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Structure, Components, and Interfaces of the Airborne Prism Experiment (APEX) Processing and Archiving Facility

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Abstract—The product generation from hyperspectral sensor data has high requirements on the processing infrastructure, both hardware and software. The Airborne Prism Experiment (APEX) processing and archiving facility has been set up to provide for the automated generation of level-1 calibrated data and user-configurable on-demand product generation for higher processing levels. The system offers full reproducibility of user orders and processing parameters by employing a relational database. The flexible workflow software allows for the quick integration of novel algorithms or the definition of new processing sequences. Reprocessing of data is supported by the archiving approach. Configuration management based on the database enables the control over different versions of processing modules to be applied. The system is described with a focus on the APEX instrument; however, its generic design allows adaptation to other sensor systems.

Index Terms—Database systems, hyperspectral data calibration, on-demand processing, parallel processing, system architecture.

I. INTRODUCTION

Airborne and spaceborne hyperspectral imagers provide raster data with a high number of contiguous spectral bands [1], [2]. Every spatial cell contains a vector representing the electromagnetic spectrum reflected from objects due to interaction with solar irradiance. Given a sufficient spectral resolution, identification of materials with diagnostic spectral features is possible [3]. The ability to accurately detect specific narrow spectral features relies on precise knowledge about the position and spectral-response curve of the instrument channels [4]. The derivation of quantitative results from hyperspectral imagery requires the data to be spectrally, radiometrically, and spatially calibrated [2].

The airborne imaging spectrometer Airborne Prism Experiment (APEX) is a dispersive pushbroom system engineered to contribute to the preparation, calibration, validation, and simulation of future hyperspectral imaging space instruments and to understand the processes associated with air, water, and land at local and regional scale in support of global applications [5].

A detailed characterization of the APEX instrument must be carried out to achieve the required data quality [6]. The needed system parameters can be gathered by specific measurements carried out in the calibration home base (CHB) [7]. Data collected during the CHB phase are subjected to postprocessing and subsequently fed into the processing system for a sensor-model inversion, converting digital numbers to at sensor radiiances and applying corrections to achieve data uniformity [8].

System calibrations of the APEX instrument are slated to be carried out on a regular basis. The collected calibration data sets provide means for long-term system-performance analysis. Short-term changes of a limited set of instrument characteristics can also be observed by using the in-flight characterization (IFC) facility [5]. Recording IFC data at the start and end of each flight strip may be used to assess the stability of the instrument over shorter periods of time.

APEX offers configurable on-chip binning, enabling users to optimize signal-to-noise ratios (SNRs) for specific applications. The availability of binning and the changing instrument characteristics imply that every flight data set will be defined in a differing spectral space where the dimensions are given by the spectral bands.

A processing and archiving system must therefore be engineered to deal with the aforementioned instrument dynamics and the high volume of data typically produced by hyperspectral imagers. It furthermore acts as data source for the user, offering products at several processing levels via online order pages and on-demand processing facilities.

The nature of hyperspectral data cubes is well suited for parallel processing with spatial-domain partitioning being a logical approach [9]. The system architecture must therefore include the aspect of concurrence issues for all resources that may be accessed by several processes in parallel.

In this paper, we present the structure of the APEX processing and archiving facility (PAF), decomposed into storage and processing components and their internal and external interfaces. Decomposition has been recognized as a powerful
technique to handle complex systems in many areas of engineering and science [10]. It allows us to study the resulting components and their interactions in detail. Interfaces are used to provide external abstractions of components and define the communication between components.

A case study based on a limnology application (estimation of water constituents) illustrates the processing flexibility and the interactions of the system components and external entities via well-defined interfaces.

II. SYSTEM REQUIREMENTS

The requirements for the APEX PAF listed hereafter are the result of studies (APEX Phase B [11] and SPECTRA project [12]) previously carried out by the Remote Sensing Laboratories (RSL), Zurich.

A. Product-Level Support

Data pass through several well-defined stages during the processing from raw instrument data to end-user products. Data at these distinct stages are referred to as level-\(N\) data, where \(N\) is the number of the stage. The system must support these conceptual levels. Within the APEX project, levels are defined as follows [13].

<table>
<thead>
<tr>
<th>Level name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>level-0</td>
<td>Raw data as produced by the instrument (digital numbers).</td>
</tr>
<tr>
<td>level-1</td>
<td>Radiometrically, spectrally, and geometrically calibrated uniform data (radiances).</td>
</tr>
<tr>
<td>level-2</td>
<td>Surface-reflectance data: corrected for atmospheric and topographic influences.</td>
</tr>
<tr>
<td>level-3</td>
<td>Application-oriented products.</td>
</tr>
</tbody>
</table>

B. Archiving

Flight-scene and calibration data in their raw formats are the foundation of the data chain. Any higher level product can be reprocessed based on the raw input, and its archiving is thus compulsory. The archiving strategy for higher level products is based on a tradeoff between processing time and storage space required, influenced by the user demand of a certain level. Therefore, radiometrically corrected data (level-1) are archived, as they represent a base for higher level processing while an atmospherically corrected data cube will be processed on demand and may be deleted once downloaded by the user.

In this manner, the archiving strategy is defined for all product levels.

C. Web Access and User Transparency

On-demand processing of higher level data is supported by generalized interactive web product-order pages.

Such pages must be dynamically built to reflect the access and processing rights of the current user. Selection of available products must be possible in the domains of acquisition time, spatial position, and processing levels. The provision of georeferenced quicklook images supports the user during the selection process.

