are no visible 180° cycles in the graphs. But, at $\theta_r = 56°$, a polarization pattern appears. We suspect that the presence of a close reflecting building may be responsible for this (visible in Fig. 2). If the plate were a mirror, at this angle, we would have seen the building image on the plate, while at the angles 31° and 45° we would have seen the blue sky image. Whatever the cause is, Fig. 8C indicates the presence of polarized light.

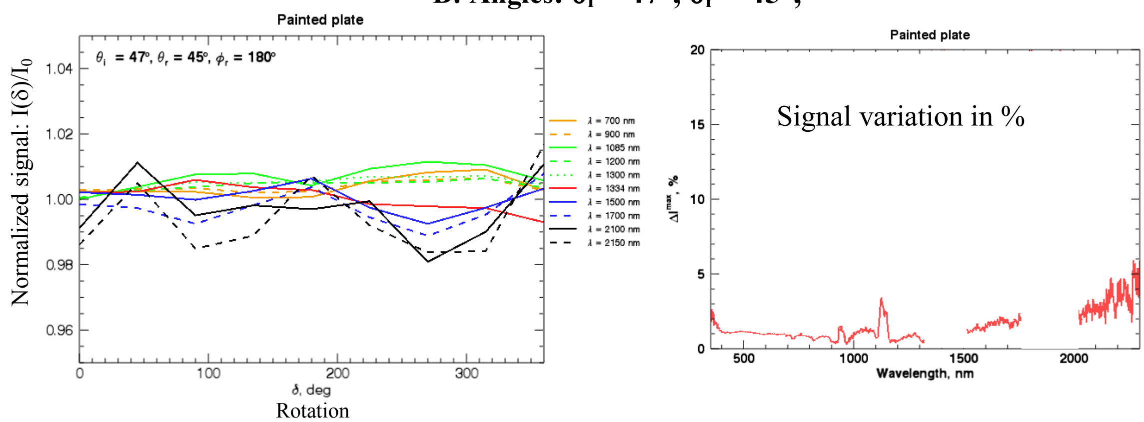
Note that a perfect blue sky is a very rare meteorological condition at the location where this experiment was held. The experiment was done while there was enough blue sky around the sun to assure a constant luminosity during an acquisition sequence. But with the side looking view, there were always tinny clouds in the zone of the reflected FOV (field of view) such as illustrated in the diagram of Fig. 4. This may be the cause of such signal variation in Fig. 8.

