OPTIMIZED WORKFLOW FOR APEX LEVEL 2/3 PROCESSING

Daniel Schläpfer[1], Jens Nieke[1], Francesco Dell'Endice[1], Andreas Hüni[1], Jan Biesemans[2], Koen Meuleman[2], and Klaus I. Itten[1]

1. University of Zürich, Dept. of Geography, RSL, Zürich, Switzerland; dschlapf@geo.unizh.ch
2. VITO, Mol, Belgium; jan.biesemans@vito.be

ABSTRACT

Hyperspectral instruments such as the Airborne Prism Experiment (APEX) require optimized workflows for higher level data processing. In this paper, a strictly sequential workflow is compared to a workflow which reduces redundancies throughout the processing chain. The new workflow is designed in a product-oriented way. Major modules from all hyperspectral applications are described and put in a logical structure, and implementation principles for optimized interaction between various processing modules are depicted. As various experts are expected to provide algorithms for APEX data processing, implementation rules are provided for easy integration of contributed products and processor modules. Further options of processor optimization are compiled in an overview. Finally, a short analysis on the basis of an example data set shows radiometric impacts on data dynamics and data loss if the standard workflow is compared to the optimized workflow, which is based on raw geometry. The results show significant improvements in both speed and accuracy oand provide a valid basis for future processor development.

INTRODUCTION

The processing of airborne imaging spectroscopy data towards consistent end user products is a challenging task. Complete processing systems are well known from modern satellite remote sensing instruments such as MODIS (1) or MERIS(2) but they are not yet common for hyperspectral imagers. As hyperspectral data become available on a regular basis, standardized processing has become more important and helps to increase the value of such systems significantly.

A strict discrimination between level 2 preprocessing (i.e. atmospheric and geometric correction) and level 3 product generation is hardly feasible in an optimized workflow. The specific end products often require customized preprocessing. Therefore, an optimized workflow is to be implemented for the upcoming Airborne Prism Experiment APEX (3). Such a process shall combine both level 2 and level 3 processing steps. Optimization is done with respect to maximum radiometric accuracy, open interfaces for application developers, and fastest possible processing time.

The first goal of optimization is encompassed by defining synergies between the various processing steps to avoid redundancies. Herewith, radiometric problems through multiple resampling and inappropriate preprocessing are avoided. The complete product processing workflow is defined based on the expected end products. Basic processing modules are then identified as a core of the level 2/3 processor. Such modules are, e.g., spectral classification, atmospheric correction, BRDF correction, or DEM preprocessing. The requirements for those modules have to be compiled such that they become usable in a synergetic way throughout the whole processing chain.

On a second level of optimization, boundary conditions for the creation of modules as part of the processing chain are described. They define the structure, interfacing rules, as well as restrictions for modules to be included in the processing system. The rules are given on low level of sophistication in order to allow a heterogeneous community of researchers to contribute to the system. Such an open layout should provide optimal extendibility of the higher level processor. Furthermore, it potentially allows also processing of other sensor data once the interfaces are adapted.

The third goal of optimization is high processing speed without sacrifying radiometric accuracy. Improved speed is (partially) achieved by reducing the amount of data to be processed. This can be done by working in raw scan geometry and shifting the spatial resampling (i.e., the geometric rectification) step to the very end of the process. Thus, radiometric consistency is optimized by avoiding any spatial resampling. Some analyses that judge the impacts of this change in workflow on the quality of the results are shown later in this paper. For that purpose, the implications of atmospheric processing on raw geometry in comparison to resampled geometry are evaluated on an example data set.

The presented system shall be implemented as part of the APEX science centre (4) in the course of the first years of APEX operation and will allow a wide variety of standard data products. The experimental Central Data Processing Centre (CDPC) as described in this proceedings (5) is worked out according to this principle. The CDPC shall be the base system for operational implementation of the APEX processing and archiving facility (PAF) and any higher level APEX processor modules.

BASIC PROCESSING WORKFLOW

The traditional hyperspectral processing workflow is a sequential procedure from raw imagery to rectified and calibrated imagery, further to surface reflectance data and finally to products. This led to the respective processing level definitions for APEX; i.e., level 0: raw data, level 1: calibrated radiance data, level 2: surface reflectance data, and Level 3: application oriented products. This structure has the obvious disadvantage that the same data set has to be processed multiple times for each of the levels. An optimized workflow tries to avoid redundancies by organizing level 0/1 and level2/3 in slightly different ways as depicted in Figure 1.