The specification of processing parameters must reflect the technical specification of the sensor in question, thus different configurations such as binning modes or calibrations must be handled transparently for the user.

Information on the previous orders of the current user and their status must be available.

D. Auxiliary Data Support

Auxiliary data include the following: 1) spectral vicarious calibration data, 2) meteorological information supporting atmospheric corrections, 3) digital surface models for orthorectification, and 4) miscellaneous in situ observations used for model building and validation, e.g., for limnology applications where suspended matter (\(sm\)) concentrations are used to model the contribution from particulate backscattering to infrared radiances prior to atmospheric correction.

E. Parallel Processing Capability

The typical data volume of hyperspectral image cubes puts high demands on the processing power. Parallel processing is a solution to deal with these needs and is expected to play a major role in future remote-sensing applications [9]. Parallelization relies on task and data decomposition patterns, producing parts that can be processed concurrently. Some processes for radiometric and geometric correction can be decomposed into highly independent subtasks [14]. In practice, a flight-campaign cube can be broken down into individual flight strips which themselves may be further decomposed into blocks of several frames or even single frames for low-level processing. The primary data will thus be independent; however, parallel processes will share additional processing parameters such as calibration parameters, and the system must be engineered to handle such concurrent resource access.

F. Reprocessing Functionality

On-demand processing enables users to define module parameters online, thus customizing their output product. In case of problems appearing in the delivered products, a full record of the order parameters must exist to allow a reprocessing of the data. The system must therefore keep track of all incoming user product orders, including all processing settings. This includes keeping track of module versions by configuration management of the system.

G. Flexible Higher Level Processing

Flexibility is required at higher processing levels to support the APEX platform in its role as a test bed for new algorithms and to allow the definition of application-specific processing step sequences [13].

This specifically requires a framework that assists the flexible concatenation of processing modules, thus allowing the following conditions: 1) the setup of special processing sequences such as for the retrieval of limnology parameters where standard atmospheric corrections may not be applicable [15]; and
Fig. 1. APEX PAF data-flow diagram.

2) the quick and easy integration of new processing modules provided by collaborating researchers and developers.

III. SYSTEM OVERVIEW

The APEX PAF is hosted by the Flemish Institute for Technological Research (VITO) in the APEX Operations Center (AOC) at Mol, Belgium [5].

The APEX PAF is defined as the combination of all hardware and software components and their interfaces required for handling and processing APEX imagery and its related data. This paper focuses mainly on the software part of the APEX PAF and the interaction of the system with the external entities in their function as data sources or sinks.

From a dataflow perspective, the three main functionalities of the APEX PAF are as follows: 1) the storage of system calibration measurements obtained at the beginning of every flight season and their subsequent processing to obtain calibration coefficients; 2) the storage of incoming raw flight data streams and according level-1 imagery after radiometric, geometric, and spectral calibration and; 3) the creation and distribution of higher level product data based on user orders.

Fig. 1 shows the data-flow diagram of the APEX PAF (ADFD). Dashed lines denote system boundaries; external entities are shown as rectangles, processes as circles, data sinks as two parallel horizontal lines, and data flows as uni- or bidirectional edges. The ADFD shows the structure of the PAF and the interaction of its components. As a general rule, a processing component must exist in between two data sinks, where external entities are also treated as data sinks. The process description defines the operations applied to the data during their transfer from one storage component to the next. Interaction between processing and storage components relies on defined interfaces.

The following three sections describe the following features: 1) the external entities to the APEX PAF and their interaction with the system based on well-defined interfaces, 2) the storage components, and 3) the processing components.

In order to ease the understanding of the entities and components within the following sections, please keep referring to the ADFD, which shows all described objects and their respective links. The reader may also wish to refer to the case study presented later in this paper, as it illustrates the interaction of the components in a succinct manner.

IV. EXTERNAL ENTITIES AND INTERFACES

A. APEX

Airborne Prism Experiment is a dispersive pushbroom system with 28° field of view. Two spectrometers cover the spectral range from 380–2500 nm, both having an across track resolution of 1000 pixels [5]. At a typical flying height of 3500 m above ground with an aircraft speed of 310 km/h and
a typical integration time of 22 ms, resulting pixel sampling intervals are 1.75 m across track and 2.45 m along track. Consecutive frames overlap by 33%. The unbinmed configuration offers 312 spectral bands in the visible and near-infrared (VNIR) and 199 bands in the short-wave infrared (SWIR).

Frame data plus housekeeping data are written as a binary stream to an onboard storage unit at a data rate of 50 MB/s [16]. Expected data volumes per flight campaign range around several hundred gigabytes. The inertial-navigation-system (INS) data stream consisting of attitude and global-positioning-system (GPS) data is recorded in parallel as a separate file. All data are transferred from the onboard storage to the AOC using tapes.

**B. CHB**

The CHB is located at DLR (German Aerospace Center) Oberpfaffenhofen, Germany. It comprises the hard- and software to carry out highly accurate and automated radiometric, geometric, and spectral characterizations of hyperspectral imaging sensors [17].

For geometric and spectral characterizations, the instrument is placed on columns above a granite workbench and adjusted to the axes of the bench. Collimated light beams originating from either monochromatic or panchromatic sources are reflected into the aperture of the instrument by a moveable tiltable folding mirror. Very precise computer-controlled positioning of the mirror allows subpixel illumination of single detector elements, yielding data for the construction of the pixel point spread function. Similarly, the spectral-response curve can be derived by subsequent measurements at changing monochromatic frequencies.

