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AUTOMATIC CALIBRATION AND CORRECTION SCHEME FOR APEX (AIRBORNE PRISM EXPERIMENT)

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ABSTRACT

Hyperspectral sensors provide a large amount of both spatial and spectral information. Calibration plays an important role in the efficient use of such a rich data source. However, calibration is extremely time consuming if undertaken with traditional strategies. Recent studies demonstrated that various non-uniformities, and detector imperfections drastically affect the hyperspectral data quality if not known and corrected for. The APEX (Airborne Prism Experiment) spectrometer adopts an automatic calibration and characterization strategy with the ultimate goal of providing scientific products of very high accuracy. This strategy relies on the control test master (CTM), an advanced software/hardware equipment able to control independently the instrumentation, and to process online or offline the large amount of data acquired to characterize such a sophisticated instrument. Those data, once processed by the master processor, will generate several coefficients that in turn will feed the processing and archiving facility (PAF), a software module that calibrates the acquired scenes, and corrects for artefacts and non-uniformities.

INTRODUCTION

Hyperspectral sensors provide a large amount of both spatial and spectral information. Calibration plays an important role in order to use efficiently such a rich data source. Hyperspectral scanners are calibrated by means of various techniques, which are usually applied both in a laboratory and/or during the acquisition itself via on-board instrumentation. However, calibration is extremely time consuming if undertaken with traditional strategies, i.e. by manual laboratory measurements at a few selected pixels over the detector area. Thus a compromise is necessary: only the compulsory measurements are performed, namely those concerning the spectral and the radiometric calibration (1); nevertheless these measured parameters can be sufficient to reach an acceptable accuracy of the hyperspectral products delivered to the scientific community. On the other hand, measuring several calibration parameters for all the detector pixels implies the production of a large amount of data, which would need a dedicated hardware/software environment (2,3) able to exploit such information. If calibration data are acquired also during the acquisition phases, i.e. on-board, the situation becomes even more challenging, due to the increased amount of information.

Recent studies (4,5,6) demonstrated that various non-uniformities, and detector imperfections will drastically affect the hyperspectral data quality if not known and corrected for. Thus better detector characterization and calibration are recommended. Such a goal can only be achieved if both laboratory and in-flight calibration data are acquired at several pixels on one side, and if other parameters are introduced and measured in the calibration strategy on the other side, as for instance misregistration (5,6), co-registration, and stability.

For this to be feasible in terms of both time and precision, the APEX (Airborne Prism Experiment) spectrometer adopts an automatic calibration and characterization strategy with the ultimate goal of providing high accuracy scientific products. The concept is illustrated in the further sections.

THE CALIBRATION TEST MASTER

The APEX calibration strategy focuses on the measurement of several calibration and characterization parameters at selected pixels within the detector area. For this purpose, a calibration test master (CTM) is used. The CTM is a hardware/software facility that optimizes the time needed for the calibration by automatic generation of optical stimuli. Thus no manual action is required, apart from some secondary settings, e.g. switching on/off the light sources. The CTM interfaces APEX with both a laboratory ground facility, i.e. the Calibration Home Base (CHB) (7) in Oberpfaffenhofen (Germany), and an In-Flight Calibration facility (IFC) (2). The instrumentation in both the CHB and the IFC can be controlled remotely via a computer interface, thus enabling automatic measurements.

The CTM consists of three main elements (***Figure 1***):

- *The controller* that is the core unit of the CTM.
- *The storage unit*, which is partly embedded in APEX and partly located on an external desktop.
- *The processor*, whose function is to process all the calibration data.

