Chapter 5

Retrieval of land surface parameters from satellite data

In this chapter, three studies are presented on the retrieval of land surface parameters namely, land surface reflectance, normalized difference vegetation index (NDVI) and leaf area index (LAI). The chapter is divided into three sections.

5.1 Retrieval of land surface reflectance using an atmospheric correction model for IRS data and its validation with field measurements

This section describes the retrieval of surface reflectance using a modified atmospheric correction model, 6S-code for IRS sensors. The results were validated with the surface experimental data.

5.2 Derivation of normalized difference vegetation index field over India using a physical method

This section reports development of a physical method for deriving the normalized difference vegetation index (NDVI) field for the geosynchronous satellite observations from the INSAT-3A CCD sensor. Results were compared with the NDVI obtained with the other global sensor's observations.

5.3 Leaf area index retrieval using IRS LISS-III data and validation of the MODIS LAI product over central India

This section presents retrieval of leaf area index (LAI) from the IRS LISS-III data. The IRS derived LAI were used to validate the global LAI products from MODIS sensor over Central India. Results of this study have been considered in the improvement in the MODIS LAI algorithm by NASA and Boston University research group.
5.1 Retrieval of land surface reflectance from IRS data using an atmospheric correction model & its validation with field measurement

5.1.1 INTRODUCTION

Surface reflectance is considered as the fundamental land surface parameter in remote sensing. It is the basis of all other surface parameters such as NDVI, LAI, biomass, fAPAR, NPP, NDWI, NDSI etc. The understanding of temporal variability of surface reflectance is required to obtain reliable and accurate information on the state and evolution of terrestrial environments. It is recognized as one of the key drivers of the Earth’s surface energy budget and as a suitable indicator of environmental conditions. Variables related to surface reflectance, such as albedo or surface roughness are important for climate modelling, environmental monitoring and land cover change detection and estimation (Zhao et al. 2000). Surface reflectance can be either inferred directly from ground-based instruments or satellite data. As the utility of satellite data has become more quantitative, the accurate retrieval of surface reflectance becomes increasingly important. In all these applications, a major assumption is that the reflectance response of the observed objects is indicative of their intrinsic physical and chemical properties. Unfortunately, atmospheric gases and aerosols scatter and absorb electromagnetic radiation and can, therefore, modulate the radiation reflected from the target by attenuating it, changing its spectral distribution and introducing some skylight into sensor FOV (Kaufman 1989). As discussed in chapter 3, the influence of atmosphere on the satellite measurements is quite significant, which include molecular and aerosol scattering and absorption by gases. Molecular scattering and absorption by ozone and oxygen are relatively easy to correct because their concentrations are quite stable over both time and space. The most difficult component of atmospheric correction is to eliminate effects of aerosols and WV (discussed in section 3.3). The procedure of retrieving surface reflectance or removing atmospheric contamination is called atmospheric correction. Given that optical properties of the Earth’s atmosphere are not uniform from image to image or between observation dates, corrections are needed to put multi-scene or multi-temporal satellite data on the same physical unit of reflectance in
order to monitor terrestrial surfaces over time and space. After reviewing the historical development of atmospheric correction (Liang et al. 2001), a study is presented on adaptation of atmospheric correction model for IRS sensors and retrieval of land surface reflectance from IRS data.

5.1.2 REVIEW OF THE EXISTING ATMOSPHERIC CORRECTION METHODS

Numerous investigations have dealt with empirical or analytical procedures for atmospheric corrections of satellite scenes. A summary of atmospheric correction methodologies for airborne/spaceborne data is summarized in the following table (O'Neill et al., 1995).

