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# Advanced radiometry measurements and Earth science applications with the Airborne Prism Experiment (APEX)

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ABSTRACT

We present the Airborne Prism Experiment (APEX), its calibration and subsequent radiometric measurements as well as Earth science applications derived from this data. APEX is a dispersive pushbroom imaging spectrometer covering the solar reflected wavelength range between 372 and 2540 nm with nominal 312 (max. 532) spectral bands. APEX is calibrated using a combination of laboratory, in-flight and vicarious calibration approaches. These are complemented by using a forward and inverse radiative transfer modeling approach, suitable to further validate APEX data. We establish traceability of APEX radiances to a primary calibration standard, including uncertainty analysis. We also discuss the instrument simulation process ranging from initial specifications to performance validation. In a second part, we present Earth science applications using APEX. They include geometric and atmospheric compensated as well as reflectance anisotropy minimized Level 2 data. Further, we discuss retrieval of aerosol optical depth as well as vertical column density of NOx, a radiance data-based coupled canopy–atmosphere model, and finally measuring sun-induced chlorophyll fluorescence (Fs) and infer plant pigment content. The results report on all APEX specifications including validation. APEX radiances are traceable to a primary standard with <4% uncertainty and with an average SNR of >625 for all spectral bands. Radiance based vicarious calibration is traceable to a secondary standard with ≤6.5% uncertainty. Except for inferring plant pigment content, all applications are validated using in-situ measurement approaches and modeling. Even relatively broad APEX bands (FWHM of 6 nm at 760 nm) can assess Fs with modeling agreements as high as $R^2 = 0.87$ (relative RMSE = 27.76%). We conclude on the use of high resolution imaging spectrometers and suggest further development of imaging spectrometers supporting science grade spectroscopy measurements.



## 1. Introduction

Imaging spectroscopy has emerged as an extremely efficient observational approach for mapping the Earth system (Schaepman et al., 2009a). The efficiency gain has its foundation in technical progress made on one hand, and on the improved understanding and modeling of the molecular scattering and absorption mechanisms, on the other. Imaging spectrometers—particularly airborne instruments—are frequently available nowadays, either targeting specific applications, or

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serving as 'general purpose' instruments, covering a wide range of applications (for a detailed review see Schaepman, 2009).

While the general procedure of constructing and operating airborne imaging spectrometers has reached a high level of maturity, requirements on specific instrument aspects might challenge any component of the full data acquisition chain, ranging from sensor modeling to calibration to product delivery. In particular, spectral fidelity (stability, Signal-to-Noise Ratio (SNR), etc.) was very early on identified as a key performance requirement for successful spectroscopy applications (Green et al., 1998).

Emerging satellite concepts utilizing principles of spectroscopy as their prime observational approach led to the idea to build a next generation airborne imaging spectrometer in Switzerland during the early 1990s. In fact, the idea emerged following a successful joint NASA/ESA Multisensor Airborne Campaign (MAC-Europe) in July 1991 in Europe (Itten, Meyer, Staenz, Kellenberger, & Schaepman, 1992). The funding source identified for such an endeavor was the European Space Agency's PRODEX (PROgramme de Développement d'Expériences scientifiques) program, allowing small ESA member states to develop their own instruments. A joint Swiss–Belgian team proposed to build an airborne imaging spectrometer termed 'Airborne Prism Experiment' (APEX), under the scientific lead of Klaus Itten at the University of Zurich. He served as APEX principal investigator from 1995 to 2009 and Michael Schaepman from 2009 onwards. A potential APEX system was for the first time presented to a wider public in 1997 (Itten et al., 1997).

The scientific, industrial and operational consortium of APEX was subsequently established as follows. The science lead is with the University of Zurich, tasked to perform model simulations, establish system specifications and validate instrument performance, develop a science grade processing facility, and perform the project management. The institutional partner and co-investigator VITO is responsible for the operational implementation of the APEX processor, APEX operations and data distribution. The industrial consortium is composed of RUAG Aerospace, Switzerland (integration, mechanical and electrical subsystems, navigation and control), OIP Sensor Systems, Belgium (optical subsystem), and Netcetera AG, Switzerland (readout electronics, software). In addition, ESA as overall project responsible established two further contracts, one with Sofradir, France (short-wave infrared (SWIR) detector) and the German Aerospace Center (DLR), Germany (calibration home base). APEX went into operations in 2009 and acquires science grade spectroscopy data since 2010. APEX is on lease by ESA to the University of Zurich and VITO until 2015 and thereafter under ownership of the latter two institutions.