Radiometric calibration involves two integrating spheres of which one is used for absolute calibration against the German national standard and the other for relative measurements to derive the linearity of the instrument with changing irradiance levels.

The characterization process is managed by the Calibration Test Master (CTM) software which optimizes the time needed for calibration by automatic generation of optical stimuli [7]. The CTM interfaces APEX with both laboratory ground facilities, i.e., the CHB and an IFC. The instrumentation in both the CHB and the IFC can be controlled remotely via a computer interface, thus enabling automatic measurements. This results in a consistent reduction of the time spent for calibration; therefore, additional measurements can be performed in a way that the overall APEX calibration and characterization is substantially improved.

Data gained from measurements at the CHB consist of APEX raw data frames and CTM controller logs linking each frame to the settings of the CHB. APEX data thus flow into the CHB as indicated in the ADFD (see Fig. 1).

Data are transferred to the AOC on tapes. The expected data volume ranges from 100 to 200 GB.

**C. Campaign Metadata**

Campaign metadata, also called auxiliary data, encompass all data collected during a flight campaign not stemming from the APEX sensor system. In general, metadata support the broad and long-term use and interpretation of scientific data [18]. The storage of the auxiliary data linked with the APEX instrument data in the APEX PAF is of prime importance to preserve the scientific campaign context. APEX metadata support the calibration, validation, and analysis of image cubes. Examples are as follows: meteorological data, sunphotometer readings, ground-truth maps of land cover or land use, and physical and chemical in situ measurements (e.g., leaf area index measurements of vegetated areas or specific inherent optical properties of water bodies). Auxiliary data are entered by the means of separate electronic files.

Hyperspectral in situ measurements taken by spectroradiometers are part of the imagery metadata as well, e.g., subsurface reflectance measurements acquired with water spectroradiometers. However, spectral ground data are preferably stored in the SPECCHIO database [19] rather than just supplying spectral files as part of the campaign metadata.

**D. Applanix POS/AV 410**

The APEX instrument is equipped with an Applanix POS/AV 410 v4. GPS/INS system. Such a GPS/INS system enables for direct georeferencing of the acquired imagery and is now widely used in airborne remote sensing. Direct georeferencing allows us to directly relate the collected data to the Earth by accurately measuring the geographic position and orientation of the sensor without the use of traditional ground-based measurements.

The GPS/INS system is comprised of four main components: 1) an Inertial Measurement Unit (IMU), 2) a GPS receiver, 3) a POS computer system, and 4) a postprocessing software (PosPAC).

The IMU is rigidly mounted to the sensor’s mainframe, preventing variations in their relative position and orientation, and measures the sensor’s position and orientation at a 200-Hz data rate. The GPS receiver is integrated in the computer system and has a 1-Hz logging rate. The GPS antenna is placed on top of the aircraft. During a mission, the POS/AV computer system records the IMU and GPS data together with the recording time of each image line and stores it as part of the APEX raw data stream. Both are then synchronized to a common time scale, which typically is the GPS time.

**E. GPS Base Station Data**

Differential GPS data are provided from one or several base stations located at precisely surveyed positions. The base stations, also called reference stations, calculate differential corrections for their own location and time. The correction data are usually available in the receiver independent exchange format and are used for subsequent differential GPS correction of data recorded by the GPS receiver of the aircraft.

**F. DEM Data**

For the production of orthorectified products, the following external data layers are available in the image-processing workflows: 1) the EGM96 [20] geoid model, 2) user-supplied
light detection and ranging (LIDAR) DEMs in the WGS84 datum and in latitude/longitude or UTM (e.g., above Flanders, Belgium, a LIDAR DEM at a spatial resolution of 5 m and a vertical accuracy of 7 cm for areas covered with short grass or pavement and 20 cm for areas with complex vegetation is typically being used in support of the hyperspectral campaigns), 3) the Shuttle Radar Topography Mission (SRTM) [21] DEM at a spatial resolution of 90 m (to be used as fallback mechanism if no user-supplied LIDAR DEM is available), and 4) the NOAA “GLOBE” [22] global DEM at a spatial resolution of 1 km (used as fallback mechanism to determine the mean elevation over the area covered by the image in case no user-supplied LIDAR DEM is available and the SRTM DEM contains invalid or no data).

G. Operator

User-friendly man–machine interfaces are necessary to ease the tasks of the operators and to quickly diagnose the software and hardware problems. Currently, the operator can monitor the activity of all workflows (level-0 to level-1 archiving workflow and level-1 to level-2/3 processing workflow) through as follows: 1) a platform-independent Java application which allows on-site and off-site work-flow tuning and hardware system monitoring and 2) a WWW interface toward the product and processing database (PPDB) providing access to some essential database maintenance operations.

H. User

The major user-segment of the APEX instrument will be scientific/academic users active in the domain of fundamental low-level image processing, e.g., atmospheric correction, bidirectional reflectance distribution function (BRDF) correction, and sensor design or atmospheric modeling. For this type of users, the availability of level-1 data is essential for complete control over the level-1 to level-2 correction algorithms. To serve this user-segment, level-1 products will be the lowest level products available online.

A minor user-segment will be the academic, governmental, and commercial users active in higher level application development, e.g., land-use/cover or soil/water-quality mapping. In support of this user-segment, the processing workflow is capable of generating user-configurable level-2 products on demand.

Users interact with the APEX PAF via web page interfaces. These allow the search and selection of level-1 data (see Fig. 2), the specification of processing parameters for higher level processing, and the monitoring of product orders. Imagery from different sensors can be ordered at the same time. The web interface thus allows the user to select the processing options, e.g., bands for atmospheric-correction algorithms, dependent on the sensor type (see Fig. 3).

