Calibration Methodology for the Airborne Dispersive Pushbroom Imaging Spectrometer (APEX)

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ABSTRACT

APEX is a dispersive pushbroom imaging spectrometer operating in the spectral range between 380 - 2500 nm. The spectral resolution will be better than 10 nm in the SWIR and < 5 nm in the VNIR range of the solar reflected range of the spectrum. The total FOV will be ± 14 deg, recording 1000 pixels across track with about 300 spectral bands simultaneously. A large variety of characterization measurements will be performed in the scope of the APEX project, e.g., on-board characterization, frequent laboratory characterization, and vicarious calibration. The retrieved calibration parameters will allow a data calibration in the APEX Processing and Archiving Facility (PAF). The data calibration includes the calculation of the required, time-dependent calibration coefficients from the calibration parameters and, subsequently, the radiometric, spectral and geometric calibration of the raw data. Because of the heterogeneity of the characterization measurements, the optimal calibration for each data set is achieved using a special assimilation algorithm. In the paper the different facilities allowing characterization measurements, the PAF and the new data assimilation scheme are outlined.

Keywords: APEX, imaging spectrometry, airborne imaging spectrometer, hyperspectral, environmental monitoring

1. INTRODUCTION

The Remote Sensing Laboratories (RSL) identified in 1996 the necessity to initiate a project that concentrates on the definition of an airborne imaging spectrometer which could represent a precursor mission to future planned spaceborne imaging spectrometers. This project includes the definition of an airborne dispersive pushbroom imaging spectrometer (named 'Airborne Prism Experiment' (APEX) that will contribute to the preparation, calibration, validation, simulation, and application development for future imaging spectrometer missions in space[1], as well as to the understanding of land processes and interactions at a local and regional (or national) scale[2], in support for global applications[3].
The APEX project started in 1997 by performing a feasibility study on the design of an imaging spectrometer[4], which resulted in a first performance definition[5], and a subsequent design phase[6]. Currently, various parts of APEX are being finalized in design, breadboarding and performance analysis of the processing chain[7,8] and the subsequent construction of the instrument is planned to be final in 2006.

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The calibration concept for the APEX instrument was first summarized in Schläpfer et al., 2000[9]. Now, details on design, the calibration methodology and the ways to realization of the calibration concept are documented.
The calibration methodology is based on a standardized laboratory procedure in which spectral response, geometric response, as well as radiometric gain and offset values are determined. Additionally, in-flight calibration using sensor-internal means and vicarious calibration approaches will improve the reliability of the calibrated image data. All calibration-related parameters as well as the image data are transferred to and kept by the APEX Processing and Archiving Facility (PAF). The PAF processing chain allows an efficient use of all calibration parameters and fully reproducible processing of the acquired data from raw format to calibrated radiances.

2.THE IMAGING SPECTROMETER APEX

The APEX system has been specified as a combination of user requirements, which have been derived from a survey of imaging spectroscopy applications[10] and a subsequently derived forward performance model based on these requirements[11]. Applications cover all varieties of environmental remote sensing targets and research, such as vegetation and soil. APEX's performance will also enable to contribute to other major applications, such as coastal and inland water monitoring, atmospheric, geologic, vegetation and alpine research.

Table 1: APEX Specifications

Specified Parameter	Value
Field of View (FOV)	± 14˚ deg
Instantaneous Field of View (IFOV)	0.028 deg
Flight altitude	3'500 - 10'000 m.a.s.l.
Spectral channels	VNIR: 312 (before binning), SWIR: 199
Spectral range	380 – 2500 nm
Spectral sampling interval	380 – 1050 nm: < 5 nm, 1050 – 2500 nm: < 10 nm
Spectral sampling width	< 1.5 * Spectral sampling interval
Center wavelength accuracy	< 0.2 nm
Spectral sampling width accuracy	< 0.02 * Spectral sampling width
PSF (Point Spread Function)	≤ 1.75 * Sampling interval
Spectral / Spatial Misregistration	< 0.1 pixel
Scanning mechanism	Pushbroom
Storage capacity on board	> 200 GByte
Dynamic Range	12 … 16 bit