**Signal variation caused by the rotation of spectrometer optical axis while facing the sun.**

**A: Angles: $\theta_i = 49°$. $\theta_r = 31°$.**




**B: Angles: $\theta_i = 47°$, $\theta_r = 45°$,**




**C: Angles: $\theta_i = 33°$, $\theta_r = 56°$,**

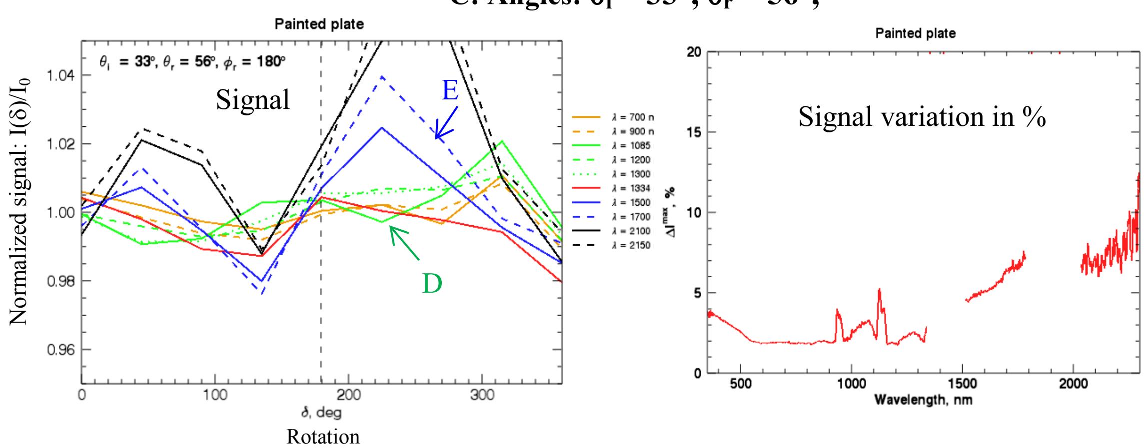



***Figure 7:** Signal variation with rotation in forward direction (in the principal plane).*

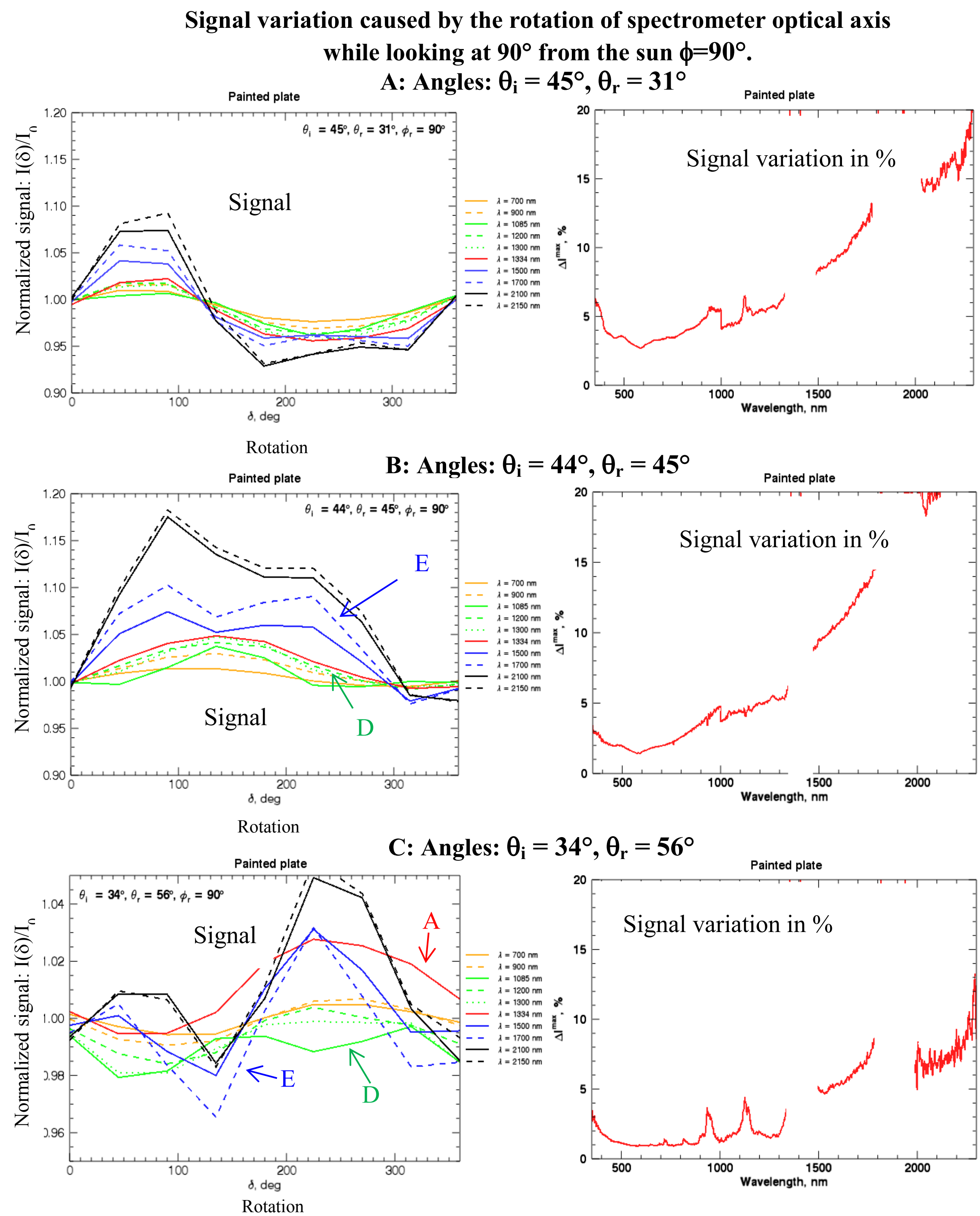



***Figure 8:*** *Signal variation with rotation in direction perpendicular to the incidence plane. Line 'A' (1334 nm) is insensitive to polarization (360° cycle). Line 'E' is extremely sensitive to the polarization and line 'D' has a polarization shift of 90° relatively to line 'E'.*