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of technique</th>
<th>Technique</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>Fast, simple and approximate models</td>
<td>LUT</td>
<td>Built around RT Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single scatter</td>
<td>Underestimates scattering contribution</td>
</tr>
<tr>
<td></td>
<td>Medium speed and fairly accurate</td>
<td>6S</td>
<td>Built around RT Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lowtran/Modtran</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slow, arbitrarily accurate</td>
<td>Spherical harmonics</td>
<td>Built around RT Model</td>
</tr>
<tr>
<td>Empirical</td>
<td>Reference target</td>
<td>Multi-target calibration</td>
<td>Regression with ground observations</td>
</tr>
<tr>
<td></td>
<td>Apparent Reflectance method</td>
<td>Uncorrected</td>
<td>Apparent reflectance method</td>
</tr>
<tr>
<td></td>
<td>Reference target</td>
<td>DOS (Dark object subtraction)</td>
<td>Subtraction of min. response</td>
</tr>
<tr>
<td></td>
<td>Reference target</td>
<td>DOS + COST</td>
<td>DOS with transmittance assumed as cosine function</td>
</tr>
<tr>
<td></td>
<td>Reference target</td>
<td>DDV (Dark dense vegetation)</td>
<td>Info. on AOT is obtained from DDV and then used to correct the image</td>
</tr>
<tr>
<td></td>
<td>Reference target</td>
<td>PARA (Path radiance approach)</td>
<td>Info. on AOT is obtained from path radiance from apparent reflectance and then used to correct the image</td>
</tr>
<tr>
<td></td>
<td>Relative (inter-image)</td>
<td>Radiometric rectification</td>
<td>Radiometric transformation of multi-date image grey levels to ref image</td>
</tr>
<tr>
<td></td>
<td>Relative</td>
<td>Contrast detection</td>
<td>AOT is obtained from the fact that Atmospheric scattering reduces contrast</td>
</tr>
<tr>
<td></td>
<td>Relative (inter-band) or Index based</td>
<td>ARVI (aerosol resistance VI), EVI (Enhanced VI)</td>
<td>Modified NDVI: blue band for reducing atmospherically induced variance in NDVI</td>
</tr>
<tr>
<td></td>
<td>Relative (PIF)</td>
<td>Pseudo invariant features</td>
<td>A linear relation for each band, based on the reflectance of “invariant objects” is used to normalize images acquired at different times</td>
</tr>
</tbody>
</table>

The methods reported in the literature for atmospheric correction can be roughly classified into some groups based upon the treatment involved in the technique, such as: invariant-
object methods, method of histogram matching, dark object methods, contrast reduction methods, and various sophisticated methods that make use of radiative transfer models.

**Invariant-Object Methods**

The Invariant-Object method assumes that there are some pixels in any given scene whose reflectances are quite stable. A linear relation for each band based on the reflectance of these “invariant objects” can be used to normalize images acquired at different times. It is a relative normalization. This method is simple and straightforward, but it is essentially a statistical method and performs only a relative correction. Another major limitation is its difficulty in correcting heterogeneous aerosol scattering.

**Histogram Matching Methods**

In the histogram matching method, it is assumed that the surface reflectance histograms of clear and hazy regions are the same. After identifying clear sectors, the histograms of hazy regions are shifted to match the histograms of their reference sections (clear regions). The idea behind this method is quite simple and it is also easy to implement. However, the major assumption is not valid when the relative compositions of different objects and their spectral reflectances are different. This method also does not work well if the spatial distribution of aerosol loadings varies dramatically.

**Dark-Target Methods**

The principle behind the dark target approach is that most of the signal reaching a sensor from a dark target on the surface of the Earth is contributed by the atmosphere. Image pixels from dark targets are therefore indicative of the amount of path reflectance. The dark target approach can take several forms. An early version involved the simple subtraction of the darkest digital signal levels (typically from a water target) from all pixels in the scene. While there have been refinements of this dark object subtraction technique (Chavez, 1988, 1989; Milton 1994), the approach still does not take into account atmospheric attenuation, which is a multiplicative effect, and results have been mixed. A better methodology is to use an atmospheric RT model to determine the AOT input that yields the observed dark target reflectance at the output, for a given spectral band. If a scene contains dense vegetation, SWIR band (around 2.1 μm) can be used to identify these dense vegetation pixels and their
reflectances have strong correlations with blue and red reflectances. Since dense vegetation has very low reflectance, they are referred to as “dark objects”. This method has a long history (Kaufman et al., 2000, Teillet & Fedosejevs, 1995, Kaufman et al., 1997, Kaufman & Sendra 1988, Liang et al., 1997, Popp 1995), and is probably the most popular atmospheric correction method. Both the MODIS and MERIS atmospheric correction algorithms (Kaufman et al., 1997, Santer et al., 1999) are based on this principle. The required existence of dense vegetation is a serious limitation to many land imagery. The empirical relations of SWIR and blue/red reflectances may vary under different vegetation conditions.

**Contrast Reduction Methods**

For regions where surface reflectance are very stable, the variations of the satellite signal acquired at different times may be attributed to variations of the atmospheric optical properties. Aerosol scattering reduces variance of the local reflectance. The larger the aerosol loading, the smaller the local variance. Thus, the local variance can be used for estimating AOT. This method has been successfully applied to desert dust monitoring (Tanre & Legrand, 1991, Tanre et al., 1988). Its assumption of invariant surface reflectance limits its global applications because under generally surface reflectance changes in space and time.

