Processing of large-volume airborne imaging spectrometer data: the APEX approach

Michael E. Schaepman, Daniel Schläpfer, Jason Brazile, and Stephan Bojinski[1]

ABSTRACT

In the framework of the APEX (Airborne Prism Experiment) pushbroom imaging spectrometer, a complete processing and archiving facility (PAF) is developed. The PAF not only includes imaging spectrometer data processing up to physical units, but also geometric and atmospheric correction for each scene, as well as calibration data input. The PAF software includes an Internet based web-server and provides interfaces to data users as well as instrument operators and programmers. The software design, the tools and its life cycle is discussed as well. Further we will discuss particular instrument requirements (resampling, bad pixel treatment, etc.) in view of the operation of the PAF as well as their consequences on the product quality. Finally we will discuss a combined approach for geometric and atmospheric correction including BRDF (or view angle) related effects.

Keywords: Imaging spectroscopy, data processing, imaging spectrometer, data correction

1. INTRODUCTION

Within the framework of the European Space Agency's (ESA) funding scheme PRODEX, an airborne imaging spectrometer named APEX (Airborne Prism Experiment) is developed. APEX is an airborne imaging spectrometer, which is part of the precursor and supporting activities for possible ESA Explorer missions devoted to the understanding of land processes and interactions at a local and regional scale. The aim of APEX is to present a new Earth observation platform that enables the reproducible measurement of the radiance field of the terrestrial surface at a local and regional scale using a well-calibrated imaging spectrometer. The derived variables are further used to quantify the important processes that are relevant in their link to the (global) carbon cycle. The prism based imaging spectrometer is well suited solving spatial and spectral scaling issues from in situ to regional scales.

The mission objectives of APEX further include acting as simulator, calibrator and validation experiment and fostering the imaging spectroscopy application development.[1,2,3] In particular, APEX will be able to simulate, calibrate and validate planned space-borne imaging spectrometer missions (e.g., SPECTRA, MERIS, CHIRS/PROBA, etc.), and can act as a radiometric transfer standard for vicarious calibration.

2. THE APEX INSTRUMENT

Technically, APEX is designed to be a pushbroom imager with approx. 300 spectral channels in the 400 – 2500 nm wavelength region, and with 1000 pixels across track and a swath width of 2.5 – 5 km depending on flight altitude. The APEX hardware consists of an airborne imaging spectrometer with an optimized spectrometer sensor design for the detection of land surface processes, a flexible aircraft integration scheme, an internal calibration facility, a laboratory calibration home base, and a Processing and Archiving Facility (PAF) for the generation of calibrated radiance data and related products. The following table lists some of the challenging specifications APEX will be built with.

1.Correspondence: M. E. Schaepman; Email: schaep@geo.unizh.ch; phone: +41 1 635 51 45; fax +41 1 635 68 46; dschlapf@geo.unizh.ch, jbrazile@geo.unizh.ch, sbojinsk@geo.unizh.ch, http://www.geo.unizh.ch/rsl/research/SpectroLab/

Parameter	**Specification**
Field of View (FOV)	± 14 … ± 20 deg
Instantaneous Field of View (IFOV)	0.48 … 0.70 mrad
Flight altitude	4’000 - 10'000 m.a.s.l.
Spectral channels	VNIR: approx. 140, SWIR: approx. 145
Spectral range	400 – 2500 nm
Spectral sampling interval	400 – 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
Smile	< 0.1 pixel
Frown	< 0.1 pixel
Bad pixels	None (requirement after electronics)
Scanning mechanism	Pushbroom
Absolute radiometric calibration accuracy	≤ 2%
Storage capacity on board (online / offline)	> 50 GByte / > 200 GByte
Dynamic Range	12 … 16 bit
Positional knowledge	20% of the ground sampling distance
Attitude knowledge	20% of IFOV
Navigation system, flight line repeatability	± 5% of FOV
Positional and attitude data	Recording of data onto a housekeeping channel.
Reliability	99% successful data acquisitions for all flights

Table 1. APEX System Specifications.

