APEX – Airborne PRISM Experiment: A new Airborne Hyperspectral Imager for the Simulation of ESA's Land Surface Processes and Interactions Mission

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ABSTRACT

Based on the present demand for airborne and spaceborne imaging spectroscopy data in remote sensing, the European Space Agency (ESA) has initiated a project to build a new generation airborne hyperspectral imager named APEX. APEX is an acronym used for Airborne PRISM Experiment, where PRISM is the main payload on one of ESA’s planned Earth Explorer Missions Core Missions named LSPIM (Land Surface Processes and Interactions Mission). APEX is a pushbroom imager with 300 spectral channels in the 400 – 2500 nm wavelength region, and with 1000 pixels across track. The mission objectives of APEX are mainly being a LSPIM simulator, calibrator and validation experiment and fostering the application development for hyperspectral imaging.

The APEX hardware consists of an airborne imaging spectrometer with an optimized hyperspectral sensor design based on user requirements driven specifications for land surface processes detection.

The Processing and Archiving Facility (PAF) of APEX is customized to meet the demands of high volume data processing. The processing levels include the generation of Level 0 (system corrected), Level 1 (calibrated), and Level 2 (atmospheric and geometric corrected) products. Special emphasis is put on the calibration accuracy requirements and the repeatability of these processes.

The APEX simulator is fully based on software and allows for an independent simulation of the APEX system and monitors possible system changes in specifications during later stages.

Key words: Hyperspectral, Imaging Spectrometer, Airborne, Processing, Calibration

INTRODUCTION

The Land Surface Processes and Interactions Mission (LSPIM) consists of a scientific program leading to the derivation of more appropriate and accurate models of biosphere/geosphere processes and surface atmosphere interaction processes, formulated in terms of parameters and variables, which are well identified at each scale and unambiguously related to the quantities measurable from space. The second part is the development and provision of instruments capable of ensuring observations of key geo-biophysical parameters characterizing the state of the biosphere/geosphere system and its evolution. These data would be used in the validation and improvement of the corresponding models, as well as in advancing our understanding of scaling from local to global.

One of these instruments (namely PRISM) is defined as an observing system with high spatial and spectral resolution, directional sampling capability and, if possible, high temporal repetitivity, but not necessarily with a global coverage, for studying processes and scaling-up procedures. The primary focus of a high spatial and spectral resolution spaceborne mission are the land surface processes and their interactions with the atmosphere, concentrating on the measurement of surface characteristics such as albedo, hyperspectral reflectance, BRDF (bi-directional reflectance distribution function) and surface temperature which are linked to geophysical variables involved in biogenic processes such as productivity, evapotranspiration and nutrient cycles. The space segment of the mission would proceed in parallel with a measurement program involving a set of carefully instrumented ground sites (Berger, 1999).

The main payload of the LSPIM mission is designed as a pushbroom based imaging spectrometer (Labandibar, 1999) and is named PRISM. Two predecessor missions have been defined and appointed in order to familiarize the research community with the upcoming technology and
prepare the required retrieval algorithms for the LSPIM operational phase.

The first predecessor mission is a depointable imaging spectrometer on the upcoming PROBA platform named Compact High Resolution Imaging Spectrometer (CHRIS) (Lobb, 1999). This mission is intended to be a partial technology demonstrator to LSPIM and familiarize the remote sensing community with spectro–directional measurements from space.

The second instrument is designed as an airborne imaging spectrometer working in the 400 – 2500 nm wavelength region of the electromagnetic spectrum and is named Airborne PRISM Experiment (APEX) (Itten, 1997). APEX is intended to be a partial (eg. no thermal capabilities) LSPIM simulator. It will also contribute to the application development in the preparatory phase of the LSPIM mission. During the operational phase of the LSPIM, APEX will be used as a vicarious calibration and validation source for the spaceborne mission. In addition to these capabilities, the present specifications allow a comparison and cross–calibration of other planned or existing imaging spectrometers with APEX (eg airborne such as the DAIS 7915, AVIRIS, HyMap, CASI, AISA, etc., and spaceborne such as the Hyperion, NEMO/COIS, MERIS, MODIS, etc.). In addition to these capabilities, APEX will serve as a testbed for other future imaging spectrometer applications. APEX will be an instrument with the following unique capabilities from a technical, usage and applications standpoint:

- pushbroom imager with ≤ 1000 pixels across track and a swath width of 2.5 – 5 km,
- spectral wavelength range covering 400 – 2500 nm,
- up to 300 spectral bands, continuously and contiguously recorded,
- a spectral sampling interval < 15 nm at a spectral sampling width < 1.5 times the sampling interval, and
- the ability to provide calibrated data and a suite of user oriented products up to fully geocoded and calibrated data.

APEX is build by a joint endeavor of Swiss and Belgian institutes and industries and is funded by the European Space Agency (ESA).

### III APEX SYSTEM

#### Specifications

Based on the outcome of a feasibility study (Itten, 1997) and the subsequent modeling of the instruments radiometric performance, the specifications for APEX have been derived as listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View (FOV)</td>
<td>± 14 ... ± 20 deg</td>
</tr>
<tr>
<td>Instantaneous Field of View (IFOV)</td>
<td>0.48 ... 0.70 mrad</td>
</tr>
<tr>
<td>Flight altitude</td>
<td>4'000 - 10'000 m.a.s.l. 7'500 m nominal</td>
</tr>
<tr>
<td>Spectral channels</td>
<td>VIS: approx. 140 SWIR: approx. 145</td>
</tr>
<tr>
<td>Spectral range</td>
<td>400 – 2500 nm</td>
</tr>
<tr>
<td>Spectral sampling interval</td>
<td>400 – 1050 nm: &lt; 5 nm 1050 – 2500 nm: &lt; 10 nm</td>
</tr>
<tr>
<td>Spectral sampling width</td>
<td>&lt; 1.5 * Spectral sampling interval</td>
</tr>
<tr>
<td>Center wavelength accuracy</td>
<td>&gt; 0.2 nm</td>
</tr>
<tr>
<td>Spectral sampling width accuracy</td>
<td>&lt; 0.02 * Spectral sampling width</td>
</tr>
<tr>
<td>PSF (Point Spread Function)</td>
<td>PSF ≤ 1.75 * Sampling interval</td>
</tr>
<tr>
<td>Smile</td>
<td>&lt; 0.1 pixel</td>
</tr>
<tr>
<td>Frown</td>
<td>&lt; 0.1 pixel</td>
</tr>
<tr>
<td>Bad pixels</td>
<td>None (requirement after electronics)</td>
</tr>
<tr>
<td>Scanning mechanism</td>
<td>Pushbroom</td>
</tr>
<tr>
<td>Absolute radiometric calibration accuracy</td>
<td>≤ 2%</td>
</tr>
<tr>
<td>Storage capacity on board (online /offline)</td>
<td>&gt; 50 GByte / &gt; 200 GByte</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>12 ... 16 bit</td>
</tr>
<tr>
<td>Positional knowledge</td>
<td>20% of the ground sampling distance</td>
</tr>
<tr>
<td>Attitude knowledge</td>
<td>20% of IFOV (accelerometers, gyros, inertial navigation system or similar</td>
</tr>
<tr>
<td>Navigation system, flight line repeatability</td>
<td>± 5% of FOV</td>
</tr>
<tr>
<td>Temperature</td>
<td>Detector temperatures to be registered</td>
</tr>
<tr>
<td>Timing</td>
<td>Master clock synchronizing all measurements</td>
</tr>
<tr>
<td>Positional and attitude data</td>
<td>Recording of data onto a housekeeping channel</td>
</tr>
<tr>
<td>Reliability</td>
<td>99 % successful data acquisitions for all flights during each year of operation</td>
</tr>
<tr>
<td>Vibration</td>
<td>Anti vibration means</td>
</tr>
<tr>
<td>Optical head dimensions</td>
<td>Must fit in standard mount</td>
</tr>
</tbody>
</table>
System Performance

For a predefined number of channels the Noise Equivalent Radiance Difference (NEdL) has been calculated for AEX based three major inputs:

- the radiometric requirements given by the PRISM instrument (Del Bello, 1996),
- the subsequent modeling of the instruments radiometric performance (Schaepman, 1998), and
- a comparison of currently achieved performances of existing imaging spectrometers (e.g. DAIS 7915, HyMap and AVIRIS).