The methods involving physically based RT models overcome the problems associated with the existing methods discussed above. In the following, we briefly describe the procedure for atmospheric correction of IRS data that makes use of a RT model. Validation of surface reflectance with the ground-based measurements is also discussed. Our objective is not a method giving an absolute accuracy of the $10^{-3}$ in reflectance, but it is rather to achieve the goal of a RMSE about 10% in terms of surface reflectance in practical cases for IRS sensors.

5.1.3 DATA, MODEL AND METHOD USED IN THE STUDY

5.1.3.1 Study site and data used

The site considered in the study was Bareja (72° 38' E, 22° 52' N) situated at south of Ahmedabad city in the western India. The main advantage of this study site was it offers all the land surface targets (such as crop, sand, water, urban, plantation, shrubs, fallow land etc) varying in reflectance property, which is very essential for the present study. Satellite
data from sensors LISS-III* and AWiFS onboard IRS-P6 was used in the study. Two cloudless consecutive satellite passes on November 28 and December 22, 2003 were acquired for the experiment (Table 5.1.1). Surface reflectance measurements using spectroradiometer over various targets and atmospheric measurements using Sunphotometer useful in atmospheric correction on ground were performed concurrent with the satellite acquisitions.

5.1.3.2 Method used for atmospheric correction

Conversion of digital number to at-sensor radiance

The IRS images were converted to at-sensor radiance ($L_s$) from the digital number (DN) by using following expression,

$$L_s = \left( \frac{L_{\text{max}} - L_{\text{min}}}{(DN_{\text{max}} - DN_{\text{min}})} \right) \times (DN - DN_{\text{min}}) + L_{\text{min}} \quad \ldots(5.1)$$

where, $L_s$ is band-specific at-sensor radiance (W m$^{-2}$ sr$^{-1}$ m$^{-1}$);

DN is satellite quantized calibrated digital number,

$L_{\text{max}}$ is band-specific spectral radiance (W m$^{-2}$ sr$^{-1}$ m$^{-1}$) corresponding to $DN_{\text{max}},$

$L_{\text{min}}$ is band-specific spectral radiance (W m$^{-2}$ sr$^{-1}$ m$^{-1}$) corresponding to $DN_{\text{min}},$

$DN_{\text{max}}$ is maximum quantized calibrated DN ($2^N - 1$), $N$ is radiometric resolution and

$DN_{\text{min}}$ is minimum quantized calibrated DN (generally 0).

Above equation accounts for gain state (i.e. high/low setting) by using the respective $L_{\text{max}}/L_{\text{min}}$ values for IRS sensors, which are tabulated in table 5.1.2, for the study period.

Conversion of at-sensor radiance to at-sensor reflectance

After conversion to at-sensor radiance, each image was converted to at-sensor reflectance ($\rho_a$), which is also called apparent reflectance (assuming a uniform Lambertian surface under cloudless conditions) using equation 5.2.

$$\rho_a = \frac{\pi \times L_s \times d^2}{E_s \times \cos \theta_s} \quad \ldots(5.2)$$

where, $d$ is mean sun-earth distance factor in Astronomical unit and can be computed by,

$$d = \frac{1}{1 - 0.01673 \times \cos[0.9856 \times (J - 4)]} \quad \ldots(5.3)$$

where, $J$ is day of the year. The value of $d$ varies from 0.9838 to 1.0170 and could be assumed to be an average value of 1. By definition, at-sensor reflectance does not remove
atmospheric effects and so for full absolute correction, it must be converted to the surface reflectance \( (\rho_s) \) using equation 5.4 with the help of an atmospheric correction method.

\[
\rho_s = \frac{\pi * (L_s - L_p) * d^2}{T_v * (E_o * \cos \theta_o * T_s + E_d)} \quad ...(5.4)
\]

To derive values of coefficients appearing in the above equation one has to calculate several quantities such as solar irradiance at the TOA and ground, total atmospheric optical depth (including Rayleigh, aerosol etc.), gaseous transmission (including water vapour, ozone, oxygen, carbon dioxide etc.), atmospheric path radiance, single scattering albedo, extinction coefficient, spherical albedo etc. through atmospheric correction method. We have used the 6S-code for this purpose for IRS data discussed in the section 5.1.3.3.

