Calibration algorithms for an imaging spectrometer

Dell'Endice, F; APEX team, including the following author; Schaepman, M E
Calibration algorithms for an imaging spectrometer

Abstract

This paper presents a software calibration/characterization utility aimed to automatically perform the laboratory calibration of an imaging spectrometer. Quantitative remote sensing algorithms require well-documented instrument optical performances along with characterization of nonuniformities as, for instance, smile and keystone. Automatic calibration data acquisition and processing facilitate the understanding of the instrument properties and allow the implementation of specific correction schemes. The concept of calibration cube is also introduced as a promptly accessible data structure for the retrieval of optical properties in any detector position. A case study along with all its relevant results is also introduced, based on the Airborne Prism Experiment (APEX) imaging spectrometer. Recommendations and suggestions are also given for customized implementations of this tool.
CALIBRATION ALGORITHMS FOR AN IMAGING SPECTROMETER

Francesco Dell’Endice and the APEX team

Remote Sensing Laboratories (RSL) – University of Zurich – Winterthurerstrasse 190, CH8057 Zurich, Switzerland (francesco.dellendice@geo.uzh.ch)

ABSTRACT

This paper presents a software calibration/characterization utility aimed to automatically perform the laboratory calibration of an imaging spectrometer. Quantitative remote sensing algorithms require well-documented instrument optical performances along with characterization of non-uniformities as, for instance, smile and keystone. Automatic calibration data acquisition and processing facilitate the understanding of the instrument properties and allow the implementation of specific correction schemes. The concept of calibration cube is also introduced as a promptly accessible data structure for the retrieval of optical properties in any detector position. A case study along with all its relevant results is also introduced, based on the Airborne Prism Experiment (APEX) imaging spectrometer. Recommendations and suggestions are also given for customized implementations of this tool.

Index Terms— Imaging spectrometers, laboratory calibration, data processing

1. INTRODUCTION

Airborne and spaceborne imaging spectrometers are nowadays used in order to monitor the complex structure of the planet Earth in a quantitative way [1-4]. The precise observation of physical, chemical, and morphological parameters of the sensed target require an accurate calibration and characterization process; this is mainly true if users want to detect the variability over time and space of material characteristics. Imaging spectrometers sense the spectral of materials by using either charge-coupled-device (CCD) [5] or complementary-metal-oxide-semiconductor (CMOS) [6], each constituted of a large amount of detector elements or pixel (usually in the range of a million). Manual laboratory calibration and characterization of such an amount of pixels would require an enormous time effort. Detector non-uniformities, as for instance smile and keystone as well as point-spread-function (PSF) width variations, require the detector to be characterized at a certain number of pixels such that those “anomalies” can be correctly represented [7, 8]. As a rule of thumb, given a detector with $s$ spatial pixels and $b$ spectral pixels, a good compromise would be to calibrate and characterize at least $1/10^{th}$ of the overall number of detector pixels. If a calibration laboratory allows automatic control of the instrumentation (e.g. linear stage, rotary stage, electrical folding mirror, monochromator) then such goal can be achieved. Moved by this idea, we implemented a hardware/software utility that interface the airborne prism experiment imaging spectrometer (APEX) [9] with the light stimuli provided by the calibration home base (CHB) [10].

Figure 1: APEX in the Calibration Home Base CHB).

This utility can drive, upon initial setting of both instrument and instrumentation parameters, the full characterization process almost completely automatically. A full automatic run is allowed for spectral calibration, across-track and along-track geometric calibration, and relative radiometric calibration. The CTM is hereafter described.

2. METHODS

Let us assume that a detector with $B$ spectral bands and $T$ spatial pixels need to be calibrated and characterized in laboratory. A single spectral pixel is indicated through the letter $b$ while one spatial pixel is indicated with the letter $t$.

