A method for an accurate in-flight calibration of AVHRR data for vegetation index calculation

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A method for an accurate on-flight calibration of AVHRR data for vegetation index calculation

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ABSTRACT: A significant degradation in the Advanced Very High Resolution Radiometer (AVHRR) responsitivity, on the NOAA satellite series, has occurred since the prelaunch calibration and with time since launch. This affect the index vegetation (NDVI), which is an important source of information for monitoring vegetation conditions on regional and global scales. Many studies have been carried out which use the Viewing Earth calibration approach in order to provide accurate calibration correction coefficients for the computation of the vegetation index using the visible and near-infrared spectral channels 1 and 2 of AVHRR. In the work reported here, we present an accurate, simple and promising method using high reflective clouds as a target to calibrate the vegetation index derived from AVHRR data.

The accurate calibration of the Earth observation systems in space is now recognized as a major component of the quality of an image (see e.g. Abel 1990). The efficiency of the utilization of remote sensing data by the scientific community for the study of the global changes or by private bodies for land management and other purposes is directly related to the performances of the calibration procedures. Satellite sensors in the solar spectrum are very difficult to calibrate due to the lack of reliable on-board calibration devices. The preflight calibrations are subject to change due to the hostile environment of the sensor: outgasing, deterioration in the optronic system, variation in the spectral filter characteristics, ... Engineering responses have been brought up to this problem. Some are dealing with very sophisticated on-board calibration devices with the following drawbacks: increase in complexity, increase in weight, more demand in energy, increase in cost, possible decrease in reliability of the total system. The Earth viewing calibration approach has been recently developped as a backup solution to the possible failure or unreliability of on-board calibration devices. It is based on the knowledge of physical characteristics of some Earth phenomena as well as upon the processing of the digital imagery flowing down from the sensor itself (Koepke 1982, 1983; Fraser, Kaufman 1986; Frouin, Gautier 1987; Price 1987, 1988, 1989; Paris, Justus 1988; Teillet *et al.* 1988, 1990; Holben *et al.* 1990; Brest, Rossow 1990; Kaufman, Holben 1990). It has also been proposed as an alternative to the on-board calibration devices for the monitoring of the post-launch calibration. Such an approach has the following advantages: decrease in complexity and weight, less energy consumption, decrease in cost. Each type of approach may be phased from time to time with on-ground radiometric measurements or perfectly calibrated airborne measurements (Begni *et al.* 1986; Hovis, Knoll 1985; Smith *et al.* 1988; Gu *et al.* 1990; Hill 1990).

The radiometer AVHRR aboard the NOAA satellite series is now widely used to provide maps of vegetation index which are of high potential in vegetation studies. This index, more exactly called the normalized difference vegetation index (NDVI), is computed from the data of the visible and near-infrared channels of AVHRR once converted into reflectances. This radiometer is poorly calibrated for these channels and if not corrected, this fact prevents the generation of time-series of accurate vegetation index, which are of the highest interest in the monitoring of the vegetation for global change, for crop survey or disease warning. Many studies have been carried out which use the Earth calibration approach in order to provide accurate calibration correction coefficients for the computation of the vegetation index. Variations in time of these coefficients may be important and should be taken into account. This communication presents an accurate but still simple method to calibrate vegetation index derived from AVHRR data.

If α_i is the calibration coefficient, C_{0i} the deep space count for band i, θ_s the solar zenith angle and taking into account the solar extraterrestrial flux F_{0i}, the relation between the reflectance ρ_i derived from the spectral radiance detected by the radiometer and the integer count value on a computer tape C_i is:

$$\rho_i = \gamma_i (C_i - C_{0i}) / \cos(\theta_s) \quad \text{with} \quad \gamma_i = \alpha_i \pi / F_{0i} \quad \textbf{(1)}$$