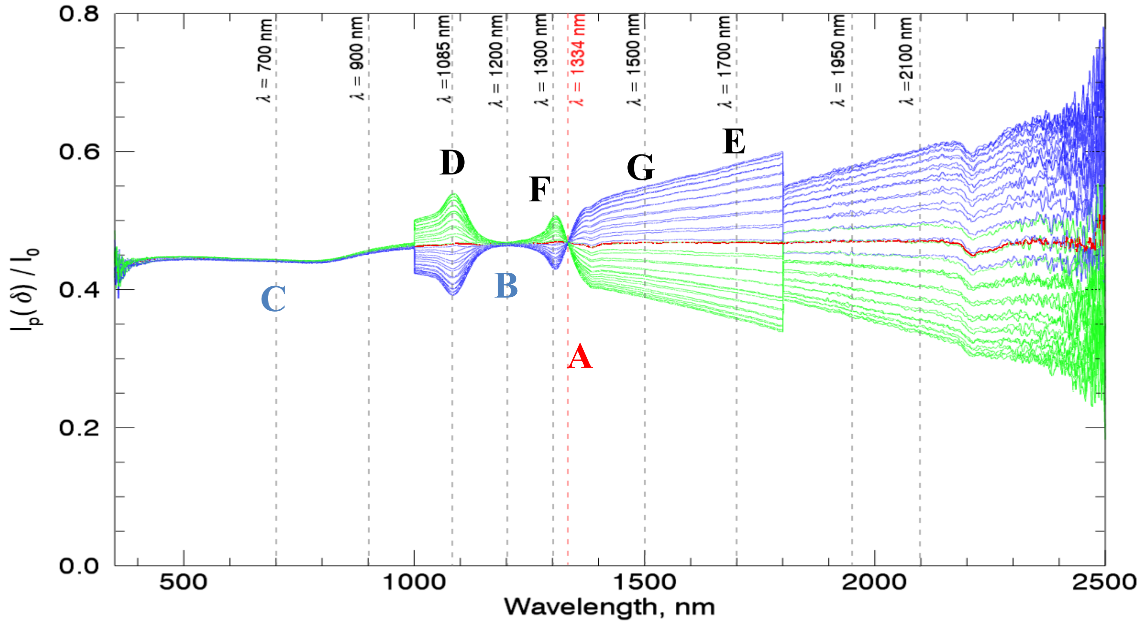



***Figure 9:*** *Polarization sensitivity of the ASD spectrometers. The red line is the mean spectra that will be registered by the ASD spectrometer if it was not sensitive to the polarization. Dash lines indicate the wavelengths which are used for presenting the results of the described experiment. Green and blue plots are the spectrometer responses for various polarization angles.*

Though, some complex polarization pattern could also be in the origin of this higher variation as it is wavelength dependent. In a previous experiment [1], the spectrometer response was measured while a polarizer was rotated in front of the optical entrance. These variable spectral responses are shown in Fig. 9. A closer look to this graph of the polarization sensitivity of the ASD spectrometers shows that the spectrometer is more sensitive to the polarization at certain wavelength than others. This helps easily distinguish the polarization imprint on the acquired signal.

There are several singular points in the ASD spectral response with polarized light: point A is very special point—for wavelength near 1334 nm the polarization sensitivity is very low but there is polarization shift by 90° for the wavelengths longer than 1334 nm in comparison with shorter wavelengths [1]. As shown in Fig. 9, for certain polarization angles, the spectral response (green lines) is higher than the average (red line) for the wavelengths shorter than 1334 nm, while it becomes lower than average for longer wavelengths; there is a contrast inversion. This effect is a normal behaviour with the gratings. It is well illustrated in Ref. 8. The gratings have different spectral efficiency for the 'S' (perpendicular to the incident plane) and 'P' (parallel) polarizations and there is somewhere a wavelength where the two spectral response cross each other.

As it could be seen from Figure 9 and in more details in Figure 10A, practically, there is no change with polarizer rotation for wavelengths 700 nm, 900 nm, 1200 nm and 1334 nm (points A, B, C in the Figure 9). Thus, any variation of the signal with rotation of the spectrometer around its optical axis for these wavelengths (as it is observed in Figure 10B) will be result of some other perturbation (i.e., alignment). As a matter of fact, the 1334 nm wavelength shows only a 360° cycle in Figs. 7 and 8.