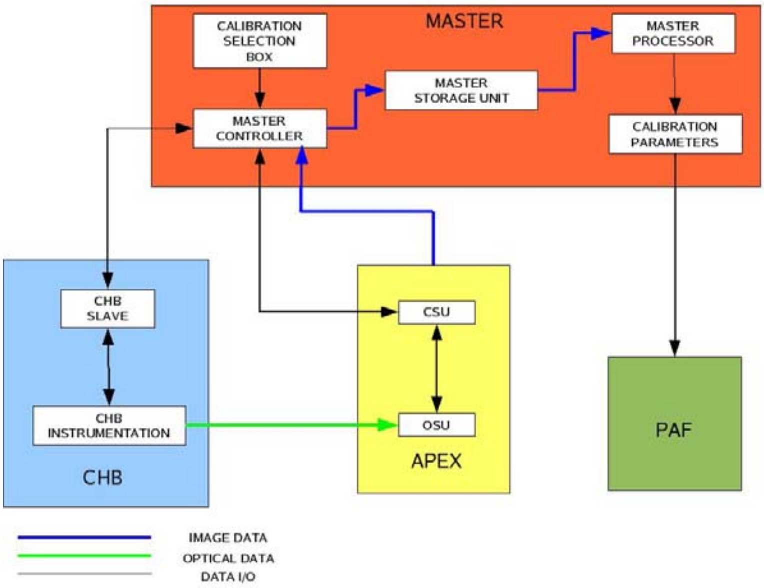

Figure 1: CTM logical working flow. The CTM interfaces APEX, the CHB, and the PAF.

The CTM controller is embedded in the APEX instrument and sets up all the necessary parameters, i.e. APEX settings (e.g. integration time) and calibration facility settings (e.g. monochromator wavelength, integrating sphere lamp intensity), for a particular calibration procedure to be performed. Once the setting is completed, the calibration measurements take place, and the acquired data are stored in the storage unit. The CTM processor is a complementary software utility, installed on a dedicated external hardware, whose goal is to generate the calibration parameters, necessary to calibrate the acquired raw data by processing all the data in the CTM storage unit. The Processing and Archiving Facility (PAF) (2) utilizes the calibration parameters provided by the CTM for the level 0 to level 1 processing.

For automated procedures a certain number of sequential sub-requests for both the CHB (e.g. folding mirror height, scan angle, lamp voltage, etc.) and APEX are generated. For each sub-request to be processed by the hardware the controller generates a well-formatted file, which in turn will be transformed into an electric and/or mechanic signal. The measurements are carried out once the sub-requests have been executed by the relevant hardware. The time needed to process every sub-request has been estimated to be about 5s but this can be reduced if no drastic changes on the setup are needed. The overall calibration phase therefore requires about one week time.

Several units of the laboratory facility can be controlled remotely, e.g. the folding mirror (i.e., height, linear position, and angular position), the monochromator (e.g., voltage, current, wavelength), the collimator and the integrating sphere (e.g. lamp combination) thus facilitating the automated approach chosen for the CTM.

CALIBRATION AND CHARACTERIZATION PARAMETERS

Several calibration and characterization procedures are applied to APEX in order to better characterize and calibrate the sensor. Procedures are applied both in laboratory and on board by means of a dedicated instrumentation or by using special methodologies on the acquired scenes, the so-called scene-based vicarious calibration algorithms.