The change in the sensor calibration r_i between the true calibration γ_i and the preflight calibration coefficient γ_i^* given on the computer tapes supplied by the NOAA is:

$$r_i = \gamma_i^* / \gamma_i \quad \textbf{(2)}$$

All the studies above-mentioned found that the deep space values did not change substantially with time and were close to the preflight values. Hence, the procedure for calibration correction only consists from the derivation of the coefficients γ_i or r_i. If ρ_i^* denotes the reflectance computed using the preflight calibration coefficient:

$$\rho_i^* = \gamma_i^* (C_i - C_{0i}) / \cos(\theta_s) = \gamma_i^* (\rho_i / \gamma_i) = r_i \rho_i \quad \textbf{(3)}$$

then the vegetation index is equal to:

$$NDVI = (\rho_2 - \rho_1) / (\rho_2 + \rho_1) = ((\rho_2^*/r_2) - (\rho_1^*/r_1)) / ((\rho_2^*/r_2) + (\rho_1^*/r_1))$$

$$= (\rho_2^* - r_{21}\rho_1^*) / (\rho_2^* + r_{21}\rho_1^*) \quad \text{with} \quad r_{21} = r_2 / r_1 \quad \textbf{(4)}$$

Hence from here on the calibration procedure for vegetation index consists in the accurate evaluation of the interband calibration by the means of the coefficient r_{21}. Some Earth's bodies present spectrally flat reflectances in the solar spectrum and the interband calibration is done by adjusting the coefficient r_{21} so that the ratio of the spectral reflectances observed over these targets is equal to 1, if other atmospheric effects can be corrected or do not change this ratio. Clouds, ocean sunglint and some deserts are such bodies. The very reflectance of the cloud is spectrally constant in most of the solar spectrum. Such a property is often used in procedures for cloud detection (see e.g. Saunders 1986; Saunders, Kriebel 1988; Wald *et al.* 1991). Moreover clouds are very frequent in satellite imagery and this renders an operational procedure possible. In the present study emphasis has been put on the clouds over the ocean but work dealing with clouds over desertic areas is under progress.

At satellite level, the reflectance observed over a cloud is a function of the very reflectance of the cloud, the albedo of the underlying surface, the water vapour distribution of the environment in which the cloud is located, the clear-sky layer above the clouds in which molecular and particle scattering take place, and gaseous transmittance.

If the reflectance of the ground is large enough with respect to the optical depth of the cloud, some of the spectral variations in reflectance observed at satellite level are due to the spectral variations of the ground reflectance. Also multiple reflections between the ground surface and a highly reflective cloud base may become important. Reflectances have to be corrected for ozone absorption if necessary. The decrease of the atmospheric diffuse reflectances as the wavelength increases is somewhat balanced by the increase of the diffuse transmittance and of the cloud reflectance. Water vapour absorption is not negligible for AVHRR 2 and helps maintening the reflectance to a more or less constant level.

In order to check the feasability of an accurate interband calibration of AVHRR data over clouds, the ratio of simulated AVHRR 2 reflectances to simulated AVHRR 1 reflectances is computed for different atmospheres and cloud parameters. Interband calibration is possible if this ratio is equal to 1 or very close to it. The radiative transfer model of Justus, Paris consists of two clear layers sandwiching a plane-parallel cloud layer. Clear-sky optical effects are treated with modified Beer - Bouguer - Lambert's law relationships and cloud optical effects are treated with the delta-Eddington method. It is fully described in Justus, Paris (1987), Paris, Justus (1988) and Justus (1989). This model does not provide bi-directional reflectances and the outputs are albedos. These albedos are equal to the reflectances observed at satellite level for vertical sighting of the scene.

Attention has been paid to the influence of the viewing angle on the ratio. The reflectance of the cloud may be seen as a function of the sun zenithal angle, the viewing angle and the optical thickness defined for a vertical path. As cloud thickness increases, the original direction of the incoming beam is lost due to multiple scattering events and the reflectance of the cloud tends towards isotropy. A simple model (Eq. 8 in King *et al.* 1990) indicates that for the wavelengths 503, 673, 744 and 866 nm, the variation in reflectance with the viewing angle decreases as the optical thickness increases but still amounts to about 2 % for an optical thickness of 100 and across the field of view of AVHRR. However, the ratios of the reflectances at these wavelengths to the reflectance at 503 nm do not vary in an appreciable way with the viewing angle, even for weak optical depth. Hence the influence of the viewing angle on the interband calibration is negligible.

