APEX – AIRBORNE PRISM EXPERIMENT:
AN AIRBORNE IMAGING SPECTROMETER SERVING AS A PRECURSOR INSTRUMENT
OF THE FUTURE ESA LAND SURFACE PROCESSES INTERACTIONS MISSION

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ABSTRACT
The European Space Agency (ESA) has identified the necessity to initiate a study that concentrates on the definition of an airborne imaging spectrometer which could represent a precursor to the spaceborne PRISM (Process Research by an Imaging Space Mission). The study included the definition of an Airborne PRISM Experiment (APEX) that will contribute to the preparation, calibration, validation, simulation, and application development for the PRISM mission. The APEX instrument is defined as an airborne pushbroom imager with 1000 pixels across track and 200 user selectable or 300 fixed spectral bands covering the wavelength range from 450 – 2500 nm. The complete APEX system will include an aircraft, navigation data, laboratory and in–flight calibration as well as a data archiving and processing facility.

The definition of the specifications of the APEX instrument is based on a sensor model taking into account various parameters. The approach used defines the radiometric properties of expected scene radiances within the operating range of the APEX instrument and derives subsequently the radiometric resolution requirements.

1. INTRODUCTION
After the successful operation of ERS–1 and ERS–2, the European Space Agency has set the scene for an environmental mission by preparing the satellite ENVISAT–1.

In formulating European Earth Observation missions beyond this, ESA is considering the development and launch of a high resolution Land Surface Processes and Interactions Mission (Readings, 1996) and intends to develop a system to investigate land surface processes and their interaction with the atmosphere (Del Bello, 1996). This includes the implementation of data acquisition from an advanced high resolution spectro-directional space sensor, and by supporting the development of the tools and techniques of data interpretation to:

- increase the understanding of biophysical processes and land/atmosphere interactions at the local scale; and
- exploiting the increase in knowledge of (small scale) processes and to advance the understanding of these interactions on a global scale by extrapolating through time and space using process models.

The space segment would be characterised by:

- a single satellite in a near-polar orbit capable of enabling the payload to access all land areas with the required geometric and temporal characteristics;
- a hyperspectral imager with the required spatial and spectral resolution covering the optical range of the electromagnetic spectrum with good radiometric accuracy and with the capability to perform directional measurements providing the required accessibility and revisit characteristics.

A preliminary design at system level of satellite instrumentation fulfilling this goal started under the name Process Research by an Imaging Space Mission (PRISM) (Posselt, 1996). This instrument will combine the main features of a visible/short wave infrared imaging spectrometer and of a thermal infrared multi–channel imager. PRISM would cover two main wavelength regions, namely the visible-short-wave infrared from 0.45 to 2.35 μm, where the instrument works as an imaging spectrometer with a spectral resolution of about 10 nm and the thermal infrared range from 8 to 12.3 μm, divided into 3
spectral bands with a typical width of 1 μm, where the instrument works as an imaging radiometer. The spatial resolution at nadir is about 50 m over a swath (image size) of 50 km. Access to any site on earth could be provided within three days (ESA ESAC, 1996).

In order to support such activities, ESA has identified the necessity to initiate appropriate studies and measurement campaigns. In this frame, the presented paper discusses a study that concentrates on the definition of an airborne imaging spectrometer which could represent a precursor of the spaceborne instrument and which will therefore be named APEX (Airborne PRISM Experiment)(Del Bello, 1995).

APEX is a project to develop an airborne PRISM simulator which will contribute to the
• preparation,
• calibration,
• validation,
• simulation, and
• application development of the PRISM mission. In addition APEX will be an advanced imaging spectrometer serving as a testbed for other imaging spectroscopy applications (Itten, 1997).

2. THE APEX INSTRUMENT

APEX will be an instrument with the following uniqueness in technical, usage and applications standpoint:
• pushbroom imager with approx. 1000 pixels across track and a swath width of 2.5 – 5 km
• spectral wavelength range covering 450 – 2500 nm
• 200 user selectable and predefined bands, adapted to the specific mission and application
• a spectral sampling interval < 15 nm at a spectral sampling width < 1.5 times the sampling interval
• provides calibrated data and a suite of user oriented products up to fully geocoded and calibrated data.

2.1 The Imaging Spectrometer Optomechanical Subsystem

The ground imager maps the ground (swath of ±14°) 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 image has to be colour corrected in the total spectral range between 450 and 2500 nm. Behind the ground imager a beam splitter will be placed to separate the spectral range in a visual and an IR 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 of the spectrometers.

Prisms will be selected as dispersing elements. The light scattering in a system containing gratings is considered to be a risk that cannot be taken. For the visual channel, the prism materials CaF₂ / ZnS are selected, for the IR channel the prism materials are CaF₂ 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.

2.2 Detectors and Front End Electronics

In the APEX instrument two detectors are needed to cover the specified spectral range:
• A VIS detector, sensitive in the spectral range 450 - 950 nm (Si CCD)
• An IR 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 FEE for the visual 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 by an ADC.