**Field experiment**

The field experiment including surface and atmospheric measurements was carried out at Bareja site on the day of satellite acquisition. Reflectance measurements were obtained on 28 Nov. and 22 Dec. 2003 on various targets using FieldSpec HH spectroradiometer (ASD Inc., USA) and 99% reflecting spectralon panel. In total 200 spectra were averaged to obtain the reflectance values of 10 fields. A field photograph of this is shown in figure 5.1.1. The working wavelength range of spectroradiometer was 325 to 1075 nm.

![Field photograph of spectral reflectance measurements over wheat crop](image)

Figure 5.1.1 Field photograph of spectral reflectance measurements over wheat crop
It was optimized and dark current reflectance measurements were made before obtaining any measurements. A set of reflectance curves representing various surface targets used in the study is shown in Figure 5.1.2. Atmospheric measurements of AOT and WV content were carried out at the time of satellite acquisitions using Microtops-II Sunphotometer.

![Reflectance curves for different surfaces](image)

**Figure 5.1.2.** Example of measured spectra using the spectroradiometer on ground at the time of satellite pass

### 5.1.3.3 Modification and use of 6S-code for IRS sensors

The complete flow diagram showing the various steps implemented for derivation and validation of surface reflectance from IRS-P6 sensors are shown in figure 5.1.3. The satellite digital number images (figure 5.1.4) were converted to the TOA reflectance images using equations 5.1 and 5.2. The TOA reflectance images were converted to surface reflectance using a 6S RT code (Vermote et al., 1997a) in inverse mode. The original 6S-code works for several global sensors such as NOAA-AVHRR, SPOT, Landsat-TM/MSS/ETM+, Meteosat, GOES, MODIS etc., but does not support IRS spectral channels. A modification was done by incorporating the spectral and radiometric characteristics of IRS sensors, so that the code now works very well for IRS sensors also. Various inputs such AOT and WV measured synchronous to satellite acquisition time, altitude of targets, viewing geometry, climatological ozone content etc. were supplied as inputs to 6S-code for retrieving surface reflectance. The continental aerosol model was used in the study.
Figure 5.1.3. Flow diagram showing procedure for derivation and validation of surface reflectance from IRS-P6 (Resourcesat) data

Figure 5.1.4. LISS-III* image showing part of study region with some field measurement sites over Bareja, 28 November 2003
5.1.4 RESULTS AND DISCUSSION

The order of magnitude of various atmospheric properties is very important to have an insight to the physics of the RT model used for the purpose. Some of the important atmospheric properties obtained in this study are summarized in the form of graphs and shown in figures 5.1.5 and 5.1.6. Solar irradiance available at the TOA in four spectral channels of IRS-P6 LISS-III* sensor is shown in figure 5.1.5a. These values decrease from 1848 to 237 W/m²/µm (section 3.1) as wavelength increases for green to SWIR channels. A modified solar radiance reaches the ground after travelling through the atmosphere and it can be partitioned in the direct and diffuse irradiance, where direct is unperturbed irradiance and diffuse is modified irradiance because of the atmosphere. Figure 4b represents the percentage between direct and diffuse irradiance, which varies with wavelength since atmospheric effects are greater at low wavelength (green) and smaller at high wavelength (SWIR). Thus the solar irradiances that reach the ground in form of direct (diffuse) in the four spectral channels are approximately 706 (392), 699 (290), 552 (151) and 152 (13) (all in W/m²/µm) for green, red, NIR and SWIR, respectively.

Table 5.1.1. Details of satellite data used, solar zenith ($\theta_s$) and azimuth ($\phi_s$) angles along with atmospheric measurements performed synchronous to the satellite acquisitions

<table>
<thead>
<tr>
<th>Date</th>
<th>Path/Row</th>
<th>$\theta_s$ deg.</th>
<th>$\phi_s$ deg.</th>
<th>Water vapour/g/cm²</th>
<th>AOT at 550 nm</th>
<th>$O_3$ content/cm-atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 28</td>
<td>93/55 (LISS-III*)</td>
<td>42.69</td>
<td>161.24</td>
<td>1.64</td>
<td>0.388</td>
<td>0.30</td>
</tr>
<tr>
<td>2003</td>
<td>93/54 (AWiFS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec. 22</td>
<td>93/55 (LISS-III*)</td>
<td>49.15</td>
<td>158.06</td>
<td>1.25</td>
<td>0.482</td>
<td>0.30</td>
</tr>
<tr>
<td>2003</td>
<td>93/54 (AWiFS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spectral dependence of various atmospheric optical properties which are governed by the atmospheric absorption and scattering are shown in the figure 5.1.6. The total atmospheric optical depth (figure 5.1.6a) with the individual optical depth of Rayleigh and aerosol show a systematic reduction as wavelength increases. The total gaseous transmission along with the individual transmission characteristics of WV and ozone are shown in figure 5.1.5 b, c.
and d. The most interesting and important feature seen is in the WV transmission graph, where a typical WV absorption feature is observed for NIR band, that reduces the transmission from 0.99 to 0.94. This is because of the presence of a WV absorption band near 0.81-0.82 μm (Zuev, 1974). This feature of IRS NIR channel should be noted since it has been believed that the IRS NIR channel (0.77-0.86 μm) is quite free of WV absorption. This is the case when water vapour is about 1.64 g/cm², and this effect could aggravate when amount of WV becomes large.