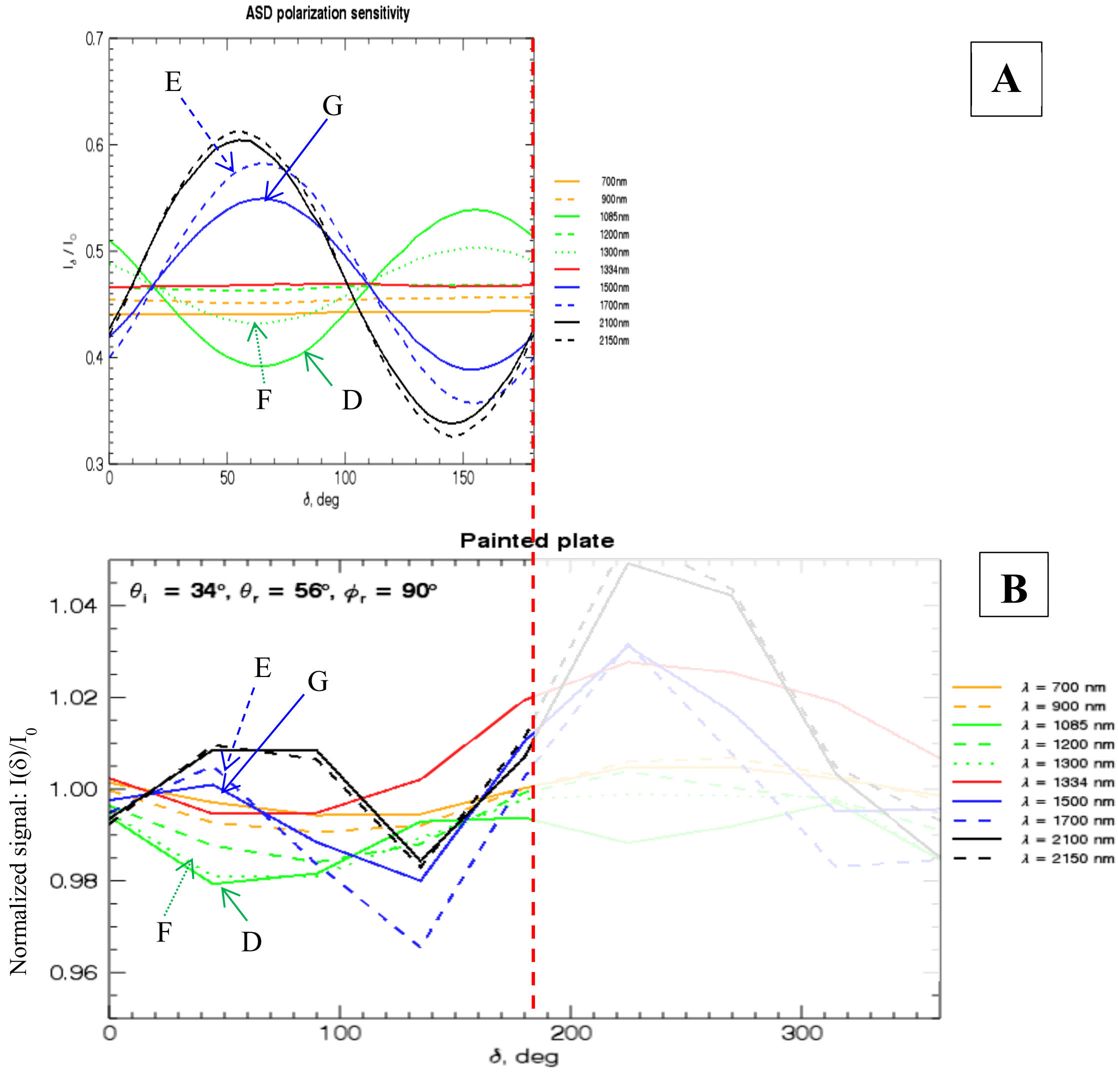



***Figure 10:*** *Characteristic features of the polarization: 180° cycle and, the inverse behavior of the signals for the SWIR wavelengths smaller than 1334 nm (i.e., 1085 nm, 1300 nm) to those with higher wavelength (i.e., 1500 nm, 1700 nm, 2100 nm, 2150 nm).*

However, in addition to the double cycle in the signal variation for others wavelengths, the signal contrast inversion behavior for the SWIR wavelengths shorter than 1334 nm (i.e., 1085 nm, 1300 nm) compared to those with longer wavelengths (i.e., 1500 nm, 1700 nm, 2100 nm, 2150 nm, Figure 8B) is a clear indication of polarization effects on the acquired signal. Point D (1085 nm) and point E (1700 nm) are identified in Figs. 7, 9 and 10 to highlight the polarisation contrast inversion signature. As it could be seen from Figure 10B, even the amplitude of polarization sensitivity for these wavelengths changes in proportion to those for completely polarized light (Figure 10A), i.e., $I_\delta/I_0$ (1700 nm, point E) > $I_\delta/I_0$ (1500 nm, point G) as well as $I_\delta/I_0$ (1085 nm, Point D) > $I_\delta/I_0$ (1300 nm, point F).