I. Spectroradiometer Data

Ground-based hyperspectral signatures are collected for the following reasons: 1) basic investigation of the relationship between physical or biochemical properties and the electromagnetic reflectance of objects and 2) calibration, validation, and simulation of remote-sensing imagery and its data products.

A thorough collection of metadata describing the sampling process and the surrounding environment enables long-term usability and data sharing between research groups [23], [24]. This is of high importance when acquiring spectral in situ data during a flight campaign as the imagery plus the auxiliary data will be disseminated to users lacking the intrinsic knowledge of the circumstances of data capture.
One example of metadata usage is the description of illumination and viewing geometry in support of spectrally directional measurements. Such data, usually acquired by a goniometer, can be used to analyze the anisotropic reflectance characteristics of objects and to retrieve the BRDF, which is fundamental to the correction of remotely sensed data [25].

The usage of native spectroradiometer data files is recommended, as they include a host of useful metadata that may be gleaned automatically for subsequent storage in a spectral database.

J. SPECCHIO System

SPECCHIO is a system designed to hold reference spectra and spectral campaign data obtained by spectroradiometers [26], [27]. It comprises two components: 1) a relational database schema and 2) a Java application for data input, maintenance, and output. The metadata model contains parameters relevant for long-term usage and data sharing.

SPECCHIO is available as a free online tool for users to test the system and exchange data (for more information refer to the SPECCHIO web site: www.specchio.ch).

The SPECCHIO database stores ground-based spectral signatures and their associated metadata in a relational database schema on a MySQL5 [28] database server. The data model implements the 34 dimensional metadata space defined by the parameters as listed in Hün et al. [26].

The normalization step carried out on the data model during engineering supports nonredundant data entries for group updates where one metadata dimension is set to a common value for several spectra [24].

The SPECCHIO application is implemented as a Java 2 [29] application which allows full flexibility on local file system operations. Being based on Java keeps the software operating system independent, which is of importance in a heterogeneous computing environment. The application, thus, runs on any platform with a Java virtual-machine installation and connects to the database via TCP/IP on a configurable port.

The main task of the software is to provide user interfaces and processing functionality for the input, editing, and output of spectral data. Data input is highly automated and includes the extraction of metadata from the data sources. This addresses the problem of users being deterred from entering their spectral collections due to overly complicated procedures [26]. Metadata editing is optimized by the concept of group updates where several spectra can be updated to refer to one metadata parameter value. Data retrieval is implemented by the interactive definition of constraints on metadata space dimensions. The space is thus projected to a subspace containing the queried data set [24].

K. Spectral Simulation Models

Measurements of a remote-sensing instrument can be interpreted to describe the radiative properties of the observed media (e.g., soil, vegetation, atmosphere) [24], [30]. Any quantitative interpretation of remote-sensing data relies on performing the inversion of a model. Models can be conceptual, empirical, or based on the mathematical representation of the physics underpinning radiation transfer as implemented into radiative-transfer (RT) models [31]. The last decades have seen significant advances in the development of RT models for the purpose of retrieving useful information from remote-sensing data in a number of application areas [30], [32]. RT models such as the leaf optical properties model PROSPECT [33], [34] and the Scattering by Arbitrarily Inclined Leaves (SAIL) canopy bidirectional reflectance model [35] have been developed to describe coupled processes that occur at leaf and canopy level, respectively, when light is intercepted by plant canopies. They have been widely used to interpret the reflectance in terms of vegetation biophysical characteristics [36]. SAIL, nowadays, exists in several versions, one of them being GeoSAIL, which is a combination of SAIL and a geometric model to simulate discontinuous canopies [37]. Another well-known RT model is forest light interaction model (FLIGHT) [38], being a 3-D ray-tracing model using Monte Carlo techniques for the RT within crown boundaries and deterministic ray tracing between the crowns and other canopy components. GeoSAIL and FLIGHT have recently been used to describe the canopy reflectance at scene level for subsequent estimation of forest-fire fuel properties [39]. As for applications in the domain of vegetation analysis, comparable models exist for water-constituent retrieval (e.g., modular inversion and processing scheme [40], [41]), atmosphere research (e.g., MODerate spectral resolution atmospheric TRANsmittance algorithm and computer model (MODTRANS) [42]), or land-surface processes description (e.g., PROcess oriented Modular EnvironmenT and Vegetation model (PROMET-V) [43]). Models have further been developed for correction of directional effects in remote-sensing data [44], [45], and a growing number of simulation models also account for BRDF effects (e.g., SAILH [36], [46]). Application-specific simulation models will be incorporated in the APEX PAF for the generation of spectral reference data for level-2 (e.g., BRDF corrected reflectance data) and level-3 product generation (e.g., plant biochemical distribution maps, inland water-constituent maps, etc.).

V. STORAGE COMPONENTS

A. Data Archive

The archiving hardware system is a dedicated cluster of about 30 dual-processor machines (3.2-GHz Intel XEON) and about 45 TB iSCSI Storage Area Network storage. The hard-disk arrays and the workstation nodes are interconnected via two 1-Gb/s iSCSI interfaces, and the partitions of the archive and user-order database system are managed through the Linux Logical Volume Management software, which allows for online reconfiguration of the storage capacity of the logical volume.

