Field spectrometer measurement errors in presence of partially polarized light; evaluation of ground truth measurement accuracy

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Abstract: Considering that natural light is always partially polarized (reflection, Rayleigh scattering, etc.) and the alteration of the spectral response of spectrometers due to the polarization, some concerns were raised about the accuracy and variability of spectrometer outdoor measurements in field campaigns. We demonstrated by simple experiments that, in some circumstances, spectral measurements can be affected by the polarization. The signal variability due to polarization sensitivity of the spectrometer for the measured sample was about 5-10%. We noted that, measuring surfaces at right angle (a frequently used measurement protocol) minimized the problems due to polarization, producing valid results. On the other hand, measurements acquired with a slant angle are more or less accurate; an important proportion of the signal variability is due to the polarization. Direct sun reflection and reflection from close objects must be avoided.

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References and links

1. Introduction
For the development of hyperspectral sensing technologies, field measurement campaigns are often conducted to acquire airborne and ground spectral data. This data must be accurate as possible because analysis and processing technique depends on it. Unfortunately, the measured data always suffer of a certain level of variation caused by various factors [1] concerning the optical propagation (the properties of the atmosphere, timing of measurement), environmental (sources of illumination, illumination variation due to cloud passage and wind, haze), experimental issues (target inhomogeneity, acquisition geometry, instrument FOV (field of view), instrument instability/noise, sampling strategy, non-simultaneous sampling of
target and reference panel and time delay between successive samples, calibration procedure [1,2], surrounds and operator, etc.). Careful consideration must be given to all of these factors, in order to identify and minimize the effect of different sources of error. With a good measurement protocol, most of these artefacts can be attenuated (e.g. by using reflectance standard measured in exactly the same irradiation and reflectance beam geometry as the sample).

To obtain functional relationship between the instrument output and the real reflective properties of the target, several features of the instrument itself as well as the experimental setup must be well known. In this context, recent experiments with an Analytical Spectral Devices (ASD) FieldSpec spectrometer in polarized light [3,4] demonstrated that the sensitivity of the spectrometer to the polarization in some circumstances could be also sources of signal variability. This instrument is composed of three spectrometers each covering its own spectral region (VNIR, SWIR1 and SWIR2) [2]. The measurements can change by as much as 50% in SWIR2 (by changing the polarization angle). Also, in the presence of polarized light, bending the optical fiber produces unpredictable changes of the spectral response [3,4]. The spectrometer sensitivity to 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 polarization. This raises the interrogation about the validity of field measurements done with the spectrometer, such as the ASD FieldSpec, when light is partially polarized (which is often the case).

This paper demonstrates by simple experiment, the impact of the partially polarized natural light on the spectral ground truth measurements due to polarization sensitivity of the spectrometer. A better understanding of this source of measurement artefacts, allows defining a better acquisition protocol and getting better data or, at least, avoiding the measurement conditions favorable to generate measurement artefacts.

In the next sections, we describe the behavior of the ASD FieldSpec spectrometers in presence of polarized light, the possible sources of polarization in field measurements and the effect of partially polarized light interaction with the instrument on the signal variability. The experimental setup is described in Section 2 and measurement series are described in Section 3. The results and their interpretation are presented in Section 4.

1.1 Alteration of the spectrometer spectral response by the polarization

Recent experiments, done with the ASD FieldSpec spectrometers, demonstrated that these spectrometers are excessively sensitive to the polarization and are prone to generate artefacts, particularly when the polarizer is rotated or when the optical fiber is moved [3,4]. The signal variation in polarized light was tested by placing a polarizer between the emitting integrating sphere and the spectrometer entrance. If the spectrometer was not sensitive to the polarization, placing the polarizer between instrument optical entrance and the non-polarized light source ‘I₀(λ)’ would simply cut the signal output by the polariser transmittance ‘T_p(λ)’ and by 50% for any orientation of the polarizer. The expected signal measurement ‘M(λ)’ should be:

$$ M(\lambda) = \frac{I_0(\lambda)}{2} T_p(\lambda) S(\lambda) $$

where S(λ) is the instrument spectral response. In Fig. 1(c), the relative signal (divided by I₀) is the red line. This is the expected instrument spectral response. However, as it is demonstrated in Fig. 1, when the polarizer is rotated, the spectral response of the instrument is completely modified. This is some kind of surprise. Hence, the real instrument spectral response (which depends on the polarization angle) must be represented by ‘S(λ, ϑ)’, so the measurement ‘M(λ, ϑ)’:

$$ M(\lambda, \vartheta_p) = \frac{I_0(\lambda)}{2} T_p(\lambda, \vartheta_p) S(\lambda, \vartheta_p) $$

(2)
depends on the coupling between the polarizer angle \( \vartheta_T \) and the privileged polarization axis \( \vartheta_S \) of the spectrometer.

To better understand the spectrometer reaction to the polarization, the spectra measurement \( M(\lambda, \vartheta) \) were acquired for all input polarization angles \( \vartheta \), by rotating the input polarizer by step of 5 degrees and this measurement series was repeated for several fiber bending (presented in Fig. 2). From these measurements, the maximum and minimum measurements were used to calculate the polarization contrast \( P_c(\lambda) \), which is presented in Fig. 3. This polarization contrast indicates how the spectrometer is sensitive to the polarization.

\[
P_c(\lambda) = \frac{\max(M(\lambda, \vartheta)) - \min(M(\lambda, \vartheta))}{\max(M(\lambda, \vartheta)) + \min(M(\lambda, \vartheta))}
\]

Fig. 1. Polarization sensitivity of the ASD spectrometers: a) The signal variation in polarized light was tested by placing a polarizer between the emitting integrating sphere and the spectrometer entrance. b) The instrument sensitivity is presented as a function of the polarization angle (over a cycle of 180 degrees) for various wavelengths. c) Variation of the spectral response presented for all polarization angles. The red line is the mean spectrum that would be registered by the ASD spectrometer if it was not sensitive to the polarization. Vertical dash lines indicate the wavelengths which are used for presenting the results of the described experiment. Note the phase inversion between the wavelengths identified by the letters D and F and the wavelengths identified by G and E. Wavelength A and B are not sensitive to the polarization angle.

Several observations can be done from these graphs:

- The signal variation is different for different wavelengths [Fig. 1(b) and 1(c)]. The polarization sensitivity generally increases with the wavelength [Fig. 1(c)].

- For the VNIR band, the spectrometer is made of a steady grating and an array detector. This grants certain stability to the spectrometer. For the SWIR1 and SWIR2 bands, the spectrometer use single detectors with oscillating gratings. The angular position of the gratings, relatively to the incident light beam, is different for each wavelength. This changing mechanical configuration makes the detectors more or less sensitive to the incident polarization.

- Curiously, some wavelengths (visible and SWIR1 at 1200nm) seem not affected by the polarization [Fig. 1(c)].
- Near 1334nm the spectrometer response has an inflection point for all polarization orientations (Point A in Fig. 1(c)). Above this point, there is a sensitivity inversion. This is caused by an angular shift of 90° of the polarization angle for the privileged polarization axis of the grating [5]. Hence, points D and F have a polarization shift of 90° relatively to point G and E in Fig. 1(c).

- For a given wavelength, the signal change over a 180 degrees cycle due to the instrument sensitivity to the polarization, such as shown in Fig. 1(b).

![Fig. 2](image1.png)

Fig. 2. In presence of polarized light, variations of the spectrometer response for 3 cases of gentle optical fiber bending.

![Fig. 3](image2.png)

Fig. 3. Spectral polarization contrast (Pc) of the spectrometer for two different fiber bending.

