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In-flight interband calibration of the AVHRR data by a cloud-viewing technique

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ABSTRACT: A significant degradation in the responsivity of the AVHRR radiometers aboard the NOAA satellite series, affects 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. This study deals with the interband calibration of AVHRR visible and near-infrared data by means of an cloud-viewing technique. This technique is simple to implement and can be used in real-time. It is also well-suited to the processing of large time-series of data. Results are presented for various NOAA satellites and are in full agreement with the calibration degradation model proposed by NOAA and various authors.

1 INTRODUCTION

The visible and near-infrared data (channels 1 and 2) of the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA satellites are widely used in quantitative applications in vegetation studies by means of the Normalised Difference Vegetation Index (NDVI). The AVHRR instrument is not equipped with on-board calibration of channels 1 and 2. Degradation of the responsivity of these channels cannot be accounted for and comparison of data between years cannot be done. Successive AVHRR radiometers may even induce discontinuities in time-series of NDVI. It 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, easy-to-use method to calibrate vegetation index derived from AVHRR data.

The Earth viewing calibration approach has been recently developed 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 (see e.g. Abel 1990).

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:

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

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

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

All published studies (see e.g., Abel *et al.* 1990; Rao 1990; Rao, Chen 1994) found that the deep space values did not change substantially with time and were close to the pre-flight 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 pre-flight calibration coefficient:

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

2. THE CASE OF THE VEGETATION INDEX

The true vegetation index NDVI is equal to:

$$\begin{aligned} \text{NDVI} &= (\rho_2 - \rho_1) / (\rho_2 + \rho_1) \\ &= ((\rho_2^*/r_2) - (\rho_1^*/r_1)) / ((\rho_2^*/r_2) + (\rho_1^*/r_1)) \\ &= (r_{12}\rho_2^* - \rho_1^*) / (r_{12}\rho_2^* + \rho_1^*) \quad (4) \end{aligned}$$

with $r_{12} = r_1 / r_2$

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_{12} .

3. CLOUDS AS TARGETS FOR CALIBRATION

Some Earth's bodies present spectrally flat reflectances in the solar spectrum and the interband calibration is done by adjusting the coefficient r_{12} 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 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.

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. Such cases must be avoided and only clouds over ocean areas should be examined, out of the sunglint area.

Asmami, Wald (1993) examined the potentials of the cloud-viewing technique for the interband calibration and for various instruments, with special emphasis on the calculation of the NDVI vegetation index. They analysed NOAA-9 data over several parts of the world ocean, and used the radiative transfer model of Paris, Justus (1988) for a cloudy atmosphere in order to guide the processing and help

in understanding the results. 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 interband calibration for such clouds. Attention has been paid to the influence of the viewing angle on the ratio; it was found that the influence of the viewing angle on the interband calibration is negligible. From their findings, it appears feasible to use reflectances observed at satellite level over clouds for interband calibration, at least for the spectral bands not located in oxygen or water vapour absorption windows.

They proposed a method for the particular case of the AVHRR sensor, which they calibrated against the calibration degradation model proposed by Kaufman, Holben (1993), for eight NOAA-9 images, most of them acquired in summer 1988. While they should have found a value of 1.0, they found 1.01 with a standard-deviation of 0.01. The accuracy was similar to that claimed by Kaufman, Holben (1993).

The effects of viewing angle upon the correction factor r_{12} have been examined by processing portions of images and have been found negligible if any. This confirms the theoretical findings (see also King *et al.* 1990).

4. AN ALGORITHM FOR INTERBAND CALIBRATION

The Asmami, Wald method is the core of the proposed algorithm. It has been slightly improved and constraints have been added to increase reliability and robustness for a better operational implementation. The algorithm selects within an image the clouds which are appropriate for interband calibration. It is based upon the results of the numerical simulations and is made up of a set 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 NOAA-9 images. Optical thickness of appropriate clouds is comprised between 10 and 70. 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.

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 algorithm puts conditions on the population of ocean pixels of medium reflectances. It applies to cloudy pixels, and is the following:

- 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 thickness is respectively 10, 15, 20, 30, 70 and 200 (see e.g. King 1987). Define a sixth class which lower limit is 0.4 and the higher limit, the highest reflectance a cloud can take. This class contains all the cloudy pixels, having a reflectance greater than 0.4. This constitutes the population of 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. This ensures 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, that is 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, that is 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 1 to reflectance in channel 2;
- the mean temperature for these same pixels should be less than 260 Kelvin. This prevents non-cloudy high reflective ocean pixels to corrupt the results. Otherwise reject the scene;

- compute the mean value of these ratios.