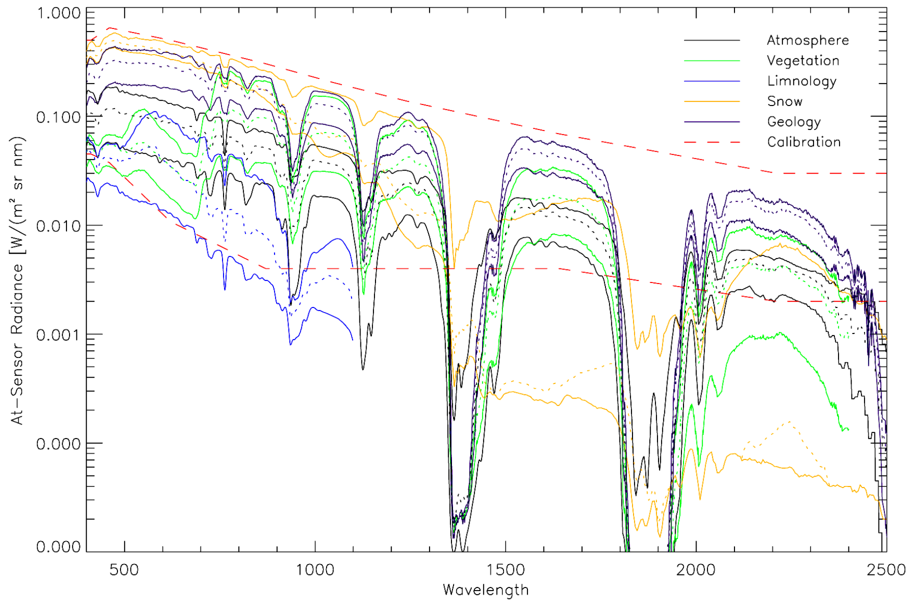

Figure 1 Minimum and maximum radiance levels for six applications in the solar reflected wavelength range.

The APEX instrument is initially designed to cover most of the relevant land applications, and therefore for each potential application to be covered by APEX, a detailed scientific analysis has been performed and the requirements in terms of SNR were derived. In addition, the spectral band specific APEX radiance values have been derived using a performance model with a minimum and maximum radiance definition approach. The following figures list the application specific minimum and maximum radiance requirements before saturation and noise, as well as the corresponding SNR figures.[4,5]

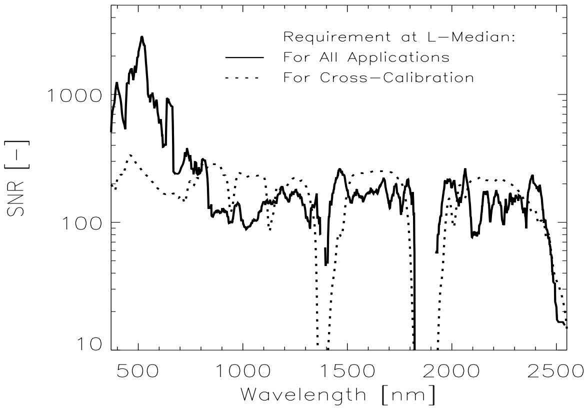

Figure 2 SNR requirements for APEX at median radiance of all applications in comparison to cross-calibration as depicted in Figure 1.

The final APEX design that was chosen is depicted in the Figure 3. Design details include a separation of the instrument into a thermally controlled housing with three layers: an optical base plate with the spectrometer, an electronic plate with the font-end electronics and the cryocooler, and finally the calibration plate with the in–flight calibration facility (IFC) and the spectral and radiance filter wheel. A baffle is added to the base plate underneath the instrument to reduce stray light and provide a counter–weight for the integration of the instrument onto a stabilized platform.