Table 5.1.2. Sensor specific coefficients used in the study. (Source: Lₘₐₓ, Lₘᵦᵣ from image header and E₀ from Pandya et al. 2007 and discussed in section 3.1)

<table>
<thead>
<tr>
<th>Satellite/Sensor</th>
<th>Channel</th>
<th>Lₘᵦᵣ</th>
<th>Lₘₐₓ</th>
<th>E₀</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wm⁻² sr⁻¹ μm⁻¹</td>
<td>Wm⁻² sr⁻¹ μm⁻¹</td>
<td>Wm⁻² μm⁻¹</td>
</tr>
<tr>
<td>IRS-P6 LISS-III*</td>
<td>Green</td>
<td>0.0</td>
<td>120.64</td>
<td>1848.92</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>0.0</td>
<td>151.31</td>
<td>1576.79</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>0.0</td>
<td>157.57</td>
<td>1093.38</td>
</tr>
<tr>
<td></td>
<td>SWIR</td>
<td>0.0</td>
<td>3.397, 1.644*</td>
<td>237 50</td>
</tr>
<tr>
<td>IRS-P6 AWiFS</td>
<td>Green</td>
<td>0.0</td>
<td>523.40</td>
<td>1853.28</td>
</tr>
<tr>
<td></td>
<td>Red</td>
<td>0.0</td>
<td>407 50</td>
<td>1580.42</td>
</tr>
<tr>
<td></td>
<td>NIR</td>
<td>0.0</td>
<td>284.25</td>
<td>1083 57</td>
</tr>
<tr>
<td></td>
<td>SWIR</td>
<td>0.0</td>
<td>46.45</td>
<td>237 86</td>
</tr>
</tbody>
</table>


The atmospheric intrinsic contribution in terms of radiance (called path radiance) and reflectance are given in figure 5.1.6 e and f, which also show a decreasing trend with increasing wavelength. It varies from 26.11 for green to 0.31 for SWIR channel equivalent of reflectance of 6% and 0.5%, respectively. This trend is quite obvious because the scattering process dominantly governs the path radiance term and the scattering is higher for low wavelength region as compared to high wavelength region. The single scattering albedo and extinction coefficient for continental aerosol model are shown in figure 5.1.6 g and h. The single scattering albedo represents the ratio between the aerosol scattering coefficient and the total extinction coefficient (scattering and absorption) (Coulson, 1988; Kaufman 1989).
Figure 5.1.5. Solar irradiance available (a) at TOA level and (b) at ground level in LISS-III* spectral channels for 28 Nov. 2003 satellite pass on over Bareja, India

It represents the percentage of light beam, which will undergo scattering in a single scattering event. Its value lies around 0.9, which says aerosols are more of scattering type. Histograms of the four spectral channels pertaining to the corrected and uncorrected data are shown in the figure 5.1.7. An important inference can be drawn from this figure is that the atmospheric correction procedure reduces the response of the lower reflecting targets (less than ~10%) and increases the higher reflecting targets (greater than ~10%). Thus in a way it increases the contrast between the dark and bright pixels. This property of the atmosphere seems to be independent of the wavelength and governed by the target reflectance values as clearly seen from the figure 5.1.7. After retrieving surface reflectance, the spectral signatures are plotted for five different classes (figure 5.1.8). The spectral signatures of all the targets show a good agreement to the typical ground signature.
Figure 5.1.6. Spectral dependence of atmospheric optical depth, total gaseous transmission, water vapour transmission, ozone transmission, atmospheric intrinsic radiance, atmospheric intrinsic reflectance, single scattering albedo and extinction coefficients in continental aerosol model conditions, for IRS-P6 satellite pass on 28 Nov. 2003 over Bareja, India
Comparisons with ground measured reflectances

