Spectral features: an overview

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ABSTRACT

This article will give an overview of all effects that determine the spectral features amplitude (SFA). The origin of spectral features is explained and methods are indicated that can be used to minimize the SFA. Spectral features are observed in the ratio between two spectra of sun calibration measurements. Mechanisms helping to reduce spectral features are spectral averaging, angular averaging, and temporal averaging. It will be shown what optical design choices can be made in order to benefit from these SFA reducing mechanisms. In the final chapter some insight in the modeling is given where four types of diffusers are compared.

Keywords: Calibration, speckles, aging, optical design

1. INTRODUCTION

Spectral features are present in the spectra as measured in earth observation satellites during sun calibration. Spectral features are those wiggles in the spectra that are caused by speckle effects. The amplitude of spectral features (SFA) can be easily higher than 1% if no proper care is taken, while the accuracy requirement of the earth observation satellites often are stricter than 0.01%. In the past couple of years many articles[1-3] have been written and the present paper gives an overview plus a number of new insights.

In the following sections speckles are given as the origin of spectral features. Some general statistical properties will be given. From these basics some simple scaling rules will be derived that will help to get a first estimate for a calibration unit design.

The speckles are due to the presence of a diffuser in the calibration unit that is required to make the system insensitive to the angle of incidence of the sun light.

1.1 Speckles

When monochromatic, coherent light is scattered by a rough surface this will result in a speckle pattern on a observation plane, i.e. an intensity distribution with bright and dark spots. This speckle pattern is obtained since the intensity in each point is obtained via coherent addition of all scattering locations on the rough surface.

Figure 1 gives an example of a speckle pattern. The size of the speckles scales linearly with the wavelength of the light and is further determined by the N.A. or f# of the optical system. In case there are no optics between the rough surface and the observation plane the speckle size is determined by the separation between the two planes and the size of the illuminated area on the rough surface.

In Fig.2 a side view of a speckle pattern is given from which it can clearly be seen that not all bright spots have equal intensity.

For a normal speckle pattern the most common intensity is dark and the histogram will show a 1/x-like behavior where x stands for the brightness, i.e. the higher the intensity, the less points will have that intensity.

The sun is a source with a very wide spectral range and will in general not produce an observable speckle patterns. In an earth observation instrument very often a spectrometer is present where the bandwidth per detector pixel will be in the order of one nanometer or of tenths of a nanometer or even less. Due to this small wavelength band speckles will be observed. The number of speckles on a detector pixel, and their intensity will determine the measured intensity for the pertaining wavelength band.

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Since speckle patterns are created by interference the intensity distribution over the detector will strongly depend amongst others on wavelength, changes in layout of the system, and on the angle of illumination.

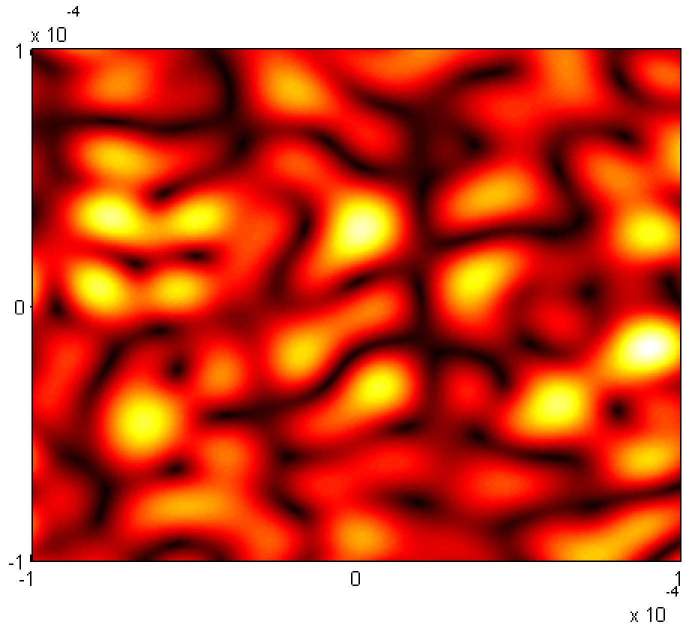

Figure 1 Example of a speckle pattern. Observe that the bright areas are not equally bright.