NEdL values are listed in Table 2 at instrument level and will be constantly verified against the laboratory calibration facility. The NEdL values of the intermediate channels of the APEX instrument can be obtained by linear interpolation between the given values (all wavelengths are listed in [nm] and radiances in [W/(m² ster nm)]).

Table 2: APEX NEdL Performance

<table>
<thead>
<tr>
<th>Wvl. (nm)</th>
<th>NEdL</th>
<th>Wvl. (nm)</th>
<th>NEdL</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0.00028432</td>
<td>1500</td>
<td>6.43E-05</td>
</tr>
<tr>
<td>500</td>
<td>0.00026628</td>
<td>1600</td>
<td>5.99E-05</td>
</tr>
<tr>
<td>600</td>
<td>0.00024825</td>
<td>1700</td>
<td>5.85E-05</td>
</tr>
<tr>
<td>700</td>
<td>0.00023675</td>
<td>1800</td>
<td>5.56E-05</td>
</tr>
<tr>
<td>800</td>
<td>0.00020513</td>
<td>1900</td>
<td>4.70E-05</td>
</tr>
<tr>
<td>900</td>
<td>0.00016775</td>
<td>2000</td>
<td>3.69E-05</td>
</tr>
<tr>
<td>1000</td>
<td>0.00013613</td>
<td>2100</td>
<td>3.12E-05</td>
</tr>
<tr>
<td>1100</td>
<td>0.00011313</td>
<td>2200</td>
<td>2.98E-05</td>
</tr>
<tr>
<td>1200</td>
<td>9.59E-05</td>
<td>2300</td>
<td>3.12E-05</td>
</tr>
<tr>
<td>1300</td>
<td>8.15E-05</td>
<td>2400</td>
<td>3.69E-05</td>
</tr>
<tr>
<td>1400</td>
<td>7.14E-05</td>
<td>2500</td>
<td>5.13E-05</td>
</tr>
</tbody>
</table>

Calibration

Based on the inherent flexibility of the APEX instrument integrating it into a given choice of aircraft within less than three hours, frequent laboratory calibration cycles are foreseen to monitor the stability of the instrument. The key requirement for it is a total radiometric accuracy of ≤ 2% at any time, traceable to a primary standard. The inherent design properties of pushbroom scanners do not allow for a continuous scan of a reference source during data acquisition. The calibration strategy for APEX has therefore been adapted to this special need.

The laboratory calibration procedure of APEX includes radiometric, spectral (and wavelength), and geometric calibration for all channels and all detector elements. The radiometric calibration is performed using an integrating sphere, which is traceable to a predefined standard. This (reference) sphere will also be used to intercalibrate a sphere that is built into the instrument itself by establishing it as a secondary standard. The traceability of the instrument sphere is in the range of ≤ 2% to the laboratory sphere.

The spectral calibration using a double monochromator aims at a center wavelength accuracy of 0.2 nm and the combination of the geometric and spectral calibration will result in the knowledge of the spectral sampling width at an accuracy of less than 2%. The geometric calibration is performed using a moving slit perpendicular to the scanlines. Based on these calibration efforts the response function, frown and keystone effects can be characterized to an extent less than the required 0.1 pixels.

During operation in the aircraft and in the laboratory calibration, the instrument is sealed in a closed housing where pressure and temperature are kept constant. Before and after any image run is acquired (a run here typically indicates a continuous recording of up to 80'000 scanlines), the internal depointing mirror is directed into the internal integrating sphere measuring typical scence radiances before closing the shutter to assess dark current. This process allows the reconstruction of possible drifts effects of the instrument during the data acquisition. In addition to these efforts, vicarious calibration experiments are carried out during the flight year in order to support the evaluation of the expected performance during normal operation.

