Performance Requirements for Airborne Imaging Spectrometers

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ABSTRACT

We present an approach to translate scientific requirements into instrument specifications by using a forward model for generic airborne imaging spectrometers in earth remote sensing. Based on scientific requirements, for each relevant variable detectable using imaging spectroscopy, ground reflectance spectra have been provided by specialists in their field of expertise. Relevant changes to be detected in the observed variable are used to derive critical delta reflectances. Realistic mission scenarios are subsequently combined with theses delta reflectances and a radiative transfer code to determine spectral NedL values at the sensor level. The combination of various fields of application in terms of detectable variables and the use of realistic mission scenarios leads to the determination of various NedL levels that are determined at given at sensor radiances. Using this concept, manufacturable specifications can be derived from scientific requirements.

Keywords: Imaging spectrometer, performance analysis, imaging spectroscopy, specifications, airborne.

1. INTRODUCTION

APEX (Airborne Prism Experiment) is an airborne imaging spectrometer, which is part of the precursor and supporting activities for possible ESA Explorer missions devoted to the understanding of Land Processes and Interactions. APEX will be able to simulate, calibrate and validate planned space-borne imaging spectrometer missions, and can act as a radiometric transfer standard for vicarious calibration.[1,2,3,4]

The APEX instrument has been initially designed to cover all relevant land applications, when it turned out that certain applications (e.g., data acquisition at solar noon over snow at the equator) drive the instrument performance to very high requirements, but are very likely never to be covered. The scope of this paper is to refine the scientific, operational and calibration requirements developed during the previous phases in order to establish mission objectives for an airborne imaging spectrometer operating between 400 and 2500 nm. For each potential application to be covered by APEX, a detailed scientific analysis is performed and the requirements in terms of SNR are derived. A model approach to translate scientific requirements into engineering specifications is discussed. In a future operational phase of APEX, this model and a simulation tool (e.g. SENSOR)[5] will also be available for the continuous monitoring and updating of the expected APEX performance.

2. COMPILATION OF SCIENTIFIC VARIABLES

The first step of this approach is to compile relevant variables for various applications as they are commonly used in imaging spectroscopy. The baseline for the choice of variables is made using a proposal by Green[6], discussing a classification of potential applications within imaging spectroscopy. Following this proposal, a number of

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internationally known specialists have been contacted and the following subdivision into individual application is defined:

- Calibration, validation and simulation variables,
- Signatures of the atmosphere,
- Variables associated to vegetation processes and retrieval prospects from high spectral resolution imaging systems,
- Geology, soils and minerals,
- Inland water quality monitoring (limnology),
- Seasonal snow cover,
- Air quality in urban areas, and
- Dimensionality of imaging spectrometer data.

All these contributions resulted in a representative list of available methods, relevant parameters, and variables used in imaging spectroscopy. A full list of 55 variables defined within this compilation using relevant methods in imaging spectroscopy are listed in the following table. Variables that are set in bold are finally being selected as input parameters for the subsequent model scenario. The reduction of the initial 55 variables to the final 16 is based on the relevance given in the contributions as summarized above. Based on this choice of 16 variables, varying concentrations, combinations, and permutations are computed and fed into the forward at sensor model that will finally help to support to derive the NedL for each application. The variables subsequently have been used in the predefined model scenario for a given set of realistic radiometric situations. The geology and dimensionality variables have been adapted to the specific requirements of the individual applications.

Table 1. Summary of all compiled and **selected** variables for the model input.

