Characterizing integration time and gray level related non-linearities in a NMOS sensor

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We report a non-linearity effect related to the integration time in a double-beam spectroradiometer equipped with two NMOS sensors. This effect can be explained by the addition of photoelectrons produced by the radiant flux on the sensors during the readout phase to the photoelectrons produced during the measurement phase. A new method is proposed to characterize and correct both gray-level and integration-time-related non-linearities (GLIT-NL) in NMOS sensors. This method is experimentally simple and outperforms other commonly used correction procedures.

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1. Introduction

Spectroradiometers are used in the field and in the laboratory to measure land surfaces reflectance factors from spectral radiance measurements, and to collect information about their properties. However, the acquisition of accurate and comparable data is challenging due to both environmental and instrumental issues [1, 2]. Among the latter, non-linearity features of detectors need to be properly assessed. A radiometric detector is said to be linear if its response—once the dark signal has been subtracted—is proportional to the number of collected photons. Linearity is usually affected by various factors, such as charge leakage during the readout phase [3], supraresponsivity [4], saturation and anti-blooming switches [5] or the electronic transformations required to convert photoelectrons to digital numbers (DN) [6]. During the non-linearity characterization and correction, the signal generated by the sensor in the absence of light (dark signal) must be subtracted. It must be considered that this dark signal is not constant, but is a function of the temperature (T) and the integration time (t_{int}), this is the time interval during which light reaching the sensor is accumulated and collected to generate the analogic signal [7].

In the case of the sensors installed in field spectroradiometers, non-linearity is usually corrected as a function of the gray level measured [8-10], this is the discrete brightness value produced by the analogic-to-digital conversion of the photocurrent generated in a pixel. Photoresponse of these sensors is usually almost linear during most of their dynamic range. However, [11] reported a non-linear photoresponse larger than the specified by the spectrometers manufacturer in a double-beam field spectroradiometer (UniSpec DC, PP Systems, Amesbury MA,

USA). This response was modeled as a function of the gray level, as it is usually done for this type of instruments. Nonetheless subsequent and more extensive repetitions of the calibration experiment revealed the existence of inconsistencies between the modeled photoresponses for the same instrument. Therefore, the existence of other sources of non-linearity than the gray level was analyzed.

As a result, we propose in this work a methodology to characterize and correct non-linearities that depend both on gray level and the integration time referred hereafter as GLIT-NL (Gray-Level and Integration-Time-related Non-Linearity correction). The technique requires the same experimental setup that is needed to implement other usual methods that characterize gray level dependencies of photoresponse [8]. Specifically, the GLIT-NL method requires measuring a constant radiance source with different integration times. Therefore, it could be easily implemented in most spectroscopy laboratories.

2. Methodology

A. Experimental Setup

In this work we characterize and correct the non-linearity of two spectrometers integrated in a Unispec DC double-beam field spectroradiometer. The core of the instrument consists of two MMS-1 modules (Carl Zeiss, Inc., Thornwood, NY, USA), named from now on as “module 1” and “module 2”. Each one is equipped with a silicon diode array S8381-256Q NIR-enhanced sensor (Hamamatsu Photonics K.K., Tokyo, Japan). This is a Negative-module Metal-Oxide Semiconductor (NMOS) linear image sensor, with 256 pixels of 25 μm pitch each. The spectral sampling interval is 3.3 nm, the spectral resolution -Full Width

at Half Maximum (FWHM) is less than 10 nm, and it covers a spectral range from 300 nm to 1100 nm. The analog-to-digital converter (ADC) has 16 bits of dynamic range. Measured noise floor (at 25 ± 2.5 °C) and saturation values are 26.7 DN and 65534.0 DN in module 1, and 28.2 DN and 64999.0 DN in module 2. Like most of the NMOS sensors, it uses a charge integration method to read out the signal. In this method, the generated charge is temporarily stored in the junction capacitance and each photodiode is sequentially read through an output line. Therefore, unlike CCDs sensors, there is no pixel-to-pixel charge transfer, and each pixel is independently read [12, 13]. In the Unispec DC, the fixed readout frequency is about 250 Hz. This instrument does not have shutters to enable the automatic recording of a dark signal; however, it provides temperature readings through a sensor located inside the spectroradiometer.