APEX is designed to be a dual prism dispersion pushbroom imaging spectrometer using a common ground imager. The spectrometer consists of a collimator that directs the light transmitted by the slit towards the prisms, where a dichroic beam splitter separates the two spectrometer channels into the VNIR (Visible/Near Infrared, 380-1000 nm), and SWIR (Shortwave Infrared, 930-2500 nm) wavelength range. Following the dispersion of the prism (two for the VNIR, one for the SWIR), the spatially and spectrally resolved lines are re-imaged on the detector arrays. The light is dispersed onto 1000 spatial pixels across-track for both channels, with 312 spectral rows in the VNIR and 199 spectral rows in the SWIR. Flexible, programmable on-chip binning will allow summarizing the spectral bands to a total of about 300 spectral rows for both detectors. APEX will be supported by four major external facilities. This includes the Science Center, the Operations Center, the Calibration Home Base and the Processing and Archiving Facility.

3. APEX PROCESSING AND ARCHIVING FACILITY PAF

The APEX Processing and Archiving Facility (PAF) manages the data from acquisition and calibration to processing and dissemination. The processing chain is based on analyzing in-flight acquired image data, housekeeping information (e.g., navigation data, temperature), and on-board calibration data. Frequent laboratory measurements allow the characterization and calibration of the geometric, radiometric and spatial sensor parameters. Using the outcome of the sensor calibration, the raw image data are converted to at-sensor radiance in SI (le Système international d'unités) units, traceable to a certified standard (e.g., NIST, NPL, PTB).

It is expected that individual flight campaigns will collect data on the order of 100's of GB that need to undergo an offline chain of data correction and characterization processes based on previously acquired laboratory and in-flight calibration parameters. This processing chain includes conversion of raw data values into SI units, bad pixel replacement, and corrections of smear, stray light, smile and frown anomalies. A simplified block diagram of the planned processing is illustrated in Figure 1. The data acquisition process produces the top four components on the left side in the Raw Data column. The lower two components are produced during inter-mission characterization measurements of the instrument which take place in the laboratory, during the flight or vicariously. The analysis of the characterization measurements will result in calibration parameter files. The required calibration parameters for L1 processing and quality control are summarized in Table 2. All parameters must be accompanied by variances that quantify their uncertainties. Additionally, any correlations between the parameters' errors, which may be induced by the instrument characterization procedure, should be quantified.