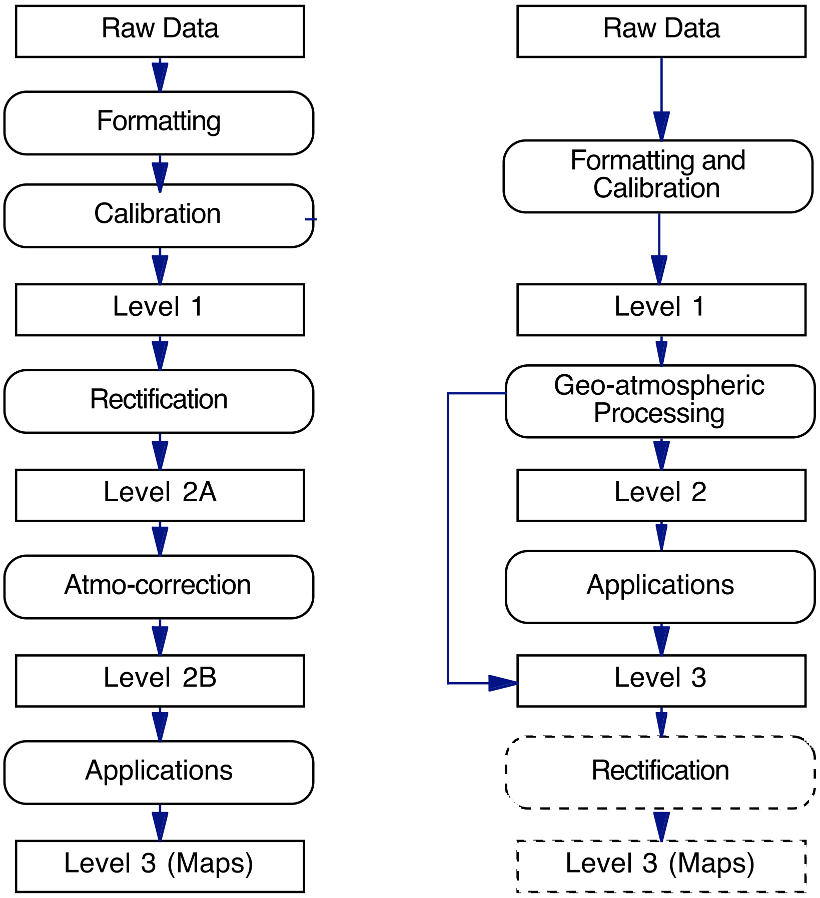

Figure 1 Workflow and level definitions as used in this paper. Left: standard workflow; right: optimized workflow.

The major differences between the standard workflow and the proposed optimized workflow are:

- formatting and specifically the calibration is done in one processing step on a frame-by-frame basis(6, 7),
- geometric and atmospheric correction are closely linked to each other for pixel-wise geometric inputs to radiometric processes (8, 9),
- side outputs of atmospheric correction procedure such as albedo products are Level 3 outputs by themselves and do not need any further optimization, and
- scientific parameters ('applications') are calculated from uniform but unrectified radiometrically corrected imagery.

The rectification step includes a resampling to map geometry. It inherently involves potential data loss and modification due to interpolations routines. Therefore, this step is shifted to the very end of the processing (see below for an analysis of the effects). For the APEX case, it is planned to deliver unrectified imagery and to provide means for data browsing and resampling of the data to the end user. Further analysis on the radiometric impact of this workflow is given later in this paper.

THE APEX LEVEL 2/3 PROCESSOR

The APEX higher level processor (level 2/3) has been designed after identifying the expected products of a hyperspectral instruments. Thereafter, logical relationships which lead to these variety of products have been drawn, leading to a complete workflow layout. Figure 2 gives an overview of the processing system.