In contrast with satellite missions, where the data stream is usually continuous, airborne missions are carried out on a commercial basis, meaning that, for every airborne imaging mission, there is a client who is paying for the imaging mission. Therefore, it is rather difficult to determine the effective storage needs. Given the impressive data rate of 50 MB/s during data...
acquisition, it was chosen to only archive the raw and level-1 data. Higher level data will not be archived. However, all parameter settings used to generate the higher level product will be stored in the database system to ensure full product traceability.

B. PPDB

The PPDB is implemented as a relational database on a MySQL5 database server. It is the heart of the processing workflows, since it keeps track of all input and output settings needed by these workflows. It offers full traceability of users, image products, and image-product processing history. The database system uses a generic data model, which works with any airborne imaging sensor.

The PPDB is the single source for the dynamic building of the product-order web pages. It maintains the links to the archived products and contains information about the sensors, the product orders, and specific processing parameters. Furthermore, the software versions of processing modules can be tracked, offering the operator the choice to reprocess data with some different module version.

C. Spectral Reference Database

The spectral reference database is currently a conceptual component only that will be implemented along with higher level processing in the APEX PAF.

Certain higher level processing algorithms may need spectral reference data, e.g., identifying materials by spectral matching, tuning of models for subsequent inversion, BRDF corrections, or spectral albedo product generation. The database approach allows for the dynamic selection of data subsets based on metadata queries, e.g., relevant vegetation spectra of a given region describing a phenological state can be selected by applying a spatiotemporal constraint on the metadata space.

The data model of the spectral reference database is based on the SPECCHIO data model but is enhanced to support derived spectral information such as BRDF. However, the main reasons of separating the external SPECCHIO database from the internal reference database of the APEX PAF are as follows: 1) the provision of stable controlled data; 2) version control of the reference sets in order to enable reprocessing of data at a later stage; and 3) the preprocessing applied for increased performance of higher level processes.

The SPECCHIO database is highly dynamic in its content due to constant user interaction, resulting in added, changed, or deleted data sets. These dynamics are attenuated by the separation into two components connected by the spectral reference generator process controlling the data transfer.

Spectra are stored in SPECCHIO as vectors in spectral spaces defined by the channels of the capturing spectroradiometers. Application of reference data in algorithms processing hyperspectral imagery may necessitate a previous convolution to the bands of the imaging instrument. Such preprocessing can be handled by the spectral reference generator, resulting in reference sets optimized for direct application in algorithms while minimizing the storage space in the reference database.

D. Working Pool

Given the volume of the expected data stream, introducing parallelism is inevitable. Since the processing of hyperspectral imagery or photogrammetric camera images is very data intensive, it was decided to combine the task/data decomposition pattern in combination with a master/worker program structure pattern to implement concurrency [47].

Due to the large data volume, the Working Pool was implemented on file servers with fast internal disks configured in Redundant Arrays of Inexpensive Disks (RAID-0).

The processing workflow ensures system scalability by the concurrent handling of multiple masters. The masters are mutually independent subsystems by as follows: 1) allocation of a dedicated fileserver and thus of a dedicated working storage and 2) assignment of dedicated workers, who pull jobs from a specific master only and access the common working directory of the master.

E. FTP Account

Upon successful processing of a user order, the user is informed via the WWW interface about the status and file-transfer-protocol (FTP) download point. However, if huge data volumes have been ordered, the possibility exists to forward the data on external hard drive(s). New password-protected FTP accounts are created for every order, and only the authorized user may download the products within a limited timeframe.

VI. PROCESSING COMPONENTS

A. Product-Order Page Generation

The product-order web pages are created dynamically by reading the relevant information from the PPDB. Page creation is based on Java Server Pages technology and utilizes the Apache Struts framework [48].

The user can browse the level-1 image table of the PPDB using a WWW interface. Once a selection of images is made, the user can order the level-1 data or define custom level-2/3 processing actions on the selected images. The processing-order details are submitted back to the web server and subsequently handled by the order-creation process.

User-access control for both data and processing actions is implemented based on the role-based access control model [49].

B. Order Creation

Processing orders that have been defined via the WWW user interface are handled on the web server to generate new records in the relevant tables of the PPDB.

The master or masters of the processing workflow constantly check the database system for new incoming product orders and adjust their job queues accordingly to accommodate these new processing requests. Masters can be configured to only listen to orders submitted by certain users or user groups. The workers installed on the working nodes then pull jobs from the master queue and return the process return value to the master.
Fig. 4. Scheme of the Master/Worker pattern showing a cluster comprising one Master and two Worker nodes.

Orders are being served according to the “first-in–first-out” principle. However, operators have the possibility to change the priority of orders upon explicit user request via the Java Workflow Monitoring Application (see Fig. 4 and Section VI-C1 Workflow Manager).

C. Level 0–3 Processing

The level 0–3 processing is shown as one process in the ADFD; however, it comprises several different major processing subcomponents which are described hereafter.

1) Workflow Manager: The Workflow Manager implements the job-pulling model with respect to job scheduling (simplicity, fault tolerance, load balancing) according the Master/Worker and Task/Data Decomposition patterns [47]. Multi-threading or message-passing interface is not being used in the algorithmic components; the workflow is optimized for processing a large quantity of images instead of processing single images as fast as possible. This also keeps the algorithmic code as “simple” as possible to enhance cooperation with other scientific/academic groups [50].

Java is used to implement the Master/Worker workflows via message passing through reliable TCP/IP sockets. C++ is the preferred language for algorithmic components, but Fortran 77, Java, and IDL are also supported.