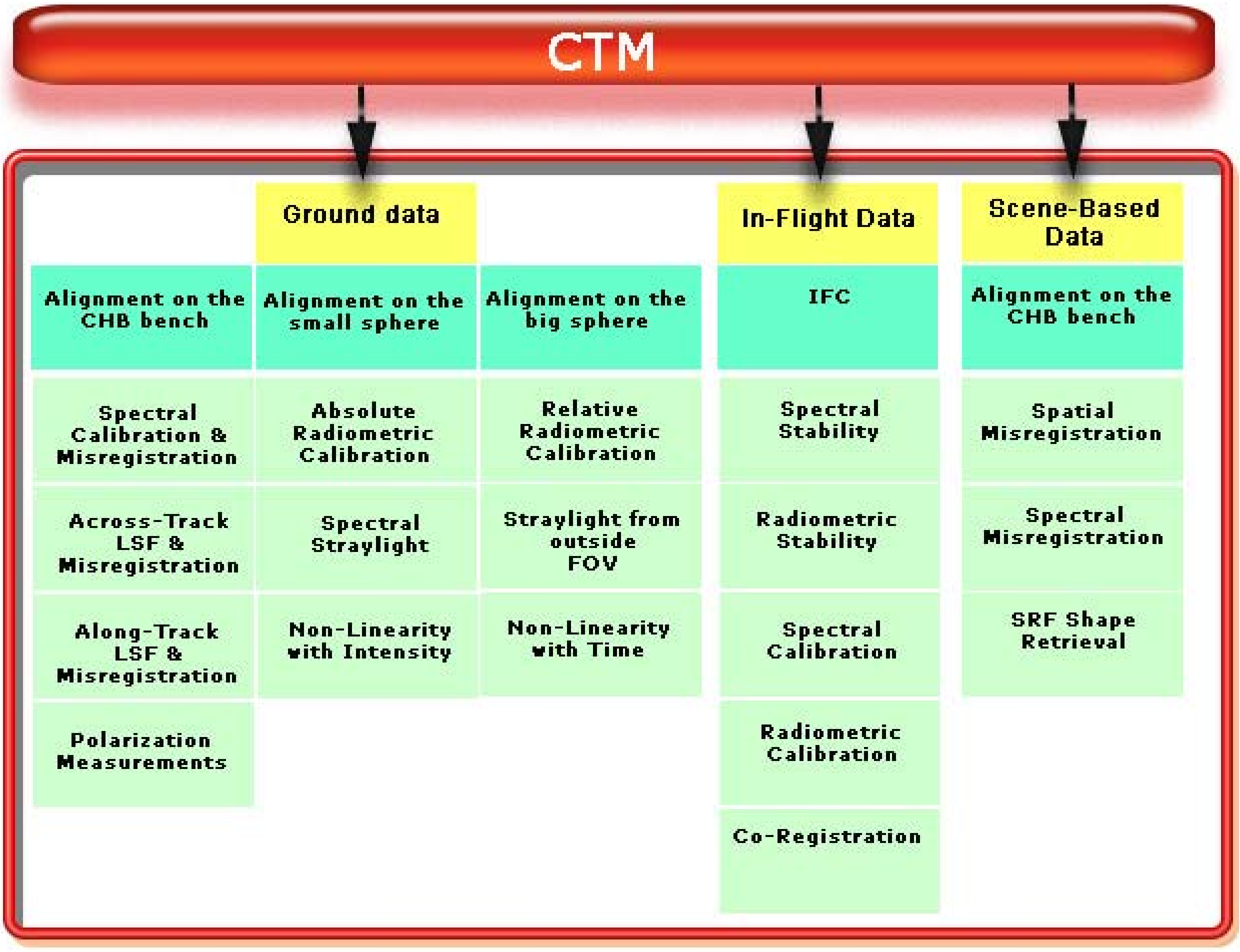

Figure 2: Data acquired by means of the Calibration Test Master (CTM), using the CHB, the IFC, and scene-based algorithms.

These procedures produce several parameters that can be grouped as follows (***Figure 2***):

- *Ground parameters*: generated by processing the data acquired by the laboratory facility, i.e. the CHB.
- *In-Flight parameters*: generated by processing the data acquired by the on-board calibration facility, i.e. the IFC.
- *Scenes parameters*: generated by processing the recorded real scenes.

As mentioned earlier, the CHB can be controlled remotely by the CTM. This is mainly possible because an engine-driven folding mirror with two degrees of freedom is used in order to redirect the illumination source beams on a specified detector position. Thus, the time saved in performing the common hyperspectral calibration procedures (i.e. spectral calibration and radiometric calibration) is employed to increase the number of characterized pixels, but it is also used to perform additional characterization measurements such as straylight from inside and outside the field of view (FOV), point spread function (PSF) across as well as along track, polarization measurements and so on. PSF measurements are important in order to understand both the spectral and spatial resolution performances of the detector. Besides the folding mirror, two integrating spheres of different sizes allow the absolute and the relative radiometric detector calibration as well as the measurement of non-linear detector behaviours with time and light intensity in order to model the sensor when close to saturation limits.

On the other side the IFC facility performs other characterization measurements that further increase the amount of information at detector level, e.g. co-registration in across-track, along-track and spectral dimensions, radiometric stability and spectral stability. Co-registration, meant to measure the change on detector performances with temperature and pressure, starts actually at laboratory level, where a first set of calibration data is acquired at standard environment conditions. The IFC plays also another important role on the decision-making process for the calibration strategy. The degradation of the detector performances is constantly monitored and compared with the laboratory results. If the difference between the on-board results and the laboratory results is such that the best detector performances cannot be guaranteed, then the operational phase has to be stopped and APEX has to be characterized and calibrated once again in the CHB.