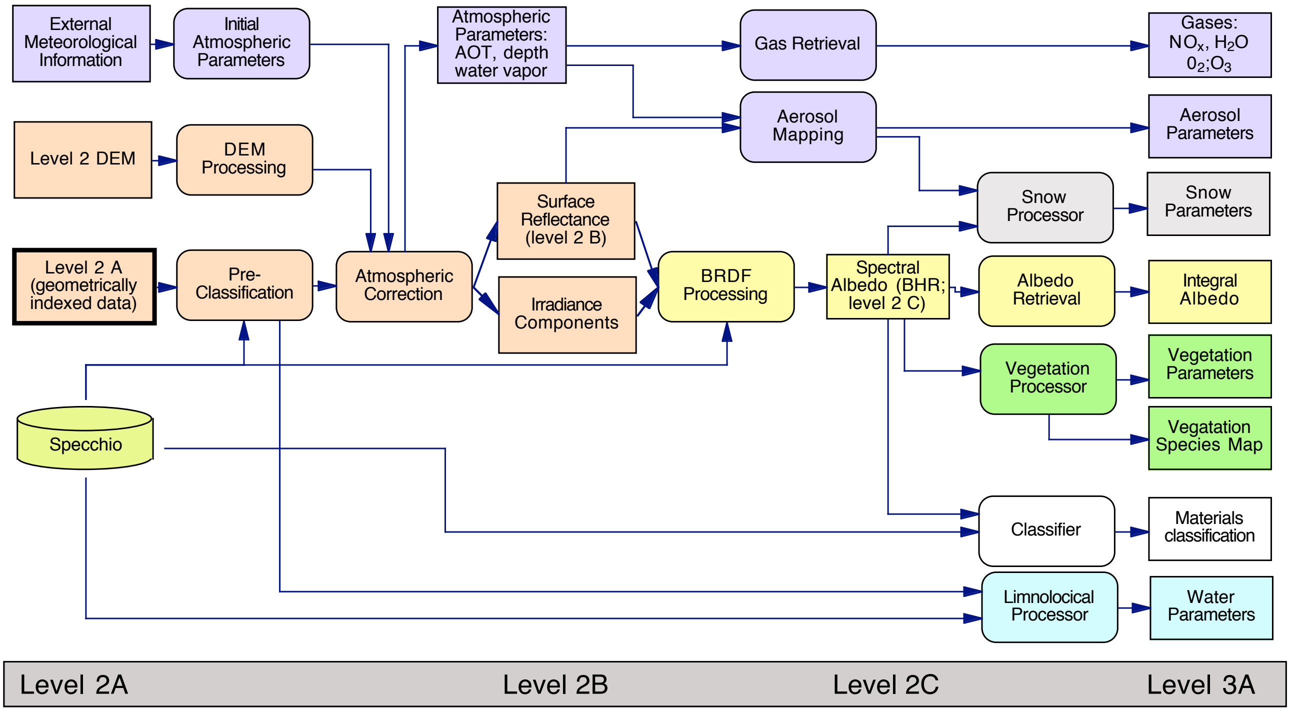

Figure 2: APEX Level 2/3 processor overview flowchart.

The following details have to be considered for the implementation of this workflow:

- For atmospheric and limnological processing and parameter retrieval, the calibrated at-sensor radiance data is required as input.
- Pre-classification is required for atmospheric correction (i.e., water/land) but also for the selection of the products to be produced.

- Surface spectral albedo data are a precondition for accurate classification. A robust BRDF correction is therefore an important tool for a complete processing system.
- The DEM needs to be processed for optimal radiometric representation of a scene, which leads to at least two version of the DEM. At the same step, the DEM is resampled to acquisition geometry.
- The resampling to cartographic geometry is the last step to be performed on the imagery - all processing as depicted in Figure 2 is done in the original geometry.
- Archiving of the products is done in a multi-purpose operations centre (i.e., the CDPC for APEX; 5).

The following major modules are identified for the whole Level 2/3 processor (cf. the colour coding in Figure 2).

Atmospheric Correction

Atmospheric and topographic correction modules produce surface reflectance outputs valid for the effective observation geometry and illumination conditions only (9). This quantity is by its nature a weighted mixture between bidirectional and hemispherical-directional reflectance (10) and thus it is related to the relation between direct and diffuse irradiance, respectively. Subsequent correction for the BRDF effects or angle-dependent processing is therefore required for further analyses of non-Lambertian objects.

An optimal correction requires a pre-classification to distinguish between water/dark objects and land/bright objects. This classification is used for aerosol and water vapour retrieval algorithms. Furthermore, the DEM needs to be prepared appropriately, such that it represents the radiometrically relevant surface. Side outputs of the atmospheric correction are the retrieved water vapour map and the used estimate of aerosol content. Atmospheric correction has to be done iteratively for correction of adjacency effects and for the inclusion of atmospheric parameter estimates. However, not more than 1-2 iterations are expected.