This algorithm contains a number of limits of classes and some other numbers, which have been defined from the analyses of Asmami, Wald. It has been checked that a relative change of 10 % of these values does not induce noticeable change on the assessment of the correction factor r_{12} .

5. RESULTS FOR VARIOUS SATELLITES

The above algorithm was tested in a number of cases, covering various areas (Northern Pacific ocean, tropical Atlantic, Gulf of Biscay, Western and Eastern parts of the Mediterranean sea, Barents sea). It was implemented in routine operations, some of them outside Ecole des Mines de Paris. These operations provide correction factors which were then sent to me. Many thanks are due to the company GM-Images which supplied many of the results. It should be noted that these routine operations were all aiming at the mapping of the sea surface temperature, and that they mostly used cloud-free scenes. This impeded a continuous assessment of the correction factor.

For NOAA-7, -9, and -11, when several computations of the correction factor r_{12} have been made over a period of 50 days, they are averaged over this period before reporting in Figures 1 to 3. Otherwise, the single value is reported. For the other NOAA satellites, since the number of assessment is very limited (3 or 4), the values are reported in Tables 1 and 2.

In the Figures, our approach is called the 'cloud method'. The assessments made by this method are compared to the models proposed by Kaufman, Holben (1993), and Rao, Chen (1994), and to other assessments made by Teillet *et al.* (1990), Justus (1989), Santer *et al.* (1991), and Vermote, Kaufman (1995). It should be noted that the last three methods are also using clouds, but highly reflective ones for the last two methods.

The 'cloud method' provides assessments which are in very good agreement with the others. The correction factors are most often less than those of Vermote, Kaufman (which are most often the highest). They are very close to the model of Rao, Chen, and close to that of Kaufman, Holben, despite the fact that the latter was used by Asmami, Wald to establish that method.

The deviation of the correction factor r_{12} from 1.0 is large and varies in time, often decreasing as the time since launch increases. This means on the one hand that time-series of NDVI should be corrected for the degradation of the calibration of the AVHRR instruments, and on the other hand, that periodic assessments of this correction factor r_{12} should be made.

6. PRACTICAL IMPLEMENTATION

This method is composed of a few elementary operations and can be easily implemented. If a cloud detection procedure is applied, then these clouds can be automatically screened and when suitable the interband calibration is computed. But it will also work by using a simple threshold to detect cloud (reflectance should be greater than 0.4 over the ocean for a pixel to be declared as cloudy).

Given an AVHRR image containing five channels of raw data, the practical implementation can be the following:

- convert raw digital numbers of channels 1 and 2 into albedo by means of the standard NOAA procedure using the pre-flight calibration values: γ_i and C_{0i} ;
- convert albedo into reflectance ρ_i^* , by dividing the albedo by $\cos(\theta_s)$, where θ_s is the solar zenith angle. Actually, one should take into account the daily correction of the distance from the earth to the sun, but it is not necessary here;
- reject non-ocean pixels;
- avoid sunglint (see e.g., Wald, Monget 1983) or simply use only pixels for which the viewing direction (azimuth) is close to the sun direction. In the case of an afternoon overpass of the satellite, keep only pixels located in the eastern part of the swath. This step is not mandatory, because the test on the mean temperature avoids such cases. However it may corrupt the statistics of the population of medium to high reflectances, and a scene may be rejected while it contains suitable clouds;
- reject pixels which reflectance is lower than 0.4 in channel 1. The remaining pixels are 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;
- define a sixth class which lower limit is 0.4 and the higher limit is arbitrarily set to 2.0 for sake of simplicity. This class contains all the cloudy pixels and hence provides the population;
- 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. Otherwise reject the scene;
- each of the second, third and fourth classes must contain at least 10 % of the population of cloudy pixels. Otherwise reject the scene;
- the first class must not contain more than 20 % of the population of cloudy pixels. 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. Otherwise reject the scene;

- compute at each pixel entering one of the four first classes, the ratio of the reflectance in channel 1 to reflectance in channel 2;
- compute for these same pixels the mean temperature. This temperature should be less than 260 Kelvin. Otherwise reject the scene;
- compute the mean value of these ratios. This provides the quantity r_{12} ;
- compute the NDVI according to Equation 4.

7. 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, it has been demonstrated that an accuracy (rms.) better than 5 % can be achieved in a simple way. The method is made up of elementary procedures, and has been proven to be robust. It has been implemented in routine operations, and has given reliable and accurate results without the help of an operator. The method was developed using a few images of NOAA-9 in summer 1988, and has been applied to various satellites, from TIROS-N to NOAA-11.

