FIRST TEST RESULTS OF THE AIRBORNE DISPERSIVE PUSHBROOM SPECTROMETER APEX

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ABSTRACT:

APEX (Airborne Prism EXperiment) is a project being developed by a joint Swiss-Belgian consortium on behalf of the European Space Agency ESA-PRODEX programme. It comprises an airborne dispersive pushbroom imaging spectrometer, a Calibration Home Base (CHB) for instrument calibration operations and a dedicated data Processing and Archiving Facility (PAF). A unique In-Flight Characterization (IFC) unit is integrated within the optical sensor, providing pre- and post- data-take characterization data to monitor the instrument stability along the mission and improve the delivered data. The imaging spectrometer sensor is operating in the solar reflected wavelengths range between 380 nm and 2500 nm, by means of two dispersive spectrometer channels that partially share the optical path. The achieved resolution amounts to 1000 spatial across track samples over an overall FoV of 28°, with more than 300 configurable spectral bands. The instrument has been engineered to provide high quality data for scientific applications, in particular focusing on topics as limnology, vegetation, snow and soil analyses among others, and to simulate and support the development of future spaceborne remote sensing instrumentation. The APEX PAF includes (a) the calibration of the acquired data from raw instrument data stream to physical units, (b) geometric and atmospheric correction for each scene, and (c) instrument calibration data management. APEX is now in a pre-operational setup and testing activities, including fine-tuning, extended calibration operations and test flights are taking place. This paper outlines the system validation procedures as well as preliminary performance results.

1. INTRODUCTION

The Airborne Prism EXperiment (APEX) is a project being developed by a joint Swiss-Belgian consortium of industries (RUAG Aerospace, OIP Optical Systems and Netcetera) under the lead of research institutes, the Remote Sensing Laboratories (RSL) of the University of Zurich and VITO-TAP. The APEX consortium is developing an airborne dispersive pushbroom imaging spectrometer designed and engineered to contribute to the remote sensing community by providing land coverage at local and regional scale in support of global applications and to support the preparation, simulation, calibration and validation of future spaceborne imaging spectrometers (J. Nieke, 2005 and K. Itten, 2008).
The emphasis in the APEX instrument design is to retrieve reliable and traceable measurements from airborne imaging spectroscopy data, characterized by high spectral, radiometric and geometric accuracy. The targeted data accuracy relies upon three main factors: (a) provision of a highly precise instrument by the industrial partners, (b) detailed instrument calibration and characterization of the performances by means of the Calibration Home Base (CHB) hosted at DLR Oberpfaffenhofen, Germany (P. Gege 2009) and (c) accurate data calibration process and higher level product generation at the APEX Processing and Archiving Facility (PAF) hosted at VITO in Mol, Belgium (A. Hueni, 2009 and J. Nieke, 2008).
In addition, another focus of the project is to offer a flexible scientific instrument to the remote sensing community (Dell'Endice 2009). APEX supports the achievement of scientific requirements of an imaging mission with extended customization of acquisition parameters by means of the software BinGO. The APEX PAF supports the investigation and development of research products with flexible integration of processing modules into the workflow.
The APEX project is now facing the conclusive steps of Phase C/D. After the assembling and testing phase at sub-unit and unit level, the APEX system is undergoing tests at full system level to assess the performance of the whole system process. Due to the complexity of the system, to the number of activities involved and to the targeted performance to validate, the concept driving the testing activities is fundamental. The understanding of the APEX instrument performances is an evaluation process, and a critical spirit is required to judge procedures and performances.
This paper will first introduce the APEX instrument; the testing approach will be then described and a brief summary of the achieved results presented.

2. THE APEX SYSTEM

2.1 The sensor

APEX is based on a pushbroom dispersive spectrometer realized by OIP Optical Systems and designed to provide

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spectra in the solar reflected radiation range between 380 ÷ 2500 nm. The sensor (Figure 1) comprises two optical channels that partially share the optical path until the prism dispersive elements, of which the first also splits the radiation contribution into two channels by means of a dycroic beamsplitting surface. The radiation in the 950 ÷ 2500 nm range is dispersed by the first prism and then imaged on the SWIR detector by means of a dedicated focusing lens assembly. The radiation in the 380 ÷ 1000 nm range is instead reflected toward a second prism dispersive element and imaged on the VNIR detector by means of a dedicated lens assembly. The SWIR detector is a CMOS based custom model realized on behalf of ESA by Sofradir, and provides 199 spectral rows (i.e. detector pixel row along the spectral direction). The VNIR detector is a CCD from E2V, and provides 335 spectral rows, that can be combined on chip. The combination of spectral rows is also referred to as binning. The bands to be combined are defined via a *binning pattern*. A default binning pattern is programmed at APEX system boot, but any configuration can be uploaded when required, in order to achieve application tailored performances with specific spectral resolution (or Spectral Sampling Interval, SSI), selectivity (Full Width Half Maximum, FWHM) and improved SNR (ISO-VIM, 2007).
APEX has a Field of View of 28°, sampled with 1000 pixels.