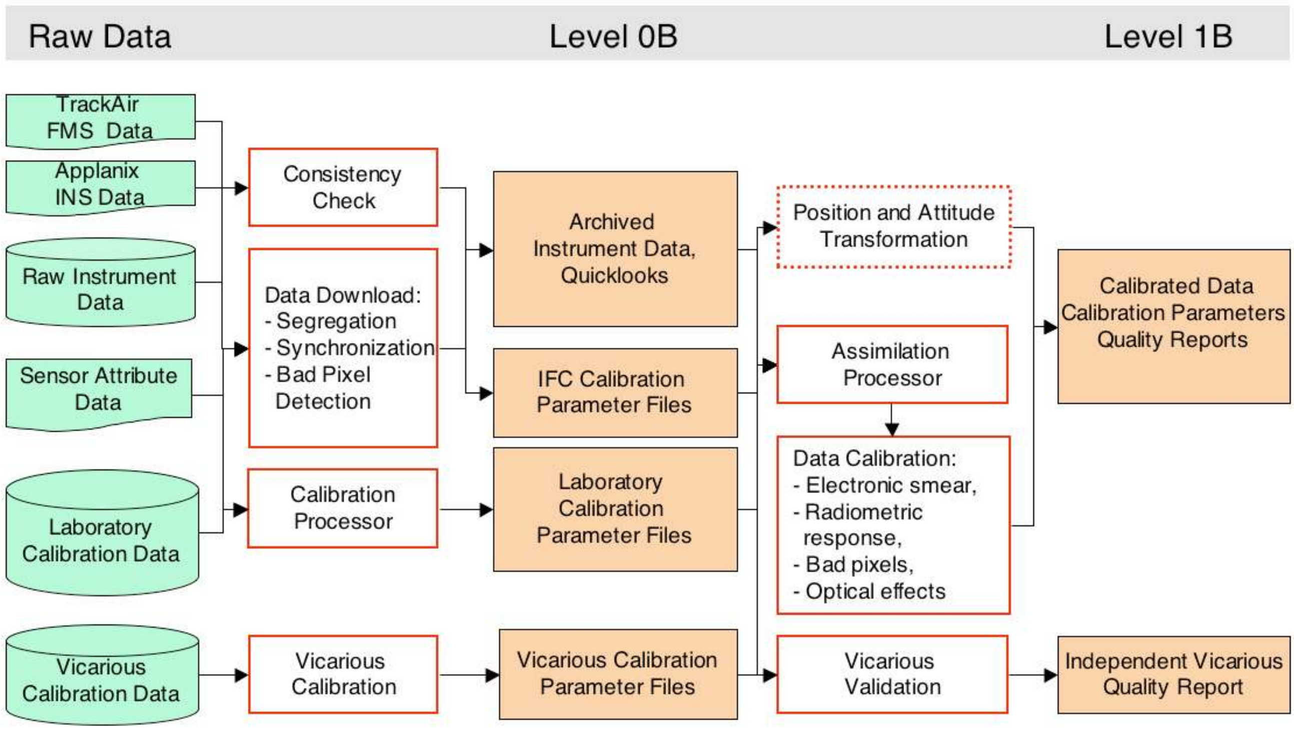

Figure 1: Generalized processing data flow from raw data until calibrated at-sensor Level 1 B.

Since the raw data is generated during the flight in the onboard computer, this data need to be transferred to the off-line PAF computer. During this data transfer, quick consistency checks are made, and some simple constant-time operations can be performed such as bad pixel detection as well as generation of a high-resolution composite RGB pseudo-color quick-look image. As a result, a calibrated at sensor radiance cube will be generated in the first processing step. This data will be channel wise corrected for spectral and spatial non-uniformities. Further processing steps will generate surface reflectance taking into account environmental conditions, such as the topography and atmosphere.

Table 2: PAF calibration parameters for L1 processing and quality control

Parameter	L1 processing	Quality control
Gain	X	
Dark current	X	
Straylight / ghost	X	
Center wavelength	X	
Center across-track angle	X	
Filter / window transmission	X	
IFC DNs	X	X
2-d PSF		X
Polarization sensitivity		X
Temperature sensitivity		X

The PAF will generate three categories of products, i.e., standard, custom and research products. Whereas standard products are the result of automatic processing, they are generated for each flight/campaign. An example is the above mentioned Level 1B product. The second category of products are the custom products generated after special request and/or with user interaction. These products require semi-automatic processing of validated methods / algorithms. This is why they will be available upon user-request. An example would be an atmospherically and topographically corrected Level 1B product, where the user delivers correction measurements (in form of vicarious calibration results) or a special digital elevation model. The third category of products consists of research products, which will be processed by operator (or via special web-based GUI). This kind of product is available to dedicated scientific users only. The goal is to test new methods / algorithms, which are under development and still need to be validated. This research product generation is supported by the PAF software using a flexible plug-in structure. Algorithm developers are able to provide their own algorithms, so that third party users are able to make use of new routines and scientific calculations. A documentation of the algorithms is provided by the developers in form of algorithm theoretical basis documents.

4.THE APEX CALIBRATION TOOLS

Based on the inherent flexibility of the APEX instrument a large variety of characterization measurements are foreseen to ensure a high calibration accuracy. It consists of frequent laboratory calibration cycles in the calibration home base (CHB), the 'In-Flight' Characterization facility (IFC), the making use of natural targets (e.g., Fraunhofer lines etc.) and the final assimilation of the measurements in the PAF.

4.1. Calibration Home Base CHB

The Calibration Home Base (CHB) with dedicated spectral, radiometric and geometric calibration facilities allows full laboratory characterization and calibration of APEX. The CHB is located at DLR in Oberpfaffenhofen near Munich (Germany).

The CHB consists of a 1.6 m integrating sphere to enable the radiometric calibration and an optical bench for the spatial and spectral calibration of APEX. The entire set-up makes use of high stable design mechanism, such as a rigid granite optical bench, a perfect isolated fundament (seismic block) and special air bearings. This is why a high positioning accuracy in the range of microns and arc seconds can be guarantied.