The deviation of the correction factor r_{12} from 1.0 is large and varies in time, often decreasing as the time since launch increases. This means on the one hand that time-series of NDVI should be corrected for the degradation of the calibration of the AVHRR instruments, and on the other hand, that periodic assessments of this correction factor r_{12} should be made.

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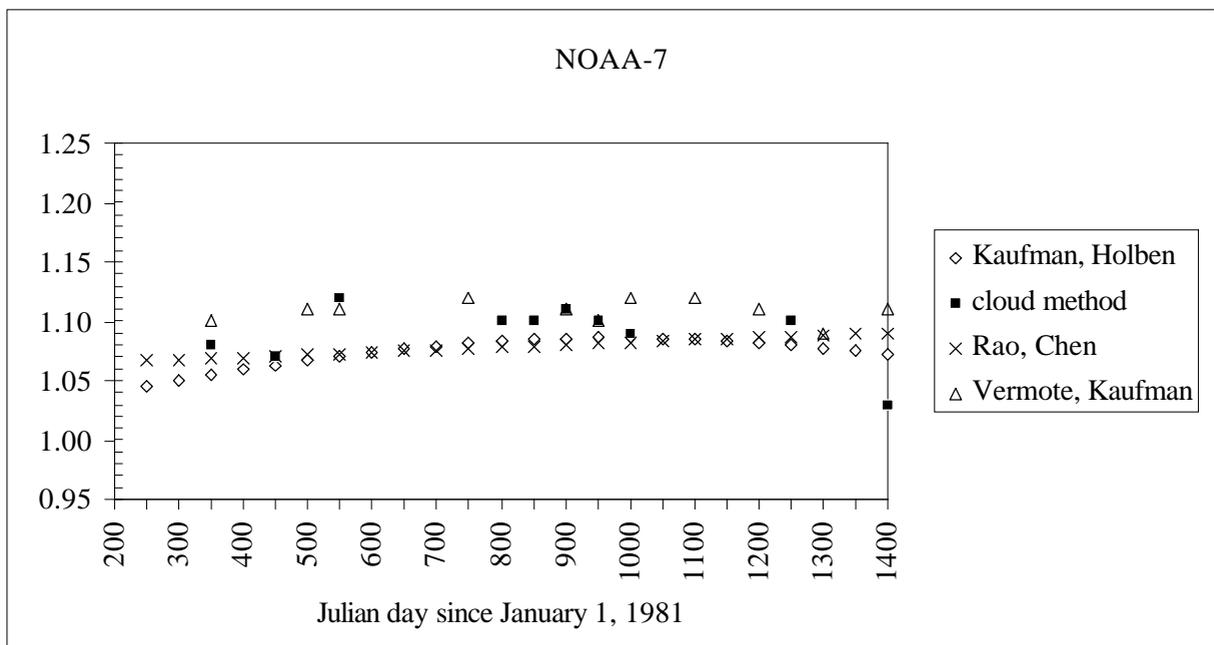


Figure 1. Correction to the ratio of AVHRR channel 1 to channel 2 for NOAA-7. When computed with the pre-flight values, this ratio should be multiplied by this correction factor r_{12} . The results of the cloud method are compared to the models of Kaufman, Holben, and Rao, Chen, and also to other results.