The non-linearity characterization experiment was carried out at the Environmental Remote Sensing and Spectroscopy Laboratory (SpecLab), belonging to the Spanish National Research Council (CSIC). The experimental setup was similar to the one described in [11]. A 10 W power-stabilized radiance source irradiated an ASD RTS-3ZC integrating sphere (Analytical Spectral Devices Inc., Boulder, Colorado), coated with highly reflective (>95%) Zenith Polytetrafluoroethylene (Sphereoptics Hoffman LLC, Contoocook, NH, USA). Two optical fibers, each connected to one of the MMS-1 modules of the Unispec DC were placed so that their fields of view were included within an open port of the integrating sphere. In order to investigate the linearity of each sensor, forty different integration times ranging between 4 ms and 714 ms were randomly set. Ten spectra were simultaneously acquired with each module for each integration time.

Prior to non-linearity characterization, the dark signal was measured and modeled as a function of the temperature and the integration time. The ends of the optical fiber cables connected to each module were covered to avoid sampling any radiation. 3134 dark spectra were acquired at different integration times that ranged between 4 ms and 1000 ms. Meanwhile the instrument's temperature was modified between 9.5 °C and 45.4 °C using a Raypa DOD-90 drying oven (R. Espinar, Terrasa, Spain).

B. Dark Signal Characterization

A negative relationship of the dark spectra (N_{dark}) with the temperature at low integration times was detected; which could be explained by the presence of an electronic bias (N_{bias}) that decreased linearly with the temperature. This bias was added to the dark signal resulting exclusively from the thermally-generated signal (N_0), which is proportional to the integration time and also varies with temperature. Consequently, we assumed that the dark signal measured in each pixel (i) is the sum of two contributions, as shown in Eq. (1). The abovementioned N_{dark} measurements were used to estimate the coefficients (a and b) in Eq. (1) by means of a least-square fitting. This way, for each measurement, the expected value of N_{dark} could be predicted as a function of the instrument's integration time and temperature as:

$$N_{\text{dark},i} = N_{\text{bias},i}(T) + N_{0,i}(t_{\text{int}}, T) = (b_{0,i} + b_{1,i}T) + t_{\text{int}}(a_{0,i} + a_{1,i}T + a_{2,i}T^2), \quad (1)$$

C. Non-linearity Characterization

We define the gray level recorded in each pixel and exclusively linked to the amount of collected electrons as:

$$N_{\text{meas},i} = N_{\text{phot},i} + N_{\text{dark},i} - N_{\text{bias},i} = N_{\text{phot},i} + N_{0,i}. \quad (2)$$

where $N_{\text{phot},i}$ is the gray level produced only by the incoming photons falling directly on the pixel, expressed in digital numbers (DN). Therefore, the $N_{\text{phot},i}/t_{\text{int}}$ ratio (in DN/ms) must be proportional to the radiance (L), that would be estimated through a radiance calibration factor for each pixel. This factor is not required for the characterization of the non-linearity, hence we will hereafter refer to the above-mentioned ratio as “instrumental radiance”, using the notation $L^*_{\text{phot}} = N_{\text{phot}}/t_{\text{int}}$. Therefore, based on Eq. (2) we obtain:

$$L^*_{\text{meas},i} = L^*_{\text{phot},i} + L^*_{0,i}. \quad (3)$$

where $L^*_{\text{phot},i}$ is proportional to the radiance over the pixel and $L^*_{0,i}$ (N_0/t_{int}) is proportional to the thermally-generated signal and does not represent radiance. See Table 1 for a complete definitions of the variables used.

Table 1. Variables and functions definition

Variables and functions definition	Symbol	Units
Pixel	i	-
Temperature	T	°C
Integration time	t_{int}	ms
Dark signal	N_{dark}	DN
Electronic bias signal	N_0	DN
Thermally-generated signal	N_{bias}	DN
Measured signal	N_{meas}	DN
Photo-generated signal	N_{phot}	DN
Radiance	L	W m ⁻² sr ⁻¹
Measured “instrumental radiance”	L^*_{meas}	DN/ms
Photo-generated “instrumental radiance”	L^*_{phot}	DN/ms or DN/(cd m ⁻²)
Thermally-generated “instrumental radiance” (does not represent radiance)	L^*_0	DN/ms
Normalized “instrumental radiance”	L^*_{norm}	-
Non-linearity correction function related to the integration time	$\mathfrak{R}_{\text{IT}}(t_{\text{int}})$	-
Non-linearity correction function related to the gray level	$\mathfrak{R}_{\text{GL}}(N_{\text{meas}})$	-
Residuals from the $\mathfrak{R}_{\text{IT}}$ fitting	ε	DN/ms
Leakage factor	B	ms
Gray level corrected measured “instrumental radiance”	$L^*_{\text{measGLcor}}$	DN/ms
Corrected photo-generated “instrumental radiance”	L^*_{cor}	DN/ms