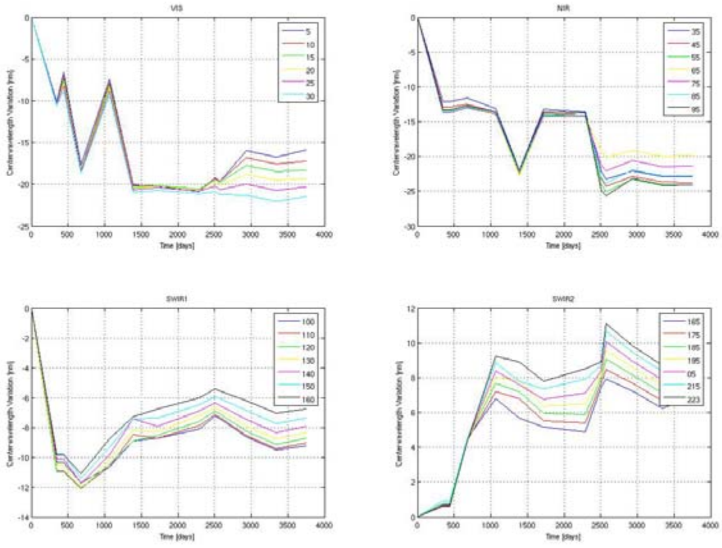

Figure 3: Absolute centre wavelength variation vs. time for the AVIRIS sensor, as measured in the laboratory.

A stability analysis has been performed on the AVIRIS (1) calibration data over a period of almost ten years for both the centre wavelength (***Figure 3***) and the spectral sampling interval. For instance, the centre wavelengths change constantly. Abrupt variations correspond to substitutions of optical detector elements and these cases necessitate a new laboratory characterization phase. On the other hand, smoother changes correspond to a degradation of the detector performances. However, if such degradation can still guarantee a satisfying performance then the operational phase could continue. The APEX strategy foresees an on-board monitoring of the most significant calibration parameters to check whether a significant degradation took place and performances are compromised. If multi-temporal analysis, also called change detection, has to be performed for a ground target, then these monitoring parameters can be used in order to compare the scenes acquired at different times.

In order to measure spectral stability, the IFC is equipped with a set of four different filters:

- A standard reference SRM material 2065 filter from NIST.
- A bandpass 694 nm filter.
- A bandpass 1000 nm filter.
- A bandpass 2218 nm filter.
- A NG4 filter.

These elements are mounted on a rotating filter wheel. The NG4 filter is used to avoid detector saturation at maximum radiance level in the VNIR channel. The 1000 nm bandpass filter is used in order to measure the APEX properties in the overlapping region between the VNIR and SWIR detectors. The radiance coming out of the IFC lamp will pass through one of the aforementioned filters and it will reach the detector. By comparing different measurements over time is possible to quantify the spectral stability as well as the radiometric stability. These measurements are performed before and after every flight section and will be represented by dedicated parameters. These filters are also used for in-flight spectral calibration, namely by using the rare Earth materials filter, which has predefined absorption characteristics.

Recently, it has become feasible to retrieve and/or refine instrument characteristics by analyzing acquired scene data as opposed to synthetic laboratory data acquisitions. This is achieved by the (a) the acquisition and maintenance of precise reference databases of known physical phenomena, (b) increasing sophistication of engineering techniques for the juxtaposition of calibration references (e.g. cross-hairs of known angle and thickness) within the image data, (c) decreasing effort needed to run scores of model simulations permuted over varying parameters for the purpose of inverse data fitting and (d) sophistication of algorithms for retrieving various characteristics. Among the first instance of scene-based hyperspectral instrument characterization was the use of a spectrum-matching technique for improving wavelength calibration (8), that was later refined (9). A process for the detection of spectral line curvature including bandwidth as well as band centre shifts was refined by Neville (10). The APEX calibration strategy foresees the use of these algorithms for the retrieval/refinement of spectral response function (SRF) shape as well as band centre and bandwidth (11,12). Retrieval and refinement of spatial characterization will be applied using a method for spatial misregistration detection (13) and correction (6). Currently, scene-based calibration/characterization cannot fully replace laboratory calibration but it can supplement and validate them as well as possibly increase instrument “up time” in between intensive full laboratory calibration/characterization campaigns.

THE APEX CALIBRATION AND CORRECTION PARAMETERS

Several sets of data are acquired during the calibration/characterization phase in order to get the highest knowledge of the APEX system. The automatic calibration concept is a pioneer in the field of the calibration of hyperspectral sensors, in the sense that the saved time in performing the traditional procedures will be used to measure other parameters. The amount of calibration data can be large; a coarse estimation indicates that such data will be around half a terabyte. Thus, a dedicated software (e.g. parallel computing) and/or hardware (e.g. cluster or grid) strategy becomes compulsory, as a common CPU will not be able to process this amount of data in an acceptable short timeframe. Parallelization (14) of the data processing scheme will be used for APEX in order to satisfy the high computational power demand. These issues of processing setup and computing architectures are however not further elaborated in this paper. Our main objective will be to describe the calibration parameters that will be retrieved by processing calibration/characterization data.