Field	**Variables**
Calibration and Validation	**NedL [W/(m2 sr µm)]**
	Lmax [W/(m2 sr µm)]
	Dynamic range [bit]
	Polarization for the complete FOV
	Linearity
	Accuracy of the absolute rad. calibration
	Accuracy of the relative rad. calibration
	Ground resolution
	Swath width
	Flight altitude H
	Tilting (pointing) possibility
	Spectral range [nm]
	Number of spectral channels
	Spectral bands width
Atmospheric Signatures	**Aerosol (total amount)**
	Water vapor (column)
	Aerosol characteristics
	Oxygen
	Ozone and Methane
Vegetation	**Leaf Area Index (LAI)**
	Leaf orientation
	Leaf size and shape
	Canopy height
	Canopy water mass
	Chlorophyll content
	Water content
	Temperature
	Surface soil moisture
	Roughness
	Residues
	Organic matter
	Soil type
	FCover
	FAPAR
	Albedo

Minerals / Soils	**Iron (Fe2+, 3+)**
	Al-OH-, Mg-OH-
	Carbonates
	Organic carbon
	Clay minerals
	Soil color, moisture, and roughness
Rocks / Minerals	$10 \leq x \leq 1000$ (depending on spectral feature)
	Wavelength range 400 nm - 10 µm
	FWHM << 25 nm (for most of the features), important ones require < 15 nm
Limnology	**Chlorophyll a**
	Inorganic particulate matter
	Gelbstoff
Snow and Ice	**Grain size**
	Impurities / Optical depth
	Surface liquid water
	Seasonal snow cover
Urban (Air Quality)	Nitrogen Oxide (NO2)
	Ozone (O3)
Algorithms	Contiguous spectral coverage
	≥ 7 contiguous spectral bands per feature

3. THE NEDL MODEL

A model for the analysis of the variable specific relation between radiance and delta radiance is proposed and implemented. The model is capable to retrieve delta radiance specifications at any predefined radiance level for any number of independent imaging spectroscopy variables as derived in the previous chapter. The radiometric sensitivity analysis (or the NedL model) is based on the following principles:

- A predefined set of variables are selected according to their relevance and importance,
- Critical at-surface delta reflectance is propagated to at-sensor signal using a forward simulation approach to substantiate the requirements,
- A (well defined) minimum of a-priori knowledge is used to constrain the model,
- The modelling is based on standard radiometric situations to avoid specification on rare cases, and
- Uncertainties in the atmospheric propagation are not included in the analysis.

A schematic view of the selected model approach is outlined in Figure 1. Based on various application requirements, a reflectance model is used to derive reflectance signatures for each selected variable most relevant for this application. The resulting reflectance signatures are the data basis for the forward modelling approach. The reflectance is fed into a standard radiative transfer model, which converts these surface data into at-sensor radiances. At the sensor level, the delta radiances are now available for further analysis and selection of critical areas. The final results are the scientific requirements in terms of radiometry at sensor.

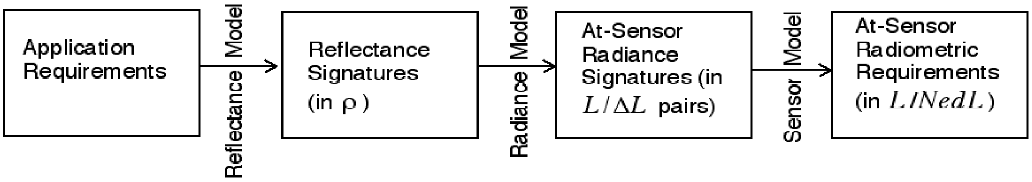

Figure 1: The NedL approach.

The selected approach allows a consistent determination of NedL at predefined radiance levels and is generally applicable. This means that the approach can be easily expanded with additional applications or variables and the type of sensor can be adapted as well (e.g., satellite, ground-based).

1. Input Variables

The variables according to Table 1 are compiled and grouped with their radiometric scenarios. The indicated variables for vegetation and their requirements are listed in Table 2.

Table 2. Vegetation requirements and scenarios.