3. DATA CALIBRATION AND PROCESSING

The APEX processing and archiving facility (PAF) manages the data from acquisition and calibration to the processing and dissemination. The generic data calibration and processing concept is depicted in Figure 4. The processing chain is based on inflight acquired image data, housekeeping information (e.g., navigation data, temperature), and on-board calibration data (using the above mentioned IFC). Moreover, a dedicated calibration home base allows the calibration of the geometric, radiometric and spatial sensor characteristics[6]. Using the outcome of the sensor calibration, the raw image data is converted to at-sensor radiance in SI units, traceable to a certified standard (e.g., NIST, NPL). The second major step derives surface reflectance under consideration of the environmental conditions. Optional HDRF correction algorithms[11] are later used to convert the directional reflectance values into nadir-normalized reflectance. The derivation of scientific data products is supported using a flexible plug-in structure in the PAF and documented in standard ATBD’s (Algorithm Theoretical Basis Document).

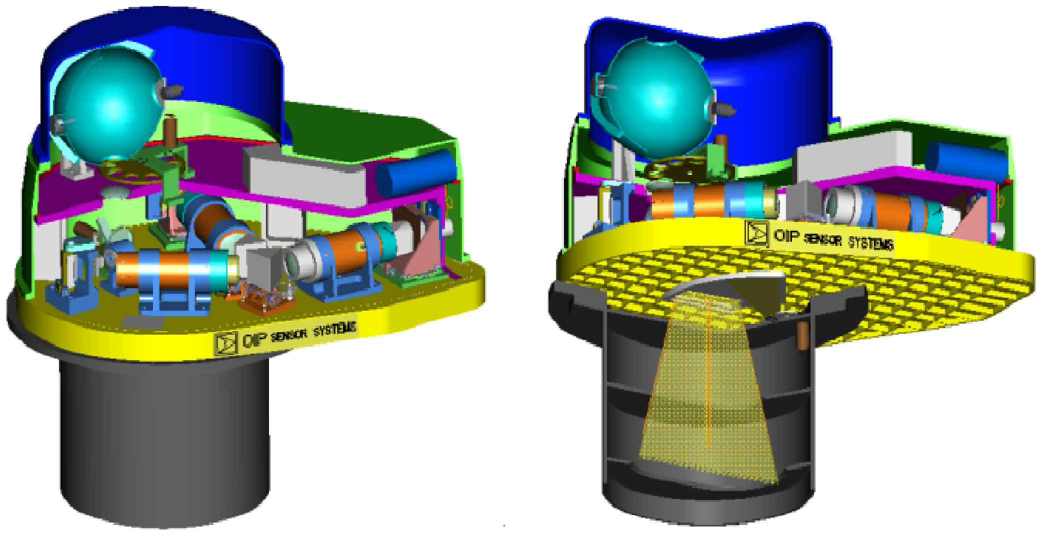

Figure 3 APEX integrated instrument view (left: front; right: bottom–front) (© OIP Sensor Systems 2002)