Atmospheric Parameter Retrieval

Atmospheric aerosol and gas distributions are retrievable from radiometrically calibrated imagery (11, 12). An iteration of the parameter retrieval with the atmospheric correction increases the accuracy of the retrieval and also improves the surface reflectance product. Initial parameters based on external radio-soundings can be used to minimize the uncertainty of aerosol retrieval by describing the current status of the atmosphere (pressure, temperature, humidity, and planetary boundary layer height). The surface reflectance output from the atmospheric correction step is then used as input for spatial aerosol parameter retrieval.

Further data from (e.g.) sun-photometers or AERONET (13) could be used to calibrate and validate the aerosol retrieval, although on a rather scientific than operational basis. The outputs of the atmospheric correction procedure are an essential input for high accuracy parameter retrieval. These parameters would finally allow for a second order atmospheric correction in the iterative feed-back loop as mentioned above.

Spectral Database and BRDF Processing

The spectral database SPECCHIO (14) is a repository for spectral field campaign and reference signatures. Spectral data sets can be built by queries in metadata space. These sets are consequently used for (e.g.) the creation of spatiotemporal optimized classifiers, thus assisting the classification of natural and man-made materials.

The BRDF correction utilizes models and data sets typical for the various classes appearing in the imagery. According directional dependent data sets are supplied by the spectral database. The correction scheme then corrects for the relation of the effectively measured directional reflection to a completely hemispherical reflection (15). Such correction requires a selection of BRDF types on the basis of a classification of the surface reflectance data. This process leads to a bihemispherical spectral reflectance (10) for each pixel, i.e., to the spectral albedo. This object property is well suited for most algorithms working directly on individual spectra since no directional dependency is left after correction.

Classification

For urban and geological sites, classification schemes need to be developed which make optimal use of APEX data. Methods like the USGS Tetracorder (16), the MESMA approach (17), but also standard methods such as the spectral angle mapper are well suited to be used for classification of large areas. Their consistent usage requires corrected spectral albedo products as an input in conjunction with radiometrically compatible reference spectra from the spectral database SPECCHIO. A classifier optimized for the European environment will be validated and implemented as part of the processing chain. Note that another pre-classification is done on at-sensor radiance data at the very beginning of the processing chain and will only provide rough classes such as water, cast shadows, and forests as output-masks.

Limnology Processor

This processor uses at-sensor radiance in a water-related atmospheric correction procedure, which resolves the atmospheric contribution, air-water interface effects and the sub-surface water reflectance. Within this procedure, sunglitter, adjacency effects and bi-directionality of the underwater light field are corrected. The resulting sub-surface water reflectance is based exclusively on inherent optical properties (IOPs) and bottom albedo, where applicable.

The retrieval of water constituents (chlorophyll-a, yellow substance, suspended sediments) from sub-surface water reflectance is achieved by an iterative fitting algorithm, which adjusts measurement-derived and modeled underwater reflectances. In shallow water, bottom properties such as substrate type, vegetation density or water depth are derived additionally. The algorithms used are part of the Modular Inversion & Processing System (MIP) (18). This processing is independent from additional ground truth measurements since it is based on the inversion of consistent physical models.

Vegetation Processor

The vegetation processor contains two major modules. The first module is based on physical-based radiative transfer models to retrieve quantitative estimates of biochemical and biophysical canopy parameters. Coupled radiative transfer models on the leaf and canopy level inverted against measured canopy reflectance are able to retrieve vegetation parameters such as LAI (Leaf Area Index), fPAR (fraction of Photosynthetic Active Radiation) and leaf biochemistry. The module will be specific for different vegetation types and provides an empirical backup algorithm similar to the MODIS LAI/fPAR product (19) if the physical-based retrieval fails.

A second module strives to discriminate the vegetated land surface into plant functional types and further into dominant plant species distribution if possible (20). The module will make use of the improved spectral information content provided by APEX relatively to a comprehensive spectral database in order to discriminate effectively between vegetation species. As such, it's a subprocess to the generic classification module.

Snow Processor

Recently an approach to retrieve snow physical parameters was successfully applied to multispectral sensors GLI and MODIS (21) and will be adapted for APEX higher level products: To relate the reflectance of snow to its physical properties such as grain size and snow impurities, radiative transfer can be used to simulate at-sensor radiances of APEX as a function of the snow grain size between 50 and 2000 µm and the mass fraction of soot ranging from 0.02 to 2.5 ppmw (parts per million by weight). Taking also into account dependencies of the radiances on the observation geometry (solar zenith angle, sensor view angle, and relative azimuth angle between the sun and the sensor) and different aerosol models, look-up tables (LUT) for retrieving the appropriate grain size and soot are created. An inversion enables the best "fit" of the measured quantities to the precalculated LUT.