In addition to the spectrometer sensitivity to polarization, an undesirable behavior of the optic fiber output was found; the optical fibers rotate the polarization axis. This fact is usually
well known by people from the optical fiber community, but not from the community of the spectrometer users. With un-polarized light, the fiber bending has very few effects on the spectral response, typically less than 1%. But with polarized light (polarizer inserted between the integrating sphere and spectrometer entrance) and without rotating the polarizer (i.e. for some fixed position), the bending consequence is catastrophic. As it shown in the Fig. 2, the spectral response changes considerably even for a small fiber bending, although the polarizer is not rotated.

For each (very light) bending (and for the same polarizer position), the polarization contrast (Pc) changes. In general, for different fiber geometry, the pattern of the Pc is the same but not the amplitude [Fig. 3]. However, changing the fiber geometry rotates considerably the output polarization axis by an unpredictable amount. Moreover, the output polarization angle is different for each spectral band (the ASD spectrometer has 3 gratings and 3 detectors), but it is practically constant within a spectral band [3]. Except, in the middle of the SWIR1 waveband near 1334 nm, where the inflection point was observed [Point A in Fig. 1(c)], the polarization angle shifts suddenly by 90° [Fig. 1(b)].

Thus, taking into account these particularities of polarization sensitivity of ASD spectrometers, a special attention must be done when the measured light is polarized and an adequate acquisition procedure [4] have to be adopted to maintain the spectral response under control.

1.2 Source of natural polarization

The ground truth measurements are taken under natural irradiation conditions (or ‘illumination’ if only the visible band is considered). The natural irradiation is already partially polarized. The downwelling irradiance is the sum of the direct sun light and a diffuse component. The direct sun irradiance is not polarized. However, the diffused component of down welling irradiance (blue sky) is generated by scattering of the incident sunlight by atmospheric constituents (gas molecules (Rayleigh-scattering), aerosol (Mie-scattering)). In the spectral band covered by ASD spectrometers (350 nm to 2500 nm), Rayleigh scattering is a strong source of polarization [6]. The plane of polarization of scattered light is perpendicular to the plane containing the incident and the scattered ray [7]. The scattering creates a band of maximum polarization at angles 90° away to the Sun. In a very clear sky, the degree of linear polarization in this band can reach 90% per cent, but it typically is lower due to molecular anisotropy [6, 8]. Away from the 90° arc (from the Sun) of maximum polarization, the degree of polarization decreases smoothly, reaching 0% near the Sun or in the opposite direction [6]. Unpolarized incident light scattered in forward direction continues to be unpolarized [7]. The sky polarization pattern will move across the sky with the change of the Sun position [8]. To this downwelling component, the backscattering of the upwelling radiation reflected by the ground can be also considered. These interactions induce a polarized component. Other sources of polarized light are the ambient illumination, i.e., the parasitic reflections from near surfaces (e.g. building, shiny objects, and smooth water surfaces). 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).

1.3 Signal variability

During field campaigns, the measured target is under natural illumination conditions. It is known that the measurement variability is quite high because of several factors: atmospheric conditions, wind, clouds, proximity of the operator, 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 reflectance 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,
– the spectrometer is sensitive to the polarization axis of the sensed light and
- moving the optical fiber from the Spectralon to the target changes the optical fiber bending, which rotates the polarization axis.

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?

2. The experiment

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. As it was demonstrated, the ASD FieldSpec spectrometer has a privileged polarization axis where its sensitivity is maximal. 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 on the instrument in order to prevent the unpredictable change of studied spectrum due to its displacement during measurements.

2.1 Hypothesis

When the instrument is rotated on its optical axis, the signal measurement changes. After completing a rotation cycle, 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 degrees cycle: polarization is involved; a polarizer at 0 or 180 degrees has the same effect;
2. the signal change over a 360 degrees cycle: 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 always the same part of the target.