The Imaging Spectrometer Optomechanical Subsystem

The ground imager maps the ground (swath of ±14…20°) on the spectrometer slit of 50 mm height and 0.05 mm width. High image performance is required in order to provide maximum energy throughput at the slit and to define the swath width precisely. The ground imager has to be colour corrected in the total spectral range between 400 and 2500 nm. Behind the ground imager a beam splitter will be placed to separate the spectral range in a VNIR and a SWIR channel. The use of a beam splitter in front of the collimators allows to choose more suitable glasses for the colour correction and for improving the transmission within the reduced number of spectral bands. The two collimators project the light coming from the slit towards the dispersive elements (eg. prisms) of the spectrometers. For the visual channel, the prism materials CaF$_2$ / ZnS are selected, for the IR channel the prism materials are CaF$_2$ and Sapphire.
Finally detector lenses are selected to provide spatially and spectrally resolved images on the matrix detectors. The VIS detector is tilted by 30° to correct for image height differences at the individual wavelengths. The IR detector lens consists of three off-axis aspherical mirrors. The use of reflective elements simplifies the color correction, supports the compensation for image bending and improves the total throughput for better signal to noise ratios.

Detectors and Front End Electronics

In the APEX instrument two detectors are needed to cover the specified spectral range:

- A VINR detector, sensitive in the spectral range 450 - 950 nm (Si CCD)
- An SWIR detector, sensitive in the spectral range 900 - 2500 nm. (Choice of HgCdTe or InSb detectors)

The detectors for the APEX instrument have to be two dimensional array detectors. To meet the specification on resolution, in the spectral and spatial direction the detector arrays must at least have 1000 pixels in spatial, and 200 in spectral direction. The remaining pixels in spectral direction will be used for spectral binning in order to reduce the influence of bad pixels present on the detector.

The FEE for the VINR CCD detector will be realized by using photocapacitors and CCD readout structures. The analogue output signal of the CCD is sampled and converted to digital data using an ADC. The HgCdTe detector will be read out using a CMOS circuit. The array consists of a number of addressable x and y multiplexers. The detectors will be glued in their holders. Alignment (translation) will be done making use of shims. To reduce dark current noise, the IR detector needs to be cooled to a temperature of ≈80° C. Cooling is achieved by means of a cooling engine. Care has to be taken that no vibrations caused by the cooling engine disturb the image quality of the system.

Electronics Unit

The electronics unit consists of the video electronics unit, the framegrabber unit, the data storage unit and the user interface unit which incorporates four basic operating modes to control the APEX instrument:

- Mission preparation – before a data acquisition mission, all parameters and sequences are determined and stored in the system
- Calibration mode – the calibration sequence is initiated and the calibration data are stored
- Acquisition mode – the instrument stores the data coming from the detectors
- Stand–by mode – all the values stored or transferred into the instrument stay active but no acquisition is done

The proposed video chain of the systems consists of an analogue ASIC that grants for the necessary stability. The next device is an internal offset loop correcting the offset recorded from some darkened border pixels of the detectors. Finally the ADC converter will take care of the signal conversion to be fed into the framegrabber. The framegrabber itself is capable of transferring 300 lines of 1000 16 bit pixels each 40 ms.

The calibration mode will be used in the laboratory where the operator has the choice of addressing basically all moving parts and controls in the APEX system. During a real data flight, the instrument will be first in calibration mode and over the desired test site in acquisition mode. A moving window display will be used in the APEX control unit to monitor the functionality of the detectors. The framegrabber unit, the data storage unit and the user interface unit are mounted in racks that are located in the cabin of the aircraft. The video electronics unit is a part of the APEX instrument.

Auxiliary Components

In order to make the APEX system operational, the following auxiliary components must be available in addition to the imaging spectrometer:

- an aircraft platform,
- a stabilized platform or equivalent anti–vibration and shock absorber means,
- a differential GPS and accelerometers (and/or gyro, INS, etc.),
laboratory calibration hardware,
equipment for temperature and pressure control,
and
an operator with a dedicated flight or mission plan.