The Paris, Justus model has been ran for various combinations of the input parameters. Since this model defines an atmosphere by the ozone and water vapour contents, the air temperature at ground level and its lapse rate, the pressures at ground level and tropopause, some modifications of the typical values given for each standard atmosphere are possible. The influence of the error in measuring ozone upon the interband calibration can thus be assessed for example.

It appears that with respect to the scope of the study, the most important among the various parameters are the optical depth and the altitudes of the base and top of the cloud. Under reasonable conditions, some clouds may serve as targets for interband calibration. In particular the clouds must have a large optical depth but too much reflective clouds (*i.e.* very large optical depths) are not suitable. Reasonable changes in the granulometry of the cloud have little effects on the interbande calibration for such clouds. These conclusions guide the processing of AVHRR data and also serves as an help to understand the results given by the image processing.

The AVHRR images used in this study are for the satellite NOAA-9. Three sets of data have been processed:

- data from the archives of CNES. They are covering France and include parts of the gulf of Biscay and the gulf of Lion. These 41 images are superimposable and are for a period ranging between April and October 1988;

- GAC data (University of Lille). These 10 images cover parts of the gulf of Benin. Period is April 1985;

- LAC data (University of Lille). These 14 images cover parts of the Pacific ocean off the Canadian coast. Periods are March 1986 (4 images), March 1987 (5 images) and March 1988 (5 images).

A first processing of all the three data sets has been made in the following way:

- calibrate digital counts into reflectances according to the NOAA recommendations and to the corrections proposed by Kaufman, Holben (1990);

- reject non ocean pixels;

- reject pixels which reflectance is lower than 0.65 in channel AVHRR1. This correspond to a typical optical depth of 25 (see e.g. King 1987);

- compute at each pixel the ratio of the reflectance in channel 2 to reflectance in channel 1;

- compute the statistical distribution of this ratio for the scene and derive the mode, the mean and the standard deviation.

The detailed results are not given here. In table 1 are reported some synthetic results. The mean ratios obtained for each scene within a set of images compose new data sets. From these sets are extracted mean, standard deviation, minimum and maximum.

data set	mean	standard deviation	minimum	maximum
Benin	1.04	0.04	0.95	1.10
Pacific (all)	0.95	0.02	0.89	0.98

Pacific (1988)	0.95	0.02	0.92	0.98
France	1.01	0.03	0.95	1.06

Table 1 Statistical parameters for the image sets.

Examinations of the images and of the climatic conditions demonstrate that the various values strongly depend upon the type of cloud and of its optical depth. These conclusions are sustained by numerical simulations. The Benin data set contain many convective clouds which optical depths are greater than 100. The top of such highly-reflective clouds is at high altitude. The numerical simulations for tropical atmosphere indicate that in that case the ratio AVHRR2 / AVHRR1 should be greater than 1 and increases as the optical depth or the altitude of the cloud-top increases. The Pacific data set as well as the France one contain different clouds. Many of them are of lower optical depth. In that case, the model predicts lower typical values for the ratio which are in accordance with the 0.95 found for Pacific. In that case, too, the ratio increases as the optical depth or the altitude of the cloud-top increases. The different mean value given for France (1.01) can be explained by the fact that the 15 images processed have been selected for the large amount of cloud coverage they exhibit (greater than 70 %) and hence, they may present many clouds with high albedo for which the ratio is close to 1.