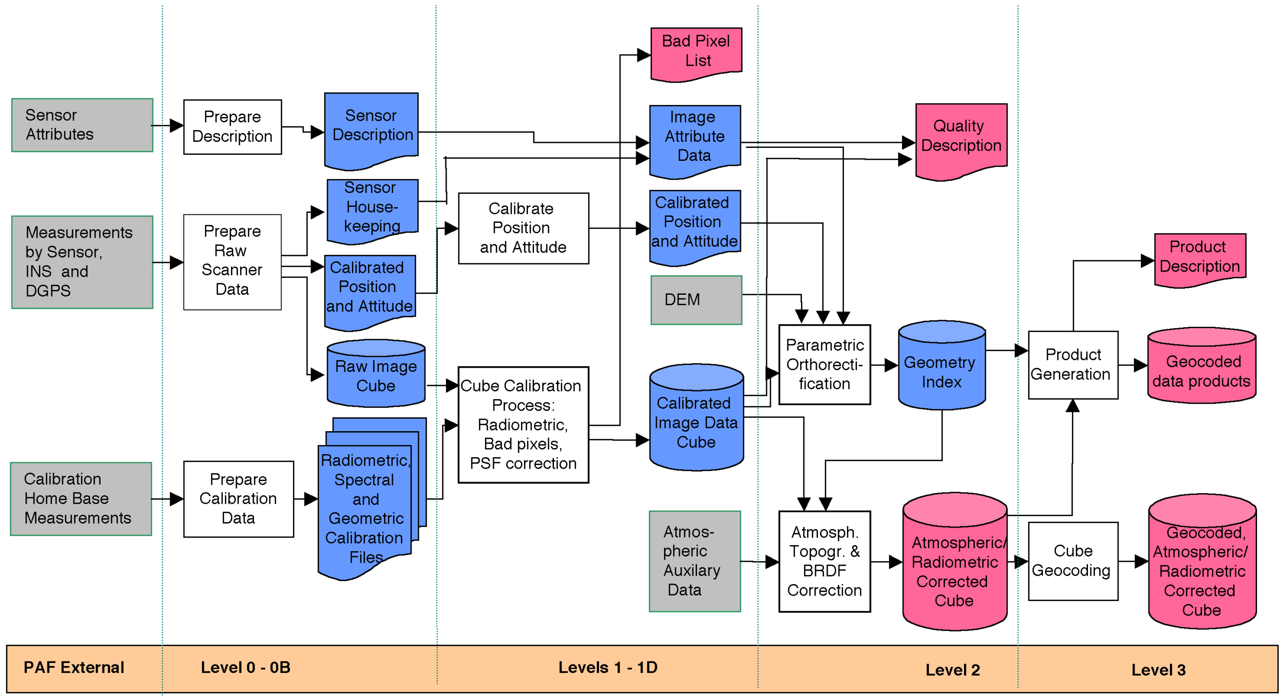

Figure 4 Main data flow for the APEX processing facility

3.1 Data calibration

The data calibration is performed in the Level 1 processing chain of the PAF. The main task is the conversion of the image data from digital numbers to radiance values [W/(m^2 sr nm)] by applying the corrections for spectral, spatial and radiometric distortions. This step is performed using the laboratory calibration data as well as the internal calibration facility data.

APEX has to cope with 'bad pixels' (i.e. non-functional pixels on the detector, where the quantum efficiency drops below 50%). These bad pixels will affect image quality, since approx. 0.5 – 2% of all detector elements (i.e. approx. 1300 –5200 pixels for the SWIR detector and approx. half of them for the VINIR detector) may be malfunctional. The pixel replacement process is based on a bad pixel map which is a result of the laboratory calibration. Linear interpolation techniques in both the spectral and the spatial dimension of both detectors will be used for data reconstruction. Reconstructed values are provided in the final data product as well as the calibrated bad pixel map in order to allow for individual exclusion of bad pixels in data products.

Variation in the spatial point spread function (PSF) will affect the image quality significantly. These effects are corrected using filter techniques in combination with the laboratory calibration files, and a sensor movement model derived from navigation data. In addition to PSF corrections at the level of integration time and aircraft movement, optical effects such as across-track asymmetry and variation of the PSF, as well as frown (keystone) and smile effects will result in spatial and spectral resampling of the image data. Various prototypes are being tested and the chosen approach will be documented in the corresponding ATBD. In any case, these effects impose large constraints on computing requirements, so only very efficient deconvolution and interpolation algorithms will be used, as proposed in Janssen[7].

3.2 Preprocessing

Geometric and radiometric effects significantly influence apparent image quality and need to be compensated in order to allow a quantitative validation of reflectance products. The prerequisite for a physical correction of geometric and atmospheric effects is an accurate description of the scanning and illumination geometry for each individual pixel of any image. Two procedures for geometric and atmospheric processing are combined and optimized with regard to the specific characteristics of APEX data[8,9].