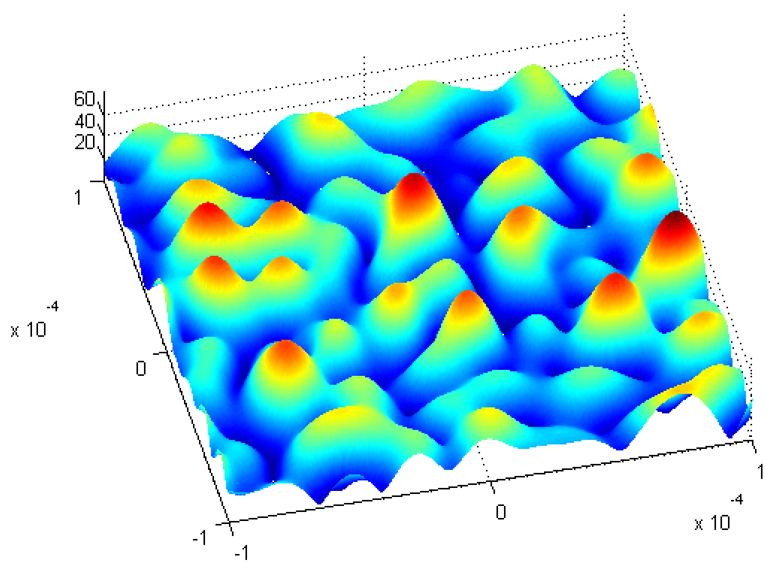

Figure 2 Side view for the speckle pattern shown in Fig.1.

Since speckle patterns change with about every change that can be imagined it is very likely that two recordings of spectra will not be identical in the case that the intensity per detector pixel depends on the speckle statistics. The standard deviation of the ratio between two spectra is the spectral feature amplitude (SFA). In case this value is zero, the speckle distribution has not changed between the two recordings. In normal use of the calibration unit for solar calibration the two speckle patterns will be independent and will therefore result in a non-zero SFA. As stated earlier, the SFA value can be far higher that the accuracy requirement of the instrument. The calibration unit will have to be designed such that the

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SFA is lower than the accuracy requirement. In case this can not be obtained via optical arrangement, temporal averaging will be the final solution. During a measurement the illumination angle of the sun will change which will lead to averaging and thereby reduction of the SFA.

1.2 Basic scaling rules

This subsection will give some general rules that will give a feeling on how high the SFA will be. A thorough analysis is required to get the actual SFA value that is to be expected. To this end a computer package has been made that has been verified several times with experimental data to proof its validity.

The speckle size depends linearly on the wavelength which means that the number of speckles on a given area scales inversely proportional with the square of the wavelength. The change in intensity on a detector pixel is most often due to one speckle more or less on that pixel. That effect will be larger when there are less speckles to begin with. This means that the SFA will increase with wavelength. Since not all speckles are equally bright the wiggles in the spectral features spectrum are not equally strong.

In case that bandwidth per detector pixel is infinitely small the SFA will purely depend on the number of speckles per detector area. In all practical situations the bandwidth per pixel will be in the order of 0.1 – 1 nm. If the change in speckle pattern is highly dependent on the wavelength, within that small wavelength band some averaging will take place. This averaging is indicated as inner-pixel averaging since it occurs within the bandwidth of a single pixel. Analysis has shown that the feature period, as a function of wavelength, increases quadratically with wavelength. This means that owing to inner-pixel averaging the SFA value will in general be low in the UV region while it is already high in the visible and near infrared. Choice of the proper diffuser and optical arrangement can result in a low enough SFA from the UV up to the 1 μm region.

Since the sun is used as light source during calibration another averaging mechanism is already present even for an instantaneous measurement: angular averaging. The opening angle of the sun is about 0.5 degrees and is was found that angular changes as small as 0.001 degree can be large enough to arrive at an independent speckle pattern. This small angular range is only valid for the right diffuser type and optical arrangement. As was found for the inner-pixel averaging also the effect of angular averaging will reduce for increasing wavelengths. The amount of angular change needed to arrive at an independent speckle pattern depends on the size of the speckles, the number of independent speckle patterns that fit in the 0.5 degrees will therefore be smaller for longer wavelengths.

The final averaging mechanism that can be used is coherence averaging. This mechanism is only present for diffusers with more than one scattering surface. If the light is scattered by different surfaces such that the light arriving at the detector is originating from locations that are separated by more than the coherence length of the light, these contributions have to be added incoherently resulting is a lowering of the contrast in the speckle image which in its turn results in a lower SFA value.