IMPLEMENTATION RULES FOR APEX SCIENCE PRODUCTS DEVELOPERS

APEX data products are implemented as Level 3 processing modules in the APEX PAF. Such modules shall be easy manageable within the whole processing system and should adhere to a minimum standard for interoperability and processing workflow optimization. The resulting minimum requirements are as follows:

- the software code/binary runs in a Linux/Unix environment,
- the module is callable from an Unix prompt – e.g., by a shell script wrapper,
- the algorithm in its standard form does not access a graphical user interface. Routines which may be used with or without GUI (e.g., by setting a flag) are also acceptable,
- the module may invoke sub-processes in different language environments,
- the software is documented with a README file describing all arguments and parameters and containing a link to algorithm description. The description may also be a part of the shell script header, and
- input and output files adhere to the ENVI file format standards.

Product modules reach an operational status after thorough testing within a research environment. They must fulfil the following additional technical requirements:

- the module returns a well defined exit status,
- it creates a log file, which contains processing log and error messages,
- the processing time for one scene is below 3 hours,
- the software makes use of the APEX PAF internal data structure,
- the source code (and all internal parameters) is well documented and written in a modular design,
- the caller program (shell script) contains a header which is automatically parsable by the PAF, and
- an user manual in PDF or Tex format is provided, including the description of the algorithm(s).

Such algorithms are finally to be published in recognised journals or conference proceedings and can thus be referenced by the APEX science group and data users.

Recommendations to Developers

Principally, developers are free in using any kind of environment for development of scientific algorithms. The following recommendations shall help to ease the integration of the algorithms in the APEX chain.

Developers are encouraged to use standard languages for the development. The default development environment for the APEX PAF is IDL (ITT Corp.). Other recommended languages are standard C, C++, and TCL/TK. Dedicated libraries for APEX data i/o, processing, and storage can be provided to developers upon request.

Input and output files shall be based on the ENVI (ITT Corp.) file formats which have been established as one de-facto standard for hyperspectral data and are supported by many third party software packages. The raw processor interface shall be separated from potential graphical user interfaces. This is necessary for easy integration of the processing module into the APEX PAF.

A module ready for integration basically should contain the code and a compiled software version which is executable on a Linux 64bit operating system. A 'Readme'-file describing the code, its usage, and applicable references (this may also be a part of the Unix script header) together with an unix wrapper to the code are further parts of a complete package.

PROCESSOR OPTIMIZATION

The processor can be enhanced and improved in various ways. Hereafter, some aspects are mentioned which certainly need further elaboration if they are to be included in the processing system.

Splitting the data in spectral subgroups (e.g., water/vegetation) may help to economize on processing time. Also, varying spectral binning patterns may be required for the modules. It is recommendable to do any spectral splitting or binning within the methods in order to avoid a multiplication of the original data.

Spatial binning is an option to increase SNR which is specifically suited for the retrieval of aerosol or water constituents. Here, the binning may be applied to distance as much as 100 meters. The intermediate binned products are not to be stored as long as the procedure is well defined and intermediate binning processes are logged.

One should think on how to integrate the products into local or global physical models (which is not yet foreseen in the processing workflow). This will lead to better validation and higher versatility of the products for non-scientific end users. In the same context, automatic validation of the products would be of interest. However, this is hardly feasible in an operational system since it requires the identification of suited samples for validation.

Multi-temporal processing is currently not included in this scheme but would be of interest for creation of time series. A meta-module would be required to perform such analyses which typically pulls together the information from various sequential flight campaigns.

EVALUATION RESULTS

As a preliminary evaluation, parts of the processing workflow for Level 2/3 are tested using data from the HYMAP sensor system, acquired in Vordemwald Switzerland, 2004 (22). The data was calibrated to level 1 by the data provider. Geocoding is done using the PARGE application to an accuracy of 1 pixel RMSE (8). Subsequently, relevant quality criteria for level 2/3 are identified and quantified.