A special design will be realized for the calibration bench, where the spatial and spectral characterization measurements of APEX will be performed over the entire swath of ±14 degrees. Due to the overall system mass, APEX will be kept in fixed position during the characterization measurements; the calibration bench consists of collimators (stimulus assembly) with move- and tiltable folding mirror underneath the instrument. The principle is shown in Figure 2. This set-up offers the possibility of using two different stimuli (compare collimator 1 and 2 in Figure 2), i.e., two different collimators. These collimators, which will provide different spot sizes on the detector, what is desirable for the spectral and spatial calibration tasks. The concept also allows an automated execution of the measurement cycles.
The CHB is currently in the design and bread-boarding phase; first characterization measurements are planned with the subsequent acceptance testing of the APEX instrument.

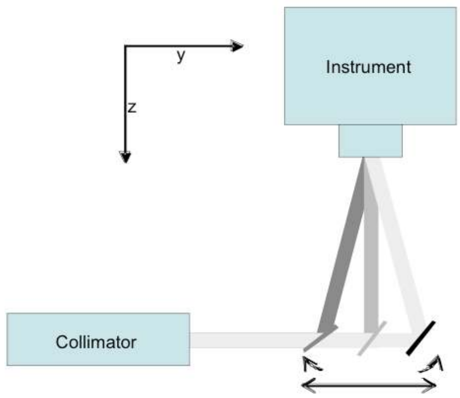

Figure 2: Schematic view of a set-up with fixed APEX instrument, fixed collimator and move-/tiltable folding mirror

4.2. 'In-Flight' Characterization facility IFC

An integral part of the APEX spectrometer is a built-in 'In-Flight' Characterization facility (IFC), where a mirror will be shifted in the optical path to reflect the light of the internal stabilized QTH (Quartz Tungsten Halogen) lamp in the optical path of the spectrometer. The on-board calibration measurements are enabled using a filter-wheel, a fiber bundle and a diffuser (see Figure 3). The filter-wheel consists of filters to permit spectral and radiometric calibration. Examples for a spectral filters are a set of interference filters and the special rare earth material filter SRM2065. In Figure 4, the spectral absorption features of the filter are plotted vs. the wavelength.
In the form of a secondary calibration standard, the IFC measurements will be performed just before and after the flight over the observed target, which allows tracing the stability of APEX during the flight campaigns.