Therefore the parameters issued out of the laboratory facility are described hereafter. The first point we take care of is related to the classical radiometric calibration, i.e. the passage from the raw digital numbers to physical units (e.g. radiance units). The radiometric calibration itself allows determining the relationship between these two entities, taking into account both the dark current level and the instrument exposure time; usually this step ends by identifying the gain coefficient and the dark current baseline for every pixel of the two APEX sensors (i.e. the VNIR detector and the SWIR detector). Non-linear behaviour with both time and light intensity is also here investigated, and a dedicated parameterization of the radiometric equation will take these effects into account; this will avoid, for instance, any kind of unfruitful use of the acquired data when we operate close to the saturation detector limit.

The spectral calibration, due to the automatic strategy, can be performed at several spatial locations and at several spectral channels with sub-pixel precision. The first advantage is that the interpolation between measurements, necessary to determine the centre wavelengths of the unconsidered pixels, will be much more precise; furthermore possible non-linear behaviour in the relationship between band number and wavelength will be better identified. It is worth to mention that in the classical approach the spectral calibration is performed in only a few spectral (1) channels. The second advantage is related to the fact that the same measurement is performed in several spatial (i.e. across-track angles) positions; the current baseline approach foresees 9 different spatial locations. It means that spectral misregistration, also called smile, can be detected, and eventually correct for. The last benefit is due to the sub-pixel precision; the SRF shapes will be known and help to understand how the incoming light signal is dispersed along the pixel in terms of spectral resolution, where the spectral resolution equals to the FWHM of the response function, if a Gaussian-like shape is assumed.

The geometric calibration consists essentially of measuring both the across-track and along-track line spread function (LSF). Even in this case, several spatial positions and several spectral channels will be investigated at sub-pixel level. Determining the LSF is necessary in order to retrieve both the across-track and along-track point spread function (PSF). By knowing the PSF at different CCD locations, we are able to identify spatial misregistration in both spatial dimensions. Nevertheless, changes of the PSF shapes can be used to identify possible variations of the spatial resolution and eventually correcting for it by degrading (smoothing) the image selectively to the broadest PSF within one dimension (5).

The parameters issued of the spectral and of the geometric calibration can be used to correct for misregistration artefacts. If one wants to correct for each of them step by step, the data loss will not be negligible, and the value of such a scheme would be doubtful. A potential strategy would be to combine, for every pixel, all these coefficients together, in order to get a unique weighting value for a unique pixel; by doing so the correction can be performed in only one step. This will reduce drastically the amount of information that is going to be lost. On the other side, such a correction is not strictly necessary if the instrument characterization reveals that the APEX instrument meets the demanded requirements in terms of performances (e.g. spectral resolution and spatial resolution). Nevertheless, questions arise if we look for spatial and/or spectral uniformity, that is, uniformity of the response functions along the spectral direction or spatial direction respectively; it could imply that some of the corrections can be omitted. However, the corrections for the along-track artefacts shall be keep separated from the spectral/across-track coefficients as the shape of the along-track response function depends on the chosen integration time.

Straylight measurements will take place during the laboratory phase. Straylight from inside the field of view (FOV) and spectral straylight data can be processed in a way that a correction coefficient can be retrieved for each one of them. These two coefficients can be eventually combined together in order to generate for every pixel a unique straylight coefficient. Straylight from outside the FOV is also measured but this value cannot be used for correction because it is extremely scene-dependent, but it will be used for characterization. In reality, the other straylight coefficients are also scene-dependent but their influence is constantly affecting the pixel light conditions even in presence of a ghost image as, for instance, a cloud.

A set of different polarizing filters is also used in order to identify polarization influences but these data will be used for characterization only, as the polarization is drastically scene-dependent. From the hardware point of view, APEX could be equipped with two removable scramblers in order to reduce such an influence. They will be used if priority has to be given to spectral or spatial resolution respectively; otherwise no scrambler is mounted. The polarization measurement ends the procedures to be performed in the CHB.