Parameter	**Level(s)**	**Delta Signature**
Chlorophyll (Cab) [µg/cm2]	25, 45, 70	+10%
Leaf Water (Cw) [g/cm2]	0.005, 0.01, 0.02	+10%
LAI [m2/m2]	0.5, 2.0, 6.0	+10%
Boundary conditions (input parameters used for Prospect / SAIL)	Structure Parameter: N=1.5 Dry Matter: 1.25 * Cw Leaf angle inclination: 58 Hot spot parameter: 0.1	n/a
Sun zenith angle	0°, 18°, 48°	-
Flight altitude	7.5 km a.s.l.	-
Ground altitude	0.2 km a.s.l.	-
Wavelength range	400 - 2400 nm	1 nm

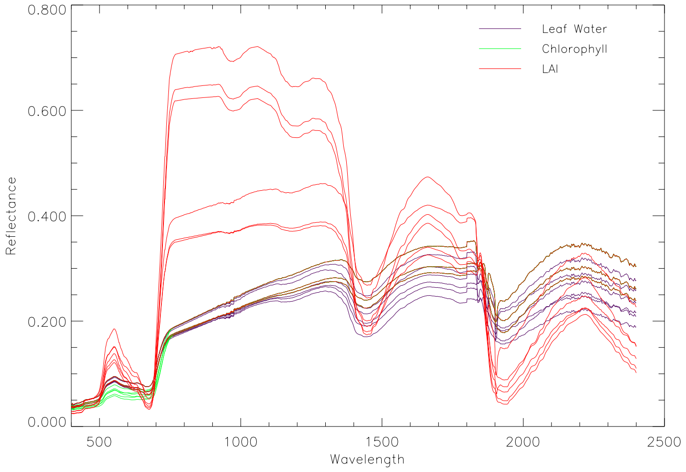

Figure 2: Typical reflectance levels for three vegetation relevant variables (e.g., Chlorophyll (25-70 µg/m^2), Leaf Water (0.005 - 0.02 g/m^2), and LAI.(0.5 - 6 m^2/m^2)). The sun zenith angle is varied between 0 and 48 degrees.

Figure 2 displays the change of the parameters in terms of absolute reflectance as described in Table 2. Finally Figure 3 lists the absolute delta reflectances for all vegetation variables and radiometric situations. For each application a similar plot of all absolute changes is produced.

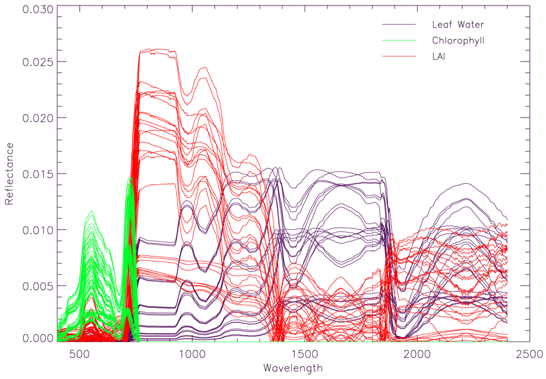

Figure 3: Absolute delta reflectance signatures of all variables considered in the vegetation analysis. Negative deviations (e.g. between 1500-1700 nm) appear as positive signatures for validation purposes.

All applications are treated in a similar manner, except for calibration, since the NedL values are there provided directly and need not to be modelled. The surface reflectance spectra are then simulated at typical irradiance levels and directions to account for BRDF effects and illumination amount.

2. Radiometric Sensitivity Analysis

The radiometric simulation scheme allows simulating the at-sensor delta-radiance on a 1 nm spectral resolution level. The reflectance signatures are then transferred to at sensor radiances using the MODTRAN4[7] radiative transfer code. The radiometric signal is analyzed *unchanged*, leaving the method of parameter retrieval open to the scientists.
The analysis is defined using the following steps:

- Use of variable-defined delta reflectance spectra for each application,
- Derive variable-specific radiance and delta radiance levels at the sensor,
- Calculate the delta radiance in dependence of radiance per wavelength,
- Fit a generic instrument limitation function to all modelled L/∂L pairs,
- Extract spectral NedL per application,
- Retrieve generic minimal (absolute), median, and maximal (absolute) radiance levels based on all variables,
- Derive spectral NedL values at the three specified radiance levels, and
- Retrieve overall NedL curve from application specific values based on scientific judgement and spectral averaging.

