NDVI Sensitivity to Atmospheric Water Vapor as a Function of Spectral Bandwidth[1]

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ABSTRACT

The Normalized Difference Vegetation Index (NDVI) has been an important data product of the AVHRR series of instruments that have flown on the NOAA polar orbiting satellites. This index has been extensively used to monitor global vegetation and to study deforestation. As planning begins for follow-on versions, a proposal has been made to improve the robustness of the index by narrowing the spectral bands that are used in the NDVI calculation to reduce sensitivity to atmospheric water vapor. Without dramatic improvements in instrument design, this narrowing will also degrade the instrument's signal-to-noise ratio. In this paper, results are presented of an investigation into the sensitivity of the NDVI to water vapor as a function of the width of the spectral bands. Consideration was also given to the increase in instrument noise. This study concluded that spectral bandwidths of around 50 nanometers centered on two water vapor transmittance windows provide sufficient insensitivity to water vapor without significantly degrading the instrument's noise performance. However, it should be noted that changing the bandwidths from the current AVHRR will complicate the use of the index for long term environmental studies by changing the values obtained for similar scenes.

BACKGROUND AND INTRODUCTION

The Normalized Difference Vegetation Index (NDVI) has been an important data product of the Advanced Very High Resolution Radiometer (AVHRR) series of instruments that have been carried by the NOAA polar orbiting satellites. The NDVI has been used to monitor global vegetation (Gatlin, et al., 1984), crop growth (Schneider and McGinnis, 1982) and to conduct deforestation studies (Malingreau and Tucker, 1987). The historical database acquired by the AVHRR has proven the utility of long term satellite data collection through these and other scientific applications.

The next generation of NOAA polar orbiting satellites (NOAA KLM) are slated for launch beginning in 1996 and will continue the collection of NDVI data with an improved version in this series known as the AVHRR/3 (Owens, et al., 1989). While the main improvement in this instrument will be the addition of a band at 1.6 μm for vegetation moisture stress and snow/cloud discrimination, improved signal-to-noise ratio's are also planned.

While this next generation has yet to be launched, planning has already commenced for the satellite series to follow. The NOAA OPQ series (Needham, 1992) has been proposed to meet the needs of operational meteorological and environmental monitoring in the next century. The imaging radiometer which will continue the collection of data for NDVI is to be known as the Visible, Infrared, Scanning Radiometer (VIRSR) and incorporates several improvements and changes from the AVHRR/3 instrument.

The specification for the VIRSR (GSFC, 1991) calls for improvements in the radiometric accuracy as well as changes in the spectral bandpasses of several of the bands. In particular, the two bands which are used in the NDVI calculation are proposed to be substantially narrower but with higher signal-to-noise ratio as compared to the AVHRR/3. These conflicting requirements will be demanding to satisfy.

A goal of reducing the spectral bandwidth of these two bands is to reduce the sensitivity of the measurements to atmospheric water vapor. Since the primary application of these channels is to measure surface characteristics, unknown and highly variable atmospheric water vapor results in "noise" and complicates interpretation of the data. This change in the bands should result in increased consistency in the NDVI measurements. However, it also will dramatically change the characteristics of the measurement and complicate the use and interpretation of the index for long term studies.

The goal of the work described here was to investigate the tradeoff between spectral bandwidth and noise with NDVI sensitivity to atmospheric water vapor as the metric. First a brief review of the NDVI is given, followed by a description of the simulation model used in the analysis. Next, the results of the water vapor sensitivity are presented as well as the impact of noise on the NDVI. Finally, the results are interpreted and summarized.

NDVI CHARACTERISTICS

The NDVI is calculated from the radiance[2] measured by two bands in the red and near infrared as shown in Equation 1.

$$NDVI = \frac{L_{NIR} - L_{RED}}{L_{NIR} + L_{RED}} \tag{1}$$

The basic concept of the index relies on the large difference in reflectance of healthy vegetation between the near infrared and the chlorophyll absorption which occurs in the red portion of the spectrum. This difference is large for surface areas consisting of vegetation but is small for other cover types which usually have less spectral variation between these bands. The difference is normalized to reduce the impact of factors that are not related to surface cover.

