Relationship between atmospherically corrected normalized vegetation index and split-window brightness temperature difference

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Abstract: Estimates for atmospheric effects in the visible, near infrared and thermal infrared channel data from the Advanced Very High Resolution Radiometer (AVHRR/2) have been made. Raw and atmospherically corrected normalized difference vegetation indices (NDVIs) are found to be highly correlated with a squared correlation coefficient ranging from 85 to 99% and there is a contrast enhancement of about 2 to 3 when NDVIs are computed after the application of atmospheric correction. There is no unique relation between raw and atmospherically corrected NDVIs. Therefore, atmospheric correction should be applied on an individual scene basis.

Examination of a relationship between atmospherically corrected temperature differences in the split-window channels and NDVIs revealed that for certain locations these two parameters are uncorrelated and for some areas they are partially correlated, the squared correlation coefficient ranging from 0 to about 50%. This implies that these two parameters contain partly the same and partly different information about the land surface cover. Therefore, there seems to be a possibility of improving land-use land-cover classification by using these parameters instead of raw NDVIs alone.

1 Introduction

The Advanced Very High Resolution Radiometer AVHRR/1 is an older type 4-channel instrument which was first flown on the TIROS-N satellite. The later version, sometimes referred to as AVHRR/2, has five spectral bands alias channels. Table 1 shows the spectral characteristics of these instruments. In addition to TIROS-N, the AVHRR/1 has been flown on even series of NOAA satellites starting on NOAA-6 and AVHRR/2 has been included in odd numbers of NOAA satellites since June 1981 when it was flown on NOAA-7 (Needham, 1983). When the first version of the instrument was flown on TIROS-N in 1960 the main objective had been to study and monitor climate and weather. With advancing technology the radiometer improved to VHRR and then to AVHRR. The data from these recent instruments (i.e. AVHRRs) have been useful not only for meteorology, these data have been found to be of immense value for studying and monitoring the properties of the Earth's surface, for example, obtaining sea-surface temperatures with high relative accuracies (better than 0.5 deg K), detecting and monitoring thermal fronts, locating upwelling areas, estimating photosynthetically active vegetation on the land surface, detecting water pollution, dust storms, heat sources, etc.
TABLE 1
AVHRR/1 and AVHRR/2 spectral characteristics

<table>
<thead>
<tr>
<th>Channel/Band</th>
<th>AVHRR/1†</th>
<th>AVHRR/2‡‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58 - 0.68*</td>
<td>0.58 - 0.68</td>
</tr>
<tr>
<td>2</td>
<td>0.725 - 1.1</td>
<td>0.725 - 1.1</td>
</tr>
<tr>
<td>3</td>
<td>3.55 - 3.93</td>
<td>3.55 - 3.93</td>
</tr>
<tr>
<td>4</td>
<td>10.5 - 11.5</td>
<td>10.30 - 11.30</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>11.50 - 12.50</td>
</tr>
</tbody>
</table>

* 0.55-0.90 \(\mu m\) on Tiros-N satellite
† Tiros-N, NOAA-6, 8, 10 satellites
‡‡ NOAA-7, 9 satellites

The fifth channel in the AVHRR/2 (now channel-4 and channel-5 are called split-window channels) was included primarily for gaining a better split-window channels was included primarily for gaining a better understanding of sea-surface temperature (SST) field in terms of its absolute accuracy. This is because according to theoretical calculations for atmospheric transmittance there should be differential atmospheric attenuation properties inherent in the split-window channel data and this information would be valuable in applying atmospheric corrections to these data for the determination of SSTs. However, split-window channel data are finding other interesting applications over the land, for example, detection of thin cloudy pixels, rock type detection (see, proceedings of 2nd AVHRR data users meeting, 1986, 15-16 April, RAL, abstracts only), and potential use in land-use land-cover classification Singh (1986a). These applications are based on the physical assumption that the emissivity of surface material should be a function of wavelength. Since the actual surface temperature is a sensitive function of emissivity, the brightness temperatures (using unit emissivity) calculated from the split-window channel data and their differences for a given pixel should contain information about the wavelength dependence of emissivity. Therefore, this differential temperature should be useful in identifying different surface cover types.

