VICARIOUS CALIBRATION OF
THE PROBA/CHRIS IMAGING SPECTROMETER

Andres Kuusk¹, Joel Kuusk¹, Mait Lang¹,², and Tõnu Lük½

¹Tartu Observatory
²Estonian University of Life Sciences

andres@aai.ee, joel@aai.ee, lang@aai.ee, tonu.lukk@neti.ee

ABSTRACT

Vicarious calibration of the Compact High-Resolution Imaging Spectrometer CHRIS on-board the PROBA satellite was performed using the top of canopy reflectance of mature forest stands at Järvselja test site in Estonia. Satellite data were atmospherically corrected with the 6S atmospheric radiative transfer software using AERONET data of atmosphere optical properties and look-up-table method. Adjacency correction was applied as well. Top of canopy reflectance of forest stands was measured with a custom-designed airborne spectrometer. All applied corrections are described, and analysis of errors is presented. CHRIS calibration coefficients of 2005 are too low in Mode 3 bands 4 and 18, too high in band 11, and probably too low in bands 1 and 2. The updated calibration coefficients of the CHRIS sensor were applied to all scenes acquired over Järvselja test site on 10 July 2005.

1. INTRODUCTION

Calibration procedures of optical sensors of large satellites have been developed for years and calibration is provided by a mixture of on-ground and in-orbit measurements (Slater et al., 1996; Slater and Biggar, 1996; Thome et al., 1997; Abdou et al., 2002). Preflight calibrations are subject to change during launch and exposure to the space environment. With increasing time since the launch the role of in-orbit methods increase, however, small platforms offer limited scope for on-board calibration facilities. Therefore, some vicarious method should be considered as an option. For the vicarious calibration of large operational satellites (Landsat, SPOT, MISR) which measure continuously large areas one can choose bright stable targets at good atmospheric conditions (Abdou et al., 2002). The small acquisition resource of the Compact High-Resolution Imaging Spectrometer (CHRIS) on board the PROBA satellite (Barnsley et al., 2004) – two or three sites of about 17×17 km per day – limits opportunities for the vicarious calibration of the spectrometer. At the same time, a small satellite is limited in keeping stable conditions of its instruments and along with long-term changes in detector sensitivity the sensor response may change on every orbit with changing temperature in the instrument section of the satellite (Cutter, 2004). Therefore, more frequent vicarious calibration of sensors is needed, in ideal case for every acquired scene. Begiebing and Bach (2004), and Guanter et al. (2005) reported problems in the calibration of the CHRIS near infrared (NIR) bands comparing CHRIS-derived reflectance spectra to ground truth measurements. They suggested a revision to the CHRIS NIR calibration, which was done by the CHRIS team in 2005 (Cutter and Johns, 2005).
In July 2005 the CHRIS/PROBA measured a forestry test site at Järvselja, Estonia in excellent weather conditions. The test site serves as a training base for the forestry students of the Estonian University of Life Sciences, and has also served as a test site for the VALERI project (VALERI, 2005) and the POLDER mission (Deschamps et al., 1994). CHRIS data are used both in forestry studies and for the validation of vegetation radiative transfer and reflectance models. While in forestry studies small scaling errors in stand reflectance over the whole scene may not be a problem, for the validation of radiative transfer models high accuracy of reflectance data is needed.

In the CHRIS scene over hemi-boreal forest test site at Järvselja in Estonia we cannot find bright targets large enough for satellite measurements. Therefore, in this paper the CHRIS calibration is validated against top-of-canopy directional reflectance of large forest stands measured on board a helicopter. Revised calibration coefficients are suggested which are used for the processing of CHRIS scenes 5703, 5705 and 5707 of 10 July 2005. Three forest stands in these scenes are the stands of the Database of Optical and Structural Data for the Validation of Radiative Transfer Models, (Kuusk et al., 2009).

2. STUDY SITE

The Järvselja test site is in Estonia, centered at 27.26° E 58.30° N. The landscape is very flat, about 50 m above sea level. There are 3561 regularly managed stands in the 10×10 km VALERI site and 515 stands in the 3×3 km square, the latter is more thoroughly studied subset of the VALERI site. A forest stand is defined as a geographically unified area which has a relatively uniform species composition and is managed as a single unit. Regular forest inventory is performed every 10 years, the last complete set of measurements is from 2001. In the inventory, several forest parameters such as species composition, age, breast-height diameter, tree height, site type, etc. have been recorded for every stand. In the CHRIS scene 5703, there are 3197 stands which are described in the forestry database. A more detailed description of the test site is provided in (Kuusk et al., 2005).