As described in 2.A, in order to characterize the non-linearity we varied the integration time of the measurements keeping constant the power of the radiance source; this way a perfectly linear sensor would produce a constant $L^*_{\text{phot},i}$ in each pixel. Non-linearity in the sensors used in field spectroradiometers is usually related with the gray level measured [8, 13]. To analyze this relationship, we computed a value L^*_{norm} for each pixel as the

ratio of L_{meas}^* to a reference L_{meas}^* spectrum acquired with an intermediate integration time of 431 ms. Notice that in [8] this responsivity is calculated dividing $L_{\text{meas},i}^*$ by the maximum value of $L_{\text{meas},i}^*$ instead.

Fig. 1 shows L_{norm}^* vs. N_{meas} for all the pixels of module 2 located between positions 32 and 202, where noise is low. For each particular pixel, the trail of related points represents the different acquisitions, where the integration time ranges between 4 ms and 741 ms. As expected, the responsivity decreases at the highest gray levels [8, 13]. However in those pixels irradiated by a high radiant flux, such as pixel 128, its behavior is completely different than in those pixels irradiated by a low radiant flux, such as pixel 32. On one hand, in pixel 128 L_{norm}^* seems to be hyperbolically related with the integration time. On the other hand, in pixel 32 any fitting that took into account the different error bars would led to an almost constant L_{norm}^* curve within the whole integration time range. A relationship between responsivity and the integration time had been previously reported [3] in CCD detectors. Since light is not blocked during the readout phase, the phenomenon could be explained by the leakage of a significant amount of electrons during this phase due to pixel irradiation. In that case, the effects on responsivity would be larger the more similar the readout and the integration times are.

For this reason, non-linearity was modeled as a function of both the gray level and the integration time. Two functions were defined and fit to correct each type of non-linearity. On one hand, $\mathfrak{R}_{\text{IT}}(t_{\text{int}})$ is the non-linearity correction factor related to the integration time, and it was defined as a hyperbolic function as in [3]. On the other hand, $\mathfrak{R}_{\text{GL}}(N_{\text{meas},i})$ is the non-linearity correction factor related to the gray level; it was defined as a polynomial [8, 11].

Since all the measurements were affected to some degree by both types of non-linearity, the residuals (ε) from fitting of $\mathfrak{R}_{\text{IT}}$ were assumed to be related with $\mathfrak{R}_{\text{GL}}$. This way, both functions could be fit. To characterize $\mathfrak{R}_{\text{IT}}$ two parameters were fit for each pixel: A , which represents the L_{meas}^* that the measurements should ideally yield; and B , which is related to the readout time and the leakage effect and encompasses the dependence of $\mathfrak{R}_{\text{IT}}$ on the integration time:

$$L_{\text{meas},i}^* = A_i \mathfrak{R}_{\text{IT}}(t_{\text{int}}) + \varepsilon_i(N_{\text{meas},i}) = A_i \left(1 + \frac{B_i}{t_{\text{int}}} \right) + \varepsilon_i(N_{\text{meas},i}). \quad (4)$$

where

$$\mathfrak{R}_{\text{IT}} = 1 + \frac{B_i}{t_{\text{int}}}. \quad (5)$$

After a first estimation of A and B , the residuals $\varepsilon_i(N_{\text{meas},i})$ were obtained. By considering that they carry all the information about the non-linearity respect to $N_{\text{meas},i}$, they allow $\mathfrak{R}_{\text{GL}}$ function to be expressed as the ratio between a non-linear function ($L_{\text{meas},i}^*$) and a linear function ($L_{\text{meas},i}^* - \varepsilon_i$) respect to $N_{\text{meas},i}$:

$$\mathfrak{R}_{\text{GL}}(N_{\text{meas},i}) = \frac{L_{\text{meas},i}^*}{L_{\text{meas},i}^* - \varepsilon_i(N_{\text{meas},i})} = \frac{N_{\text{meas},i}}{N_{\text{meas},i} - \varepsilon_i(N_{\text{meas},i}) t_{\text{int}}}. \quad (6)$$

and a polynomial function was fit to it.