The Aircraft and Navigation

The APEX instrument, when installed in an aircraft, will be in a protected and closed and temperature stabilized environment. The structure containing the APEX instrument has an optical window made of sapphire. During take-off and landing a mechanical shutter will be closed in order to protect this window.

A list of proposed survey aircraft for the operational missions of APEX. The crew will consist of an aircraft pilot and the APEX operator. In order to guarantee the geometric quality of the recorded scenes accurate navigation data have to be provided. At present the concept is to use the autopilot of the aircraft plus differential GPS and an inertial navigation system, and to record this data simultaneously to the actual scene.

Data Processing and Calibration

The data acquired with APEX is transferred to the PAF using either tape, hard drives or high speed Internet connection and is stored in sequential order (BIP, Band Interleaved by Pixel). The raw data is subdivided in a first step into in-flight calibration data and runs. These runs again are subdivided into scenes, where the first n scenes will have 1500 scanlines each and the last scene will complete the run. All coregistered spectral channels of one scene are then represented in a ‘data cube’.

The image header is stored into the PAF database for each scene. All subsequent access to any type of data is then administrated through the PAF database. The radiometry remains unchanged throughout Level 0 processing. After the segregation the following information is available in distinct data entities:

- Raw image cube: max. 16 bit digital numbers of the original measurements of the sensor in unchanged byte interleaved representation (BIP),
- Image header: header information related specifically to the cube, containing dimensions and basic attribute data (e.g. date, sensor, channel interleave, description),
- Pre/post run calibration data: data taken by the sensor shortly before and after the scene scan process,
- Dark current: measurements on the obscured part of the for dark current drift monitoring, and
- Housekeeping: synchronization information, temperature of the detectors and further status reports per scanline.

The position and attitude data is processed in a separate data stream. It therefore has to be prepared in a dedicated module and is concatenated to one file per cube containing all positional and angular data per scanline. General sensor attribute data such as the field of view, the PSF characteristics, and the amount and distribution of bad pixels on the detector are initially known from the laboratory characterization or from the manufacturer and are not subject to change during normal instrument operation.

Two final data products are generated automatically for control purposes from the above mentioned process:

- A consistency report is automatically created from the raw image data to register missing data elements and possible recording failures.
- A quicklook file is processed for the visual assessment of the acquired scene. The quicklook will be immediately available for download to the end users.

The second preparation process deals with the creation of standardized calibration files. Three types of calibration files can be stored within the APEX PAF: spectral response information, the geometric PSF, and radiometric calibration constants. Spectral response and geometric PSF calibration can only be measured in the laboratory. The corresponding files contain information about the detector response functions (spectral and geometric across track) and the geometric footprint of the sensor along track.

The radiometric calibration files may origin from two different sources. Quasi-continuous gain characteristics can be measured in the laboratory. They are parametrized to obtain calibration gain and offset values and a linearity measure of the response. The second source for radiometric calibration are the in-flight measurements. These values are transformed directly to calibration gain and offset values per detector element. This information will be used in conjunction with a calibration drift model and compared to the laboratory measurements and is used for validation purposes. Figure 4 depicts the Level 0 data flow in the PAF.

Figure 4.: Level 0 Data Preparation Process

All relevant system calibration is performed in the Level 1 processing chain. This includes the calibration of position and attitude data to absolute angles and coordinates of the airplane on a separate track. The main task in this level remains the calibration of raw data to physical measures by applying the correction for spectral, spatial and radiometric distortion. A linear calibration model is assumed, resulting in 1000 x 300 x 2 different calibration constants for the sensor.

The bad pixel specification for APEX is defined at the electronics level and assumes no bad pixels. Since there will be bad pixels present (approx. 0.5 – 2 % of all detector elements may be malfunctioning) and this effect is considered using two different strategies. A complete replacement is performed if bad pixels produce missing or wrong data elements. Spectral interpolation is preferred for that process since natural spectra usually are highly correlated in the spectral domain, while they often vary with discrete features present in the spatial domain. The replacement may be repeated after atmospheric correction to avoid introducing artifacts. This process is based on the bad pixel map supplied by the manufacturer. Spectral resampling may has to be applied if spectral binning is used at the detector level. If some of the binned pixels are bad, the data has to be resampled using the signal of the spectrally neighboring channels (Schüpfner 1999). This effect may introduce larger uncertainties to some spectra but cannot be handled in a absolute manner (see Janssen, 1997).