3. DATA

3.1 CHRIS images

CHRIS is an imaging spectrometer on-board the experimental satellite PROBA (Barnsley et al., 2004). Mode 3 images were acquired for one near nadir and two backscattering (hot-spot side) viewing geometries on 10 July 2005. Acquisition details are listed in Table 1, and wavelengths and bandwidths of Mode 3 spectral bands in Table 3. The nadir images of the scene 5703 were used in this study.

<table>
<thead>
<tr>
<th>Scene number</th>
<th>5703</th>
<th>5705</th>
<th>5707</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td></td>
<td>10 July 2005</td>
<td></td>
</tr>
<tr>
<td>Observation zenith angle, deg</td>
<td>7.62</td>
<td>37.23</td>
<td>56.71</td>
</tr>
<tr>
<td>Observation azimuth angle(^{(a)}), deg</td>
<td>-22.46</td>
<td>19.79</td>
<td>23.43</td>
</tr>
<tr>
<td>Ground resolution, m</td>
<td>17×17</td>
<td>21×19</td>
<td>29×19</td>
</tr>
</tbody>
</table>
Top-of-canopy hyperspectral reflectance of forests was measured with a custom-designed VNIR spectrometer system UAVSpec, mounted onboard a helicopter. The spectrometer system UAVSpec was based on the 256-band NIR enhanced miniature spectrometer module MMS-1 by Carl Zeiss Jena GmbH, with the front-end-electronics (FEE) by Tec-5 AG Sensorik und Systemtechnik. It had a wavelength range of 306-1140 nm, 15-bit digital output, and noise level of 2-3 bits. The spectrometer system included a web camera and a GPS receiver for position tracking. There were sensors for recording the temperature of the spectrometer and the FEE. A laptop PC running Linux operating system was responsible for system control and data acquisition. The spectrometer system operated autonomously: it was started when the helicopter was still on the ground, and did not require an operator’s intervention during the flight. All the acquired data were stored on the laptop’s hard drive.

Hyperspectral reflectance of stands was measured with the UAVSpec spectrometer system on 26 July 2006. The spectrometer system was mounted rigidly at the chassis of a Robinson R-22 helicopter, looking in the nadir direction during straight flight at a constant speed. Data from the spectrometer were collected approximately 3-5 times per second. Web camera images, position data from the GPS receiver, and sensor’s temperature were recorded once per second. Measurements were made from the height of 100 m above ground level in cloudless conditions, flight speed was 60 km/h. During helicopter measurements the spectrometer was equipped with fore-optics which restricted the field-of-view (FOV) to 2º. The measurement conditions are reported in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>26 July 2006</td>
</tr>
<tr>
<td>Time</td>
<td>9:14-9:47 GMT</td>
</tr>
<tr>
<td>Sun zenith angle</td>
<td>40.6º - 39.3º</td>
</tr>
<tr>
<td>Sun azimuth angle</td>
<td>156.6º - 168.9º</td>
</tr>
<tr>
<td>Observation zenith angle</td>
<td>0º</td>
</tr>
<tr>
<td>Platform altitude</td>
<td>100 m</td>
</tr>
</tbody>
</table>
3.3 Supporting measurements

A FieldSpec®Pro VNIR spectrometer by Analytical Spectral Devices, Inc., equipped with a cosine receptor and a disk for screening direct Sun flux was used for the measurement of spectral diffuse $D_\lambda$ and total $Q_\lambda$ irradiance during the CHRIS acquisition and airborne measurements. The measured ratio $D_\lambda/Q_\lambda$ compared to that simulated with 6S atmosphere radiative transfer (RT) model (Vermote et al., 1997) using AERONET Level 2 atmosphere data for Tõravere station (Holben et al., 1998) is plotted in Figure 1. The aerosol optical depth $\tau_{550} = 0.080$ during the CHRIS acquisition was very low – about three times less than in the profiles by Elterman (1968) which are often used in simulation studies.

During helicopter measurements the optical depth of the atmosphere was even smaller than during the CHRIS acquisition in July 2005, as shown in Figure 1.