The master node maintains a job queue (see Fig. 4). Filling of the job queue can be triggered by new events in the file system, PPDB, or by other software components. The worker threads that carry out the actual processing run on the worker nodes and are controlled by worker handler threads running on the master (see Fig. 4). Master and worker nodes can be monitored and configured by a workflow monitoring and configuration application. The communication is handled via sockets with specific port numbers assigned to masters and workers, indicated by the numbered rectangles within the application/workstation entities in Fig. 4.

The worker nodes can be made to request jobs from a job queue at the moment they have got the central-processing-unit (CPU) power available to process another job. Job pulling has the following advantages over job-pushing software systems: 1) load balancing, 2) fault tolerance, and 3) simplicity [50].

Load balancing: The load on a workstation strongly depends on the characteristics of the images being analyzed. The computing load only becomes clear during the actual processing. Job pulling results in a load-balancing scheme that takes the CPU load of each workstation into account. In case of job pushing, this is significantly more complex: The component that sends the job has typically little information to determine the load of the workstation to which the job is pushed. Mechanisms that make the load information available to the supervisor are complex and will require third-party middleware software. Job pulling inherently allows these differences in CPU time to be taken into account. Furthermore, it automatically adapts to the computing power of the workstation.

Fault tolerance: Workstations that have crashed, e.g., due to Ethernet interface failures, are unable to request further jobs. Therefore, the load is automatically balanced over the remaining workstations that are operational. In case of job pushing, the supervisor needs a mechanism to determine whether workstations are operational or not.

Simplicity: In case of job pulling, no details of the CPU power of the different workstations or the types of jobs they are executing need to be known to the supervisor. Nor does the supervisor need to know which workstations it is supervising and whether they are operational or not.

2) Level 0–1: The level 0–1 processing takes level-0 data as input and generates a calibrated and uniform at sensor radiance cube, referred to as level 1. The correction scheme is derived from the inversion of the sensor model consisting of three distinct parts: 1) the optical model describing the optical aberrations; 2) the bad pixel model describing the resulting data loss, also dealing with saturation; and 3) the radiometric model that accounts for the transformation of at-sensor photon flux to recorded digital numbers [51].

Characterization data obtained in the CHB and postprocessed by the CTM, the so-called calibration cubes, are used for the parameterization of the inverse model. The PPDB holds the information to provide the correct calibration cube based on a timeline selection, i.e., CHB characterizations result in time slots where one specific calibration cube is valid for all flight data sets acquired during the cube’s slot.

Level-0–1 processing utilizes the Working Pool as source for the input files and destination for the output files. The Working Pool is instantiated and filled with the required data by the Workflow Manager prior to level-0–1 processing calls.

3) Level 2–3: The higher level processing workflow for hyperspectral data is normally a sequential procedure from raw imagery to rectified and calibrated imagery, further to surface reflectance data, and finally to products. The respective processing level definitions for APEX are “level 2” for surface reflectance or spectral albedo data and “level 3” for application-oriented products. Within the APEX PAF, an optimized workflow is foreseen which tries to avoid redundancies by organizing level 2/3 in a product-oriented modular system (see [13]).
Fig. 5. Level-2/3 processing scheme of APEX.

Fig. 5 shows an overview of the processing flow after level-1 processing up to final data product maps. The geometric processing is split in two parts—before starting with the level-2 processing, all pixels are indexed with their geographic location, and the DEM-related parameters are resampled to the raw-image geometry. The rectification step is done only on the final data products (i.e., level 3b) to avoid resampling artefacts and processing overhead. Spectral reference data are a crucial input to this processing chain and are used for both level-2 and level-3 processing steps.

MODTRAN [42] derived atmospheric lookup tables and well-prepared digital elevation models are the required main data sources for the atmospheric and topographic correction of the imagery.

Further inputs provided by the processing database system (PPDB) are required for most of the product generator modules, e.g., the tuning of respective models parameters, which are inverted for the parameters of interest.

### D. CTM Processor

The CTM consists of three main elements: 1) the controller, being the core unit of the CTM; 2) the storage unit, partly embedded in APEX and partly located on external storage units; and 3) the processor, which processes all the calibration data.

The CTM controller is embedded in the APEX instrument and sets up all the necessary parameters, i.e., APEX settings (e.g., integration time) and calibration facility settings (e.g., monochromator wavelength, integrating sphere intensity), for a particular calibration procedure (e.g., spectral calibration, radiometric calibration, geometric calibration) to be performed efficiently. Once the setting is completed, the calibration measurements take place, and the acquired data are saved on the storage unit as frames along with the corresponding metadata. Each frame has a spatial and a spectral dimension, where the size of the latter depends on the spectral band configuration, i.e., binning. The CTM processor is run inside the APEX PAF and processes the acquired frames by using dedicated algorithms. Depending on the calibration procedure, the CTM processor will generate one or more calibration layers, containing calibration parameters for each detector pixel with VNIR and SWIR channels handled separately. Examples of parameters are as follows: center wavelength or full-width at half-maximum. Stacking all the calibration layers per detector results in a calibration cube per channel (VNIR and SWIR) (see Fig. 6).

In order to distinguish between external calibration sources, i.e., the CHB, and internal calibration sources, i.e., the IFC, separate VNIR and SWIR calibration cubes are generated per source.