The potential data loss and its related loss in data dynamics are quantified on the atmospherically corrected data. The relative deviation from original data is calculated by subtracting the results from the two workflows in original geometry and dividing by the optimal value in each pixel *i* such that:

$$\Delta\rho_{Loss,i} = \frac{\left|\rho_{std,i} - \rho_{opt,i}\right|}{\rho_{opt,i}} * 100\% \,, \tag{1}$$

where $\rho_{std,i}$ is the result from standard workflow, back-transformed to raw geometry using the nearest neighbour technique. $\rho_{opt,i}$ are the reflectances after atmospheric correction in raw geometry. The standard deviation of the values $\Delta\rho_{Loss,i}$ serves as quality parameter for the deviation between raw-geometry based atmospheric correction and the processing of resampled data. For the example data set it was found to be 6.4% for nearest neighbour resampling and 11.8% for bilinear interpolation in the rectification process. Note that the relatively high values stem from spatial mis-registration due to the applied resampling steps and are not radiometric errors in a strict sense. Consequently, the mean of this value is close to zero for both resampling methods. The spatial distribution of these differences for the example data set is given in Figure 3. High variations are appearing for the bilinear resampling case along spatial patterns of the image, whereas the variations for nearest neighbour resampling are mainly due to the box-based spatial filtering required for adjacency correction of the image in the atmospheric correction step.

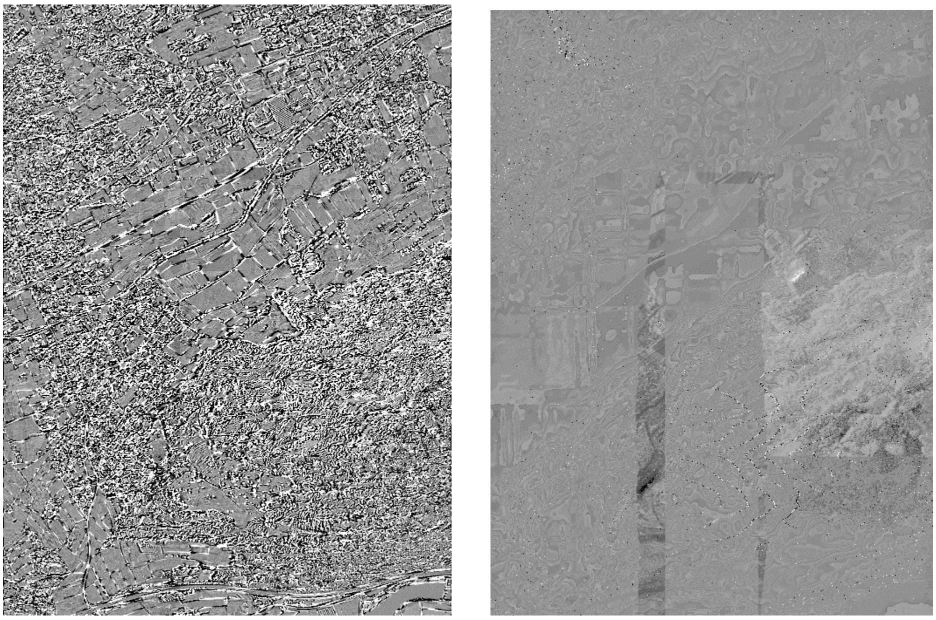

Figure 3 Difference image between raw geometry based processing and resampled processing by bilinear resampling(left) and nearest neighbour (right); scaled to a range of ±2% at 1187 nm.

Data loss and duplicate pixels are found by simply counting the number of lost and resampled pixels after nearest neighbour resampling from original geometry (at nominal resolution of 5.8 meters) to a target geometry of 5 meters resolution. The slightly improved resolution follows the rule of thumb of using 10-20% better resolution for a low-loss resampling. The relative number of lost original spectra is also a measure for the data loss when applying linear interpolation - every lost pixel is related to an interpolation of adjacent pixels at one data point. In this case, the original measurements are not fully lost but smoothed out on a 50% level of original sensitivity.

	Standard Workflow	*Optimized Workflow*
cube dimensions	1201 x 3410 x 124	512 x 2595 x 124
size per processed data cube	1 GB	0.35 GB
image data interpolation steps	uniformization, rectification	uniformization (inherent to HYMAP)
processing time for spectral reflectance product	17 min 34 s (94% for band sequence)	6 min 34 s (92% for band sequence)
relative data loss	0.4%	0%
duplicated pixels	19.7%	0%
nearest neighbour deviation	6.4% (relative standard dev.)	0%
nearest neighbour deviation	0.1% (relative mean)	0%
bilinear interpolation deviation	11.8% (relative standard dev.)	0%
bilinear interpolation deviation	0.3% (relative mean)	0%
data dynamics (at std. dev.)	51.93% (bilinear); 53.51% (nearest neighbour)	53.54%
output spatial resolution	5.0 m	5.8 m

Table 1 Processing differences between standard workflow and optimized workflow for a HYMAP-based example data set.