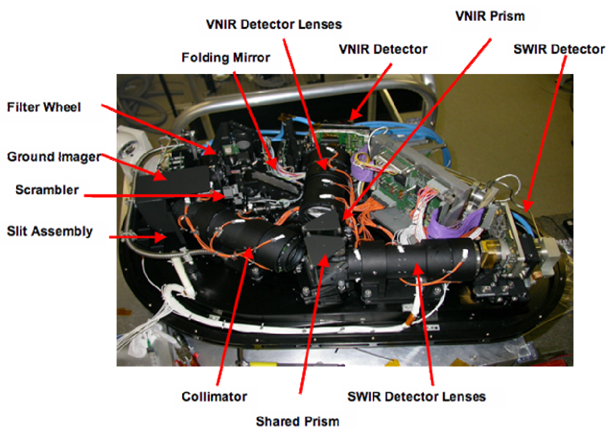

Figure 1 - an insight into the assembled APEX sensor

The APEX sensor is equipped with an In-Flight Characterization unit (IFC). The objective of this unit is to support the accuracy analysis of the instrument during standard flight operations by providing a stable radiometric, geometric and spectral input to the system in order to study and analyze the APEX system behavior, and in case derive correction coefficients to improve the quality of the imaged ground scenes. The IFC unit is composed of a stabilized 75 W QTH lamp installed in the spectrometer's baffle compartment and a filter wheel comprising filters with specific spectral features: a Rare Earth Materials, a neutral density (gray) and 3 band pass (color) filters. For the geometric stability survey of the system, two thin wires have been glued on the instrument slit. The shadow of the wires projected on the detector will provide information to investigate the effects of environmental and internal factors (such as differential pressure differences and temperatures) on the system.

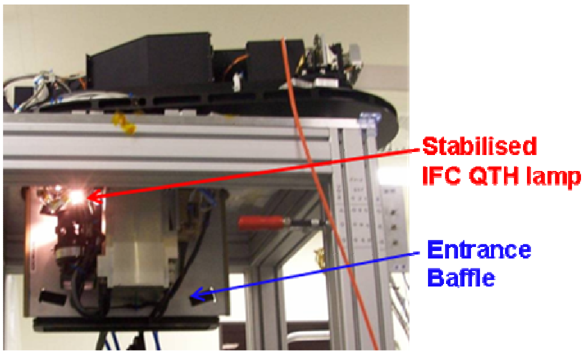

Figure 2 – the IFC lamp installed in the baffle

The IFC lamp light is collected from the baffle compartment's housing and driven inside the optical sensor by means of a glass fiber. In order to achieve a distributed irradiance over the detectors' field of view, the light beam passes through a diffuser system, and is injected into the standard light path by means of a series of movable optical parts.

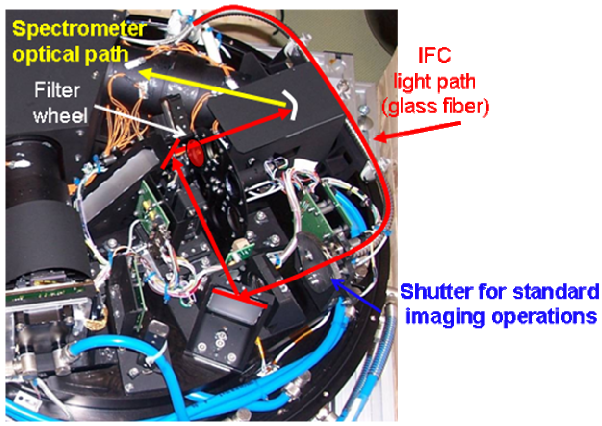

Figure 3 – the integration of the IFC optical path inside the APEX optical sensor.