The main goal of the laboratory calibration is to define the following pixel-dependent parameters:

- Centre wavelengths $\lambda(b,t)$
- FWHM of spectral response functions $f(b,t)$
- Radiometric gains $g(b,t)$
- Radiometric offsets $d(b,t)$
Let us also assume that the detector is affected from the following pixel-dependent non-uniformities:

- Smile \( s(b,t) \)
- Keystone \( k(b,t) \)
- Spatial FWHM variations across-track \( a(b,t) \)
- Spatial FWHM variations along-track \( l(b,t) \)

It is obvious that a specific calibration strategy needs to be implemented in order to measure all the aforementioned parameters. It should be also noted that only some of the non-uniformities have been considered here; for instance, straylight, smear, polarization effects shall be also accounted for. Imaging spectroscopy data [11-20] are usually distributed along with a calibration file that usually includes center wavelengths, FWHM of the spectral response functions, radiometric gains and offset, all along with uncertainties. The imaging spectroscopy data users generally accept and not question the following assumption:

*The calibration coefficients are the same for all the detector spatial pixels.*

The classical calibration problem is formulated as it follows:

**Equation 1: the classical laboratory calibration approach.**

\[
\begin{align*}
\lambda(b) &= \lambda \quad \forall t \\
\tilde{f}(b) &= f \quad \forall t \quad \text{with} \quad k(b,t) = 0 \quad \forall b, \forall t \\
g(b) &= g \quad \forall t \quad \text{with} \quad a(b,t) = 0 \quad \forall b, \forall t \\
d(b) &= d \quad \forall t \quad \text{with} \quad l(b,t) = 0 \quad \forall b, \forall t
\end{align*}
\]

In other words, it is assumed that the calibration parameters are constant and the calibration file applies to all pixels in the detector field-of-view (FOV). More in details, it is assumed that the detector is not affected from any kind of non-uniformities; a measurement of the sensor performances along a preferred spatial direction is then enough to characterize and calibrate the whole detector. The basic assumption of the classic calibration approach has to be seriously criticized and questioned. The consequences of the refutation of such an assumption are relevant mostly for pushbroom scanners, while the classical approach can still be used for whiskbroom sensors where only one spatial pixel is scanned through the field-of-view. Whiskbroom scanning systems are less affected from non-uniformities because there is no “cross-contamination” between adjacent pixels: they can be considered as being one-spatial pixel systems. Pushbroom instruments, in comparison, can be referred to as multiple-spatial pixels systems; the spatial cross-contamination between adjacent pixels recorded at the same time influences the spectral and radiometric performances. The problem is now reformulated as follows:

**Equation 2: an innovative laboratory calibration approach.**

\[
\begin{align*}
\lambda &= \lambda(b,t) \\
\tilde{f} &= f(b,t) \\
g &= g(b,t) \\
d &= d(b,t)
\end{align*}
\]

The optical performances of the detector have to be measured in several spatial positions in order to properly characterize the spatial variation of the non-uniformities. The problem is then to establish a precise measurement setup that allows such a complex calibration and characterization strategy that otherwise would be not possible. The input to such an approach is state-of-the-art calibration lab, referred to as Calibration Home Base (CHB), belonging to the German Aerospace Center (DLR) and located in Munich, that allows automatic operation of the main calibration instrumentation [21]. A series of classical equipment (e.g. a monochromator covering the range between 350 and 2500 nm, and two integrating spheres) can be operated automatically; the characterization of the pushbroom detector performances along its FOV is facilitated through the use of a moving motor-driven folding mirror. For more details refer to [21]. By means of this setup, the problem stated in Equation 2 can be directly solved through a sequence of well-establish measurement procedures. A series of algorithms has been implemented and grouped under the name of Calibration Test Master (CTM). The CTM consists of a twofold software package:

- Controller Unit: it interfaces the instrument to be characterized and calibrated with the calibration equipment.
- Processor Unit: it analyze the measurement data and provide the calibration and characterization coefficients.

The CTM controller is implemented in TCL while the CTM processor is coded in C and developed in MATLAB. Once the sensor and the CHB parameters are set, the calibration and the characterization take place in an automatic manner for all the selected spatial pixel locations. This approach minimizes the manual intervention, increases the number of pixels subjected to calibration and characterization, and provides a complete and accurate understanding of the detector spectral, geometrical and radiometric performances. Nevertheless, the optimization of the measurement setup requires some additional time and preliminary tests have to be carried before running the full software suite.