2.2 Experimental setup

Taking in account the instrument polarization sensitivity particularities and polarization of the natural illumination, this simple experimental setup was prepared:

1. The spectrometer was put into a cylinder which could rotate around its longitude axis (shown in Fig. 4(a)).
2. To eliminate the effect of unpredictable behavior of the optical fiber, it was toughly fixed to the spectrometer body (shown in Fig. 4(b)).
3. Optical fiber input was positioned on the cylinder axis (shown in Fig. 4(c)), assuring 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 illumination and observation conditions, but for different orientation of the privileged polarization axis of the instrument. It is supposed that in the case the measured light is polarized, this polarization will interact with the instrument polarization sensitivity and a double cycle (over a 360-degrees rotation) will be observed in the variation of the signal measurement.

Fig. 4. Experimental setup: rotating barrel and fixation of the optical fiber inside the cylinder.

2.3 Instrument stability

We first tested the instrument with an integrating sphere, which is not a polarized 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 in polarized light

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 [Fig. 1(c)].

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 around 1 degree.

From [9], we know that the optical fiber has a measured total FOV of 26 degrees (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 degrees, i.e. from the left to the right side at half maximum of sensitivity. This central 12 degrees of FOV is responsible for 85% of the detected signal. The remaining FOV (between 12 and 26 degrees) has only a marginal sensitivity.

The alignment of the optical-fiber FOV was measured in laboratory. We found two pointing errors:

1. approximately 1 degree off axis error between the alignment of the optical fiber bundle and the rotating barrel axis and
2. approximately 1 degree off axis error between the optical-fiber bundle axis and its FOV axis. The bundle contains 57 optical fibers and, probably, their ends are not perfectly aligned in the terminal mounting.

2.6 The target

For the experiment, we used a painted gray-green flat plate put horizontally on the ground [Fig. 5]. The reflected incident beam from the smooth flat surface will be partially linearly polarized with the dominant electric vector perpendicular to the principal plane (polarization ‘S’).

![Fig. 5. 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.](image)

3. Measurement series

The measurements made for the painted plate were taken for two instrument orientations:

- Instrument acquire the forward reflection (facing the sun, $\phi = 180^\circ$, the instrument is in the principal plane)
- Instrument put in 90° to the principal plane ($\phi = 90^\circ$, side looking in Fig. 6)

![Fig. 6. Geometry of measurement setups.](image)

The spectra was taken for 9 positions of instrument rotation around its optical axis varying from $\delta = 0^\circ$ to $360^\circ$ with increment of 45 degrees, and for different pointing nadir angles, i.e. for $\theta_r = 0^\circ$(nadir), 31°, 45° and 56°.

When starting a measurement series ($\delta = 0$), the spectrometer stares at the scene and a white reference is acquired. The following measurements are done relatively to this starting calibration. Hence the recorded spectra are the measurement ratio: $M(\delta)/M(0)$. Examples are given in Fig. 7 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.

4. Measurement interpretation

The graphs presented in this section show how the spectrometer reacts when it is rotated on its optical axis by the angle \(\delta\). In an acquisition sequence, the rotation starts with \(\delta = 0\). The following rotation steps are done by increment of 45°. For specific wavelengths, Figs. 8 and 9 present the signal variations caused by the cylinder rotation.

![Spectral variation as a function of the sensor rotation angle](image)

Fig. 7. Example of spectral measurements for two rotation angles. At the beginning, a white reference is done. When the cylinder rotates on its axis, the spectrum changes. This is this change \(M(\delta, \lambda)/M(0, \lambda)\), versus the cylinder rotation \(\delta\), that is reported in the following figures for various wavelengths.

4.1 Painted Plate

Figure 8 presents the results of this experiment for the painted plate. For detector looking at the nadir [Fig. 8(a) where \(\theta_r = 0°\)], the signals (for different wavelengths) show a sinusoidal amplitude variation that is about 2% in VNIR and SWIR1 and rise up to 3-4% in SWIR2. The sinusoidal variation cycle is 360°; there is no sign of polarization in this measurement. This pattern could result of the combination of a slight alignment error and a small inhomogeneity of the observed panel in the FOV.