The visible channel-1 and near infrared channel-2 data from the AVHRR instruments have been regularly used for mapping and/ or monitoring vegetation index (for example, see Hayes and Cracknell, 1986, Justice et al. 1985, Schneider and McGinnis, 1982, Townshend and Tucker, 1985). The rationale behind this application is that photosynthetically active vegetation absorbs solar irradiation having wavelength which lies within channel-1 spectral band width whereas it strongly reflects channel-2 wavelengths. The smaller the absolute difference of reflectivities in channel-1 and channel-2, the smaller is the amount of vegetation. This difference increases with the amount of vegetation with the exception of dense forests for which this difference tends to saturate.

Several relations have been proposed and examined for vegetation mapping (for example, see Curran, 1980, Hayes, 1985).
At present the most routinely used relation with the AVHRR data is the so-called Normalized Difference Vegetation Index (NDVI) which is defined as

\[
\text{NDVI} = \frac{\text{DN2} - \text{DN1}}{\text{DN2} + \text{DN1}} \quad (1)
\]

where DN1 and DN2 are digital count values in channel-1 and channel-2, respectively. Because of band ratioing nature of equation (1) there should be a partial compensation for satellite data contamination due to atmospheric effects as well as for certain defects, such as the effect of solar elevation, solar irradiance on the surface, topography (Justice et al., 1985). This is the primary reason for routine use of equation (1). The reason for equation (1) not being able to correct completely for various effects which contaminate remotely sensed data and which have just been cited, is that the effect of each cause in channel-1 data is not proportional to that in channel-2 data. Holben and Justice (1981) indicate and Holben (1985) shows that the band ratioing approach as used in equation (1) does not remove atmospheric effects completely. Also, there is nothing like a perfect Lambertian surface; the AVHRR uses a large cross-track scan swath angle of ±55.4 degrees and Duggin et al. (1982) show that there is a large variability in NDVI with the swath angle. They attribute this drawback in NDVI values to the non-Lambertian nature of real surfaces and to the Sun-target-sensor geometry. Singh and Cracknell (1985) conclude that the above effect in NDVI is due to yet another cause, that is, due to natural or man made surface topography.

Mapping and/or monitoring vegetation index using data from meteorological satellites have been carried out on a local scale (Hayes and Cracknell, 1986, Schneider and McGinnis, 1982), on continental scale (Townshend and Tucker, 1985) as well as on global scale (Justice et al., 1985). The NDVI values have also been used in an attempt for land-use land-cover classification (for example, see Norwine and Gregor, 1983, Townshend and Tucker, 1985). It has been observed that several land-cover types have the same value of vegetation index (Townshend and Tucker, 1985). Therefore, land-cover classification using NDVI values alone is expected to have limited success. Because of atmospheric, solar irradiation, topographic and solar elevation effects on the NDVI values, one would expect to obtain different NDVI for the same surface (on the same day) when the surface is viewed under different Sun-target-sensor geometric conditions. It has not yet been possible to correct NDVI values for these effects completely. Therefore, vegetation maps should give only a qualitative, nevertheless valuable, impression. Similarly, vegetation classification using NDVI is in its infancy.

Singh (1986a) shows that there might be a possibility of extracting more than one (i.e. NDVI) parameter from the AVHRR data and the information content in these parameters could complement and supplement each other for improving the accuracy of land-use land-cover classification. Goward et al. (1985) have demonstrated by using Heat Capacity Mapping Mission (HCMM) satellite data from thermal infrared channel (10.5-12.5 μm) that...
the thermal channel data are inversely but partially correlated to the surface greenness and they propose a new satellite for vegetation index-thermal emission information in land energy and mass balance studies on a finer scale than could be obtained from the AVHRR data. Witt et al. (1985) show the capability of thermal channel data for improving land classification accuracy by merging HCMM and Landsat-MSS (multispectral scanner) data over a large and diverse metropolitan region with man-made and natural cover types.