Then, $N_{\text{meas},i}$ was corrected using the function $\mathfrak{R}_{\text{GL}}$:

$$L_{\text{measGLcor},i}^* = \frac{N_{\text{meas},i}}{\mathfrak{R}_{\text{GL}}(N_{\text{meas},i}) t_{\text{int}}}. \quad (7)$$

and both functions were fit again using the gray-level-corrected “instrumental radiance” $L_{\text{measGLcor},i}^*$ in the place of $L_{\text{meas},i}^*$ in Eq. (4). The errors from the second fit were added to the ones previously got and used both to calculate $\mathfrak{R}_{\text{GL}}$ by Eq. (6).

Fig. 2 shows the fit of $\mathfrak{R}_{\text{IT}}$ in the pixel 128 of the module 2; the “instrumental radiance” is plotted against the integration time. As can be seen, data initially cannot fit the hyperbolic model, especially those corresponding to the largest gray levels. However, the accuracy of the fit improved when the $\mathfrak{R}_{\text{GL}}$ correction function is applied. Once fit the two non-linearity correction functions it was observed that the magnitude of the leakage charge, represented by B , was not independent of the pixel position. That is because every pixel is irradiated at different level and it was obtained that B was tightly linked to the gray-level-corrected “instrumental radiance” calculated from Eq. (7), which suggests that the observed leakage depends on the irradiance striking the pixel. Therefore, B was not used as a constant coefficient associated to each pixel, but modeled as a function of the measured $L_{\text{measGLcor},i}^*$. A single model was adjusted for each module using data from all the pixels to estimate coefficients C and D :

$$B = C - \frac{D}{L_{\text{measGLcor}}^*} \log \left(1 + \frac{L_{\text{measGLcor}}^*}{D} \right). \quad (8)$$

Prior to the fitting, those data that showed the highest noise levels were discarded.

After characterizing the responsivity of each spectrometer module; the correction of non-linearity can be accomplished as:

$$L_{\text{cor},i}^* = \frac{L_{\text{meas},i}^*}{\mathfrak{R}_{\text{GL}}(N_{\text{meas},i}) \mathfrak{R}_{\text{IT}}(t_{\text{int}})} - L_{0,i}^* = \frac{L_{\text{phot},i}^* + L_{0,i}^*}{\mathfrak{R}_{\text{GL}}(N_{\text{meas},i}) \mathfrak{R}_{\text{IT}}(t_{\text{int}})} - L_{0,i}^*. \quad (9)$$

Here it has been assumed that the non-linear correction does not have a significant impact on $L_{0,i}^*$, therefore the same value has been used for both the corrected and the non-corrected dark signals.

D. Validation

In a pixel with a perfectly linear responsivity, $N_{\text{phot},i}$ is a linear function of the number of photons impinging on the pixel during the collection phase. This way, the rate of the gray level measured to any variable that modifies the amount of collected photons, e.g. integration time or radiant flux, would be constant. For this reason, in order to validate the GLIT-NL correction model, we assessed its ability to reduce the variability of this ratio, represented by $L_{\text{meas},i}^*$. On one hand, we used different integration times under a constant radiance; on the other, we also used a constant integration time under different radiance levels. In this second case, $L_{\text{meas},i}^*$ was calculated as the ratio of $N_{\text{phot},i}$ to the corresponding luminance value set in the light source (Table 2).

The performance of the GLIT-NL method was compared with the non-linearity correction method commonly applied to field spectroradiometers and proposed by OceanOptics (OOLIT) [8]. This method only takes $\mathcal{R}_{\text{GL}}$ into account. Moreover, in order to assess the impact of the integration-time-related non-linearities on this method, we determined two different $\mathcal{R}_{\text{GL}}$ correction functions, each based on a different experimental dataset (Table 2). The first correction function, from now on called OOHIT - Ocean Optics correction using High Integration Times-, was established by using spectra that had been acquired with integration times much larger than the readout time of the sensors. OOHIT was calibrated in a previous work [11] using the same experimental setup and instrumentation; the minimum integration time was 50 ms. A second correction model, OOLIT - Ocean Optics correction using Low Integration Times-, was established by applying the OOLIT method to the data acquired for the GLIT-NL calibration dataset. In this case, the minimum integration time was 4 ms and data had to be smoothed using RLOWESS [14] prior to the model fit.