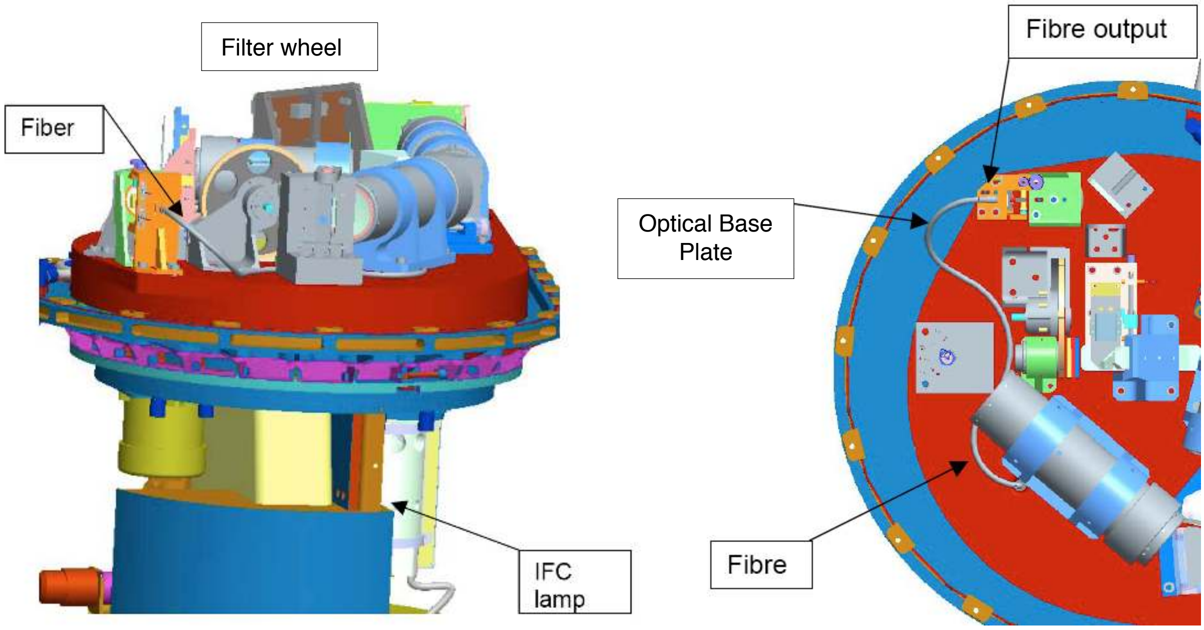

Figure 3: The In-Flight Characterization unit (IFC) enables relative spectral and radiometric calibration. The radiance of a stable light source is transferred via fiber to the optical path of the spectrometer.

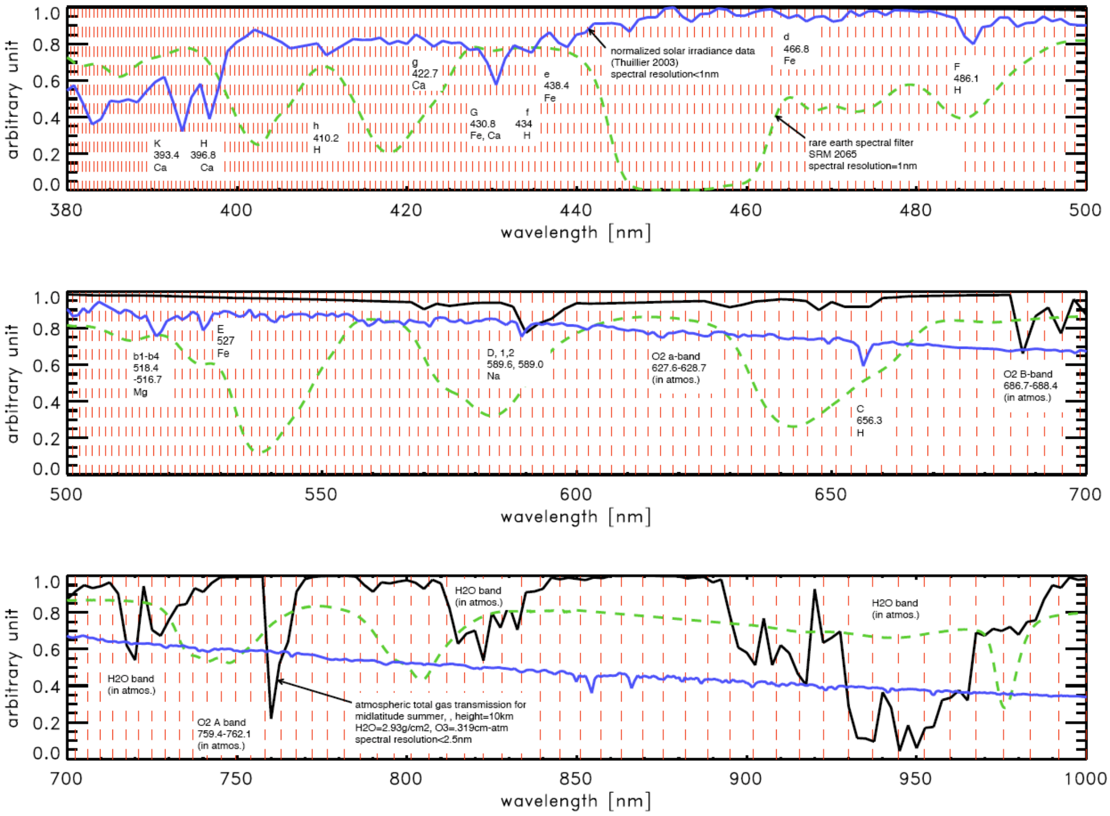

Figure 4: Spectral calibration will be enabled using the spectral information of atmospheric (black line), solar absorption (blue line) features and the spectral filters within the IFC. The rare earth filter SRM 2085 is indicated as dashed green line. In the figure the center wavelength of 312 VNIR spectral bands (before binning) are shown as vertical dashed red lines.