The calibration cubes are used to parameterize the inverse sensor model during the level-0–1 processing, calibrating the acquired scenes and correcting for artifacts and nonuniformities.
TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy (RMS)</th>
<th>POS/AV 410</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position (m)</td>
<td>0.05 – 0.30</td>
<td></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Roll and Pitch</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>Heading (deg)</td>
<td>0.015</td>
<td></td>
</tr>
</tbody>
</table>

E. Archiving Workflow

The archiving workflow stores the original data as a base for reprocessing, triggers the level-0–1 processing of the incoming sensor data stream augmented by positional data, and subsequently produces self-descriptive level-1 image files. These Hierarchical Data Format (HDF5) files contain all relevant metadata besides the lossless compressed image data, such as the following: sensor interior orientation, sensor exterior orientation as measured by the sensor-integrated GPS and IMU, boresight angles (offset angles between IMU and sensor reference frames), raw and/or DGPS-corrected IMU time series, sensor spectral-response curves, and orthorectified quick-looks. The production of self-descriptive level-1 files delivers a starting point for level-2/3 product generation.

The PPDB is updated by the archiving workflow in order to list the newly archived level-1 file in the product-order web interface accordingly.

F. PosPAC

The PosPAC [52] software is used for the postprocessing of GPS/INS data. The procedure is semiautomatic and requires operator interaction, mainly for the acquisition and selection of the optimal GPS Base Station data, as data quality of base stations can differ due to the satellite geometry, an effect termed position dilution of precision. The processing typically commences with the differential correction of the aircraft-recorded GPS data with Base Station GPS data. The differentially corrected GPS data are then integrated with the raw measurements of the IMU system. Together with the synchronized recording times of the APEX sensor, this yields the exterior orientation parameters of every image line in the Earth-centered Earth-fixed reference frame of GPS. These data are stored in smoothed best estimated trajectory files and are used for georeferencing of the APEX imagery in the level-2 processing chain.

With good mission planning and proper flight operations, together with good multiple base station GPS data, the APEX POS/AV system should be able to provide absolute accuracies after postprocessing as listed in Table I [53].

Thus, APEX data can be corrected up to (sub)pixel-level accuracies for the common ground resolutions of 2–5 m.

G. DEM Feed

The DEM Feed process loads new DEMs to the archive. The reference to the physical storage location of DEMs and their spatial extent is stored in a dedicated table in the PPDB. This DEM information is subsequently used during the order page creation, giving the user the choice of selecting the most appropriate DEM for topographic corrections.

H. Spectral Reference Generator

The spectral reference generator is currently a conceptual component only that will be implemented along with higher level processing in the APEX PAF.

The spectral reference generator will handle data input into the spectral reference database. It will implement the following features: 1) control mechanisms that create stable reference data sets; 2) version control of data sets by tagging, thus enabling reprocessing; and 3) transformations, such as sensor convolutions, to be applied to raw measurements or modeled data for direct usage in higher level processing algorithms.

I. Operation Control

The main operation monitoring and control is being served by a lightweight platform-independent Java “monitoring tool” which can communicate with all running workers and the master(s) on a subnet over a TCP/IP socket. This software module is intended to present the workflow operator with a quick overview of the workflow status and offer tuning of the worker load by increasing or decreasing the number of active threads and changing of the master-order-queue priority. The Nagios host and service monitoring software [54] is being used for hardware system monitoring.

VII. CASE STUDY

The sequence of processing steps and the interaction of the external entities and system components is demonstrated hereafter on the example of a limnology study. To illustrate the possible performance of such processing, the case study is concluded by an example of processing metrics.

Specialized higher level processing is used to estimate water constituents like chlorophyll a (chl-a), sm, and gelbstoff (y) [40].

Water bodies are some of the darkest natural targets. This implies that the sensor must deliver high SNR and be well calibrated: 1) Both SNR and radiances tend to be low in the 400–500-nm wavelengths, which are important for separating chl-a and y contributions to the spectrum; and 2) the near-infrared channels (800–900 nm) exhibit low readings over water bodies but are essential for the separation of atmospheric and aquatic backscattering, which is in turn needed for an adequate atmospheric correction. Thus, successful retrieval of atmospheric influences on the spectra depends on accurate sensor calibrations.

APEX is therefore shipped to the CHB at the start of every flight season and characterized over a time period of several days. The CHB data are then transferred to the AOC where the archiving workflow ensures the archiving of the raw data, the generation of the calibration cubes by the CTM process, and the update of the PPDB. All data acquired after this instrument calibration on the CHB will make use of the respective calibration cubes during the level-0–1 processing.

The first flight campaign of the season is timed for the peak of the yearly spring algae bloom. APEX is programmed to a special binning pattern that optimizes the SNR in the blue
wavelengths, and data are acquired over a freshwater lake to support a study on the spatial dynamics of the algae-bloom phenomenon. Data are delivered to the AOC on tape, read to a hard disk in the processing system, and augmented by base-station-corrected positional data using the PosPAC system and by the correct instrument calibration cubes, which are used by the subsequent level-0–1 processing. Placing the data in a special input directory automatically triggers the archiving workflow, which in turn archives the raw input data, registers the new raw imagery in the PPDB, starts the level-0–1 processing, archives the level-1 product, and updates the PPDB with the newly created product information.

The customer now has the ability to order level-1 or higher level products via the web order page. Depending on the desired level-3 product, standard level-2 processing may not apply. This is the case for the limnology example where a physically based algorithm for inland water-constituent retrieval applies a specialized algorithm for atmospheric correction, requiring an initial value of \( \text{sm} \) concentration. The aerosol optical thickness (AOT) used for the correction can then be estimated, as the nonatmospheric signal over water is attributed to backscattering from particulate matter.