The surface reflectance spectra are modelled to at-sensor radiance values using realistic situations. In case no limitations are given, the following assumptions are made: sensor altitude 7.5 km, ground altitude 0.2 km (except for snow), sensor at nadir. Three geo-atmospheric situations (tropical, midlatitudes, nordic) have been selected for most of the applications in order to account for the variation of illumination and atmospheric conditions. The MODTRAN4 radiative transfer code with the MODO[8] utility is used for these radiance simulations. The extracted radiance spectra are convolved to a generic APEX sensor having a spectral resolution of 7.5 nm at FWHM (what corresponds to a SI of 5 nm).

3. Generic Radiance Levels

For all applications and variables a realistic number and variation of situations has been modeled so far. This group is analyzed by searching the minimum and maximum radiance within each application. The minimal radiance for calibration is added separately since it does not represent a specific variable. Furthermore, the minimum and maximum expected radiance at a 0 and 100% reflecting target is included in Figure 4.

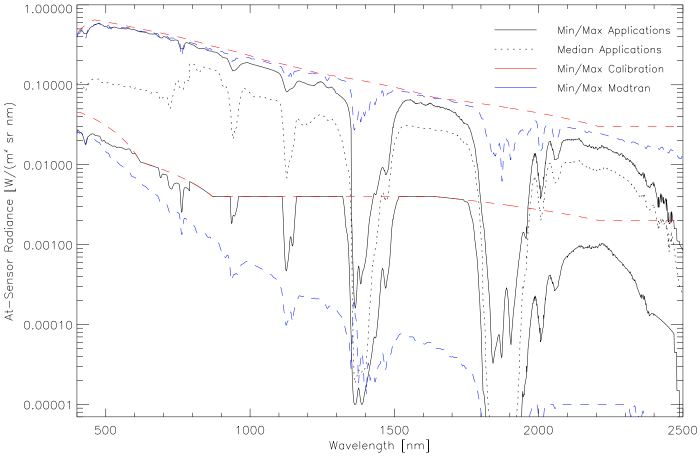

Figure 4: Generic minimum, median, and maximum radiance levels for all applications including a MODTRAN simulation for a minimum and maximum situation.

For the upper radiance level (‘saturation level’), the application-derived value in the VIS/NIR part of the spectrum is in good agreement with the absolute maximum as derived from MODTRAN4 and the one defined for calibration purposes. In the SWIR part of the spectrum, the absolute maximum of all applications is about 30% lower than the signal of a 100% reflecting target under optimal conditions. A compromise has to be found in these wavelength ranges to avoid saturation in standard cases while keeping the dynamic range as wide as necessary.

4. Delta Radiance Signatures

The retrieval of the signatures requires that all application/variable requirements be normalized to specified radiance levels. Secondly, a selection criterion based on scientific judgement is set up to keep only relevant spectral areas per variable for the derivation of the final radiometric requirements.

The individual value of the delta radiance depends on a the absolute radiance value. For every variable, the most demanding combination needs has been searched from all simulated radiance/delta radiance-pairs. A square-root function is fitted to every single point for that purpose. It is derived from the assumption, that the noise of a sensor increases with the square root to the number of photons (the so-called photon-noise). The derived functions can now be used to normalize the critical data points to a predefined radiance level.

The method allows the retrieval of the relations for all variables at any radiance level independently. A flexible exclusion process and scientific knowledge is required to narrow the critical wavelength ranges per variable and to derive a combined result. The following approach is chosen for specific wavelength selection:

- Generation of L/dL pairs at generic minimum, median, maximum radiance per variable for the lowest data point at each wavelength (1 nm resolution),
- Exclude pairs of lowest significance,
- Calculate combined NedL from remaining variables per wavelength, and
- Calculate SNR based on the three radiance levels (and NedL).