![Figure 1: Diffuse-to-total irradiance ratio $D_\lambda/Q_\lambda$ from simulations with the 6S RT model, and FieldSpec measurements during PROBA overpass (10.07.2005) and helicopter measurements (26.07.2006).](image)

4. DATA PROCESSING

4.1 Destriping of CHRIS images

The preprocessing of the CHRIS data cannot perfectly avoid analogue offset errors of recorded signals (Cutter, 2004), therefore, the destriping of images was performed assuming that striping is caused mainly by sensor offsets. The destriping function was found for every image as the difference between column mean values and smoothed column mean values using 9-point Hamming window (Rabiner and Gold, 1975). The mean value of three destriping functions for every band (scenes 5703, 5705, and 5707) was used for all three respective spectral images.
### 4.2 Atmospheric correction

Satellite-based measurements of the radiative signature of terrestrial targets are always affected by the chemical and physical properties of the overlying atmosphere. Highly accurate, reliable and preferably physically based correction schemes are thus required to quantitatively link space-borne measurements with the structural and spectral characteristics of a given vegetation target.

Several procedures have been developed for the atmospheric correction of satellite remote sensing data. A comprehensive overview of atmospheric correction procedures can be found in (Liang, 2004). Thorough comparisons of various procedures of the atmospheric correction of Landsat Thematic Mapper images are reported by Hadjimitsis et al. (2004), and Song and Woodcock (2003). In this paper atmospheric correction was performed with atmospheric RT package 6S (Vermote et al., 1997) using the look-up-table (LUT) method suggested by Kuusk (1998). Atmospheric correction was performed in two stages. First, with the 6S model a LUT was generated which links top-of-atmosphere (TOA) radiance to top-of-canopy reflectance. The later was calculated with the multispectral homogeneous canopy reflectance model MSRM (Kuusk, 1994) varying ground vegetation parameters. The MSRM model served as the underlying surface in the 6S model, and leaf area index, soil reflectance, and leaf optical parameters were varied in a reasonable range characteristic for the test site in order to produce TOA radiance values in the range similar to what we have in the CHRIS images. In the calculation of TOA radiance the TOA spectral irradiance and the optical parameters of the atmosphere are needed. The solar spectrum by Neckel and Labs (1984) is used in 6S. An AERONET Sun photometer (Holben et al., 1998) is working at Tartu Observatory, 45 km from the test site, and the 6S model has tools for using AERONET sun-photometer data directly. Aerosol optical thickness, size distribution and refractive index, and amount of water vapor in the atmosphere were determined from the Level 2 data of the Sun photometer measurements. Ozone data are available from NASA/GSFC Total Ozone Mapping Spectrometer (TOMS) at their web-page (McPeters, 2007) and air parcel trajectories of HYSPLIT (2007) for 10 July 2005, it was concluded that significant differences in atmosphere properties over a distance of 45 km were not possible, only small changes in the amount of aerosol and water vapor may have been present. On this basis the diffuse spectral fluxes in the atmosphere and the diffuse-to-total ratio of spectral irradiance $D/\Omega$ were calculated with the atmospheric RT model. Simultaneous to the CHRIS acquisition the $D/\Omega$ ratio was measured at the test site with a FieldSpec®Pro VNIR spectrometer. In Figure 1 we see that this ratio in case of simulated diffuse and total irradiances using AERONET aerosol optical thickness (at 550 nm $\tau$=0.080) exceeds the measured ratio 5-25%, dependent on the wavelength. This discrepancy may be caused by differences in the separation of total flux to direct and diffuse fluxes. The FOV of the Sun-photometer is 1° while the FieldSpec cosine receptor was screened with a disk which screened about 9° in the Sun direction during the sky flux measurements. In the 6S model the direct flux is collimated.

Although the relation between the simulated TOA spectral radiance and top-of-canopy reflectance is almost linear, the created LUTs were approximated by a second order polynomial separately for every CHRIS band and every view direction,

$$\rho_{\lambda,j}(b_{\lambda,j}) = a_{2\lambda,j}b_{\lambda,j}^2 + a_{1\lambda,j}b_{\lambda,j} + a_{0\lambda,j}. \quad (1)$$

Here, $b_{\lambda,j}$ is the TOA radiance, and $\rho_{\lambda,j}(b_{\lambda,j})$ is canopy reflectance at wavelength $\lambda$ in the acquisition geometry of the CHRIS scene $j = 5703$. Equation (1) was applied also to scenes 5705 and 5707 for the calculation of top-of-canopy reflectance using the TOA radiance measured by CHRIS. This procedure was applied separately to every pixel in every spectral image. The advan-
The advantage of using LUT compared to the built-in procedure of atmospheric correction in the 6S model is considering the directional dependence of diffuse fluxes scattered from vegetated surface and its variations as a function of wavelength, leaf area index, and other canopy parameters.