2.2 The APEX system

The APEX system setup inside the aircraft is represented in the figures below. Two parts can be distinguished: the sensor mounting with its support units and the operator's workstation. The sensor (Figure 4) is mounted on a Leica PAV30 stabilizing platform. To prevent thermal effects on the optical performance of the sensor, the Environmental Thermal Control box (ETC box, partially open in the picture) is installed on the aircraft interface. The box creates a closed environment around the sensor. Both the ETC box environment surrounding the sensor and the sensor itself are controlled and stabilized by means of a Thermal Control Unit.
To avoid the internal setup, and in particular the optical elements, to be contaminated by external factors the APEX sensor is sealed and the internal atmosphere filled with nitrogen.

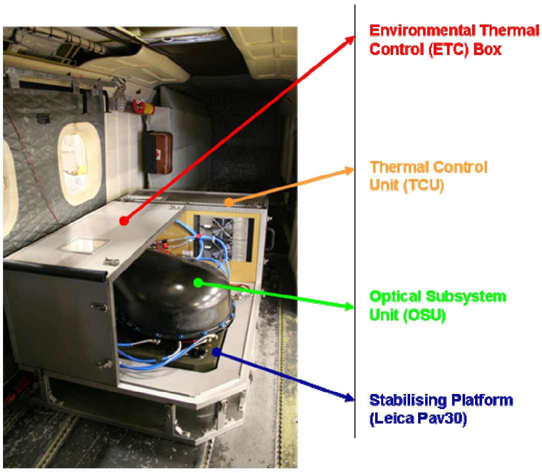

Figure 4 - the APEX sensor installed into the DLR Do-228

The operator's workstation (Figure 5) is made of a rack shelf in which are integrated the APEX control system, the storage (solid state disks and tape) unit and the flight support units (Applanix positioning system and Track'Air aerial survey system). These units are interfaced via LAN to the user interface running on a ruggedized laptop.
The overall mass of the whole APEX system is 350 kg.

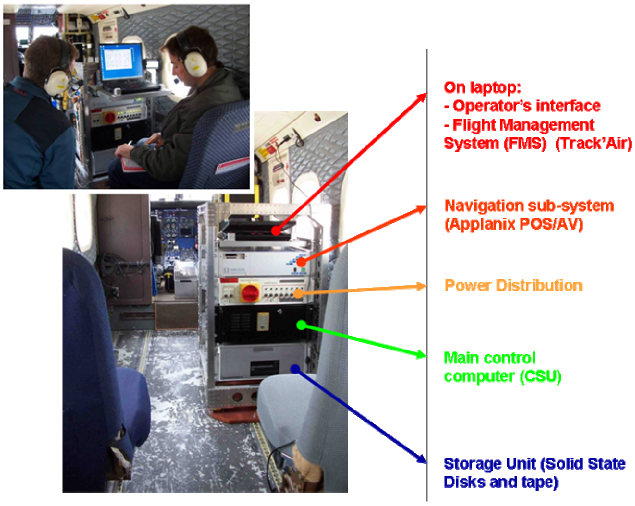

Figure 5 - the operator's rack installed into DLR Do-228.

3. TESTING ACTIVITIES

As introduced in §1, APEX is a complex prototype system that is facing the last steps of project's Phase C/D. After an extensive period of testing at sub-unit and unit level, the system had been assembled and verification at full system level could start. The activities in this frame, involving the industrial as well as the institutes team, can be split into three phases: (a) instrument calibration and characterization at the CHB, (b) processing activities and (c) flight activities. These testing activities are conceptually stream-like structured (Figure 6), but correlated as knowledge acquired during one phase may iteratively provide new inputs to the precedent phases.