Finally, the relative dynamics are calculated as relative standard deviation of the atmospherically corrected data in raw processing workflow in comparison to standard workflow. The loss in data dynamcis is minimal for nearest neighbour resampling and still relatively small for bilinear interpolation. The results are compiled in Table 1. The figures of merit are averaged over the whole spectral range of the HYMAP sensor where applicable.

Improvements of the optimized workflow are most significant in data amount and processing time. Doubling the total amount of data origins in the higher spatial resolution but also in the non-rectangular area which is typically covered by an airborne flight pattern. As expected, the experiment shows a linear relation between data size and processing time. Furthermore, optimal conditions are inherent to the raw-geometry based workflow with respect to data loss and interpolation artefacts. Drawbacks of the standard processing are less significant for the data dynamics parameter, where a relative loss in dynamics (and a related loss of information, cf., 23) of about 3-5% is observed.

CONCLUSIONS

A workflow has been proposed which is optimized with respect to operationality, interoperability, speed and data quality. For APEX being a scientific instrument, operationality and interoperability is achieved by standards which are easy to use by a broad range of scientists working on application developments. A complete processing workflow beyond the traditional level 1/2/3 separation reduces redundant processing steps and allows higher efficiency of the process. Speed and data quality is optimized by raw-geometry based processing throughout the whole processing chain. It could be quantitatively shown that typical deviations in a range of 6-12% can be eliminated when optimizing the workflow. At the same time, the overall speed of the processing can be improved by a factor of 3 or more.

A streamlined level 2/3 workflow has been proposed based on product requirements. The individual modules have been identified but will need further adaption for optimal integration in the APEX processing chain. The presented higher level processing will be implemented within the APEX processing and archiving facility. By providing aid through the APEX science center and gathering knowledge from contributing scientists, the goal of a complete processing system remains achievable within the years of APEX operation, starting in 2008 and additional applications may be added without any conflicts to existing procedures. The such invented technology and the application processor can easily being transferred to other processing chains for hyperspectral instruments grace to its open architecture.

ACKNOWLEDGEMENTS

The valuable inputs from RSL SpectroLab on scientific products are acknowledged, specifically from Ben Koetz, Daniel Odermatt, Felix Seidel, and Matthias Kneubühler.

REFERENCES

1 Masuoka E., Fleig A., Wolfe R.E. and Patt F., 1998. Key Characteristics of MODIS Data Products. IEEE Trans. on Geosc. and R. S., Vol. 36, No. 4: pp. 1313-1323.

2 Levrini G. and Delvart S., 2004. MERIS Product Handbook. Version 1.3, ESA.

3 Nieke, J. et al., 2004. APEX: Current Status of the Airborne Dispersive Pushbroom Imaging Spectrometer. In: W.L. Barnes and J.J. Butler (Editors), Earth Observing Systems IX. SPIE, Maspalomas, Spain, pp. 109-116.

4 Nieke, J., Itten, K.I., Debruyn, W. and team, a.t.A., 2005. The airborne imaging spectrometer APEX: from concept to realisation, 4th EARSeL Workshop on Imaging Spectroscopy, Warsaw.

5 Biesemans J, S Sterckx, E Knaeps, K Vreys, S Adriaensen, J Hooyberghs, K Meuleman, P Kempeneers, B Deronde, J Everaerts, D Schläpfer & J Nieke, 2007. Image processing workflows for airborne remote sensing. In: 5th EARSeL Workshop on Imaging Spectroscopy, (EARSeL, Bruges, Belgium).

6 Kaiser J.W., Schläpfer D., Brazile J., Strobl P., Schaepman M.E. and Itten K.I., 2003. Assimilation of Heterogeneous Calibration Measurements for the APEX Spectrometer, International Symposium on Remote Sensing. Sensors, Systems, and Next Generation Satellites VII. SPIE, Barcelona, Vol. 5234, pp. 211-220.

7 Schläpfer D., Kaiser J.W., Brazile J., Schaepman M.E. and Itten K.I., 2003. Calibration concept for potential optical aberrations of the APEX pushbroom imaging spectrometer, Remote Sensing. Sensors, Systems, and Next Generation Satellites VII. Sensors, Systems, and Next Generation Satellites VII. SPIE, Barcelona, Vol. 5234, pp. 221-231.