In forward direction, for viewing angle \(\theta_r = 31°\) [Fig. 8(b)], 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 degrees rotation cycle.

Close to the Brewster’s angle, i.e., \(\theta_r = 56°\), [Fig. 8(c)], the signal pattern becomes more complex as polarization effect become stronger. The double polarization cycle appears for wavelengths in SWIR1 and SWIR2 bands. It became more evident, especially for SWIR2 band where the instrument polarization sensitivity is very high. The polarization imprint (the 180° cycle) dominates over the alignment error (the 360° cycle) in the signal variation (caused by the rotation). Also, the wavelength identified by the letters ‘D’ end ‘E’ [Fig. 8(c)] shows the typical phase opposition caused by the variation of the sensor spectral response versus the polarization angle (see Fig. 1(b)). The combined error for \(\lambda > 1350\) nm is higher than 5% and increase with longer wavelength up to 10%.
For the side looking observations (perpendicular to the incidence plane), the signal intensity is lower (not sensing the specular sun reflection) but the relative signal variation is higher [Fig. 8(d) and 8(e)]. The signal variation increases with the wavelength and raise up to 20% for view angle $\theta_r = 31^\circ$ [Fig. 8(d)]. However, for $\theta_r = 56^\circ$ [Fig. 8(e)] the signal variation due to the polarization is very similar to those observed for $\theta_r = 56^\circ$ in the forward direction [Fig. 8(c)].

**Signal variation caused by the spectrometer rotation for Nadir observation.**

[Graph a]

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

[Graph b, c, d, e]

Fig. 8. Signal variation caused by the rotation of the spectrometer on the optical axis: a) for nadir observation; b) for observation in principal plane for $31^\circ$ angle of observation; c) for observation in principal plane for $56^\circ$ angle of observation; d) for observation in direction perpendicular to the incidence plane for $31^\circ$ angle of observation; c) for observation in direction perpendicular to the incidence plane for $56^\circ$ angle of observation. Red line ‘A’ (1334nm) 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’.
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 does not sense the sun specular reflection, but the specular reflection of the blue sky. At $\theta_r = 31^\circ$ [Fig. 8(d)] there are no visible 180° cycles. But, at $\theta_r = 56^\circ$, a polarization pattern appears [Fig. 8(e)]. 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 such as illustrated in Fig. 6. This may be the cause of such signal variation in Fig. 8(d). Whatever the cause is, Fig. 8(e) indicates the presence of polarized light.

A closer look to the Fig. 1(c), presenting the variable spectral responses of ASD spectrometers due to its polarization sensitivity, shows that the spectrometer is more sensitive to the polarization at certain wavelengths than others. This helps easily distinguish the polarization imprint on the acquired signal. There are several singular points in the spectral response with polarized light: point A is very special point – for wavelength near 1334nm (for this spectrometer) the polarization sensitivity is very low. Also, this is the wavelength where there is polarization shift by 90 degrees for the wavelengths longer than 1334nm in comparison with shorter wavelengths [3]. This is visible in Fig. 1(c). For certain polarization angles, the green lines are the dominant spectral responses for the wavelengths shorter than 1334nm, but over this wavelength these same polarization angles produce the spectral response minima; there is a contrast inversion. This effect is a normal behavior with the gratings. It is well illustrated in [5]. The gratings have different spectral efficiency for the ‘S’ (perpendicular to the incident plane) and ‘P’ (parallel) polarizations and there is somewhere (depending on the grating parameters) a wavelength where the two spectral response cross each other.

As it could be seen from Fig. 1(c) and in more details in Fig. 9(a), there is practically no change with polarizer rotation for wavelengths 700nm, 900nm, 1200nm and 1334nm (points A, B, C in the Fig. 1(c)). Thus, any variation of the signal with the rotation of the spectrometer around its optical axis for these wavelengths (as it is observed in Fig. 9(b)) will be result of some other perturbation (i.e. alignment, etc.). As a matter of fact, the 1334nm wavelength shows only a 360° cycle in Figs. 8(c) and 8(e). Atmospheric conditions also contribute to create signal variation (i.e. illumination variation), but these variations are not correlated with the cylinder rotation (180 or 360 degrees cycle).