The second step in the atmospheric correction procedure involves the removal of adjacency effects by 2-D deconvolution. This is because the atmosphere acts as a low-pass filter which degrades satellite images. Additional degradation is caused by the scattering of light in the foreoptics of the spectrometer. The recorded image is a convolution of the top-of-canopy radiance pattern and point spread function (PSF) of the system atmosphere-sensor (Banham and Katsaggelos, 1997),

\[ g(x, y) = p(\xi, \eta) \otimes f(u, v), \]  

where \( f(u,v) \) is the original (ideal) image, \( p(\xi, \eta) \) is the PSF of the system, and \( g(x, y) \) is the recorded (degraded) image, \( \otimes \) denotes the convolution in the x-y-space.

Degraded images can be restored using Wiener filtering in the Fourier space (Banham and Katsaggelos, 1997; Podilchuk, 1998). The convolution of the original image and PSF in the x-y-space (Eq. (2)) can be performed by filtering in the 2D Fourier space

\[ G = P \cdot F, \]  

where \( G, P, \) and \( F \) are the Fourier images of \( g(x, y), \) \( p(x, y), \) and \( f(x, y), \) respectively. The original image is restored by the inverse filtering

\[ \hat{F} = G \cdot W, \]  

where \( W \) is the Wiener filter (Podilchuk, 1998)

\[ W = \frac{P^*F}{|P^*|^2F + S_n}. \]  

Here the superscript * denotes the complex conjugate and \( S_n \) is the noise spectrum. Inverse Fourier transform of the filtered spectrum \( \hat{F} \) returns the corrected image \( \hat{f}(x, y). \)

The PSF of the atmosphere as a function of aerosol optical thickness was estimated by Liang et al. (2001) in numerical simulations,

\[ p(s) = f_1(\tau)\exp(-q_1s) + f_2(\tau)\exp(-q_2s), \]  

where

\[ f_1(\tau) = 0.03 \tau \]  
\[ f_2(\tau) = 0.071 \tau^3 - 0.061 \tau^2 - 0.439 \tau + 0.996 \]  
\[ q_1 = 1.424 \text{ km}^{-1} \]  
\[ q_2 = 12916 \text{ km}^{-1}. \]  

Here \( s \) is the radial distance from the pixel (km) and \( \tau \) is the optical thickness of the atmospheric aerosol.
The noise spectrum $S_n$ was assumed to be exponentially increasing with spatial frequency, its magnitude was estimated using signal/noise ratio from the CHRIS documentation (CHRIS, 2002), and the mean reflectance of every spectral image.

Unfortunately, the horizontal range of the adjacency effect seems to be overestimated in (Liang et al., 2001) - the corrected red and NIR reflectance of a narrow lake in the scene turned to negative values. Reflectance of natural water bodies may be well below 1% (Froidefond et al., 2002; Novo et al., 2004; Feng et al., 2005; Cannizzaro and Carder, 2006) but cannot be less than zero. This was the criterion for recalibrating the scale parameters $q_1$ and $q_2$ of the PSF by a factor of 4,

$$q_1 = 5.70 \text{ km}^{-1}$$

$$q_2 = 5.17 \cdot 10^4 \text{ km}^{-1}.$$  

The contribution of adjacent targets to stand reflectance is largest in the red band (band 8), it is plotted in Figure 2 where every dot represents a stand. There are 3197 stands described in the forestry database in the CHRIS scene 5703. In other bands the relative variance of scene radiance is smaller and therefore the adjacency correction is smaller than in the red band.

![Figure 2: The role of adjacency correction in the CHRIS Band 8](image)

4.3 Airborne measurements

Several technical aspects related to the MMS-1 spectrometer module should be noted. First of all, spectral aliasing affects the NIR signal of the spectrometer. Second order blocking filter which is directly coated on the sensor is not perfect. It lets some visible light cause aliasing effect in NIR spectral domain. Secondly, straylight contributes to the signal at wavelengths where the sensitivity of the sensor is low. To overcome these metrological problems, we corrected the measured signal for spectral aliasing and straylight in the following way. The spectrometer was illuminated through a double monochromator and, while scanning the monochromator over the spectral region of the spectrometer, instrument function was measured for all the bands of the spectrometer. By deconvolution, the original signal was restored for every measured spectrum (Kostkowski,
This correction changed the recorded signals over our targets by a factor between 0.98-1.007 in blue and green bands, 0.93 in red bands, less than 1.01 between 765-925 nm, and the factor increases up to 1.08 at 1020 nm.