The overall point spread function (PSF) describes the blurring of the spatial information by the electro-optical parts of the system and the movement of the airplane. It can be described as a convolution function and influences the image quality significantly. This effect can be corrected with filter techniques using the laboratory calibrated PSF together with movement models at some point. The Level 1 data flow is given...
in Figure 5 below.

![Figure 5: Level 1 Processing Concept](image)

**V SENSOR MODEL AND SIMULATION**

The consistent software based simulation of imaging spectrometers is not possible without appropriate information on its operating environment, the observed scene and the related geometry between sun, observer and object. A dedicated software model has therefore been built for APEX in order to complete the following tasks:

- Evaluation of sensor specifications and their possible changes,
- Optimization of sensor parameters and observation conditions for a certain task (e.g. cost, development risk, etc.),
- Evaluation and adaptation of existing processing algorithms (e.g. calibration, etc.),
- Efficiency and robustness testing of dedicated processing chains,
- Error and uncertainty estimation, and
- Cost-versus-quality considerations.

All these abovementioned tasks are modeled using SENSOR (Software ENvironment for the Simulation of Optical Remote sensing systems) (Börner, 1999). The basic concept behind SENSOR is to concentrate all relevant knowledge of hardware of the remote sensing system (e.g. optical distortions, stray light, dark signal, pixel response non-uniformity, etc.), the source of radiance (e.g. the sun), the atmosphere, and the observed object (e.g. landuse class, slope, aspect) into one model. SENSOR pursues a similar philosophy as other end-to-end simulation approaches (e.g. SENSAT (Richter 1990)).

Figure 6 depicts a general flow diagram of SENSOR. From left to right all essential input parameters, the processing modules, and the outputs (also input parameters for the next processing step), are given.

![Figure 6: SENSOR data flow chart](image)

SENSOR consists of three main parts, basically the geometric part (ray tracing), a radiative part, and the system charaterization part.

**Ray Tracing**

The ray tracing module determines the geometric relation between the observed object (represented by a Digital Elevation Model (DEM)), the radiant source and the remote sensing system applying a ray tracing algorithm. Subsequently an artificial flight line over a DEM is simulated resulting in information about the position of the sensor (x, y, z), and it’s attitude (roll, pitch, yaw). Pixel rays describe then the viewing direction vector of each detector element at all times during the simulated flight. The determination of the coordinates of the object points on the DEM and their properties – the landuse class of the object, the sky view factor, the normal vector, and the surface temperature – is the next step. Starting from a certain detector element, the pixel ray is tracked until a surface element is hit. For reasons of computing efficiency, DEM surface elements are subdivided into two triangles per patch. The size of the DEM elements and the ground sampling distance of the remote sensing system should be approximately the same. The task of ray tracing is to find the triangle, which is seen of a certain detector element.

After projecting the pixel ray – by assigning each pixel a position and a viewing direction – the intersection points between the pixel ray and the DEM are calculated. The computational speed of this procedure depends on the geometry of the remote sensing system (e.g. field of view), the flight motions, and the DEM parameters (height differences, resolution, and roughness). This procedure is performed once per spatial pixel, independent of the number of spectral channels. The output of the ray tracing procedure is the geometry of the object points observed, the intersection points with the DEM, the normal vectors of the observed DEM elements, and the properties of the object.
points observed. These object properties allow to define a link to a spectral library which can contain measured or simulated reflectance spectra.

**Radiative Transfer**

After the determination of the geometric properties, the at-sensor-radiance for each pixel is calculated. The radiative transfer describes the influence of the earth’s atmosphere on the solar irradiance. SENSOR uses data simulated by MODTRAN (Berk, 1989).

Internally, SENSOR applies a sub-channel model assuming that all spectral channels of the remote sensing system are built by a number of sub-channels. Width and sampling distance of the sub-channels are set to 1 nm, since MODTRAN’s internal minimum step width (1 cm⁻¹) corresponds to a step width of 1 nm at the uppermost wavelength being relevant for APEX (2500 nm or 4000 cm⁻¹).