Table 2. Validation Scheme Summary

Tested datasets			
Dataset	Radiance Source	Modified variable	
GLIT-NL experiment	10 W tungsten bulb	Integration time	
FSF Inter-comparison	Hoffman Engineering LS-65-8D (Tungsten) Luminance/radiance standard source	Radiance	
Ocean Optics Lamp	Mercury-argon calibration source	Integration time	
Correction models compared			
Model	Calibration dataset	t_{int} range (ms)	Correction functions
GLIT-NL	GLIT-NL experiment	4 - 741	$\mathfrak{R}_{\text{IT}}, \mathfrak{R}_{\text{GL}}$
OOLIT	GLIT-NL experiment	4 - 741	$\mathfrak{R}_{\text{GL}}$
OOHIT	Reference [11]	50 - 1350	$\mathfrak{R}_{\text{GL}}$

The three models GLIT-NL, OOHIT and OOLIT were used to correct three different datasets. Firstly, the correction model was applied to the same data used for characterization of GLIT-NL, previously described. Secondly, the correction was applied to spectra acquired with the Unispec DC from a Hoffman Engineering LS-65-8D Luminance/radiance standard source at the NERC Field Spectroscopy Facility, University of Edinburgh. In this experiment, the integration time was kept constant at 122 ms, and the power of the radiance source was changed between

171.3 cd/m² and 3426.2 cd/m². In this case L_{meas}^* was calculated as the ratio of $N_{\text{phot},i}$ to the corresponding luminance set in the light source. This way, the possible effect of supraresponsivity [15], not directly considered in the GLIT-NL model, was at least partly assessed. Additionally, corrections were also applied to a set of narrow-band spectra that were acquired using a mercury-argon calibration source (Ocean Optics, Dunedin, FL, USA) with different low integration times: 4 ms, 6 ms and 7 ms, to avoid saturation. The models that describe $\mathcal{R}_{\text{GL}}$, Eq. (6), and B , Eq. (8), rely on the assumption that the behavior of all the pixels is the same, though differences could exist. Since the emission spectra of the mercury-argon lamp and of the tungsten lamps used in the other experiments are very different, this allowed testing if this assumption could be accepted.

3. Results

A. Dark Signal Characterization

A dark signal model was fit for each pixel. For the pixels in modules 1 and 2 the coefficients of determination (R^2) were 0.995 and 0.994 respectively. Relative Root Mean Squared Error (RRMSE) was 2.83% in module 1 and 2.53% in module 2. Fig. 3 shows the different models for a single pixel belonging to module 2. The predicted bias and dark signal (a) and the dark readings (b) are depicted as a function of the integration time for three different temperatures. As can be observed from the figure, the bias decreases with the temperature and is usually larger than N_0 . The dark signal ($N_{\text{bias}} + N_0$) increases with the integration time and also (and to a larger extent) with the temperature.

B. Non-linearity

The spectra acquired for the non-linearity characterization practically covered the dynamic range of the spectroradiometers. Maximum N_{meas} values were located at pixel 126 in module 1 and at pixel 128 in module 2. For the rest of the pixels, gray levels decreased towards the sensor's ends to almost dark signal values. The function $\mathcal{R}_{\text{GL}}$ characterized from the residuals in the fit of the $\mathcal{R}_{\text{IT}}$ correction function. For $\mathcal{R}_{\text{GL}}$, the RRMSEs of the fit were 0.30% and 0.40% in modules 1 and 2, respectively. Fig. 4 shows $\mathcal{R}_{\text{GL}}$ fitted in module 2 vs. N_{meas} , for both the GLIT-NL curve and measured data. Moreover, the data and the curves of the models OOHIT and OOLIT are also shown. The three curves decrease slowly across most of the dynamic range and then experience a sudden drop at its upper end. The responsivities estimated by the OOHIT and the OOLIT models are lower than that predicted by GLIT-NL. Moreover, OOLIT predicts a sudden initial drop of $\mathcal{R}_{\text{GL}}$ at the lower end of the radiometric range. This results in OOLIT yielding lower values than the other two functions throughout the radiometric range under study.

The fit of the function $\mathcal{R}_{\text{IT}}$ was initially affected by the non-linearity related to the gray level. However, the $\mathcal{R}_{\text{GL}}$ correction led to an increase of the fitting accuracy and eventually the mean RRMSE was as low as 0.32% and 0.39% in modules 1 and 2, respectively. Fig. 5a shows parameter B vs. the pixel position in the spectrometer of module 2. Negative values are seen in both ends of the array, where the signal is too noisy to enable a reliable fitting. Fig. 5b shows the relationship between B and $L_{\text{measGLcor}}^*$. B grows rapidly at first and then levels off to become asymptotic to a saturation level. RRMSEs were 8.98% and 9.37% in modules 1 and 2, respectively.