Examples of these factors which are not related to surface characteristics but do affect the measurement of NDVI by a satellite include atmospheric scattering and absorption, as well as variations in the illumination and viewing conditions (Holben, 1986). Instrument biases, orbital drifts and calibration problems also affect the NDVI measurements (Gutman, 1993). The impact of variations of illumination, viewing and instrument changes are beyond the scope of this study since their effects depend minimally on spectral bandwidth. The effects due to aerosol scattering vary slowly with wavelength (Kaufman, 1989) and thus are also minimally affected by changes in the bandwidth. Absorption (primarily due to water vapor) is very much spectrally dependent. Thus, for an instrument designed to measure NDVI, the specification of the bands are primarily determined by vegetation surface reflectance and atmospheric water vapor transmittance characteristics.

SCENE AND SENSOR SIMULATION MODELS

Figure 1 graphically illustrates the characteristics of the surface reflectance and atmospheric water vapor transmittance that affect the measurement of NDVI by satellite. Two examples of surface cover spectral reflectance are included. The "Mature Vegetation" curve is an example of the typical reflectance of healthy green vegetation. The "Summer Fallow" curve is for a mixture of vegetation and bare soil typical of agricultural land early in the growing season and that has been left unplanted. These examples were adopted from the LARS data base at Purdue University (Biehl, et al., 1982).

The transmittance of water vapor is also shown in Figure 1 and was calculated using the radiance/transmittance code LOWTRAN7 (Kneizys, et al., 1988). These data are for the default Midlatitude Summer case and show the spectral dependence of atmospheric water vapor transmittance.

Above the plot contained in Figure 1 are the spectral bandpasses for the proposed VIRSR, AVHRR/3 and several hypothetical visible/near infrared radiometers. The suffix for the VNIR hypothetical instruments indicates the spectral bandwidth in nanometers. The 20 nm bandwidth set corresponds exactly to the VIRSR specification. These six spectral band sets were considered in this study to understand the effect of bandwidth on the NDVI sensitivity to water vapor. All (except the existing AVHRR/3) are centered on 0.615 μm for band 1 and 0.87 μm for band 2 which are the central wavelengths in the VIRSR specification. Given the water vapor transmittance curve shown in Figure 1, it is clear that these were chosen in spectral regions of minimal water vapor absorption.

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[2] The NDVI may also be calculated from retrieved surface reflectance. However, this is only practical in situations where the atmospheric conditions are known accurately and is not applicable to global measurements.

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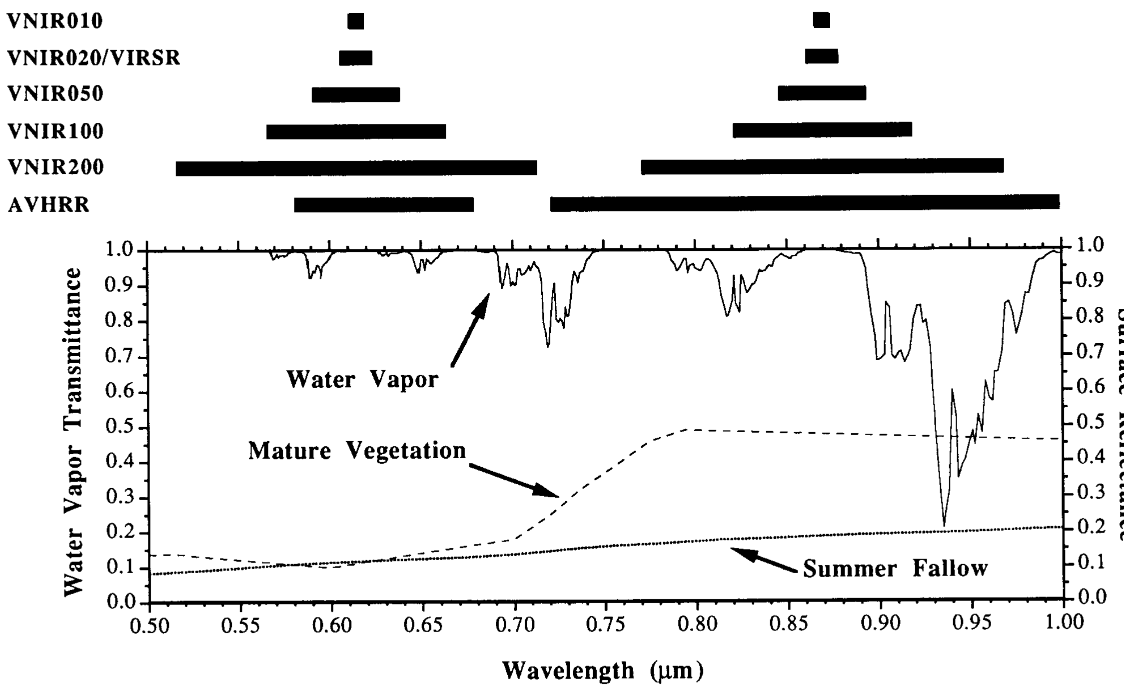

Figure 1.
Spectral characteristics of atmospheric water vapor transmittance and two surface materials. Above the graph are the spectral bandpasses for the various instrument concepts considered.