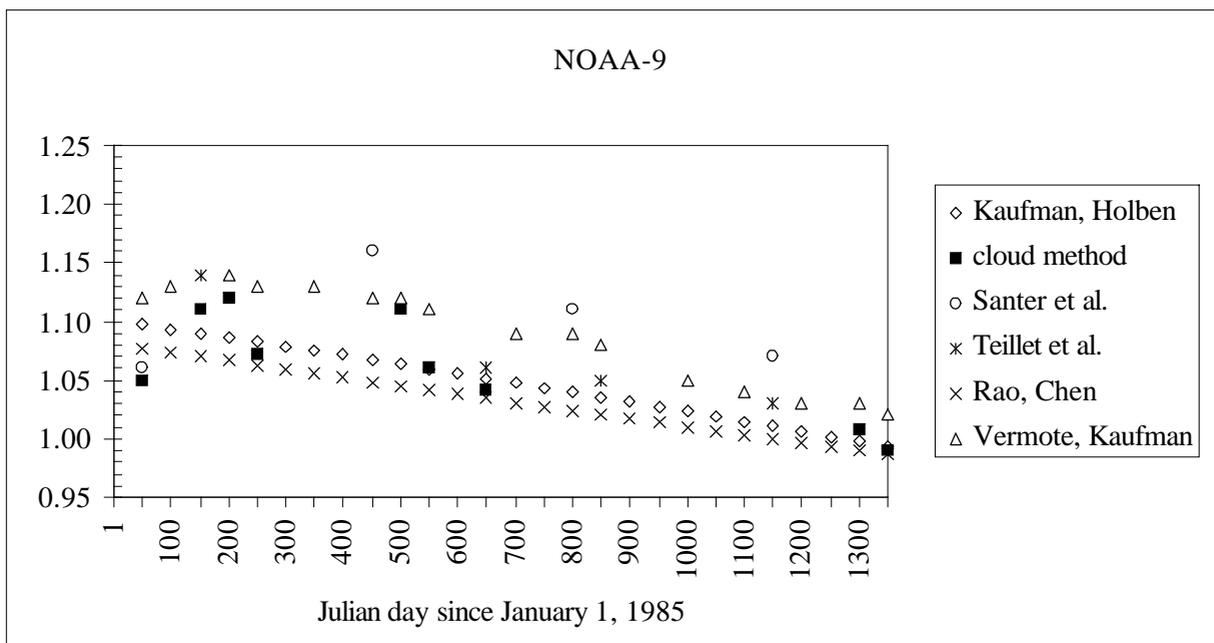


Figure 2. As Figure 1, but for NOAA-9

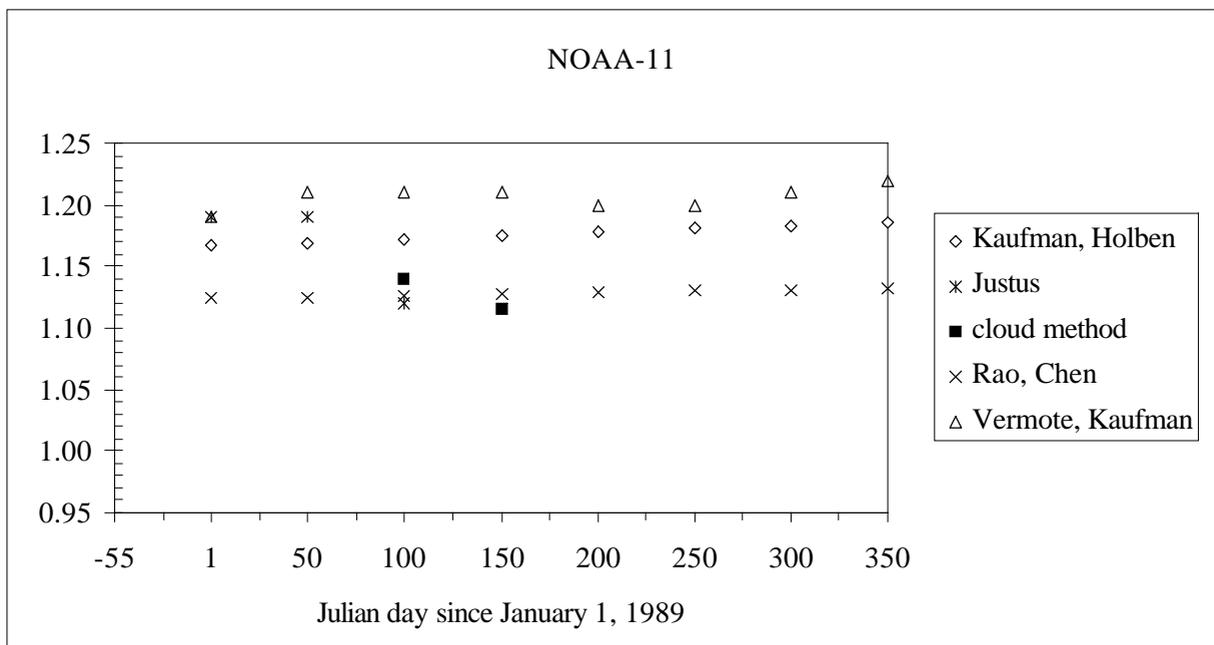


Figure 3. As Figure 1, but for NOAA-11.

TIROS-N		
Year	Julian day	Correction factor
1979	27	0.93
1980	162	1.15
1980	262	1.15

NOAA-6		
Year	Julian day	Correction factor
1979	278	1.14
1980	213	1.15
1982	183	1.10
1986	123	1.16

Table 1. Correction values to the ratio of AVHRR channel 1 to channel 2 found for TIROS-N, and NOAA-6, for several days, using the cloud method.

NOAA-8		
Year	Julian day	Correction factor
1983	262	1.17
1983	266	1.11
1985	192	1.22

NOAA-10		
Year	Julian day	Correction factor
1988	254	1.12
1988	264	1.10
1988	264	1.13

Table 2. As Table 1, but for NOAA-8, and NOAA-10.