The IFC facility allows another series of measurements. We already described the stability of radiometric and spectral parameters over time in a previous section. Other measurements are related to the co-registration artefact. A set of different detector frames will be acquired at different altitude, because our aim is to investigate how the detector system behaves at different pressures and temperatures. As the external temperature and pressure vary exponentially with flight altitude we might expect a similar dependency of the co-registration coefficients on altitude. The co-registration will be measured along the three dimensions of the hyperspectral cube. A combination of these three coefficients can be created in order to correct for such an artefact in only one step. A fourth type of co-registration that does not require a direct measurement concerns the overlapping region between the VNIR and the SWIR detector. In fact, the last few bands of the VNIR spectral region coincide with the first spectral channels of the SWIR spectral range; a dedicated analysis of the acquired scenes will identify the amount of mismatch between the two CCD’s, and a correction scheme will be applied.

Finally, scene-based algorithms will be applied to the acquired data in order to identify spectral curvature (10), spatial misregistration (6), and to retrieve SRF shape (11,12) and centre wavelength. In some cases, these procedures will generate absolute coefficients that can eventually be used to improve the correction and/or to refine the characterization of the detector. Vertical or rotational misalignments between the optical parts of the APEX system can be identified by analysing results of these methods (6). Therefore, if these misalignments are considerable, then a review of the optical system will be suggested to the optical team.

By using a calibration/characterization strategy as described above, several parameters will be generated (cf. Table 1). The three dimensions of the hyperspectral cube (i.e. along-track, across-track, and spectral dimensions) are indicated by *x*, *y*, and *z* respectively, with indexes *i*, *j*, and *k*. Spectral bands are also indicated by λ, and across-track angles by θ. Subscripts indicate in which dimension we operate while the superscripts indicate whether the coefficients vary along one or two directions. The coefficients miss the superscript *i* because we assume their values are constant over the along-track direction. Straylight from outside the FOV as well as polarization coefficients cannot be determined for every pixel and therefore a pixel-wise correction cannot be applied. By processing all the acquired raw calibration data, these parameters will be generated, and used to calibrate the real scene and correct for potential artefacts and/or non-linearities.

Table 1: *List of the generated calibration/characterization parameters.*

Coefficient	Notation	Coefficient	Notation
Radiometric gain	$G^{j,k}$	Polarization Measurement	-
Dark current	$D^{j,k}$	Non-Linearity with Time	$n_t^{j,k}$
Centre Wavelength	λ^j	Non-Linearity with Intensity	$n_I^{j,k}$
SRF shape	$\sigma_\lambda^{j,k}$	Spectral co-registration	$c_\lambda^{j,k}$
PSF shape Across-Track	$\sigma_\vartheta^{j,k}$	Across-Track co-registration	$c_\vartheta^{j,k}$
PSF shape Along-Track	$\sigma_x^{j,k}$	Along-Track co-registration	$c_x^{j,k}$
Spectral Misregistration	$\lambda^{j,k}$	Centre Wavelength Stability	$\lambda_t^{j,k}$

Spatial Misregistration Across-Track	$m_{\vartheta}^{j,k}$	Radiometric Gain Stability	$G_{t}^{j,k}$
Spatial Misregistration Along-Track	$m_{x}^{j,k}$	Spectral Curvature (Scene-Based)	$m_{\lambda S}^{j,k}$
Straylight from inside FOV	$s_{I}^{j,k}$	Spatial Misregistration (Scene-Based)	$m_{\vartheta S}^{j,k}$
Straylight from outside FOV	-	SRF retrieval (Scene-Based)	$\sigma_{\lambda S}^{j,k}$
Spectral Straylight	$s_{S}^{j,k}$		

CONCLUSIONS

The APEX instrument establishes the basis for a new characterization/calibration concept based on automatic procedures and correction scheme. This strategy relies on the CTM, an advanced software/hardware equipment able to independently control the instrumentation and to process online or offline the large amount of data required to characterize such a sophisticated instruments. The advantage of such an approach is twofold: first it allows a drastic reduction of the time to be spent in the laboratory and secondly it allows to measure more parameters than with classical calibration/characterization approaches. If several pixels in all the three hyperspectral dimensions are analyzed, then it is obvious that the whole sensor system can be more accurately characterized. The measured data, once processed by the master processor, will generate several coefficients that in turn will feed the processing and archiving facility (PAF). Therefore, the PAF will be able to calibrate the acquired scenes and, if needed, to correct for artefacts, non-linearities, and non-uniformities. Eventual upgrades to the CTM system could consist of (a) automatic application of the scene-based algorithms, which currently need to be supervised and (b) parallelization on a grid or cluster of CPUs (15).