In this contribution, we discuss the evolution of the APEX instrument starting with simulating its key performance indicators, and definition of specifications, its optical, electronic and mechanical design. We then elaborate on the calibration procedure and finally demonstrate new Earth science applications allowing monitoring the Earth surface and atmosphere with unprecedented accuracy. We finally conclude by discussing emerging instrument capabilities and applications being of relevance for future, upcoming imaging spectrometers.

## 2. APEX advanced radiometry measurements

### 2.1. APEX specifications and performance modeling

The APEX system was specified to allow simulating spaceborne imaging spectrometers, supporting mission calibration and validation efforts. The following specifications are outlined as *boundary conditions* (Schaepman, De Vos, & Itten, 1998):

- Pushbroom imaging with ≤1000 imaging pixels across track, covering a swath width of 2.5–5 km, depending on flight altitude,
- Spectral wavelength range covering 450–2500 nm,
- At least 200 programmable or 300 predefined spectral bands, adaptable to specific application requirements,
- Spectral sampling interval <15 nm and a spectral sampling width of <1.5 the sampling interval, and
- Ability to provide calibrated data and products to geocoded and calibrated data.

Further on, the dispersive system of APEX had to be based on prisms, given a requirement from European Space Agency. The initial idea was do demonstrate that the ENVISAT/MERIS design can be used in APEX as a demonstrator for a full spectral coverage mission (400–2500 nm) as well as precursor mission of a planned imaging spectrometer in space (Menenti et al., 2002).

Using the above specifications, a performance modeling approach could be initiated. First, a forward model simulating 1D generic imaging spectrometers is implemented (Schaepman, Schläpfer, & Müller, 2002). Key science requirements from various applications are compiled as a list of 55 variables used to forward model the instrument performance. Application requirements are forward simulated using a reflectance model and then converted to at-sensor radiances using a radiance model and finally convolved using a sensor specific model. This leads to the possibility to model (still noise free and in 1D space) pixel-wise requirements for a given instrument. Subsequently, certain noise components are added (Schläpfer & Schaepman, 2002) as well as a spatial component allowing to assess spatial noise as well (Börner et al., 2001). These activities finally lead to a set of performance requirements for APEX which are used as engineering specifications (Schaepman, Schläpfer, & Itten, 2000) (Table 1, Section 4.1). However, not all specifications can be simulated using the above approach, such as stability requirements over time. These specifications are either taken over from existing publications (Green, 1998; Mouroulis, Green, & Chrien, 2000) or from engineering knowledge available through the support of ESA's engineers.

### 2.2. APEX instrument description

APEX is composed of an optical system including two detector channels (Fig. 1), a mechanical subsystem, an electrical subsystem, and an in-flight calibration assembly. External to the core APEX imager is a control and storage unit (CSU), as well as a processing and archiving facility (PAF) and a calibration home base (CHB).

The optical system is a dual prism dispersion pushbroom imaging spectrometer using a path-folding mirror followed by a ground imager with a slit in its image plane (Schaepman et al., 2003). The spectrometer consists of a collimator that directs the light transmitted by the slit towards the prisms, where a dichroic coating applied to the first prism separates the two spectrometer channels into a VNIR and SWIR channel (Visible/Near Infrared 372–1015 nm; Shortwave Infrared 904–2508 nm). The dispersed light is imaged on the detectors of these two channels. A commercial-off-the-shelf VNIR detector (CCD 55-30, E2V Technologies) and a custom made SWIR detector (Nowicki-Bringuier & Chorier, 2009) are implemented. The SWIR focal plane array is a HgCdTe detecting module hybridized on a CMOS multiplexer. It has 1000 × 256 pixels with a 30 μm pitch. Integration time is variable, but limited by the detector frame rate (34.5 ms). Standard integration time is set to 29 ms [22 … 34.5 ms], resulting in almost square pixels using the default aircraft (DO-228). Its spatial direction (1000 pixels) is parallel to the detector rows and its spectral direction (256 pixels) parallel to the detector columns, which is also the readout direction on the focal plane. The detector is implemented in a dewar with a sapphire window coated with anti-reflection material (transmission >0.96). A Stirling cycle cooler allows operating the SWIR detector with low dark current at 130 K detector temperature. The mount of the spectrometer is liquid cooled using a transfer line and cold finger (Ulbrich et al., 2004). The 1000 across-track spatial pixels are recorded for both channels simultaneously. Both detectors are not fully illuminated in spectral direction, allowing non-illuminated lines to be used as dark current reference. The VNIR and SWIR detectors are externally