The orthorectification procedure retrieves the center pixel positions for each imaged pixel. These positions are stored in a resampling map, which may be used to resample the data to a regular grid. For contiguous data representation, variables and radiometric image data are resampled using a combination of nearest neighbor approaches and linear interpolation. Original measurements are preserved at the places of original data acquisition through the nearest neighbor approach, whereas distances of 3 and more pixels are resampled by a combination of NN and linear interpolation. Spectral integrity is thus preserved while spatial quality and smoothness can suffer from resampling artefacts. The nearest neighbors are derived by Delaunay triangulation or other fast buffering algorithms. The advantage of triangulation is - besides its higher accuracy - its independence from the final product resolution. The resulting TIN (Triangulated Irregular Network) is a baseline for any final image resolution.

Atmospheric and topographic correction models the direct and diffuse irradiance of each image pixel using data from atmospheric profiles and a digital elevation model. Furthermore, the radiative transfer through the atmosphere is calculated using the MODTRAN4[10] radiative transfer code. Sensor specific look-up tables are used for the retrieval of the surface reflectance

$$\rho = Func(L_s, DEM, p_{atm}),$$

where p_{atm} are atmospheric parameters such as water vapor and aerosols.

Standard atmospheric correction algorithms end up with directional reflectance values following the data acquisition geometry. For time series and mosaicking, the angular effects may still be a dominant factor in the brightness of the observed reflectance. Thus, normalization to either nadir reflectance values or to hemispherical reflectance values is required to facilitate such an intercomparison. The application of the Ambrals model (cf., Beisl[11]) has the potential for successful BRDF correction and will help to derive high quality reflectance values from APEX data.

3.3 Product generation and integration

The final delivered products from APEX will be geometrically coherent spectro-radiometric image data. The derivation of scientific data products is supported using a flexible plug-in structure in the PAF and documented in standard ATBD's. Users and scientists may propose products to be integrated in the PAF and a suite of variable will be available at this level for input into such new products (e.g., terrain related information).

In the last part of this paper, we focus on the implementation details of the PAF.

4. PAF SOFTWARE DEVELOPMENT

There are three noteworthy features of the planned PAF software development process - an iterative prototype-based development model, the amount and method of multi-environment integration, and the accommodation of mixed-level domain development contributions.

4.1 Iterative Prototype based Development model

A large application with so many stake-holders is often subject to design and implementation setbacks resulting from 'specification by committee'. Two approaches have been taken to actively counter these risks and to ensure the coherency of the overall design. First, a prototype-based, iterative development model has been selected[12]. The first iteration consists of simulating program flow using high level prototyping languages and subsequent iterations involve refining the simulated steps by gradually replacing them with more realistic modules - more realistic first in terms of data size and shape and then in terms of processing resource requirements.

The PAF is expected to continuallly undergo such additions and refinement but at every iteration a coherent understandable design and a working, realistic, process will be given highest priority. In addition, it is planned to take a modified SPID approach[13] during the planning for each iteration, where the planned tasks are reviewed and statistical estimates are upgraded for the best, most-likely, and worst case scenarios to help prioritize and re-align the project plan for that iteration.

4.2 Multi-Environment Integration

It was determined that if the control logic of the PAF were developed in a high level metaprogramming environment[14], then this environment could be used to access and integrate the strengths of many other special purpose rapid prototyping environments (see Table 2).