One way is to obtain the corresponding reflectance value of the observed object by reading it from the spectral libraries for each sub-channel. The second way to retrieve reflectance values is to access a data cube containing reflectance values for each spatial pixel. The next step is the determination of the at-sensor-radiance of each sub-channel. MODTRAN allows this calculation for a definable channel and a set of environmental parameters. Pre-calculated MODTRAN lookup-tables (LUT) are used in order to increase processing speed. The LUT’s are given for a set of values of all important input parameters. The number of entries per input parameter and their resolution has to be defined by the known APEX specifications and by expected observation conditions. An automatic procedure to generate customized LUT’s is used (Wiest, 1998). Currently, the MODTRAN LUT used for the APEX simulation consists of seven entries (six radiative contributing and the optical depth) for all combinations of the input parameters. It has a size of about 7.7 MByte. Its generation takes about half an hour on a Sun Ultra 60. The LUT can be expanded easily, e.g. by adding different aerosol models.

Two major limitations have to be overcome for this simulation. The first is the interpolation procedure to model appropriate results of intermediate input parameters, which is not trivial in a seven-dimensional data cube. In this work, the nonlinear seven-dimensional hypersphere is expanded into a linear Taylor-series and a multidimensional linear approach is used to solve the equation systems. The second one is the navigation in a multidimensional data cube. The incessantly calculation of the address of an appropriate data set is a very time consuming process. So procedures for a fast data access are necessary. The result of the module described above is the at-sensor-radiance for each spatial pixel of each image line in each spectral channel. The applied parametric approach allows a flexible use of pre-calculated MODTRAN LUT’s.

**System Characterization**

The module describes the hardware of the remote sensing system. It is divided into an optical and an electronic part.

Each spectral APEX channel is characterized by a spectral response function. It describes the sensitivity of the channel regarding to the energy in a certain range of the electromagnetic spectrum. In order to model a continuous response function, SENSOR defines the response function of each channel as a set of discrete samples (sampling distance 1 nm).

SENSOR includes as well parameters characterizing the hardware of the remote sensing system. A quasi-convolution in the spectral direction is performed by summing up the generated electrons of the sub-channels into one spectral APEX channel.

After the optical model, an electronic data processing chain is simulated. It includes certain noise sources (e.g. pixel response non-uniformity and dark signal), and an analog-digital-converter. The output is one digital number per spatial and spectral pixel, per image line. The transfer of the at-sensor-radiances to digital numbers corresponds to an inverse radiometric calibration. This procedure is performed for each spatial pixel of each line of each spectral channel. The influence of the point spread function (PSF) of the system and blurring caused by the flight motion during integration time is considered by applying convolution kernels across and along flight track. This is performed for each spectral image, considering neighboring pixels. The result is a simulated APEX data cube.

Smile and frown (keystone), caused by the optical components of APEX, are of special interest. If needed, the simulation of these effects with SENSOR may be performed the following way: For each pixel on the CCD (spatial and spectral), separate geometric calibration data are provided (simulated or measured). Then for each pixel the ray tracing procedure has to be carried out separately. After that, the radiation transfer and system hardware modules can be applied the way described above. The simulation of distortion effects using SENSOR is possible, but results in a memory and computational efficiency problem.

Currently, about 20 hours processor time on a Sun
Ultra 60 is needed to simulate one entire APEX image cube with a size of (1000 pixels across track) x (1500 image lines) x (300 spectral channels). Figure 7 shows a SENSOR simulated APEX cube.

VI CONCLUSIONS

A new airborne imaging spectrometer has been presented including its Processing and Archiving Facility (PAF) and an appropriate simulation tool (SENSOR) to verify independently the performance of the system. The presented hardware design is currently in its breadboarding phase and the instrument will be operational in summer 2002.

It has been shown that an efficient PAF is a requirement for the amount of data that is related to imaging spectrometers and the usefulness of simulation tools is important to constantly monitor the progress of the program.

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VIII REFERENCES