The wavelength selection process is based on normalisation of dL to the respective radiance value. Wavelength ranges with low signatures are excluded per variable. Scientific judgement is finally used to conclude on real sensor requirements using the thus derived radiometric numbers. Figure 4 shows an overview of all selected signatures after applying the exclusion rule. For calculation of the final results the highest requirement from all application are taken per wavelength. This figure can also be used in an inverse manner: if a sensor performance is known it can be estimated under which conditions if certain applications may lead to a success or are not realistic.

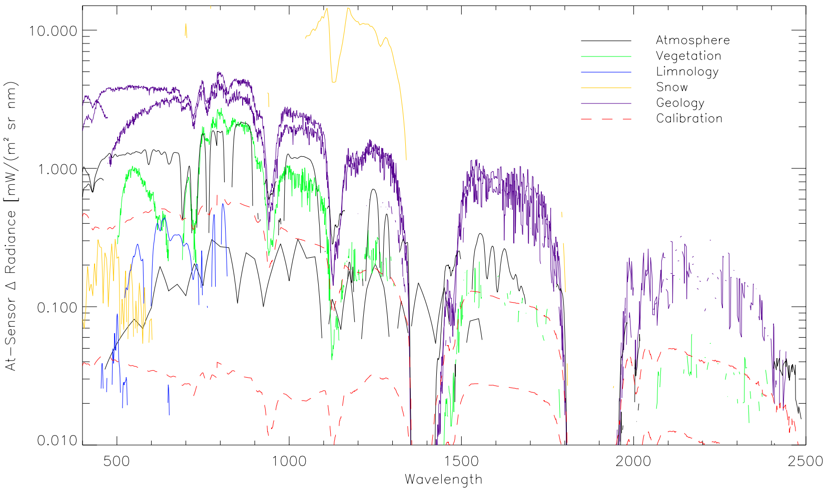

Figure 5: NedL requirements of all variables included in the analysis (plotted per application).

The required delta radiances have then been retrieved at the generic three radiance levels. Requirements may now also be retrieved at any radiance levels to fit e.g. the characteristics of laboratory radiance sources during calibration. The evaluation of such requirements is preferably done on the median radiance level since the results at the minimum radiance level have been derived partially through an extrapolation process, which does not necessarily represent the real nature of the problem, or might address a minimum situation that never occurs in reality. The maximum radiance level on the other hand is useful to determine the upper end of the dynamic range of the instrument rather than using it for dedicated parameter retrieval.

5. SNR Requirements

The delta radiance requirements are then used to calculate SNR requirements. The SNR values are provided based on the given scientific validation at the defined radiance levels. The SNR requirement is plotted in Figure 6. For the median radiance level, it varies in the range between 100 and 2000 for the VIS/NIR detector. The high SNR requirements in the visible part of the spectrum are driven mainly by the limnology application but also by atmospheric, snow and vegetation variables. This wavelength range therefore needs special attention in the sensor design. The performance in the SWIR wavelength part on the other hand can be constant at an SNR between 100 and 300, given an absolutely accurate (e.g., errorless) atmospheric correction.

The SNR results give a clear image about the wavelength range to be covered by an imaging spectrometer. It is shown that a continuous spectral coverage is highly desirable except for the 1850 nm SWIR water vapor absorption band (i.e. 1800-1920 nm), where no significant signatures have been found. The lower limit of relevant signatures is at least at 400 nm. As most models used for this analysis did not take into account lower wavelengths, the real lowest limit of interest may be substantially lower than this model limit.