8 Schläpfer, D. and Richter, R., 2002. Geo-atmospheric processing of airborne imaging spectrometry data. Part 1: Parametric Ortho-Rectification Process. International Journal of Remote Sensing, 23(13): 2609-2630.

9 Richter, R. and Schläpfer, D., 2002. Geo-atmospheric processing of airborne imaging spectrometry data. Part 2: Atmospheric/Topographic Correction. International Journal of Remote Sensing, 23(13): 2631-2649.

10 Nicodemus F.E., Richmond J.C., Ginsberg I.W. and Limperis T., 1977. Geometrical Considerations and Nomenclature for Reflectance. National Bureau of Standards, US. Department of Commerce, pp. 52.

11 Seidel, F. et al., 2005. Aerosol retrieval for APEX airborne imaging spectrometer: a preliminary analysis. In: K. Schäfer (Editor), Remote Sensing of Clouds and the Atmosphere X. SPIE, Brugge, Belgium, pp. 548-557.

12 Kaiser, J.W., Nieke, J., Schläpfer, D., Brazile, J. and Itten, K.I., 2006. The atmospheric sensitivity of the airborne imaging spectrometer APEX. In: H. Fischer and B.J. Sohn (Editors), IRS 2004: Current Problems in Atmospheric Radiation. A. Depaak Publishing, Hampton, Virginia, 4 pp.

13 Holben, B.N. et al., 1998. AERONET--A Federated Instrument Network and Data Archive for Aerosol Characterization. Remote Sensing of Environment, 66(1): 1-16.

14 Hüni, A., Nieke, J., Schopfer, J., Kneubühler, M. and Itten, K.O, 2007: 2nd Generation of RSL's Spectrum Database "SPECCHIO". ISMPSRS, Davos, Switzerland.

15 Schaepman-Strub, G., Schaepman, M.E., Painter, T.H., Dangel, S. and Martonchik, J.V., 2006. Reflectance quantities in optical remote sensing-definitions and case studies. Remote Sensing of Environment, 103(1): 27-42.

16 Clark, R. et al., 2003. Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert system. Journal of Geophysical Research, 108(E9, 5131): 5-1 - 5-44.

17 Roberts, D.A. et al., 1998. Mapping Chaparral in the Santa Monica Mountains using multiple endmember spectral mixture models. Remote Sens. Environ., 65: 267-279.

18 Heege, T., Fischer, J., 2004. Mapping of water constituents in Lake Constance using multispectral airborne scanner data and a physically based processing scheme. In: *Can. J. Remote Sensing*, Vol. 30, No. 1, pp. 77-86.

19 Myneni, R.B., Hoffman, S., Knyazikhin, Y., Privette, J.L., Glassy, J., Tian, Y., Wang, Y., Song, X., Zhang, Y., Smith, G.R., Lotsch, A., Friedl, M., Morisette, J.T., Votava, P., Nemani, R.R., & Running, S.W. (2002). Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. Remote Sensing of Environment, 83, 214-231

20 Ustin, S.L., Roberts, D.A., Gamon, J.A., Asner, G.P., & Green, R.O. (2004). Using imaging spectroscopy to study ecosystem processes and properties. Bioscience, 54, 523-534

21 Teruo Aoki, M. Hori, H. Motoyoshi, T. Tanikawa, A. Hachikubo, K. Sugiura, T. J. Yasunari, R. Storvold, H. A. Eide, K. Stamnes, W. Li, J. Nieke, Y. Nakajima, and F. Takahashi, 2007: ADEOS-II/GLI snow/ice products – Part II: Validation results using GLI and MODIS data, accepted for publication in “Cryosphere Special Issue” within Remote Sensing of Environment.

22 Huber, S., Kneubühler, M., Zimmermann, N.E. and Itten, K.I., 2005: Potential of Spectral Feature Analysis to Estimate Nitrogen Concentration in Mixed Canopies, Proc. 4th EARSeL Workshop on Imaging Spectroscopy, Warsaw, 27-29 April 2005, CD-ROM.

23 Schläpfer, D., Nieke, J. and Itten, K.I., 2007. Spatial PSF non-uniformity effects in airborne pushbroom imaging spectrometry data. IEEE Transactions on Geoscience and Remote Sensing, 45(2): 458-468.