C. Validation

Figure 6 (left column) shows $L_{\text{phot},i}^*$ spectra corresponding to the three validation datasets in module 2 (Table 2). An assessment of the performance of the three different methods is included in the same figure (right column). Figs. 6a and 6b show the same data used for the GLIT-NL calibration, Figs. 6c and 6d correspond to the spectra acquired with a fixed integration time and varying light source's luminance -notice that $L_{\text{phot},i}^*$ is in $\text{DN cd}^{-1} \text{ m}^{-2}$, and Figs. 6e and 6f show the mercury-argon lamp spectra for three different integration times. Figs. 6a, 6c and 6e depict $L_{\text{phot},i}^*$ spectra both with and without GLIT-NL correction.

Similarly, Figs. 6b, 6d and 6f show, for these $L_{\text{phot},i}^*$, the ratio of the non-corrected to the corrected standard deviations for each pixel. This ratio is a good indicator of the improvement achieved by the correction carried out with the GLIT-NL, OOLIT and OOHIT models, respectively. As can be inferred from the figure, the GLIT-NL method significantly reduces $L_{\text{phot},i}^*$ variation in each pixel, and this effect is observed for the different datasets. The comparison between GLIT-NL and the models that only characterize $\mathfrak{R}_{\text{GL}}$ reveals that the former achieves a better correction of the non-linearities, both using the calibration dataset (Fig. 6b) and also with independent data (Fig. 6d and 6f). The standard deviation of $L_{\text{phot},i}^*$ was reduced in each validation up to 10.54, 4.78 and 25.35 times (Fig. 6b, 6d and 6f, respectively) by the GLIT-NL correction; whereas the maximum drop amounted to only 6.27, 2.99 and 1.29 times, respectively, with OOHIT and to 1.76, 2.23 and 1.23 times when using OOLIT.

4. Discussion

In this work, we analyzed the non-linearity in two NMOS sensors integrated in a Unispec DC spectroradiometer. The dependence of responsivity on gray level is usually characterized and corrected in the sensors integrated in field spectroradiometers. Nonetheless, results proved that responsivity was also affected by the integration time set. This phenomenon had been previously reported in Charge Coupled Devices (CCD) imager sensor [3]. In both cases, it was concluded that the phenomenon was due to the leakage of photo-generated electrons in the photodiode during the readout phase; these electrons would be added to those generated during the integration time. However, a full characterization was not possible in [3] because the effect was dependent on three factors: (1) the radiant power's spectral distribution; (2) the lens' numerical aperture -due to the variation of the inclination distribution of the rays-, and (3) the pixel-to-pixel charge transfer along the sensor columns. The first two factors would influence the geometry of the irradiation and absorption on each pixel (i.e., the pixel region that is irradiated) and, therefore, it would affect the distribution of the photo-generated electrons in the detector bulk. The third factor would not allow the leakage effect to be characterized in each individual pixel. On the contrary, the NMOS sensors characterized in this work presented certain features that allowed the characterization of the dependency of responsivity on both, the gray level and the integration time: (1) each pixel is irradiated by a narrow spectral band (2) the spectrometer's slits and entrances would produce a constant numerical aperture, and (3) no charge is transferred across neighboring pixels because it is read out separately from each individual pixel. The two first factors would produce a constant angular distribution of radiation on the sensor, so that changes in the irradiated area would be minimal. Irradiation geometry could

still be affected by the temperature due to spectral calibration dependencies [16], and by sharp changes in the radiant power's spectral distribution with each pixel waveband. However, these changes could be considered negligible due the spectral features of the sensors characterized. The third factor makes possible the characterization of the pixels on an individual basis, since the number of photoelectrons is not influenced by the number of photoelectrons of adjacent pixels.

Though the two first factors are common to the most of the linear sensors usually integrated in field spectroradiometers, the third is not usually applicable since these are most frequently CCDs. Therefore, the characterization and correction proposed in this work could not be extended to these sensors. Nonetheless, the understanding of the phenomenon is still valuable and its presence should be kept in mind. As shown, this type of non-linearity goes unnoticed unless very low integration times, close to the readout time of the sensor, are used in the non-linearity characterization. Moreover, the responsivity of a large number of pixels must be studied across the sensor array. Thus, this effect is unlikely to be detected by the commonly applied OOINL algorithm [8], which only includes 9 pixels in its non-linearity characterization procedure. Such small sample could lead to confound $\mathfrak{R}_{\text{IT}}$ with noise in those pixels with low gray level. On the contrary, when a large number of pixels is used to characterize non-linearity, as it was the case in the present study, different pixel-position-related trends can be observed, revealing that this non-linearity is not simply noise or sensor unevenness, but a systematic effect (Fig. 4).