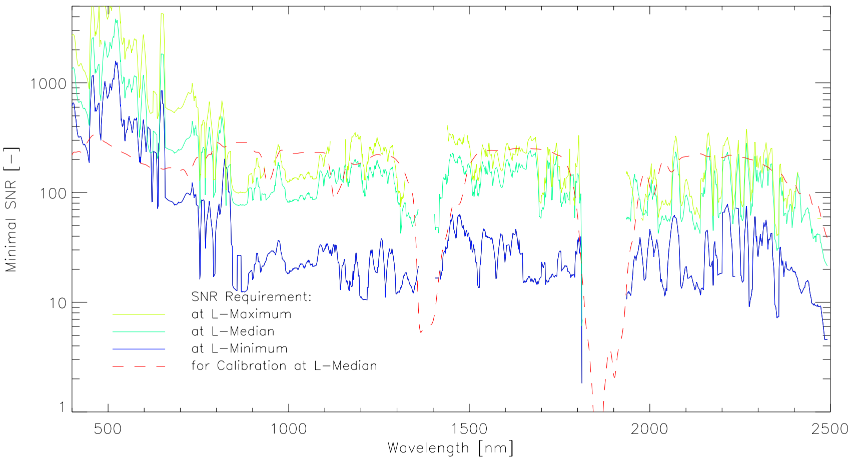

Figure 6: SNR requirements as derived from the NedL model.

4. CONCLUSIONS

Delta radiance and SNR requirements have been derived at specific radiance levels. The validation of the critical delta radiance (or SNR) curves needs to be based on scientific knowledge. Generic delta radiance levels can now be finally derived from the outputs for the derivation of the technical APEX sensor specifications. Furthermore, a recommendation on the spectral range could be made using the very same analysis results. The presented SNR values cannot be easily inverted using the presented model. The major underlying problem is that the radiative transfer code is run in a forward mode and that the inversion using real data relies on in-situ atmospheric measurements. Consequently the scientific requirements assume a 'perfect' atmospheric compensation and a perfectly calibrated instrument. In reality, this is never achievable, so when translating these requirements into engineering specifications a security margin on top of the given values must be included to take into account atmospheric uncertainties.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Schaepman, M.E., De Vos, L., and Itten, K.I.: APEX - Airborne PRISM Experiment: hyperspectral radiometric performance analysis for the simulation of the future ESA land surface processes earth explorer mission. In: Imaging Spectrometry IV, Sylvia S. Shen and Michael R. Descour, Editors, Proceedings of SPIE, Vol. 3438, pp. 253-262, 1998
2. Schaepman, M. and Itten, K.I.: APEX–Airborne PRISM Experiment: An Airborne Imaging Spectrometer serving as a Precursor Instrument of the Future ESA Land Surface Processes and Interactions Mission. Proc. ISPRS, Vol. 22(7), ISPRS Commission VII Symposium on Resource and Environmental Monitoring, Budapest, p. 31–37, 1998
3. Schaepman, M., Schläpfer, D., and Itten, K.: APEX – A New Pushbroom Imaging Spectrometer for Imaging Spectroscopy Applications: Current Design and Status, Proc. IGARSS Hawaii, p. 828–830, 2000.

4. Schläpfer, D., Schaepman, M., Bojinski, S., and Börner, A.: Calibration Concept for the Airborne PRISM Experiment (APEX), Can. J. Rem. Sens., 26/5, 455–465, 2000.
5. Börner, A., Wiest, L., Keller, P., Reulke, R., Richter, R., Schaepman, M., and Schläpfer, D.: SENSOR: A tool for the simulation of hyperspectral remote sensing systems, ISPRS J. Phot. and Remote Sens. 55(299–312), 2001.
6. Green, R., Eastwood, M., Sarture, C., et. al., Imaging Spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Remote Sens. Environ. 65:227–248, 1998
7. Berk A., L.S. Bernstein, D.C. Robertson: MODTRAN: A Moderate Resolution Model for LOWTRAN7, Report GL–TR–89–0122, Geophysics Lab., pp. 38, Bedford, USA, 1989
8. MODO, http://www.rese.ch/modo/index.html, 2001