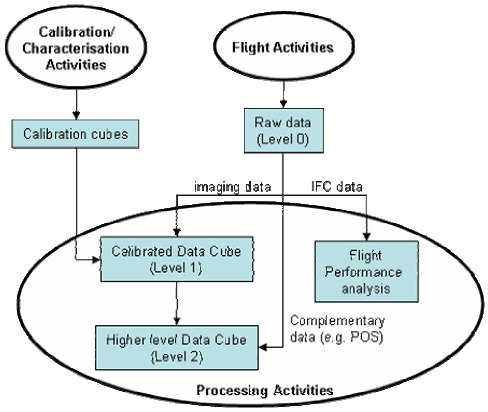

Figure 6 – simplified workflow of the APEX testing activities

3.1 Instrument Calibration and Characterization

The instrument characterization and calibration is the first necessary step to achieve an understanding of the instrument quality and bases on the underlying concept of the calibration procedure.
APEX laboratory calibration relies on the CHB, a facility realized with ESA contribution and designed to meet and validated the aspired performance of APEX.
The detailed and accurate characterization and calibration of a high resolution imaging spectrometer is resource demanding. The complex calibration procedures (Dell'Endice, 2007) rely on the Calibration Test Master (CTM) Controller, a software developed to automatize the time consuming data acquisition by controlling the CHB settings, the APEX acquisition settings and performing data acquisition and storage. The CTM Processor is a module designed and developed to process the amount of data collected and retrieve the synthesized instrument characterization and calibration information, organized into structured matrixes, referred to as *calibration cubes*.
The calibration has included, among the others, the following fundamental steps: angular calibration, spectral calibration, across-track spatial calibration, along-track spatial calibration, straylight, absolute and relative radiometric calibration. Task of this paper is to present an overview of the instrument testing activities concept, their procedures and results of general interest.
Spectral and spatial calibrations are time-consuming activities that require the investigation of the Spectral or Spatial Response Function at sub-pixel level.
The measurement procedure for the spectral calibration of a spectral row is described as an example. The spectral characteristics have been investigated by acquiring given light stimuli for 10 spectral rows for each detector, at 10 angular positions over the FoV. The light spot was optimized down to an average 3x3 pxl spot. Each measurement point required 110 slight variations of the CHB monochromator setup, controlled by the CTM-Controller. The acquisition sequence duration is approximately 5' per each point. The spectral characteristics of interest (center wavelength λ_c and Full Width Half Maximum FWHM) have then been determined for each measurement point. The spectral misregistration (*smile*), meant as the difference between the maximum and minimum center wavelength for a given spectral row ($\lambda_{c, max} - \lambda_{c, min}$), could be then measured.
The spectral resolution, or Spectral Sampling Interval (the distance between center wavelengths of adjacent pixels), has then been determined on the full spectral range by

interpolation. Also the spectral selectivity or FWHM (an index of the pixel bandwidth) has been interpolated on the remaining detector pixels.
Similar procedures have been executed for the spatial calibration and the determination of the spatial misregistration (*frown*).

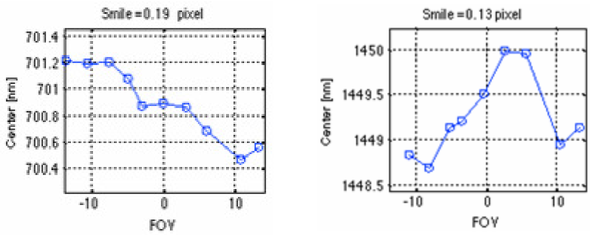

Figure 7 – center wavelengths for a VNIR (left) and SWIR (right) spectral row.

Another output of the spectral calibration is the APEX spectral selectivity, expressed in terms of Spectral Response Function (SRF) Full Width Half Maximum (FWHM) and is represented in Figure 8. In this plot the effect of binning pattern on selectivity is also evidenced. A binning pattern combines the information of adjacent spectral rows in order to obtain values of interests in terms of spectral resolution, selectivity and signal. In this Figure the spectral overlap region between the two channels, located between 950 and 1000 nm, is also evidenced.

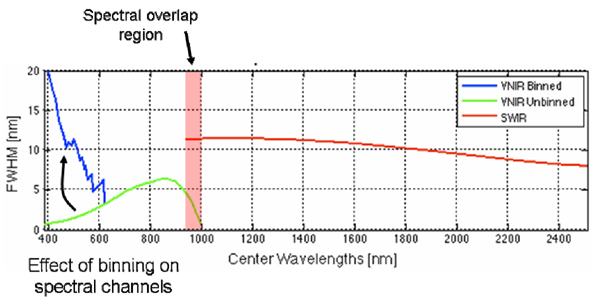

Figure 8 – APEX spectral selectivity (in terms of FWHM)

The radiometric calibration (Figure 9) provides the coefficients to convert the acquired signal per each detector pixel, expressed in terms of digital numbers, into measured radiances. Another output is the determination of the Noise Equivalent Delta Radiance (NedL), which is used for the SNR calculation. This procedure consists of two steps. The first is the absolute radiometric calibration against light stimuli whose spectrum has been characterized and certified with known uncertainty. This operation is run using the CHB small integrating sphere, that is able to only cover part of the APEX FoV. The second step is then the relative radiometric calibration, to characterize the response of the instrument to a light stimulus uniform over the FoV (also called *flat field*). The results of absolute and relative radiometric instrument calibration combined provide the coefficients needed to radiometrically calibrate the acquired data.