Finally, the dark current drift due to temperature changes was taken into account. Since it was not possible to take dark current readings during flight, those recorded before the flight were used together with MMS-1 temperature recordings and empirically measured temperature dependence of dark current,

\[ d_\lambda(T) = d_\lambda(T_0) + f(T) - f(T_0), \] (9)

where \( d_\lambda(T) \) is the dark current in case of MMS-1 temperature \( T \), \( d_\lambda(T_0) \) is the dark current measured before the flight, \( T_0 \) is the MMS-1 temperature during dark current measurement, and \( f \) is the temperature dependence of dark current (Schaepman and Dangel, 2000),

\[ f(T) = a + b \exp(cT), \] (10)

where \( a = 192.86 \), \( b = 0.97968 \), and \( c = 0.08584 \, ^\circ C^{-1} \) are empirical constants and \( T \) is the MMS-1 temperature in Celsius (\(^\circ C\)). There is no integration time in equations (9) and (10), therefore, the equations are only valid for an integration time of 120 ms. This integration time was used for measurements of the temperature dependence of dark current, as well as for airborne measurements of forest reflectance.

The recorded nadir radiance in digital counts is compared to the radiance of a calibrated Spectralon panel (Labsphere®) measured in a nearby clearing at the test site just before the airborne measurements. This way the recorded signal is converted to the directional spectral reflectance of targets. To take into account the changes in illumination conditions, spectral irradiance \( Q_\lambda \) was recorded during measurements with a FieldSpec®Pro VNIR spectroradiometer equipped with a cosine receptor,

\[ \rho_\lambda(t) = \frac{q_\lambda(t) n_\lambda(t)}{n_\lambda(t_0) q_\lambda(t_0)} r_\lambda, \] (11)

where \( \rho_\lambda(t) \) is the target spectral directional reflectance measured at time moment \( t \), \( q_\lambda(t) \) and \( q_\lambda(t_0) \) are the signals of the FieldSpec spectrometer during target measurements and calibration, respectively, \( n_\lambda(t) \) and \( n_\lambda(t_0) \) are the signals of the UAVSpec spectrometer, and \( r_\lambda \) is the spectral reflectance of the reference panel. We used a gray Spectralon panel which has reflectance factor between 0.145 and 0.180 in the spectral range 400-1050 nm.

### 4.4 Comparison of top-of-canopy and satellite measurements

Reflectance spectra of several homogeneous stands in the CHRIS scene 5703 were compared to airborne measured data. Spectral bands of the UAVSpec were combined to the equivalent CHRIS bands. The footprint of the UAVSpec spectrometer’s FOV from the height of 100 m is 9.5 m² which is significantly less than the CHRIS pixel, however, altogether 1302 recorded UAVSpec spectra over 520 CHRIS pixels over 63 homogeneous stands were involved in the comparison which represent all the dominating species at the test site. CHRIS acquisition and helicopter measurements were done at slightly different zenith angles. The reflectance change due to different view angles was corrected by numerical simulations with the forest reflectance model FRT (Kuusk and Nilson, 2000). Top-of-canopy stand reflectance from CHRIS images was reduced to nadir direction separately for every stand using species-specific stand structure parameters from the forestry database. Top-of-canopy radiance of stands in zenith and at 7.62° zenith angle and
22° azimuth angle (relative to Sun) differs in our illumination conditions about 1.10-1.15 times in visible bands and 1.05-1.06 times in NIR bands.

The ratio of the mean stand reflectance from helicopter measurements to the nadir adjusted mean top of canopy stand reflectance from the CHRIS measurements was calculated separately for every stand.

5. CHRIS CALIBRATION REVISED

The comparison of atmospherically corrected CHRIS spectra to top-of-canopy measurements revealed problems in CHRIS radiometric calibration. Results of comparison gave us correction factors for the CHRIS calibration coefficients (Table 3 and Figure 3). Correction factors $C_\lambda$ and their standard deviations in Table 3 are the mean value and standard deviation over 63 stands. Lower curves in Figure 3 show the mean value and range of stand reflectance involved in the comparison.