Component	Used By	Advantage
Interactive Data Language (IDL)	Spectroscopers	Rapid Mathematical Modelling/Visualization
Common Object Request Broker Arch. (CORBA)	All	Commodity Middleware Libraries
Relational Database Mgmt. System (RDBMS)	Data Modeller	Standard Data Modelling/Storage/Query
eXtensible Markup Language (XML)	All	Standard self-describing data format
Tool Command Language	All	Rapid Prototyping and component "Glue"
GUI Toolkit (Tk)	GUI Designer	Rapid GUI development
CGI library (Websh)	UI Designer	Rapid Web development
Custom C/C++/Fortran	Programmers	Performance

Table 2 Tools and components used for the APEX PAF software development

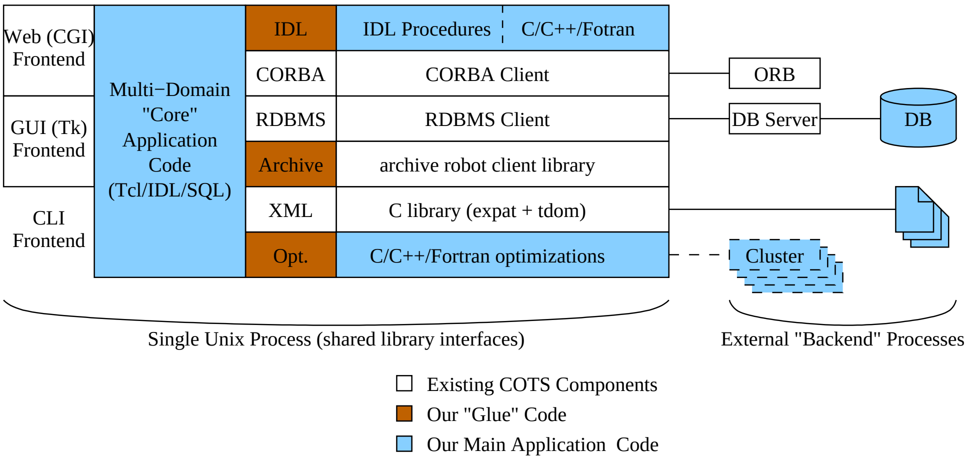

Figure 5 Integrated Processing Engine for the APEX PAF.

The Tcl programming language was chosen due its ease in "gluing together" various diverse environments while causing minimal runtime support overhead. Any programming environment that provides a C or C++ application programming interface can be directly and internally accessed by the Tcl meta language through a dynamically loadable shared library call which allows a high level of multi-environment integration. Even with in-process program and data access to other environments, it is still deemed necessary to be aware of and limit excess data copying overhead that might occur via API calls between the various programming environments.

4.3 Mixed-level domain application development

The direct affect of providing a highly "multi-lingual" development environment is the ability to enable mixed-level domain application development.[15] The development team for such an application can consist of spectroscopy experts developing core algorithms with IDL and possibly other mathematical modelling languages; database experts developing data models and queries in SQL; user interface experts developing Graphical (Tk widget based) and web (HTML) front ends; software architects analyzing overall program and data flow to maximize not just efficiency but flexibility - for example allowing calls to special-purpose CORBA-based services in the processing chain; and finally software engineers which ensure that everything glues together and can help find and re-work bottlenecks.

5. CONCLUSIONS AND OUTLOOK

Terrestrial ecosystems have been identified as being a critical component of the variability of the global carbon cycle. But given the natural diversity of landscapes, the instrumented measurement and validation approach remains challenging. Earth observation from airborne or spaceborne platforms is the only observational approach capable of providing data at the relevant scales and resolution needed to extrapolate findings of in situ (field) studies to larger areas, to document the heterogeneity of the landscape at regional scale and to connect these findings into a global view. Recent development of Earth observation satellites and airborne platforms demonstrate that imaging spectroscopy is a valuable addition to the quantification of relevant parameters supporting processes within the carbon cycle. Even though a number of imaging spectrometers are available in space (e.g., MODIS, MERIS, Hyperion), their performance relies on an integrated approach, including a sound instrument design, a well implemented calibration strategy and finally a processing chain capable of handling large amount of spectral data. Only a wide and fast dissemination of spectrometer data and their products will guarantee the required scientific attention and their inclusion in operational Earth observation systems.

ACKNOWLEDGEMENTS

This work as been performed under ESA/ESTEC contract 15449/01/NL/Sfe. The support of the Agency in general and G. Ulbrich, R. Meynart and M. Berger is acknowledged.