The HgCdTe detector will be read out by a CMOS circuit. The array consists of a number of addressable pixels using MOS transistors as switches, controlled by an x and y multiplexer.

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. The 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.

2.3 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 200 lines of 1000 12 bit pixels each 40 ms. This throughput corresponds to a data–rate of 60 Mbit/sec. If the 300 channel option is used, the data–rate will increase to 90 Mbit/sec.

In the mission preparation phase, the operator of the instrument must select 200 channels that will be recorded out of 400 lines accumulated by the detectors. The channel selection is stored in a PROM and multiple PROM’s can be selected within one data acquisition flight. An alternative concept foresees the readout of 300 predefined channels, making the selection procedure obsolete. 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. Two hundred frames corresponding to one scan line will be recorded continuously every 40 ms. 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.

3. AUXILIARY COMPONENTS

In order to make the APEX Imaging Spectrometer System operational, the following auxiliary components must be available:
- an aircraft platform
- a “closed” environment for the APEX instrument
- a stabilized platform
- a differential GPS and accelerometers
- in flight calibration means
- laboratory calibration hardware
- equipment for temperature and pressure control
- vibration and shock absorbers

3.1 The Aircraft And Navigation

The APEX instrument, when installed in an aircraft, will be in a protected and closed and temperature stabilized environment. The pod or box 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 the window.

The PILATUS PC XII Eagle is the 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. 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. A geometric analysis has shown, that roll, pitch and yaw stabilization will be necessary in order to provide a precise geometric coverage of the area at stake. The vibration decoupling shall be effected by means of shock mounts.

3.2 The Calibration

The primary goal of the calibration strategy is to achieve absolute radiometric calibration traceable to an established standard such as NIST for the acquired data. It is necessary to achieve the best possible radiometric accuracy performance in order to be able to validate PRISM and other imaging spectrometers. Further on it is considered to use standard hardware technology to reduce the amount of calibration costs for in-flight characterization. During the critical phases (takeoff, landing) of the aircraft, the instrument will be protected by a mechanical shutter. In general there is no in-flight calibration foreseen during data acquisition, but in-flight pre- and post-data acquisition calibration activities allow for the monitoring of the instrument performance.

An integrating sphere will be used in the laboratory as calibration standard for characterizing the radiometric response function. The sphere is used as a secondary calibration standard, traceable to NIST standards. An irradiance lamp source will be used in conjunction with a (double) monochromator to calibrate the spectral response function. The spectral response function for each channel covering the whole wavelength range (400 – 2500 nm) will be measured in 0.5 nm intervals using different diffraction gratings. The calibration of the geometric response function will be done using an illuminated slit that is projected perpendicular to the slit in the focal plane of a collimator. The calibration hardware will also include a PC that controls all the necessary devices and collects the calibration data.

In the laboratory, the system will be able to scan both the internal sphere and the laboratory sphere using a switchable mirror in the optical path. Built into the electronic part of the APEX, the compensation offset loop will subtract dark current estimated from the darkened border pixels of the respective detector lines during any data recording with the instrument. The traceability between the laboratory sphere and the APEX sphere can be established during these measurements.

The pre-flight calibration will be more a general functionality test of the instrument than a calibration traceable to a standard. It is suggested to use a homogenous, diffuse artificial lamp source to illuminate the instrument from below the aircraft. The instrument must be fully operational and ready for data acquisition.

The in-flight calibration is divided into three parts. The pre-scene calibration will take place just before the data acquisition. The shutter of the sphere will be closed and dark current frames are recorded while pointing the FOV into the integrating sphere. Then the shutter of the instrument opens and the built in integrating sphere illuminates a mirror that deflects the beam of the FOV towards the ground imager. After these calibration tasks, image data from the scene can be acquired. Similar to the laboratory calibration hardware, the in-flight calibration hardware of the APEX system consists of an integrating sphere calibration standard. The features associated to this sphere will be similar to the one evaluated for the laboratory use, but must – due to space constraints in the pod – be smaller in total diameter.

There will be no in-flight calibration during ground data collection. The image data acquired are only dark current subtracted. After having recorded one scene or a sequence of scenes, the internal mirror will switch and deflect the FOV towards the internal integrating sphere again.

Vicarious calibration experiments are performed on selected test flights according to experiments proposed by Schaeppman et al. (1997). For data taken in other test sites, provisions must be made to provide on site reference measurements of selected targets and the atmosphere.

4. RADIOMETRIC MODEL

4.1 Input Parameters for the APEX Model

The modelling of the APEX specifications is based on MODTRAN (Berk, 1989) at–sensor–radiances. Three different situations are modelled using an albedo of 1 as maximum level to determine the detector saturation, a constant albedo of 0.4 is chosen as SNR validation level and a 0.01 albedo as minimum level.