As Table 1 clearly states it, an algorithm must be devised which selects within an image the clouds which are appropriate for interband calibration. This algorithm is based upon the results of the numerical simulations. These results can be expressed under the form of criteria dealing with the density of probability of the visible reflectances of clouds. They express the fact that only clouds of medium reflectivity are an ideal target. They have been completely defined by the analysis of the cloudy AVHRR images. Optical thicknesses of appropriate clouds are comprised between 10 and 70. However within a cloud field optical properties may fluctuate strongly and it is necessary to investigate the density of probability of the reflectance of clouds. For example, very bright clouds may have portions of lower reflectance, which will be considered as clouds of medium reflectivity but which are still inappropriate for the calibration procedure. Thus the probability of having very bright clouds must not be too large. Similar reasoning holds with low reflectance clouds which exhibit bright portions. If too much such clouds are present, the sample of pixels representing the medium reflectivity clouds is corrupted. Indeed the density of probability should be fairly large for medium reflectances. In the following, the density of probability is approximated by the means of the histogram of the cloudy pixels.

Therefore the selected algorithm puts conditions on the pixel populations of medium reflectances, and is the following:

- calibrate digital counts into reflectances according to the NOAA recommendations and to the corrections proposed by Kaufman, Holben (1990);
- reject non ocean pixels;
- reject pixels which reflectance is lower than 0.4 in channel 1. The number of remaining pixels is somewhat arbitrarily called number of cloudy pixels;
- define five classes of reflectances: 0.4-0.5; 0.5-0.6; 0.6-0.7; 0.7-0.8; 0.8-0.9. Typical cloud optical thicknesses are respectively 10, 15, 20, 30, 70 and 200. Define a sixth class which lower limit is 0.4 and the higher limit, the highest reflectance a cloud can take (here arbitrarily set to 2.0 for sake of simplicity). Said differently, this class contains all the cloudy pixels;
- compute the histogram of the channel 1 reflectances of the cloudy pixels by scanning the image;
- the first four classes must contain at least 250 pixels when summed up, an arbitrary number ensuring some kind of statistical significance. Otherwise reject the scene;
- each of the second, third and fourth classes must contain at least 10 % of the population of cloudy pixels (ensure that medium reflective clouds are significantly represented). Otherwise reject the scene;
- the first class must not contain more than 20 % of the population of cloudy pixels (not too much low reflective clouds). Otherwise reject the scene;
- the mean channel 1 reflectance of the cloudy pixels must not be greater than 0.7 and the lower limit of the most populated class must be less than 0.7 (not too much bright clouds). Otherwise reject the scene;

- compute at each pixel entering one of the four first classes, *i. e.* for which the channel reflectance is comprised between 0.4 and 0.8, the ratio of the reflectance in channel 2 to reflectance in channel 1;
- compute the mean value of these ratios and the standard deviation.

Only a few scenes meet these requirements, all for NOAA-09. Unfortunately, it was not possible to process the Benin data set in that way. For the Pacific region, one scene is for 1985 (julian day 270), the other for 1986 (julian day 259). For both dates, the ratio is equal to 1.01. For the France data set (summer 1988), six scenes are suitable. The ratio ranges from 0.98 to 1.00 with a mean value equal to 0.99. Within these scenes, the suitable clouds have been identified as being a very widespread layer of low clouds, stratus and stratocumulus. If temperature observed in AVHRR4 is related to standard vertical profiles of temperature and pressure, the altitudes of the top of these clouds are mostly comprised between 2 and 3 km, and range from 1 to 6 km. Rain may be observed under these clouds.

The difference in ratio between the two data sets of Pacific and France and also within a same data set is slight. It is at maximum equal to 0.03 (from 0.98 to 1.01) and is close to the error claimed by Kaufman, Holben (1990) which is 0.05. Drifts with time in gain of the AVHRR sensor which are not accurately enough corrected may partly explain this difference. The standard deviation within a single scene ranges between 0.01 and 0.03. Considering the data set composed of the eight mean ratios independently of location and year, its mean is 0.99 and its standard deviation is 0.01.

The effects of viewing angle have been examined by processing portions of images and have been found negligible if any. This confirms the theoretical findings.

CONCLUSION

From these results, it can be concluded that the interband calibration of AVHRR data is possible using clouds as targets. Following the procedure described above (without using the corrections proposed by Kaufman, Holben (1990) and adjusting the coefficient r_{21} so that the mean ratio is equal to 1, it has been demonstrated that an accuracy (r.m.s) better than 5 % can be achieved in a simple way.

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