REFERENCES

1. T. G. Chrien, R. O. Green, and M. L. Eastwood, “Accuracy of the Spectral and Radiometric Laboratory Calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS),” in Imaging Spectroscopy of the Terrestrial Environment, G. Vane, ed., Proc. SPIE 1298, 37-49 (1990)
2. D. Schläpfer, M. Schaepman, S. Bojinsk, and A. Börner, “Calibration and Validation Concept for the Airborne PRISM Experiment (APEX),” in Canadian Journal of Remote Sensing (February 2000)
3. Staenz, K., T.Szeredi, and J. Schwarz, “ISDAS - A System for Processing/Analyzing Hyperspectral Data”, Technical Note, Canadian Journal of Remote Sensing, Vol. 24, No.2, 1998, pp. 99-113.
4. Nieke, J., Schläpfer, D., Dell’Endice, F., Brazile, J., and Itten, K., “Uniformity of imaging spectrometry data products - the APEX approach”, Remote Sensing of Environment, 2007, in review
5. D. Schläpfer, J. Nieke, and K.I. Itten, “Spatial PSF non-uniformity effects in airborne pushbroom imaging spectrometer data,” in IEEE Transaction on Geoscience and Remote Sensing, 45(2), 458-468 (2007)
6. F. Dell’Endice, J. Nieke, D. Schläpfer, and K.I. Itten, “A scene based method for spatial misregistration detection in hyperspectral imagery,” in Applied Optics, Vol. 46 N. 15, pp 1-14 (20 May 2007)
7. B. Suhr, P. Gege, P. Strobel, J.W. Kaiser, J. Nieke, K.I. Itten, G. Ulbrich, “Calibration Home Base for the Airborne Imaging Spectrometer APEX”, in Proc. Of 4th EARSeL Workshop on Imaging Spectroscopy, Warsaw, 27-29 April 2005

8. B.C. Gao, M.J. Montes, C.O. Davis, “ A curve-fitting technique to improve wavelength calibrations of imaging spectrometer data”, in Proc. of the 11th JPL Airborne Earth Science Workshop, volume 03-4, pp. 99-105, 2002
9. B.C. Gao, M.J. Montes, C.O. Davis, “ Refinement of wavelength calibrations of hyperspectral imaging data using a spectrum-matching technique”, in Remote Sensing of Environment, Vol.90, pp.424-433, 2004
10. R.A. Neville, L. Sun, and K. Staenz, “ Detection of spectral line curvature in imaging spectrometer data”, in S. Shen, P. Lewis editors, SPIE Algorithms and Technologies for Multispectral Hyperspectral and Ultraspectral Imagerz IX, Vol. 5093, pp 144-154, Orlando
11. Brazile, J., Neville, R. A., Staenz, K., Schläpfer, D., Sun, L., and Itten, K.I., “Scene-based spectral response function shape discernibility for the APEX imaging spectrometer”, IEEE Geoscience and Remote Sensing Letters, 3:414–418, 2006
12. Brazile, J., Neville, R. A., Staenz, K., Schläpfer, D., Sun, L., and Itten, K. I., “Toward scene-based retrieval of spectral response functions for hyperspectral imagers using fraunhofer features”, Canadian Journal of Remote Sensing, 2006, in review
13. R. A. Neville, L. Sun, K. Staenz, “Detection of keystone in imaging spectrometer data,” in Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery X, S. Shen and P. Lewis, Proc, SPIE 5425, 208-217 (2004)
14. J. Brazile, J.W. Kaiser, D. Schläpfer, J. Nieke. M. Schaepman, and K.I. Itten, “ Parallelization of APEX Airborne Imaging Spectrometer Product Generation”, in Proc. Of the 4th EARSeL Workshop in Imaging Spectroscopy, Warsaw, 27-29 April 2005
15. Brazile, J., Schläpfer, D., Kaiser, J., Schaepman, M. E., and Itten, K. I., “Cluster versus grid for large-volume hyperspectral image preprocessing”, In SPIE Atmospheric and Environmental Remote Sensing Data Processing and Utilization: an End-to-End System Perspective, volume 5548, pages 48–58, 2004