REFERENCES

1. M.E. Schaepman, L. De Vos, and K.I. Itten, “APEX - Airborne PRISM Experiment: hyperspectral radiometric performance analysis for the simulation of the future ESA land surface processes earth explorer mission”, *Imaging Spectrometry IV,* Sylvia S. Shen and Michael R. Descour, Editors, Proceedings of SPIE, Vol. 3438, pp. 253-262, 1998.
2. M.E. Schaepman, and K.I. Itten, “APEX–Airborne PRISM Experiment: An Airborne Imaging Spectrometer serving as a Precursor Instrument of the Future ESA Land Surface Processes and Interactions Mission”, *ISPRS Commission VII Symposium on Resource and Environmental Monitoring,* Proc. ISPRS, Vol. 22(7),Budapest, pp. 31–37, 1998.
3. M.E. Schaepman, D. Schläpfer, D., and K.I. Itten, “APEX – A New Pushbroom Imaging Spectrometer for Imaging Spectroscopy Applications: Current Design and Status”, *Proc. IGARSS Hawaii*, pp. 828–830, 2000.
4. M.E. Schaepman, D. Schläpfer, and A. Müller, “Performance Requirements for Airborne Imaging Spectrometers”, *Imaging Spectrometry VII*, Proc. SPIE, Vol. 4480, 23–31, 2001.
5. D. Schläpfer D., and M. Schaepman: “Modelling the noise equivalent radiance requirements of imaging spectrometers based on scientific applications”, *Applied Optics*, OSA, (accepted for print).
6. D. Schläpfer, M.E. Schaepman, S. Bojinski, and A. Börner, “Calibration Concept for the Airborne PRISM Experiment (APEX)”, *Can. J. Rem. Sens.*, **26/5**:455–465, 2000.
7. P.A. Janssen (Ed.), *Deconvolution of Images and Spectra*. Academic Press, San Diego, pp. 514, 1997.
8. D. Schläpfer, and R. Richter, “Geo-atmospheric processing of airborne imaging spectrometry data. Part 1: Parametric Ortho-Rectification Process”, *Intl. J. Remote Sens.*, (accepted for print).
9. R. Richter, and D. Schläpfer, “Geo-atmospheric processing of airborne imaging spectrometry data. Part 2: Atmospheric/ Topographic Correction”, *Intl. J. Remote Sens.*, (accepted for print).
10. A. Berk, G.P. Anderson, L.S. Bernstein , P.K. Acharya , H. Dothe, M.W. Matthew, S.M. Adler-Golden, J.H. Chetwynd Jr., S.C. Richtsmeier, B. Pukall, C.L. Allred, L.S. Jeong, and M.L. Hoke, “MODTRAN4 Radiative Transfer Modeling for Atmospheric Correction”, *Proc. 8th Ann. JPL Airb. Earth Science Workshop,* JPL Publication 55-61, pp. 55-61, Pasadena, 1999.
11. U.Beisl, *Correction of Bidirectional Effects in Imaging Spectrometer Data*. Remote Sensing Series, RSL, Zürich, Vol. 37, pp. 188, 2001.
12. B.W. Boehm, “A Spiral Model of Software Development and Enhancement,” *IEEE Computer* **21(5)**, pp. 61-72, 1988.
13. E. Miranda, E.:Planning and executing time-bound projects, *IEEE Computer* **35(3)**:73–79, 2002.
14. G. Wiederhold, P.Wegner, and S. Ceri, “Toward metaprogramming: A Paradigm for Component-Based Programming”, *Communications of the ACM,* **35(11)**:89-99, 1992.
15. A. Lédeczi, A. Bakay, M. Maróti, P. Völgyesi, G. Nordstrom, J. Sprinkle, and G. Karsai, “Composing domain-specific design environments”, *IEEE Computer* **34,(11**):44–51, 2001.