2.1. Calibration cube

The calibration and the characterization processes lead to the generation of a considerable amount of coefficients (i.e. centre wavelengths, radiometric gain and offset, smile and frown profile, point spread function across-track and along-
The CTM generates all those coefficients for all the detector pixels. Therefore, there is the need to develop a new data structure that would group all of them in the most representative way. We introduce the concept of calibration cube [22].

A calibration cube is a three-dimensional data structure; its first dimension corresponds to the number of detector across-track pixels, while its second dimension corresponds to the number of available spectral bands. The third dimension of the cube is equal to the number of calibration and characterization coefficients. Every coefficient is stored in its corresponding layer. Such a data structure provides users with an additional insight into the instrument performance and gives them the chance to better understand how the calibration itself and the non-uniformities can influence the retrieval of imaging spectroscopy quantitative products. The calibration cube provides classical calibration parameters and additional ones for every across-track pixels; from one point of view users have to deal with an increased quantity of information but, on the other side, offers a detailed series of fundamental knowledge about the sensor performances. Those calibration and characterization coefficients can be used for additional correction algorithms, for selection of the most responding pixels, for definition of consistent and reliable detector regions, for defining the uncertainty of the imaging spectroscopy methods and products.

3. DISCUSSION

This implemented and tested utility allows an intrinsic increase of calibration accuracy, thanks to the elevate numbers of calibrated and characterized pixels. Detector non-uniformities can be well characterized and the whole behavior of the CCD or of the CMOS can be completely understood. Beside the fact that all process can be completed in a relative short time (more or less about one week), this approach gives users the advantage of interpreting more accurately the scene optical properties at every spatial position. A drawback of such a technique is that a small test campaign shall be carried out before running the global automatic procedure because every sensor responds differently to the provided stimuli because.

Hence, small experiments shall be executed for every light source, principally in order to avoid that the detector under analysis goes into saturation during the measurements leading then to wrong results.

4. CONCLUSIONS

The CTM and the non-classical calibration approach have been extensively tested on APEX instrument. Several calibration campaigns have demonstrated the added value of the calibration test master. More in detail, the most relevant calibration and characterization parameters have been measured at several FOV positions. A baseline of 11 equally spaced points along the FOV has been selected and a variable number of points have been investigated in the spectral domain.

Generally, the CTM demonstrated the following advantages:

1. Consistent time saving for measurements.
2. Several measured points over the detector areas.
3. Complete characterization of the detector optical properties.
4. Reduction of the laboratory radiometric uncertainty to less than 5%.

Spectral calibration has been performed over 16 bands in the VNIR channel and 15 bands in the SWIR channel, both repeated at 11 FOV positions. A total of 341 measuring points have been acquired automatically through the CTM in about 5 hours; every calibrated point consisted of at least a series of 20 sequential measurements, necessary to resolve the spectral response function of the addressed pixel. The processing of those calibration data allowed us to properly quantify the smile distribution and the variations of the FWHM of the spectral response functions. The geometric measurements across-track and along-track have been performed in less than 2 hours in the 11 FOV positions; results of those data were the keystone profile across-track, and PSF across-track and along-track variations over the detector areas. The radiometric measurements over the integrating spheres consisted of a large number of acquired frames and let to the determination of the following parameters: radiometric gains and offsets, vignetting profile, noise equivalent delta radiances, correction coefficients for non-linearity with intensity and non-linearity with integration time, dynamic range, bad pixels map. The whole radiometric assessment took up to a working day. Including additional measurements about straylight from and outside the FOV, and polarization characterization, a full calibration and characterization campaign takes about 1 week for data acquisition and 1 week for data processing. It must be noted that the volume of calibration data amounts to 40 GB circa.

Two calibration cubes (i.e. one for the VNIR channel and one for the SWIR channel) have been generated, each one consisting of more than 15 layers containing precious calibration information. Non-uniformities could be easily characterized and used for correction schemes. Such corrections would reduce the total radiometric uncertainty to
less than 5%, which can be considered as the limit level can be tolerated in order to perform the steps following the radiometric calibration in a more consistent way. An imaging spectrometer shall grant the spectral and radiometric consistency of the measured spectral. The laboratory calibration shall support such a goal providing a full overview over the instrument optical properties.

11. REFERENCES