To simulate the spectral radiance incident at the satellite, a simulation model (Kerekes and Landgrebe, 1989) was adopted for this study. The model uses LOWTRAN7 and includes the spectral dependence of surface reflectance with diffuse "sky" irradiance as well as atmospheric scattered path radiance.

This model was used to simulate the spectral radiance under four conditions selected to study the NDVI sensitivity: 1) Mature Vegetation surface with "dry" atmosphere; 2) Mature Vegetation with "wet" atmosphere; 3) Summer Fallow with "dry" atmosphere; and 4) Summer Fallow with "wet" atmosphere. The "dry" atmosphere was simulated by using the default Midlatitude Winter water vapor profile in LOWTRAN7. The "wet" atmosphere was simulated by using the default Tropical water vapor profile. The total precipitable water for the "dry" case was 0.7 cm and for the "wet" case was 3.5 cm so there was a difference of 2.8 cm between the two. In all cases, the 1976 US Standard atmosphere was used for all other parameters. Rural haze with 23 km visibility, nadir viewing and the Sun at 40° zenith were other assumed parameters.

NDVI SENSITIVITY TO WATER VAPOR

The spectral radiances were simulated for the four cases described above and converted to instrument radiances using the spectral bandpasses for each of the instrument spectral band sets. These radiances were then used to calculate the NDVI as defined in Equation 1. Table 1 summarizes the results.

TABLE 1. *NDVI for the different atmospheric water vapor cases and the two surface cover materials*

Instrument	Mature Crop Dry	Mature Crop Wet	Mature Crop $\|\Delta NDVI\|$	Summer Fallow Dry	Summer Fallow Wet	Summer Fallow $\|\Delta NDVI\|$
VNIR010	0.34	0.35	0.01	-0.09	-0.08	0.01
VNIR020/VIRSR	0.33	0.34	0.01	-0.09	-0.09	0.00
VNIR050	0.31	0.31	0.00	-0.10	-0.11	0.01
VNIR100	0.27	0.21	0.06	-0.13	-0.19	0.06
VNIR200	0.18	0.11	0.07	-0.19	-0.25	0.06
AVHRR/3	0.61	0.57	0.04	0.33	0.27	0.06

This table shows the impact on NDVI from changes in atmospheric water vapor. Since the NDVI changes as a function of instrument bandwidth[3] it is difficult to compare the sensitivity by comparing actual NDVI values. However, it is clearly seen that the sensitivity to water vapor is much higher for bandwidths greater than 50 nanometers (VNIR050).

NDVI SENSITIVITY TO NOISE

The next generation AVHRR/3 is specified to have a signal-to-noise ratio of 9 to 1 in the red and near infrared channels for a surface albedo of 0.5% (Owens, et al. 1989). Assuming a source signal spectral radiance of 2.58 x 10^{-1} mW/(cm^2-Sr-µm) for band 1 and 1.50 x 10^{-1} mW/(cm^2-Sr-µm) for band 2 for these conditions (GSFC, 1991), the 9 to 1 SNR and the AVHRR/3 bandwidth result in a specified noise equivalent radiance (NEN) of 2.87 x 10^{-3} mW/(cm^2-Sr) for band 1 and 4.68 x 10^{-3} mW/(cm^2-Sr) in band 2. The results in this study assume this specification can be achieved.

In considering the effect on noise of narrowing the spectral bandpasses of the AVHRR/3 channels the assumption has been made that the noise is independent of the signal and thus the SNR varies directly with bandwidth. It is also assumed that a follow-on instrument will achieve the same noise equivalent radiance as the AVHRR/3. These assumptions, while conservative, may not be that unrealistic. Also, the results can then be interpreted as a lower bound on performance that could possibly be improved upon.

To investigate the impact on NDVI of these noise levels, random noise was added to the mean radiance values for the various instruments and the NDVI calculated from the resulting noisy measurements. Gaussian random numbers with zero mean and a standard deviation equal to the NEN quoted above were used for the noise. Table 2 shows the resulting standard deviation of the NDVI calculation based on additive noise only (scene radiance constant).