To improve accuracies in vegetation mapping, monitoring and classification over the accuracies obtainable from the use of NDVI alone one would like to have more parameters which are either uncorrelated among themselves or partially correlated. Note that if two or more parameters are highly correlated among themselves then they carry the same information. Under such circumstances the reliability of an algorithm will not improve by the addition of a highly correlated parameter. Toll (1985) presents such an example by using Landsat-Thematic Mapper (TM) data. The motivation behind this work is, therefore, to outline a possible way of reducing uncertainties in vegetation mapping, monitoring and classification. To do so, first an estimate of atmospheric corrections to visible, near infrared and split-window channel data will be made. Then, in search for an additional parameter, a relationship between split-window channel brightness temperature difference and atmospherically corrected NDVI will be examined.

2 Atmospheric correction procedure

A way of applying atmospheric corrections to channel-1 and channel-2 data from the AVHRR instrument has been presented by Singh and Cracknell (1986). For making an estimate of atmospheric effects in the thermal infrared data, an approach of Singh (1984, 1986a) has been followed. For completeness these procedures are summarized below.

2.1 Atmospheric correction to channel-1 and channel-2 data

The satellite-sensor recorded radiance, \( L(\lambda) \) in units of mW/(cm²srμm) is calculated from (Hughes and Henderson-Sellers, 1982 and Singh and Cracknell, 1986)

\[
L(\lambda) = 0.1 \cos \theta_s K e(\lambda) [G-DN+I]
\]

where \( \lambda \) simply designates the spectral channel centred at wavelength \( \lambda \), \( \theta_s \) is the solar zenith angle, \( K \) accounts for changes in the Sun-Earth distance, DN is the digital count, \( G \) and \( I \) are preflight calibration parameters in units of percentage spectral slope albedo per count and percentage intercept albedo, respectively (Lauritson et al. 1979) and \( e(\lambda) \) stands for

\[
e(\lambda) = \int_0^\infty E(\lambda') \hat{e}(\lambda') d\lambda'
\]

in which \( E(\lambda) \) is the solar spectral irradiance on the top of the atmosphere at normal incidence (i.e. per unit projected area) for mean Sun-Earth distance (Thekaekara et al. 1969), \( \lambda' \) is the dummy integration variable and \( \hat{e}(\lambda) \) is the spectral response function.
which is normalized to unit. The values of relative response function are read from Lauritson et al. (1979). The contribution to satellite-sensor recorded radiance arises from the Earth-atmosphere system. If one is interested in quantitative analysis of the Earth-surface then it is intuitively clear that the atmospheric contributions to remotely sensed data should be removed. An exact atmospheric correction procedure is not yet possible. In practice, some simplifying assumptions are made, namely, (a) the atmosphere is horizontally homogeneous, (b) a photon is scattered only once, i.e. single scattering albedo is unity, and (c) the Rayleigh and aerosol atmospheres are separable. With these assumptions one writes

$$L(\lambda) = L_{pR}(\lambda) + L_{pa}(\lambda) + L_{s}(\lambda) t(\lambda, \theta)$$  \hspace{2cm} (4)

where \( p \) stands for path radiance, \( R \) for Rayleigh scattering, \( a \) for scattering by aerosols, \( L_s(\lambda) \) is the diffusely reflected surface radiance which carries desired information about the nature of surface, \( \theta \) is the zenith angle of a ray from surface being viewed to the sensor and \( t(\lambda, \theta) \) is the diffuse transmittance (Gordon et al. 1983). An expression for path radiance may be written as

$$L_{px}(\lambda) = E(\lambda) K T_o(\lambda, \theta, \theta_s) \tau_x \left[ f(\psi_{-}) + f(\rho(\lambda)) P(\psi_{+}) \right]$$  \hspace{2cm} (5)

where \( x = R \) for Rayleigh scattering processes, \( x = a \) for scattering by aerosols, \( T_o \) is the two-way transmittance through the ozone layer on the top of the atmosphere, \( \tau \) is the Rayleigh or aerosol optical thickness, \( f(\rho) \) is a function of surface reflectivity, \( \psi \) is the scattering angle, the subscripts + and - stand for, respectively, forward and backward scattering. Further assumption needed at this stage is that the Earth's surface is a Lambertian surface so that the diffuse reflectance is defined by