## 4.2 Blue sky

As written in Section 2.7, the blue sky is a real source of concern. The blue sky is highly polarized. However, after having tried evaluating the influence of the blue sky polarisation on the measurement, we found that the blue sky has little effects. Fig. 11 shows an example of the blue sky raw spectrum. The DNs (digital numbers) indicated the signal intensity. The Raleigh scattering is effective in the visible band. It is almost inexistent over the 1000 wavelength. Figure 9 shows that the spectrometer is almost insensitive to the polarization in the visible band, up to 1000 nm. The Raleigh scattering above this wavelength is a minor source of illumination in the scene. Therefore, the highly polarized blue sky is not a major issue. Its influence on the measurement is far smaller than the near building surfaces, which reflect sun light with an angle close to the Brewster angle.

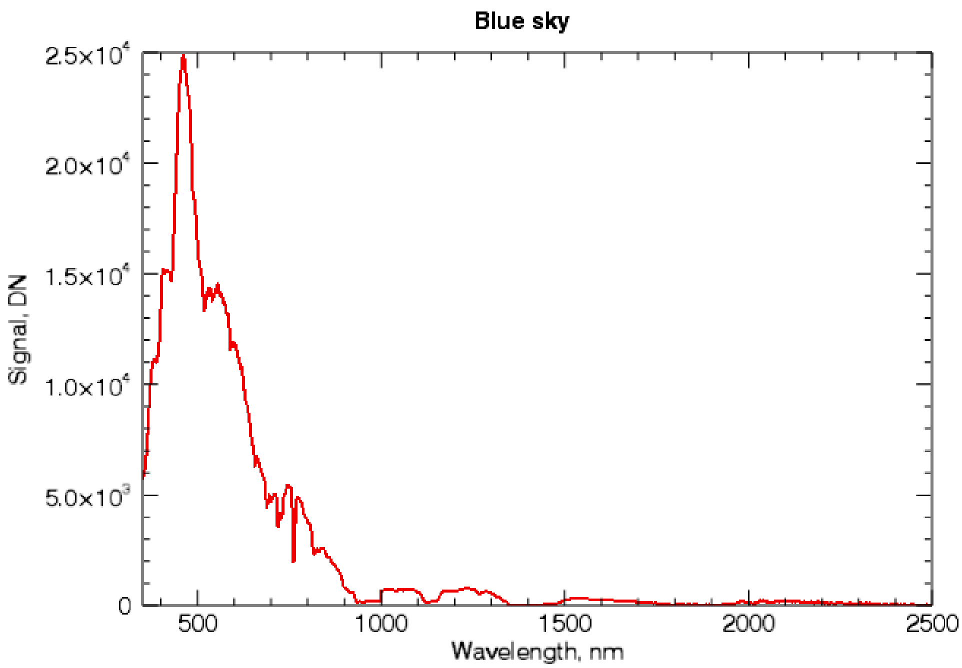



***Figure 11:*** *Raw spectrum of the blue sky.*

# 5 Conclusion

The spectrometers are sensitive to the polarization. The first conclusion from the experiment described in this paper is that the natural illumination contains enough polarization to affect the spectrum measurement.

However, the first positive finding is that the sunlight is mainly scattered in visible band where the ASD polarization sensitivity is relatively low (less than 1% for completely polarized light). Polarization effect due to the blue sky could be ignored in the visible band.

The polarization impact is more pronounced near Brewster angle of reflection for wavelengths > 1350 nm where the polarization sensitivity of ASD spectrometers is higher. For the tested target, the signal variation is about 5% higher due to the polarization. Thus, the total variation reach 10% due to the combined effect of the polarization and small imprecision in instrument alignment. This Brewster polarization is more important for direct reflection, i.e., when the sensor is face to the sun. This polarization is of less importance when the measurements are acquired with an azimuth angle of 90° relatively to the sun position.

The second positive finding is that for nadir observations the polarisation effect is very low and could be ignored. Usually, ground truth measurements are done at nadir angle and this is a good practice. For our nadir observations, the signal varied between 2–5% and this was probably caused by factors as target inhomogeneity in the FOV, imperfect axis alignment or small atmospheric variability.