The maximum level is suited to measure very high reflecting targets, such as snow or high reflecting artificial objects. The maximum level will most probably saturate over clouds, hot spot situations, and glitter resulting from reflections on the water surface. Applications related to
these reflectance levels (e.g. top–of–the–cloud BRDF measurements) are explicitly excluded from the range of APEX applications. An update to include these levels would require a remodelling process including an albedo of 1.1 over clouds at altitudes up to 6.5 km.

The validation level is used to verify the SNR specifications. The requirements for SNR are defined as the average SNR over all channels covered by one detector (e.g. VIS or SWIR) including the band positions in the water vapor absorption bands. Atmospheric applications are an important goal of APEX and therefore the specifications include all band positions inside the absorption bands.

The minimum level is defined as 0.01 albedo. This is at the same time the expected uncertainty of the RTC (Radiative Transfer Code). Inland water monitoring is an important application for the APEX instrument. Therefore the lower end of the dynamic range is defined by this minimum level.

Figure 3. APEX radiometric specifications for minimum, validation and maximum at–sensor–radiances

A major figure of interest in the expected performance on an airborne imaging spectrometer is the signal–to–noise ratio (SNR). The signal is calculated using an end–to–end sensor model (DSS, 1997; Schaepman, 1998). This allows to determine the total number of electrons arriving per detector pixel based on the modelled at–sensor–radiance using the RTC. The final estimation of the noise is calculated using the manufacturer information of the detector and the electronic noise parameters. The SNR is then derived using the total number of electrons divided by the noise–contribution of electrons.

Figure 4. SNR for all APEX channels (maximum, validation and minimum level)

The initial specification requires a SNR of ≥ 100 for the average of all channels for each detector. In this model approach, the average SNR is listed in Table 1.

<table>
<thead>
<tr>
<th>Detector</th>
<th>SNR(Max)</th>
<th>SNR(Val)</th>
<th>SNR(Min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS</td>
<td>974</td>
<td>226</td>
<td>30</td>
</tr>
</tbody>
</table>
endeavours. ESA member states may apply for flight as well for EU campaigns and other international ESA flight campaigns. Secondly it is envisaged to offer it groups. In first priority the system will be deployed in national and local interested research and applications the system for international campaigns and projects, to by a joint Swiss-Belgian team. It is anticipated to offer phase the system is owned by ESA and will be operated an operational phase of approximately 5 years. For this testing of APEX, the system will be made available for after the successful development, laboratory and flight application specific analysis methods.

5.2 Operationalization
After a successful development phase of the APEX system, the experiment will be made available for an operational phase for a wide remote sensing community interested in hyperspectral imaging and beyond. During the realization phase of the APEX, assessments of the following points must be undertaken:

- definition of a concept for a reference mission
- definition of the costs associated for such a mission
- identification of potential customers
- planning of the APEX utilization phase

To a customer, the APEX will consist of the remote sensing project team. This team will be responsible for marketing the services and applications provided by APEX, manages all the missions, and provides the customer with all the data according to the requested processing level. The aircraft operator is responsible for items such as flight planning, clearances, flight execution, etc. The flight crew will consist of the aircraft pilot and an operator associated with the correct recording of the requested scenes and the proper operation of the instrument during data acquisition.

5.3 Exploitation
After the successful development, laboratory and flight testing of APEX, the system will be made available for an operational phase of approximately 5 years. For this phase the system is owned by ESA and will be operated by a joint Swiss-Belgian team. It is anticipated to offer the system for international campaigns and projects, to national and local interested research and applications groups. In first priority the system will be deployed in ESA flight campaigns. Secondly it is envisaged to offer it as well for EU campaigns and other international endeavours. ESA member states may apply for flight coverages, and since one important task will be the applications development for PRISM, call for individual proposals will be issued and evaluated against available funding.

Since many research issues in the understanding of imaging spectrometry and the appropriate processing of the data are still to be dealt with, research institutions are encouraged to answer to corresponding Announcements of Opportunities.

National bodies such as environmental protection agencies may place orders for flight testing APEX in their operations and applications development.

Data shall be made available under special agreements, taking account of the established data and pricing policies of ESA (with the exception of purely commercial operations) and the need for covering operational costs.

6. CONCLUSIONS AND OUTLOOK
With this ESA/ESTEC initiated pre phase A study for the definition of an airborne imaging spectrometer it has been shown that the development of a well calibrated and operational imaging spectrometer within Europe can be realized. The presented concept provides an integral view of the experiment, including the calibration and data handling. The operationality of the experiment relies not only on the sensors performance in terms of SNR and other measures but also on the access to the data and the availability of the instrument to the remote sensing community.

Given that APEX is realized, not only PRISM data can be calibrated but also parts of other (space and airborne) imaging spectrometers and multispectral scanners can be validated such as the ENVISAT–1 MERIS instrument, the NASA JPL’s AVIRIS, the EU’s DAIS, and other operational instruments.

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8. REFERENCES