$$\rho(\lambda) = \pi L_s(\lambda)/E_g(\lambda)$$  \hspace{2cm} (6)

where \( E_g(\lambda) \) is the global solar irradiance on the surface whose value is not known unless simultaneous measurements are made. It is a function of solar elevation, wavelength and optical thickness. In this work we have made use of an expression presented by Singh et al. (1985) for estimating global solar irradiance. Note that the expression of Singh et al. (1985) is expected to be valid only for relatively clear sky conditions. Since that expression is based on the measurements made by Kimball (1924) there is a possibility of a better relation if measurements are made with advanced techniques and instruments.

The relations (2) to (6) are used in an iterative fashion for calculating diffuse reflectivity. Details on the iterative procedure can be found in Singh and Cracknell (1986). It should suffice to note here that the iteration converges quite rapidly, out of about twelve AVHRR sub-scenes which have been tested, most of them required only 3 or 4 iterations and the worst case needed seven iterations. The atmospherically corrected NDVI was
calculated from

$$NDVI = \frac{\rho(\lambda_2) - \rho(\lambda_1)}{\rho(\lambda_2) + \rho(\lambda_1)}$$

(7)

where the subscripts 1 and 2 refer to spectral channel-1 and channel-2 of the AVHRR, respectively. If the atmospheric correction algorithm were perfect then it would have been sufficient to define Vegetation Index (VI) as $VI = \rho(\lambda_2)/\rho(\lambda_1)$. However, the atmospheric correction method is only an approximate one. Also, it has been already pointed out in the introduction that there are many other defects or shortcomings which are present in remotely sensed data (also, see Duggin et al. 1982, Justice et al. 1985, Otterman 1983, Singh 1986a,b, Singh and Cracknell 1986 and Townshend et al. 1985). The reason for retaining the form of equation (7) similar to the form of equation (1) is, therefore, to partially compensate for those effects which are likely to be compensated.

2.2 Atmospheric correction to thermal infrared channel data

An estimation of atmospheric contributions in channel-4 and channel-5 of the AVHRR/2 data, which is summarized here, depends on the assumption of the existence of water pixels in the vicinity of land imagery of interest. The first step is to consider water pixels only and evaluate optical thickness using the relation

$$\tau(\kappa) = c_2 \cos \theta \left[ \frac{1}{T_W} - \frac{1}{T_S} \right]$$

(8)

where $\kappa$ is the inverse wavelength, $c_2$ is the second radiation constant, $T_W$ is the satellite-derived temperature corrected for non-linear responses of the sensors and for water emissivity and $T_S$ stands for atmospherically corrected sea-surface (skin) temperature. To obtain $T_S$ the method of Singh (1984) was adopted. An average value of optical thickness was calculated by considering a sizeable number of randomly distributed water pixels. This optical thickness was assumed to be the same over the land area of interest. Here we note that the atmosphere is not horizontally homogeneous and, therefore, such an approach will correct brightness temperature, $T_b$, over the land only partially. With this caution, if $T_{bs}$ represents atmospherically corrected brightness temperature (unit emissivity) for land pixel then it can be evaluated from the following relation

$$B(\kappa, T_{bs}) = B(\kappa, T_b) \exp(\tau(\kappa)/\cos \theta)$$

(9)

where $B$ is the Planck function, $\theta$ is calculated for each pixel and other symbols have the usual meanings. This procedure when applied to the data from split-window channels yields $T_{bs4}$ and $T_{bs5}$, channel-4 and channel-5 brightness temperatures, respectively. Then the differential temperature, $\Delta T$, is defined as

$$\Delta T = T_{bs4} - T_{bs5}$$

(10)
3. Data used and their quality

The AVHRR/2 data from NOAA-7 satellite which have been examined in this work were collected at 14:37 GMT on 20 August 1984 at the Dundee University satellite-data receiving station. The land area under inspection is the United Kingdom from about 50 to 55 degrees latitude. There were cloud covers on the western parts including Ireland. Water pixels were considered from the English Channel and North Sea. Because of data collection time and position of clouds there might have been some contamination of remotely sensed data by cloud shadows.