Table 3. Mode 3 spectral bands and correction factors for the CHRIS calibration coefficients

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda$, nm</th>
<th>$\Delta \lambda$, nm</th>
<th>$C_\lambda$</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>442.4</td>
<td>10.5</td>
<td>0.6373</td>
<td>0.0684</td>
</tr>
<tr>
<td>2</td>
<td>490.2</td>
<td>11.6</td>
<td>0.7658</td>
<td>0.0848</td>
</tr>
<tr>
<td>3</td>
<td>530.0</td>
<td>11.5</td>
<td>0.9687</td>
<td>0.1018</td>
</tr>
<tr>
<td>4</td>
<td>551.3</td>
<td>12.9</td>
<td>0.8756</td>
<td>0.0920</td>
</tr>
<tr>
<td>5</td>
<td>570.0</td>
<td>10.7</td>
<td>1.0063</td>
<td>0.1115</td>
</tr>
<tr>
<td>6</td>
<td>631.4</td>
<td>14.1</td>
<td>1.0439</td>
<td>0.1267</td>
</tr>
<tr>
<td>7</td>
<td>661.2</td>
<td>15.7</td>
<td>1.0587</td>
<td>0.1446</td>
</tr>
<tr>
<td>8</td>
<td>674.6</td>
<td>11.0</td>
<td>1.0720</td>
<td>0.1513</td>
</tr>
<tr>
<td>9</td>
<td>697.5</td>
<td>11.8</td>
<td>1.0281</td>
<td>0.1171</td>
</tr>
<tr>
<td>10</td>
<td>706.5</td>
<td>6.1</td>
<td>1.0973</td>
<td>0.1172</td>
</tr>
<tr>
<td>11</td>
<td>712.6</td>
<td>6.2</td>
<td>1.1456</td>
<td>0.1214</td>
</tr>
<tr>
<td>12</td>
<td>741.8</td>
<td>13.5</td>
<td>0.9907</td>
<td>0.1038</td>
</tr>
<tr>
<td>13</td>
<td>752.1</td>
<td>7.0</td>
<td>1.0294</td>
<td>0.1069</td>
</tr>
<tr>
<td>14</td>
<td>781.1</td>
<td>22.5</td>
<td>1.0116</td>
<td>0.1025</td>
</tr>
<tr>
<td>15</td>
<td>872.3</td>
<td>27.4</td>
<td>1.0028</td>
<td>0.0962</td>
</tr>
<tr>
<td>16</td>
<td>895.7</td>
<td>18.9</td>
<td>1.0208</td>
<td>0.0956</td>
</tr>
<tr>
<td>17</td>
<td>910.0</td>
<td>9.8</td>
<td>1.0021</td>
<td>0.0934</td>
</tr>
<tr>
<td>18</td>
<td>1019.3</td>
<td>43.8</td>
<td>0.8978</td>
<td>0.0848</td>
</tr>
</tbody>
</table>

$\lambda$ - mean wavelength   $\Delta \lambda$ - bandwidth
$C_\lambda$ - correction factor   STD - standard deviation of the correction factor
6. DISCUSSION

The possible errors in the vicarious calibration of a satellite sensor using ground targets as a reference could be caused by errors in atmospheric correction of satellite images and errors in reference measurements. Low aerosol optical depth and water content of the atmosphere at so high geographical latitude, and good weather conditions during the CHRIS acquisition made atmospheric correction of satellite data less sensitive to atmosphere parameters. Anyway, the estimation of the optical thickness of the atmospheric aerosol is complicated and could have substantial errors. The AERONET estimates of the aerosol optical thickness $\tau_{550}$ of Level 1.5 and Level 2.0 differ by 0.017, $\tau_{550} = 0.097$ and 0.080, respectively. So large (so small) change in $\tau_{550}$ brings along the change in CHRIS calibration coefficients by 10% and 8% in blue bands, by 1.5-4.8% in other visible bands, and by 0.7-4.1% in NIR bands.