This phenomenon had not been observed in previous non-linearity characterization experiments carried out in the laboratory because low irradiance levels and typically large integration times had been used. Though the influence of the integration time on the non-linearity of the sensor can be unnoticed, it still can influence the characterization of the gray-level-related non-linearity, as happened in [11]. As shown in Fig. 4, when this factor is not accounted for, the dependency of responsivity on the gray level is overestimated. This could be explained because, in the OOINL method, responsivity values are calculated by normalizing the L_{phot}^* to each pixel's maximum L_{phot}^* , while $\mathfrak{R}_{\text{IT}}$ induces an increase of L_{phot}^* for low integration times (Fig. 2). As expected, the overestimation of the effects of non-linearity related with the gray level was more pronounced in the OOLIT than in the OOHIT model [11], which is consistent with the hyperbolic dependence of $\mathfrak{R}_{\text{IT}}$ on the integration time.

In the Unispec DC, the integration time can be set between 4 ms and 4000 ms, whereas the sensor's readout time ranges between 2.5 ms and 3.5 ms [17]. Even though it is in fact lower since it has to be divided by the number of pixels in the sensor, -ranging then between 9.8 ns and 13.7 ns in each pixel-, this readout time is large enough to induce a significant non-linearity in the measurements. In other commercially available field spectroradiometers the integration time can also be set to be close to the readout time [18, 19], which can lead users to include this bias effect in the measurements without being aware of it.

The GLIT-NL method characterizes the function $\mathfrak{R}_{\text{GL}}$ from the residuals in the fit of $\mathfrak{R}_{\text{IT}}$. This is possible since these residuals are mainly produced by the dependency of responsivity on the gray level. However, like others methods [8, 11], the GLIT-NL assumes that the response of all the pixels of a sensor is the same. This would introduce some uncertainty in the correction procedure; however, validation shows that the differences between pixels are less relevant than the corrected non-

linearities. Other works have also reported non-linearities independent of the wavelength in photodiode arrays [9]. The calibration of a model for each sensor pixel would require that the full dynamic range was completely covered for all the pixels during the characterization experiment. Though GLIT-NL does not characterize each pixel separately, this method is experimentally affordable and easy to implement in most spectroscopy laboratories.

In the GLIT-NL model, B represents the pixel's charge leakage rate between the detection and the register phases multiplied by the readout time. Results suggest that B varies with the radiant flux impinging on each pixel, reaching a saturation level above a given radiant flux level, as if the charge leakage rate would depend on the photoelectrons generated during the readout rate until a given density of electrons is reached. For this reason, a saturation function was chosen to characterize the relationship between B and the "instrumental radiance" Eq. (8).

Since the characterization method is based on the residuals of one of the models fit, a robust validation scheme has been proposed to demonstrate that this is not just a way of improving the fit of experimental data. Therefore, the performance of the GLIT-NL method has been tested with datasets of different characteristics: On one hand, we used the data acquired for the characterization of the non-linearities; on the other, we also used independent data acquired using a different methodology or from a radiance source with a very different emission spectrum curve (Table 2). In all the cases, the performance of GLIT-NL method has been compared with other correction models. The method proposed in this work outperformed those methods that only correct for $\mathfrak{R}_{GL}$. As show in Fig. 6, validation was carried out using different radiance levels, the highest levels being reached with the mercury-argon lamp. It is worth pointing out that this is not a trivial issue, since radiance level determines the integration time to be selected and the value of B , but the radiance levels found in the field and in the laboratory can differ significantly. For instance, the maximum "instrumental radiance" levels reached by the tungsten lamps in the experiments described ranged between 60 DN/ms and 100 DN/ms, whereas in the case of the mercury-argon lamp they exceeded 5000 DN/ms. Field measurements acquired under solar irradiance during a summer clear-sky day can reach maxima L_{meas}^* between 1000 DN/ms and 3000 DN/ms with integration times between 19 ms and 39 ms. These low integration times and high radiance levels could potentially induce significant deviations in the acquired spectra. Therefore, as shown in the validation, methods that only account for $\mathfrak{R}_{GL}$ may not always be successful at correcting non-linearities in field measurements. GLIT-NL does not correct for suprasensitivity, which depends on the factor $(N/N_0) \times t_{int}$ (related with irradiance), since this effect did not become evident for the range tested with our spectroradiometer, but a very similar methodology may be developed if required.