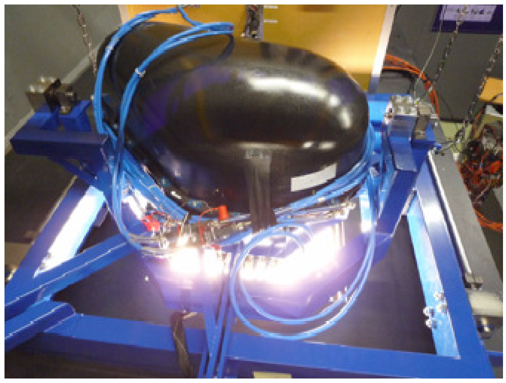

Figure 9 - the APEX installed on the CHB big integrating sphere for relative radiometric calibration.

The relative radiometric calibration evidences an irradiance distribution at detector level that is better than 80%, apart of a vignetting affecting the extreme right side, a 2% of the FoV.

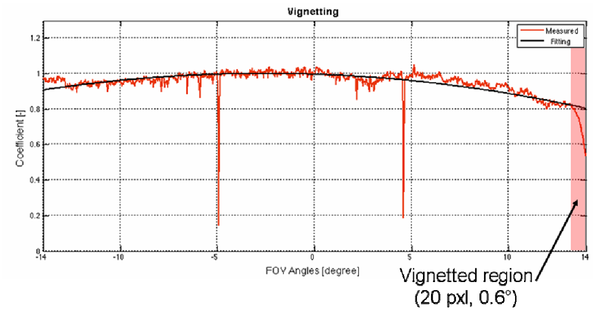

Figure 10 – APEX irradiance distribution over the detector FoV

3.2 Flight Activities

The APEX system has obtained the Airworthiness Certification for the DLR Do-228 located at Oberpfaffenhofen in April 2008. The first test flight has been performed October 31st 2008 over Wittenberge (Germany), acquiring 13 flight lines.
The data volume rate during a flight depends on a number of factors (e.g. frame rate, flight speed and altitude, binning pattern). Flying at 3.5 km above ground level at an average speed of 140 KTAS, the data volume rate is 0.45 GB/km with default binning pattern and frame rate.

3.3 Processing Activities

The APEX processing chain relies on the Processing and Archiving Facility hosted at VITO, and has been developed and tailored to process and archive and manage the APEX data during its exploitation phase. These data include (a) the raw data acquired during flights, (b) the calibration cubes, and (c) the generated products, from Level 1 (calibrated data) up to 3 (higher level products) (Schäpfer, 2007).
The development of such a processing chain can take advantage of simulated test cases, but the final fine-tuning of the processing steps can only succeed when using real instrument data. Thus, after the first APEX test flight the set-up and the validation of the several processing steps could start. Activities in the Level 0 to 1 processing involve in particular the application of the calibration cubes information

to achieve spectrally, radiometrically and geometrically calibrated data (Figure 11).

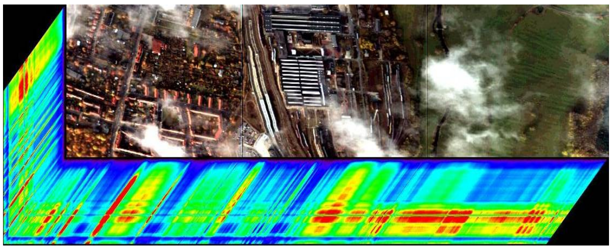

Figure 11 – first APEX data cube: a spectrally and radiometrically calibrated sample. (Wittenberge, D)

Activities for Level 2 processing are the optimization of the ortho-rectification process for geographic referencing (Figure 12) and the investigation of an atmospheric correction tailored to the APEX characteristics (Schläpfer, 2008).