The user is given the choice of different processing modules to be applied to the data and thus can directly select the water-constituent retrieval algorithm. A further choice may be the geometric rectification, which is applied at the very end of the processing chain. After confirming the processing settings, a new product order with all the specified parameters is inserted into the PPDB. The workflow, continually polling the database for new orders, schedules the processing, and the working nodes carry out the actual computation. Meanwhile, the web site reflects the current status of the processing and thus makes the progress visible to the user. The final result consists of maps for \( \text{chl-a} \), \( \text{sm} \), \( y \), and AOT. These are transferred to a new FTP account, and an e-mail is sent to the user, specifying the download point and access details.

As real APEX data were not yet available at the time of writing, a more generic example of the processing steps and execution times is presented hereafter. Table II gives an overview of the processing metrics for a typical hyperspectral image (Hymap sensor data with 126 spectral bands and 2595 scan lines). Processing was carried out on a subcluster (one Master and three Worker nodes) within a workflow at full load, i.e., the processing of this image cube was part of a multiimage level-1–2 product processing order. Processing time of the subcluster was around a fifth of total processing time of the three dual-processor machines.

### VIII. Discussion

The processing system described in this paper has been elaborated in the context of the APEX sensor; however, the underlying conceptual structure is very generic, and VITO has demonstrated that other sensors can be accommodated with little effort. However, APEX may be seen as the current biggest challenge to the system, as first, it introduces large image data volumes in comparison to most other hyperspectral sensors due to the increased number of bands, and second, the available instrument characterization data are of unprecedented detail and, consequently, need large storage spaces.

The APEX PAF introduces on-demand higher level processing with user-configurable module options. This offers the chance to use the high-performance computing environment at VITO to carry out computing intensive tasks, thus benefiting the users in terms of product generation time. It must however be stated that standard processing of sensitive and complex algorithms, such as atmospheric corrections, may currently not match the results that could be achieved by time- and man-power-consuming optimization of the module parameters. However, for nonacademic users, such standard products may already be sufficient in terms of accuracy.

The full reprocessing capability supports the application of improved processing modules to previously acquired and processed data. For example, a new version of the CTM may create calibration cubes of greater accuracy, thus necessitating a reprocessing of the original CHB data stream followed by the new processing modules available in the updated PAF.
by level-0–1 reprocessing of the related image cubes. This feature may prove useful as APEX is intended to be a scientific platform, thus new processing modules will become available over time with existing data being able to gain value by reprocessing.

The inclusion of algorithms into the processing chain depends on their degree of operationalization. Modules requiring heavy operator interaction are not suited for the on-demand product-generation approach. An example is the utilization of limnology process output for subsequent derivation of bathymetry maps. Such a method carries out a water-body correction to generate bottom reflectance [55]; however, manual interaction with an experienced operator is still needed at this point of time, rendering it unsuitable for inclusion in the workflow.

The rapid inclusion of new algorithms into the APEX PAF is an important requirement in order to support experimental processing. A standardized parameter interface is therefore essential. Algorithms are configured by Extensible Markup Language (XML)/XML Schema Definition (XSD) pairs within the workflow. The XSD defines the general scheme of all required and optional algorithm configuration parameters per algorithm. The default parameters for every algorithm and sensor type are stored in the PPDB. These defaults are used to present the operator/user an initialized GUI when defining level-1–2/3/4 processing orders. The operator/user processing settings are stored in the PPDB, and it is the responsibility of the workflow job-queue configuration software to create valid XML configuration files for every elementary processing job (i.e., setting defaults, setting user-specified parameters, definition of the actual file paths toward input maps, intermediate maps, and output maps). Thus, any new algorithm can be easily incorporated into the APEX PAF as long as a configuration via XML file is possible. XML configuration can be achieved for virtually any algorithm by using a wrapper object that translates XML parameters to internal algorithm calling syntax.

The VITO experimental processing cluster for airborne remote sensing currently contains about 40 dual-processor nodes (Intel XEON 3.2-GHz CPUs). To ensure scalability, the overall workflow system allows for multiple Master nodes and can thus be seen as a cluster of subclusters. Typically, to balance the disk I/O load, about ten Worker CPUs are assigned to a Master. The Master and Worker nodes share their own RAID-0 configured Working Pool. Masters can be configured to pull only orders from the database submitted by specific users or user groups or take only specific job types. Thus, a very flexible system can be set up, allowing for ad hoc reconfiguration according the mission and user requirements.

IX. CONCLUSION

The APEX PAF is a highly flexible system that caters for the requirements of a dedicated hyperspectral processing system, namely, as follows: 1) the handling and application of detailed system calibration parameters needed for the production of spectrally, radiometrically, and spatially well-calibrated image products; 2) scalability and parallel-processing capability through the master–worker pattern; 3) flexible definition of higher level processing steps for the easy integration of specialized processing modules; 4) product and order traceability ensured by a data model implemented in a relational database; 5) product reprocessing with different version of algorithmic components; and 6) on-demand processing and user-configurable module parameters via a web interface.

The main advancements in the field of remote-sensing imagery processing chains are as follows: 1) the provision of a highly flexible generic system that can be easily adapted to new sensors and that supports scientific experimentation within an operational setting; and 2) a level-0–1 processor creating uniform data by accounting for subpixel (frown/smile) distortions based on high-accuracy instrument-characterization data.

The APEX Science Center at the RSL in Zurich, Switzerland, is interested in collaborating with researchers who would like to test their hyperspectral algorithms on APEX data. Scientists are also invited to contribute working algorithms to be operationalized at the APEX Operation Center at VITO, Mol, Belgium.

REFERENCES


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