4. Data analysis and results

Raw NDVI values were calculated using equation (1) and for further analysis of channel-1 and channel-2 data only those pixels were considered for which the value of NDVI was positive. This constraint eliminates water pixels, and to a certain degree identifies cloudy pixels over water and land. The atmospheric correction procedure which has been summarized in section 2.1 was implemented. Then the atmospherically corrected NDVI were evaluated from equation (7). The atmospherically corrected split-window brightness temperature differences, $\Delta T$, were calculated according to the procedure outlined in section 2.2. These two parameters and raw NDVI were considered for further analysis. First a relation of the form

$$Y = mX + c$$

was sought between raw ($X$) and atmospherically corrected ($Y$) NDVI values. Although the selected image contained 512 scanlines with 512 pixels per scanline, because of surrounding waters and cloud covers, the actual number of analysed land pixels per scanline ranged from about 80 to 200. A line by line least squares regression analysis was performed in order to determine the values of $m, c$ and squared correlation coefficient. It was observed that the squared correlation coefficient varied from about 85% to 99%, the value of $m$ lay between about 2.2 to 3.5 and the parameter $c$ ranged from about -0.03 to -0.1. An important thing to note here is the variability in slope (and correlation coefficient) which suggests (i) the raw and atmospherically corrected NDVIs are highly correlated and yet there is no unique relationship between these two quantities implying that the atmospheric correction be applied to each scene, (ii) there is a contrast enhancement by a factor of $m$ after the application of atmospheric correction, and (iii) the atmospheric correction algorithm may not be exact. This one would have expected right from the onset because there are various assumptions involved as was indicated in the introduction. One point which is worth noting is that aerosols are highly variable. In this work an average type of continental aerosol has been used from Janza (1975) and this may not be true for the image considered. Next, the relation (11) was examined for a relationship between atmospherically corrected NDVIs ($Y$) and split-window brightness temperature difference $\Delta T$ ($X$). The squared correlation coefficient varied from no correlation to about 50% correlation and naturally there was a large variability of parameters $m$ and $c$. 

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Thus, these two quantities, \( X \) and \( Y \), carry different information about the nature of the surface when they are uncorrelated and when they are partially correlated they carry partly the same information and partly different information. Such a conclusion is drawn because Singh (1986a) shows that whenever there is a fluctuation in the NDVI curve, there exists a fluctuation in the \( \Delta T \) curve as well, but these fluctuations are not necessarily in phase at all places. Since \( \Delta T \) seems to carry some other information than the information content in NDVI, there seems a possibility of reducing uncertainties in land-cover classification by the combined use of \( \Delta T \) and NDVI. Perhaps it might be appropriate to note at this point that Singh (1986c) reported a possibility of retrieving yet other parameters from the AVHRR/2 data which were found to be poorly correlated among themselves. These parameters are the spectral reflectivities in channel-1 and channel-2 and NDVI. Thus, it seems that in all one may be able to extract four parameters, namely, \( \Delta T \), NDVI and spectral reflectivities in channel-1 and channel-2 for the studies of land surface properties. Further investigations along this line are underway.

5. Conclusions

The primary motivation of this work has been to see if it is possible to obtain more than one (NDVI) parameter from the AVHRR/2 data which are not highly correlated among themselves. As indicated in the introduction, similar efforts have already been made using the data from different satellites. A drawback of this is the collocation problem, different pixel sizes, different scan direction and possibly different imaging times. These deficiencies do not arise if many uncorrelated or partially correlated parameters can be retrieved from the same instrument, in this case from the AVHRR/2 data alone. From the work of Singh (1986c) and from the results presented in this paper it seems that there are four such possible parameters which can be extracted from the AVHRR data alone, namely spectral channel-1 and channel-2 reflectivities, atmospherically corrected values of normalized vegetation index and brightness temperature difference in the split-window channels. Use of these parameters for surface cover classification may result in a better quality product which remains to be investigated.

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References


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