In general it can be stated that more length in the calibration unit will be good for the angular averaging. For the inner-pixel averaging it is found that shorter distances between components is more beneficial. In case the system should have an as low as possible SFA value without temporal averaging, it is better to have some short distances in the design, while in the case that temporal averaging is needed anyway it is better to optimize the effect of angular averaging, i.e. longer distances between components.

2. DIFFUSER DESIGN

This section will give an overview of basic diffuser types and their characteristics in terms of spectral features. This section will start with differences in performance between diffusers used in reflection and transmission.

2.1 Diffuser usage

Diffusers can be used in two modes: in reflection and in transmission. In terms of both reducing the SFA value and homogenizing the intensity distribution as a function of illumination angle, a reflection diffuser is always better than a transmission diffuser. Transmission diffusers are easier to add to an existing design and are also easily stackable to tune

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the overall transmission of the system. In the following several diffuser types are specified from which all are assumed to be used in reflection. The angular spread of the light scattered by a diffuser is larger for a reflection diffuser than for a transmission diffuser which makes it more suitable for a homogenizer system, the primary function of the diffuser.

2.2 Surface diffuser

As example for a surface diffuser is a roughened aluminum surface, where the roughness is in the order of the wavelength for which the diffuser is intended to be used. This is the most simple diffuser to make and will show the highest SFA levels.

2.3 Volume diffuser

Volume diffusers contain inhomogeneities in the bulk of the diffuser by which the light is scattered. A typical example of this type of diffuser is Spectralon, which is piece of PTFE. When using this type of diffuser all types of averaging are better than for a surface diffuser. Coherence averaging is best for this type of diffuser, provided that the coherence length of the light is smaller than the penetration depth of the volume diffuser.

Apart from the benefits of a volume diffuser there are also some drawbacks. The most important one is the aging. The material has been found to degrade upon UV radiation. Special measures have to be taken to prevent this aging.

2.4 Quasi Volume Diffuser (QVD)

The QVD is basically a piece of glass, typically quartz, that is rough at two surfaces where the back facet is coated with a optically thick aluminum layer. The standard thickness of our QVD's is 5 mm but other thicknesses can be made if wanted. Coherence averaging is also in operation for a QVD but less so then for a real volume diffuser. The main averaging mechanism for a QVD is angular averaging but also the inner-pixel averaging is strongly present. Since the material exposed to the high radiation dose is quartz, a QVD does virtually not suffer at all from degradation.

2.5 Special diffuser designs

From experiments it was found that for a typical optical arrangement the SFA value for a volume diffuser and for a QVD are about equal and are below or about equal to 0.1% for the UV and visible range. Many new earth observation missions require an SFA value of 0.01% for these wavelength ranges and preferably also for the near infrared.

It was found that a QVD does not meet this requirement and a new type of diffuser was created, the SanDiff (a sandwich diffuser). It contains of a transmission QVD, a thin piece of volume diffuser (about 100 μm) followed by a reflection QVD. The transmission QVD is a reflection QVD without the aluminum coating on its rear surface such that the bulk of the light can propagate through it. This SanDiff makes optimally use of all types of averaging mechanisms. Since the piece of volume diffuser is sandwiched between two pieces of quartz it is properly protected from the damaging UV radiation that causes the degradation.

3. OPTICAL ARRANGEMENTS

It has already been mentioned in the previous sections that the obtained SFA value is not only determined by the type of diffuser but also depends strongly on the optical arrangement.

Three basic types of optical arrangements can be identified:

1) Free space mode
2) Imaging mode
3) Fourier mode

In the free space mode no optics is present between the diffuser and e.g. the entrance slit of the spectrometer. This mode of usage is very good in terms of angular averaging but suffers from very low intensity throughput. It is very useful to design an arrangement where some free space parts are included.

The imaging mode is very good to get the light spot on the diffuser exactly where you want it, i.e. on the entrance slit of the spectrometer. The intensity throughput is very good and the speckle distribution depends strongly on the exact location of

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the diffuser. Small shifts of the diffuser will already lead to independent speckle patterns. The major drawback of this mode is that the inner-pixel averaging is virtually absent since the diffuser is imaged onto the entrance slit for all wavelengths.

The third mode is the Fourier mode. Here the diffuser is placed in the front focal plane of the optical system while the entrance slit is in the back focal plane. The resulting speckle pattern does have a wavelength dependency such that some inner-pixel averaging will occur. For averaging purposes the diffuser can now best be tilted (for the imaging mode a shift is the best choice). A change of angle of incidence is more effective in the Fourier mode than in the imaging mode.