Thus, in addition to the double cycle in the signal variation for others wavelengths, the signal inversion behavior for the SWIR wavelengths shorter than 1334nm (i.e. 1085 nm and 1300 nm) to those with longer wavelength (i.e. 1500 nm, 1700 nm, 2100 nm, 2150 nm) is a clear sign of the polarization impact on the acquired signal. Point D (1085 nm) and point E (1700 nm) are identified in Figs. 8(c), 8(e), and 9 to highlight the polarization inversion signature.

As it could be seen from Fig. 9(b), even the amplitude of polarization sensitivity for these wavelengths changes in proportional manner to those for completely polarized light [Fig. 9(a)], i.e.:

\[
\frac{M(\delta)}{M(0)} \text{ at } 1700 \text{ nm} > \frac{M(\delta)}{M(0)} \text{ at } 1500 \text{ nm} \quad (\text{i.e.: } E > G)
\]

as well as
$M(\delta)/M(0)$ at 1085 nm > $M(\delta)/M(0)$ at 1300 nm (i.e. D > F).

Signal variations over a 180° cycle.

Fig. 9. Characteristic features pointing to the polarization: 180° cycle and, the inverse behavior of the signals for the SWIR wavelengths smaller than 1334nm (i.e. 1085nm, 1300nm) to those with higher wavelength (i.e. 1500nm, 1700nm, 2100nm, 2150nm).

5. Conclusion

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

One positive note is that 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.

Another positive finding is that for nadir observations (perpendicular to the surface) the polarization effect is not observed. Usually, ground truth measurements are done at nadir angle and this is a good practice. For our nadir observations, the signal varied between 2 and
5% and this was probably caused by factors as target inhomogeneity in the FOV, imperfect axis alignment or small atmospheric variations.

Finally, this experiment illustrates that when an experimenter point the spectrometer to a tilted surface, it adds a measurement error between 5% and 10% for the tested sample. This is caused by the coupling between the light polarized by the reflecting surface and the privileged polarization axis of the spectrometer. The polarization impact is more pronounced near Brewster angle for wavelengths > 1350 nm where the spectrometer is more sensitive to the polarization. The measurement artefacts are more important for direct Sun reflection, but side looking (relatively to the Sun position) may also generates artefacts if a near object (building, cloud, etc..) can be reflected by the observed surface. Even if the reflecting surface seems flat, it always has a specular reflection component (which is more important for long wavelengths). Imagine that the measured surface is a mirror, what you would see (the near building) will influence the measurement.

In conclusion, surface should never be measured with an angle (particularly close to the Brewster angle). For the measurement of a tilted surface, the Spectralon plate of reference should be placed on the target surface and it must be measured with the sensor normal to the surface. Then, remove the Spectralon plate and measure the target surface without moving the spectrometer (or the optical fiber). What should not be done is: calibrate the spectrometer with the Spectralon plate on the floor, and then redirect ASD spectrometer reading head in another direction (this change the optical fiber bending) for the measurement of a nearby target panel; this maximizes the probability of measurement alteration due to the light polarization.

Finally, the worst scenario that everybody most avoid is the measurement of a surface with a slant angle while facing the sun (like the draw in Fig. 6). Most of the surface BRDFs can be roughly modeled with a combination of a diffuse component (like a Lambertian surface) which scatters light in every direction, and a specular component (like a mirror) that produces a polarized beam. The degree of polarization of this beam increases with the angle. It is maximum close to the Brewster angle. If the sun is low in the sky, the measurement of the surface with a nadir angle reduces the production of measurement artifacts because the sensor is beside this polarized beam.

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