[3] This obvious result is due to the spectrally varying total radiance and the nature of the NDVI calculation. However, this emphasizes the point made earlier that a change in the spectral bandpasses from AVHRR/3 will significantly complicate the use of future data in comparisons with the existing database.

TABLE 2. *Standard deviation of NDVI due to random noise for constant scene conditions for the two surface types and two atmospheric water vapor cases.*

Instrument	Mature Crop Dry	Mature Crop Wet	Summer Fallow Dry	Summer Fallow Wet
VNIR010	0.03	0.03	0.06	0.06
VNIR020/VIRSR	0.02	0.02	0.03	0.03
VNIR050	0.01	0.01	0.01	0.01
VNIR100	0.003	0.004	0.01	0.01
VNIR200	0.002	0.002	0.003	0.004
AVHRR/3	0.002	0.002	0.003	0.004

Since the smallest change in NDVI of importance to the stratification of surface type is around 0.02 (Holben, 1986) these results show that AVHRR/3 instrument noise will not significantly affect the NDVI. However, if the spectral bandpasses of the follow-on instrument are significantly narrowed without improving the noise performance, instrument noise could become noticeable.

RESULTS

To better interpret the results of the previous two sections they have been plotted in Figure 2 as magnitude percent change as a function of spectral bandwidth. The sensitivity to water vapor is computed as 100 × the difference in NDVI for the two water vapor cases divided by the NDVI for the "dry" case. The results for the two surface cover classes were then averaged for the plot. The sensitivity to noise was computed as 100 × the ratio of the standard deviation in NDVI due to instrument noise to the magnitude of the mean NDVI value. This number was computed for all four cases of atmospheric water vapor and surface cover and then averaged for the plot. Corresponding values for the AVHRR/3 are also shown.

From this figure, a clear breakpoint can be seen around 50 nm bandwidth where the NDVI is relatively insensitive to atmospheric water vapor and the impact of instrument noise is insignificant even with the conservative assumptions made for the noise performance.

SUMMARY AND DISCUSSION

The impact on NDVI calculations of narrowing the spectral bandpasses of the red and near infrared bands of the satellite instrument has been studied as a function of their bandwidth. The NDVI was calculated for several different spectral bandpass sets using "dry" and "wet" simulated atmospheres. The sensitivity of NDVI to atmospheric water vapor was studied by comparing the result for the two atmospheres. The impact on instrument noise

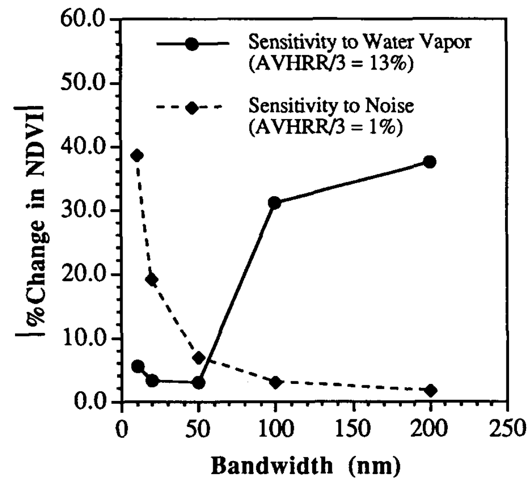

Figure 2.
Magnitude percent change in NDVI due to a change in atmospheric water vapor (solid line) and induced by instrument noise (dashed line) averaged for the two surface cover classes. Corresponding values for the AVHRR/3 are shown in the legend.

performance as a result of the narrower spectral bands was also evaluated. A reduction in NDVI sensitivity to atmospheric water vapor was obtained by narrowing the bands to 50 nanometers without significantly degrading the noise performance of the sensor, even assuming no improvement from today's technology in detector and electronics noise. A further narrowing to 20 nm does not seem to significantly reduce the sensitivity to water vapor.

It is important to note that while such a change to the instrument will improve the utility of the NDVI by reducing the impact of one source of atmospheric variation, many other factors contribute to variations in the index, and this change will not significantly affect the impact of these. In fact, previous research (Holben, 1986) has shown these other factors to be more significant (under certain conditions) than variations in water vapor. As research identifies ways to reduce the impact of these other variations, the significance of reducing the sensitivity to water vapor should be re-evaluated.

It is also important to note the vastly different NDVI simulated by the narrow band instrument as compared to the AVHRR/3 for the exact same scene. This change will complicate long-term studies without some method of cross-calibrating the old index to the new. This suggests there should be a period of overlapping data collection by the two instruments to ensure continued scientific utility.

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