Several approaches have been used to characterize non-linearity in radiometric instrumentation. Usually, the response to different irradiance levels have been characterized using methods based on the superposition of sources, but also others [9, 10]. In the case of field spectroradiometers, different integration times are frequently used to achieve a range of signal that allows the characterization [8, 11]. In these cases, results show a decrease of linearity as the signal gets close to saturation, due to different reasons (ADC, suprasensitivity...) [20]. However, the impact of the integration time has not been so usually analyzed. Reference [9] also found a decrease of linearity at larger

integration times, which was interpreted as a loss of photoelectrons during the storage of the charge.

The Unispec DC and other field spectroradiometers are frequently used to measure reflectance factors and sometimes also radiances. Reflectance factors are obtained as the ratio of two measurements over the same pixel. This means that non-linearities could mutually cancel out if they were of similar magnitude in each pixel. However, in some cases, the signal differences between the down-welling irradiance (using reference panels and / or cosine receptors) and the up-welling radiance (which is a function of the down-welling irradiance and the fraction of it reflected by the measured target), could lead to different non-linearity magnitudes that would not cancel out during the calculation of reflectance factors. As discussed in a previous work [11], non-linearities could play an especially relevant role in certain applications where both, the non-linearities and the variable of interest, depend on the irradiance level. In the context of remote and proximal sensing, examples include the quantification of radiance; the study of short-term vegetation stress by measuring slight reflectance changes related to the Xanthophyll cycle [21] and sun-induced fluorescence [22]; or the characterization of the Bi-Directional-Reflectance-Function. In all these cases the measured radiance would determine the integration time to be selected and the gray level of each pixel -and, therefore, its non-linearity. However, the integration time and the gray level would be also related to down-welling irradiance, illumination and observation angles and possibly to the vegetation physiology as well.

5. Conclusions

The GLIT-NL method is proposed to characterize non-linearities related with the gray level and the integration time in NMOS sensors integrated in MMS-1 spectrometers of a Unispec DC spectroradiometer. The method has been robustly validated, and it has been proved that linearity is better achieved when the dependencies on the integration time are characterized and corrected. The source of this non-linearity is the addition of spurious electrons due to pixel irradiation during the readout phase. Therefore, it could a potentially affect other sensors not tested here, as in [3]. Pixel-to-pixel charge transfer in CCD sensors makes no possible the application of this method; however users still should be aware of the phenomenon and avoid the use of integration times that are close to the sensor's readout time. GLIT-NL improves the instrumentation performance under large irradiance levels, when integration times close to the readout time must be set to avoid saturation. These conditions can be found both outdoors and in the laboratory. Therefore, the quantification of radiometric variables, the measurement of reflectance factors and the characterization of sensors could potentially be improved by this method. The present work's findings stress the need to match the radiance levels used for field spectroradiometers' characterization with those later found outdoors, so as to obtain reliable field measurements.

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Figures

Fig. 1. Normalized L^* norm vs. N_{meas} in pixels 32 to 202 of MMS-1 module 2. Data corresponding to pixels 32 and 128 have been highlighted. The error bars represent the 95% confidence interval

Fig. 2. L^* vs. integration time (t_{int}) during the simultaneous fit of parameters A and B in the pixel 128 of module 2 before and after $\mathcal{R}_{\text{GL}}$ correction is applied

Fig. 3. Predicted dark current and electronic bias (a) and predicted and measured total dark signal (b) vs. integration time at different temperatures. Modeled data are depicted with lines, and measurements with dots. The simulations correspond to pixel 128 of module 2

Fig. 4. $\mathcal{R}_{\text{GL}}$ correction functions in module 2, computed using three different methods

Fig. 5. Estimated B for each pixel in module 2 (a) and B modeled as a function of $L^*_{\text{measGLcor}}$ (b) in module 2

Fig. 6. Left: $L^*_{phot,i}$ spectra with and without GLIT-NL correction for the different validation datasets: calibration (a), FSF-NERC lamp (c) and mercury-argon lamp (e). $L^*_{phot,i}$ is given in DN/ms in (a) and (e) and in DN cd⁻¹ m² in (c). Right: The curves represent, for each pixel, the ratio between the standard deviation of the non-corrected data and the standard deviation of the data that has been corrected with OOHIT, OOLIT or GLIT-NL.