The radiometric quality of helicopter measurements is according to Eq. (11) determined by the gain and offset errors of spectrometers, and errors in the reference reflectance. The sensitivity of silicon-based sensors and gain coefficients do not change in the range of temperatures encountered. The applied straylight and aliasing correction removed artefacts in reflectance spectra and allow to extend the reliable spectral domain of the Zeiss MMS-1 spectrometer module. For the calibration we used a gray Spectralon panel which has random uncertainty of reflectance less than 0.005. The footprint of the FOV of UAVSpec looking vertically on the reference panel was about 3 cm during calibration, therefore, both the horizontal variance and deviation from Lambertian reflection of the reference panel may cause some systematic errors in the calibration of UAVSpec. The leveling of the UAVSpec spectrometer was adjusted on ground and verified during flight with a bubble level. Systematic error in view direction was suppressed by flying over test plots in opposite directions. Swaying of the helicopter increases the effective FOV of the UAVSpec to some extent, but does not introduce any systematic error.
Helicopter measurements were done one year later than the CHRIS acquisition in the same phase of vegetation growth and in very similar illumination conditions. Several studies confirm that there is almost no change of reflectance of hemi-boreal mature stands in the age range of 40-60 years. Some changes of forest spectral reflectance in different years are possible, caused by changes in moisture conditions. The comparative study of forest hyperspectral reflectance at the test site in dry (2006) and normal (2007) summer revealed changes up to 10% at some wavelengths (Kuusk et al., 2010). As the summer of 2006 was dry while in 2005 there was normal amount of precipitation, the suggested correction factors may be systematically over-estimated in all spectral bands but red bands of chlorophyll absorption. However, the possible error of 10% is substantially overestimated because the year 2007 was exceptional in the opposite way. The mean values of MODIS Nadir BRDF-Adjusted Reflectances NBAR_1 (red) and NBAR_2 (NIR) over 7×7 km area centered at our CHRIS scene in 2005-2006-2007 on the dates of our measurements are 0.0247-0.0311-0.0246 and 0.3381-0.3308-0.3022, respectively (MODIS, 2009). Thus, the difference in red reflectance between 2005 and 2006 is less than that between 2006 and 2007, and NIR reflectances in 2005 and 2006 are almost equal.

The impact of adjacency correction depends on the reflectance pattern of neighboring stands. In a homogeneous forested area the part of radiation reflected from a stand and scattered in the atmosphere is pretty well compensated by the impact of adjacent targets. In the whole CHRIS scene of the test site there are some stands which have high adjacency impact from targets of very contrasting reflectance (gravel roads, mowed grassland alongside of a dark stand). For some stands in some spectral bands the adjacency correction may reach even 15-20% of the stand reflectance.

The reflectance change due to different view angles of CHRIS and UAVSpec was corrected by numerical simulations with the reflectance model FRT. As stands of different structures have different angular dependence of directional reflectance (Rautiainen et al., 2004), some random error is added by this correction, its magnitude can be estimated only roughly. The stand-to-stand variance of the estimated calibration coefficients is caused mainly by different FOV of CHRIS and UAVSpec. In every CHRIS pixel used we have 2-3 airborne spectra, thus the total footprint in helicopter measurements is about 12 times less than the CHRIS pixel, which may cause different estimates of the mean value of a stand reflectance. The specific spectral signature of vegetated land causes some complications in vicarious calibration. The flickering of the correction factor at wavelengths of steep changes of canopy reflectance with wavelength may be the result of imperfect coincidence of binned spectral bands of the UAVSpec and CHRIS spectrometers.

7. CONCLUSIONS

The vicarious calibration of the CHRIS imaging spectrometer was performed using top of canopy reflectance of mature forest stands at Järvselja test site in Estonia. The CHRIS calibration coefficients applied for the preprocessing of CHRIS data of 10 July 2005 are too low in Mode 3 bands 4 and 18, too high in band 11, and probably too low in bands 1 and 2. Low signal levels in bands 1 and 2, and very large scattering of radiation in the atmosphere in blue bands do not allow to fully trust the correction factors for bands 1 and 2. In other bands the correction factors are close to 1 within the estimated variance and systematic errors. The updated calibration coefficients of the CHRIS sensor were applied to all three scenes (5703, 5705 and 5707) acquired over Järvselja test site on 10 July 2005.
8. ACKNOWLEDGEMENTS

The image data used in this paper have been provided by the European Space Agency, using the ESA PROBA platform and the Surrey Satellite Technology Ltd CHRIS instrument. This study was supported by research grants 6812, 7725 and 8290 from the Estonian Science Foundation, and by Doctoral School of Ecology and Environmental Sciences at Tartu University. The authors would like to thank the AERONET Federation for the availability of the data for Tõravere site.

9. REFERENCES