In most practical optical arrangements a mixed mode is used where some free space mode is combined with either imaging or Fourier mode. By adding free space mode the inner-pixel averaging effect is strongly enhanced.

4. MODEL AND EXPERIMENTS

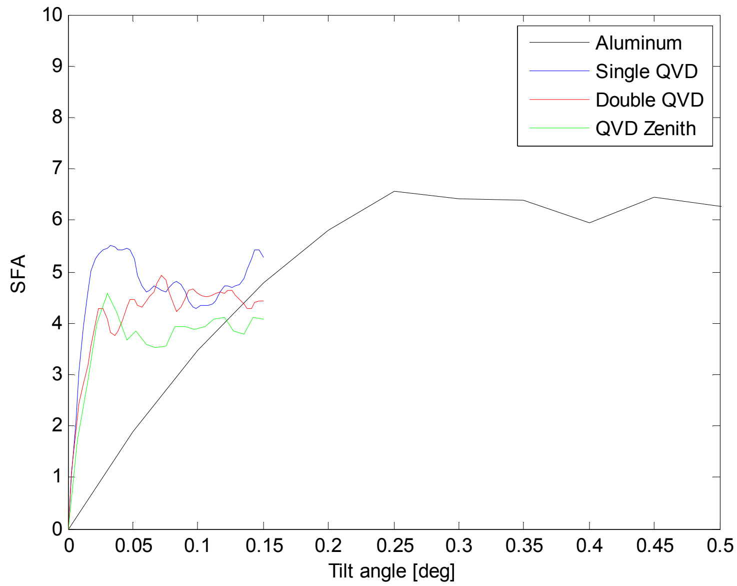

Figure 3 SFA values obtained from the ratio between two spectra where the angle was changed between the two recordings.

Figure 3 shows the result of a simulation on four types of diffusers used in our in-house testing facility; an aluminum surface diffuser, a QVD, a double QVD and the newly designed SanDiff. The optical arrangement of the testing facility has been implemented in the model and the result are verified via measurements. The agreement between model and experiments was found to be excellent.

Shown is the SFA value as a function of the tilt angle applied between the recording of the two spectra from which the ratio is calculated. That ratio should ideally be unity but there are small wiggles about that value where the amplitude of the wiggles increases with the tilt angle applied. The SFA value to which the curves approach is the instantaneous SFA of the diffuser. For the simulations the opening angle of the illuminating beam is zero and the spectral bandwidth per pixel is zero. The actual SFA value has to be extracted from the given curves in Fig.3 where the inner-pixel averaging and angular averaging is taken into account.

The following table gives the instantaneous SFA values, combined with the effects of averaging which leads to the conclusions in the final column where the performance is given with respect to the performance of QVD. SanDiff is shown to be 8 times better than QVD while aluminum is 12 times worse.

The shown results in Fig.3 have been obtained using a MatLab package. The outcome of that package has been verified using measurements with a setup wit the optical arrangement as was simulated. It was found that the simulation gives a very good prediction of what the SFA for a given diffuser type and optical arrangement will be.

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From simulations it is found that all averaging mechanisms reduce in effectiveness with increasing wavelength and that most will stop to work typically at approximately 1.5 µm (depending on optical arrangement). The period of spectral features will increase with wavelength and will finally be about equal to the pixel bandwidth. It will be clear that inner-pixel averaging will no longer take place. The same holds true for coherence averaging. The coherence length increases with increasing wavelength such that above a certain wavelength that mechanisms will also stop to work.

Table 1: performance of four types of diffusers. For the final performance QVD is set as norm. The SanDiff is found to be about 8 times better while the surface diffuser is 12 times worse.

Diffuser:	SFA	Angular sensitivity	Wavelength sensitivity	Performance relative to QVD (lower = better)
Aluminum	6.03	0.09	1	**12**
QVD	5.2	0.022	0.4	**1**
Double QVD	4.29	0.015	0.275	**0.4**
SanDiff	3.94	0.0097	0.135	**0.12**

5. CONCLUSIONS

This document gives an overview of about all aspects of spectral features. The origin is explained to be a speckle effect. From there on scaling rules are given that enable the first order design of a calibration unit. The description of the optical modes in which the diffuser can be used further enables this first order design step. To get a more quantitative number for the SFA value an analytical approach has to be followed as described in the section on model and experiments. Finally a new type of diffuser is presented, SanDiff, that enables calibration units with an SFA value in the order of 0.01% for the UV up to the near infra red band.

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