This experiment illustrates that when an experimenter point the spectrometer to a slant surface, this automatically adds a measurement error between 5% and 10%. This is caused by the coupling between the light polarized by the reflecting surface and the privileged polarization axis of the spectrometer. In conclusion, surface should never be measured with an angle (particularly close to the Brewster angle) excepted if an acquisition procedure is adapted for such a case. For the measurement of a tilted panel, the measurement should be done with the sensor perpendicular to the panel surface. The calibration must be done first with the surface of reference (the Spectralon) placed on the tilted panel, thereafter the Spectralon is removed and the panel is measured. What must not be done is: calibrate the instrument with the Spectralon on the floor, then move the spectrometer and measure a nearby panel with an angle (even worst if the spectrometer has an optical fiber whose bending changed when the optical head is reoriented).

Finally, a special attention must also be payed to the parasitic reflections from near surfaces (e.g., nearby buildings, shiny objects, smooth water surfaces) that could affect the observations and increase the signal variation due to polarization.

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# References


[1] Lévesque M.P., Dissanska M., 'Spectral and polarimetric characterisation of the goniometer components and analysis of the spectrometer behaviour in presence of polarized light', DRDC Valcartier R14-0516-0930, May 2015.

[2] Lévesque M.P., Giroux S., Ardouin J.-P., 'Measurement of the spatial distribution of the spectral response variation in the field of view of the ASD spectrometer input optics', DRDC Valcartier TR 2011-202, December 2011.

[3] George R.S., 1966. 'Polarization of the energy beam in Perkin-Elmer infrared grating spectrometers'. Applied spectroscopy, 20(2), pp. 101–106.

[4] Cronin T.W., Marshall J., 2011. 'Patterns and properties of polarized light in air and water'. *Phil. Trans. R. Soc. B* 2011 366.

[5] Caron, J. et al., 2012. 'Polarization scramblers in Earth observing spectrometers: lessons learned from Sentinel-4 and 5 phases A/B1', ICSO 2012, Corse, http://congrex.nl/icso/2012/papers/FP_ICSO-139.pdf (last access Septembre 2014).

[6] Coulson K., 2012. Solar and Terrestrial Radiation: Methods and Measurements, Elsevier, p. 334.

[7] Schott J.R., 2009. 'Fundamentals of Polarimetric Remote Sensing', SPIE Press, p. 244.

[8] Thorlabs gratings: 1 µm Blaze Wavelength Reflective Diffraction Gratings: https://www.thorlabs.de/newgrouppage9.cfm?objectgroup_id=8627&pn=GR13-0310, (last access March 2015).

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In previous works, it was found that the polarization alters the spectrometers spectral response. Considering that the natural light is always partially polarized (reflection, Rayleigh scattering, etc.), some concerns were raised about the accuracy and variability of the outdoor measurement, particularly for trial ground truth measurements. This report demonstrates that, in some circumstances, the measurement can be affected by the polarization; direct sun reflection and reflection from close objects must be avoided. However, measuring surfaces at right angle (as suggested in usual calibration procedure) minimized the alteration of the spectral response of the sensors. Hence, by respecting rigorously the measurement protocol, the ground truth data is valid. But, ground truth measurements acquired with a slant-path angle are more or less accurate; an important proportion of the signal variability is due to the polarization.

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Lors de travaux précédents, on a trouvé que la polarisation altère la réponse spectrale des spectromètres. Considérant que la lumière naturelle est toujours partiellement polarisée (réflexion, diffusion de Rayleigh, etc.), quelques inquiétudes ont été soulevées à propos de la précision et variabilité de mesures faites à l'extérieure, particulièrement pour les données vérités acquises au sol durant les campagnes de mesures. Ce rapport démontre que, dans certaines circonstances, les mesures peuvent être affectées par la polarisation; les réflexions directes du soleil et les réflexions par des objets proches doivent être évitées. Cependant, mesurer les surfaces à angle droit (tel que suggéré dans les procédures de calibration usuelles) minimise l'altération de la réponse spectrale des capteurs. Ainsi, en respectant rigoureusement le protocole de mesure, les données vérités sont valides. Mais les mesures de données vérités acquises à angle sont plus ou moins précises; une proportion importante de la variabilité du signal est dû à la polarisation.

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polarization; spectrum; calibration; remote sensing