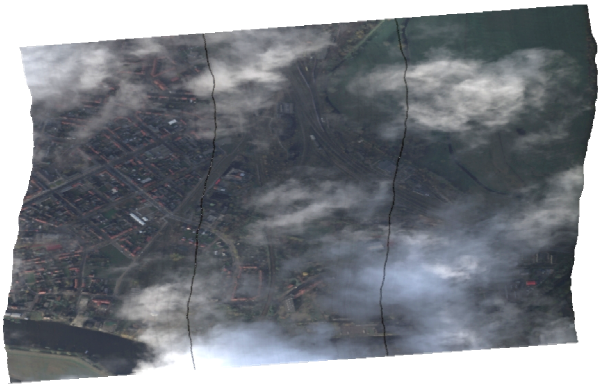

Figure 12 – first APEX data cube: an ortho-rectified sample. (Wittenberge, D)

4. CONCLUSIONS

After extensive design and development phases, the APEX instrument has reached its final state, following a substantial phase of assessing its system performance. Final adjustments and optimization are ongoing, with acceptance flights planned for summer 2009.
Availability to the scientific community will be announced following final acceptance by the principal investigators and ESA, tentatively late summer 2009.
APEX will provide the users community with unprecedented spectral resolution and selectivity and a suite of products ranging from calibrated radiances to advanced products.

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REFERENCES

Dell'Endice, F., Nieke, J., Schlaepfer, D., Hueni, A., and Itten, K. I. "Automatic Calibration and Correction Scheme for APEX (Airborne Prism Experiment spectrometer)", Proceedings of the 5th EARSeL Workshop on Imaging Spectroscopy, Bruges, Belgium, 2007

Dell'Endice F., Hueni A., Itten K.I., Schaepman M. "Sensing Earth Surface with the Airborne Prism Experiment (APEX)" Proceedings of the 6^{th} EARSeL SIG IS, Tel Aviv, Israel, 2009.

D'Odorico P., Alberti E., Dell'Endice F., Hueni A., Itten K., Nieke J. "An Algorithm for Tracking APEX Spectral Stability by means of the In-Flight Characterization Facility (IFC)", Proceedings of the 6^{th} EARSeL SIG IS, Tel Aviv, Israel, 2009.

P. Gege, J. Fries, P. Haschberger, P. Schötz, H. Schwarzer, P. Strobl, B. Suhr, G. Ulbrich, and W. J. Vreeling, "Calibration facility for airborne imaging spectrometers," ISPRS Journal of Photogrammetry & Remote Sensing, accepted 2009-01-27 2009.

A. Hueni, J. Biesemans, K. Meuleman, F. Dell'Endice, D. Schläpfer, S. Adriaensen, S. Kempenaers, D. Odermatt, M. Kneubuehler, J. Nieke, and K. Itten, "Structure, Components and Interfaces of the Airborne Prism Experiment (APEX) Processing and Archiving Facility," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, pp. 29-43, 2009.

ISO-VIM "International vocabulary of basic and general terms in metrology (VIM)" ISO Guide 99 by ISO (ISO/IEC Guide 99-12:2007

Itten, K. I., Dell'Endice, F., Hueni, A., Kneubühler, M., Schläpfer, D., Odermatt, D., Seidel, F., Huber, S., Schopfer, J., Kellenberger, T., Bühler, Y., D'Odorico, P., Nieke, J., Alberti, E., Meuleman, K., 2008. APEX - the Hyperspectral ESA Airborne Prism Experiment. Sensors, 8, 6235-6259; doi:10.3390/s8106235

J. Nieke, K.I. Itten, W. Debruyn, and the APEX team, "The Airborne Imaging Spectrometer APEX: from concept to realization," Proceedings of 4th EARSel Workshop on Imaging Spectroscopy, Warsaw (2005)

J. Nieke, K. Itten, K. Meuleman, P. Gege, F. Dell'Endice, A. Hueni, E. Alberti, G. Ulbrich, R. Meynart, and the APEX team, "Supporting Facilities of the Airborne Imaging Spectrometer APEX," Proceedings of IEEE IGARSS 08, Boston, 2008, p. 4.

D. Schläpfer, J. Nieke, F. Dell'Endice, A. Hueni, J. Biesemans, K. Meuleman, and K. Itten, "Optimized Workflow for APEX level 2/3 Processing" Proceedings of the 5th EARSeL Workshop on Imaging Spectroscopy, Bruges, Belgium, 2007.

D. Schläpfer, J. Nieke, F. Dell'Endice, A. Hueni, J. Biesemans, K. Meuleman, and K. Itten, "Optimized Workflow for APEX level 2/3 Processing" Proceedings of the 5th EARSeL Workshop on Imaging Spectroscopy, Bruges, Belgium, 2007.

D. Schläpfer, Bieseman J., Hueni A., Meuleman K. "Evaluation of the Atmospheric Correction Procedure for the APEX Level 2/3 Processor" Proceedings of SPIE ERS08, Cardiff, Great Britain, 2008