4.3. Vicarious calibration VC

Simultaneously to certain flights, vicarious calibration experiments will support the evaluation of the expected instrument performance during its operation on the aircraft. Hence, an estimate of the instrument characteristics is obtained in an off-laboratory environment.

A well-known calibration test site is overflown while simultaneous in-field spectroradiometric measurements are taken.

The objective of the vicarious calibration method is to assess by independent means the uncertainties of the data products derived from the APEX sensor outputs. All VC methods use at-sensor radiance with the most recent set of calibration coefficients of the space sensor. This radiance can be compared with the at-sensor radiance predicted from the data collection in the ground field. This is why VC methods can also be applied to judge at-sensor radiance, which were originally determined by laboratory or on-board calibration. In general, vicarious calibration methods are subdivided into reflectance-based, irradiance-based and radiance-based calibration methods[12,13]. The reflectance-based calibration method uses ground-based surface reflectance measurements of a selected validation site at the time of the aircraft overpass. In contrast, the irradiance-based calibration method relies on accurate measurements of the ground target and additional atmospheric irradiance parameters by ground-truth instruments and a model of the atmosphere such as a radiative transfer code. The radiance-based method measures the ground target using a well calibrated spectroradiometer. For all VC methods, additional field experiments are carried out, such as sky and sun photometer measurements[14] and the assessment of bidirectional reflectance effects using Field Goniometers[15,16]. At the same time, when the ground measurements are performed, APEX measures the at-sensor signals over the same ground pixel. The APEX's output (e.g. counts, voltage) is converted in radiance and thereinafter compared with the at-sensor radiance predicted from ground/airborne measurements and atmospheric modeling for the same ground pixel at the same time.

As outlined in Figure 1, the results from vicarious calibration campaigns are used in the assimilation algorithm and for independent validation of the laboratory and on-board calibration results. If significant discrepancies are found, additional re-calibration efforts in laboratory are necessary. Furthermore, the vicarious calibration campaigns are used to validate the performance and accuracy of the data processing chain.

4.4. Assimilation of calibration parameters

The APEX instrument will be calibrated using different sources, such as measurements from the CHB, the IFC, and vicariously retrieved calibration information. Each method will deliver a set of calibration parameters at various times during the APEX mission duration time. Additionally, each calibration method will deliver slightly different set of calibration parameters. Also the accuracy of the results is not constant, depending on the uncertainties of the measurements. Hence, the retrieved calibration parameters must be analyzed in a way to reflect the situation of the APEX instrument at a given time.

To find adequate parameters, the time evolution of the parameters from the heterogeneous calibration measurements are retrieved using a data assimilation technique[17]. This flexible data assimilation algorithm was implemented in the PAF in order to combine the information from all of the heterogeneous calibration measurements, as well as from the system insight. In the data assimilation a Kalman filter is combining the past observations in an optimal way at every instance in time. Under the assumption, that the system behaves linear and that the measurement uncertainty is Gaussian, the Kalman filter performs the conditional probability density propagation as described in Kaiser et al., 2003.

The data assimilation algorithm is pursued during the operational phase of the APEX instrument, monitoring possible upgrades or degradations of the system. The open architecture of the processor allows enhancements to the processor to be done on a regular basis in response to the increasing knowledge of the APEX system's stability and performance.

5. CONCLUSIONS

The calibration concept for the APEX instrument was first outlined in Schläpfer et al., 2000. This concept delivered the framework of the entire calibration and validation process of APEX. It included the tasks and definitions related to calibration from the measurement strategy to the processing chain and the quality control procedures.

In this paper some details on calibration methodology and the way to realization of the concept are summarized, such as

- the realization of the Processing and Archiving Facility PAF (version 0.3 was already released),
- design of the In-Flight Characterization facility IFC (design and breadboard activities were finalized),
- layout of the Calibration Home Base CHB (bread boarding phase already started).

The outlined calibration methodology will be pursued during the operational phase, controlling possible degradations and upgrades of the instrument. The APEX team members commit themselves to as much transparency about the system performance as possible. Based on this policy we anticipate to form a broad APEX user community, consisting of research groups focusing on imaging spectroscopy.

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