The satellite derived reflectance was compared to ground measured reflectance. Apparent (TOA) reflectances were also computed as defined in the equation (5.2), so as to give an idea of non-corrected data. Figure 5.1.9 graphically reports these comparisons for green, red, NIR channels and pooled data set of LISS-III* pass of 28 Nov. 2003. Similar analysis was carried out for the other pass on 22 Dec. 2003, but are not reported here. There is a fair degree of agreement between estimated and ground measured reflectance. The comparison shows good performance of LISS-III* sensor with high $R^2$ (0.98). TheSEE was around 9% for Green and Red, and around 14% for NIR (mean reflectance value were 0.16, 0.22 and 0.33 for Green, Red and NIR, respectively). The accuracies were similar to those observed with Landsat-TM over FIFE site (Markham, 1992). The results after atmospheric correction showed a remarkable improvement as compared to non-corrected data. It was also observed that low TOA values showed a reduction in the values after atmospheric correction, while higher values showed increase in the values.
This accords well with the theoretical considerations and with the findings of other investigations (Kaufman and Fraser 1984, Fraser and Kaufman 1985, Gilabert et al., 1994); the atmosphere acts so as to increase the low reflectance estimates (due to the path radiance) and to decrease the estimates from highly reflective surfaces (because of...
atmospheric absorption and scattering). The linear regression analysis clearly confirm this quantitative evaluations, as can be seen from the table 5.1.3. For all the bands, the expressions corresponding to the fit between the model and the real reflectance values are much better than those obtained with apparent reflectances, the slope values are closer to 1 and intercept are closer to 0 for model reflectance case. The effect of atmospheric correction is seen in the NDVI (figure 5.1.10), where NDVI values increase after atmospheric correction. That is the contrast in the red and NIR reflectances increase remarkably once the effect of atmosphere is corrected.

![Figure 5.1.10. Comparison of NDVI before and after atmospheric correction for IRS-P6 LISS-III* image, 28 Nov. 2003 over Bareja site, India](image)

Table 5.1.3. Linear regression equations for the relationships between estimated reflectances (by model or by the TOA reflectance) and the ground measured reflectances

<table>
<thead>
<tr>
<th></th>
<th>Model reflectance</th>
<th>Apparent (TOA) reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>$y = 0.733x + 0.023$, $r^2=0.98$</td>
<td>$y = 0.393x + 0.066$, $r^2=0.98$</td>
</tr>
<tr>
<td>Red</td>
<td>$y = 0.758x + 0.023$, $r^2=0.98$</td>
<td>$y = 0.452x + 0.050$, $r^2=0.98$</td>
</tr>
<tr>
<td>NIR</td>
<td>$y = 0.846x + 0.055$, $r^2=0.97$</td>
<td>$y = 0.542x + 0.056$, $r^2=0.97$</td>
</tr>
</tbody>
</table>

5.1.4 CONCLUSIONS

In this study a fundamental surface property called surface reflectance has been derived using a RT model for IRS data. The RT model was modified to correct atmospheric effects in the IRS sensor data. The satellite derived reflectance was validated with the field measurements of spectroradiometer, which showed a very good agreement with an RMSE of 9-14 percent. This study was an attempt to fill the gap of deriving surface reflectance from IRS data, which would be useful in many applications.
5.2 Derivation of normalized difference vegetation index field over India using a physical method

5.2.1 INTRODUCTION

The role of terrestrial vegetation in large-scale global process is very important in the understanding how the Earth functions as a system. This requires an understanding of the global distribution of vegetation types as well as their biophysical and structural properties and spatial/temporal variations. The NDVI represents the vigour of vegetation and is a prime biophysical surface parameter in remote sensing. The Earth observing remote sensing payloads onboard geosynchronous satellite INSAT 3A observes in red (0.62-0.68 μm), NIR (0.77-0.86 μm) and SWIR (1.55-1.70 μm) bands with 1-km spatial resolution with a swath covering one third of globe and a temporal resolution of half an hour. With its all time viewing capability, multispectral bands similar to IRS sensors, spatial resolution comparable to NOAA-AVHRR and large swath, open up the possibility for newer approaches of vegetation monitoring. It provides the opportunity to monitor, quantify and investigate regional scale changes in vegetation through observations particularly in red and NIR bands as well as vegetation indices (Vi’s). Currently moderate and coarse resolution satellite systems, such as AVHRR, MODIS, SPOT4-VEGETATION, SeaWiFS and GLI provide VI products on operational basis. VI’s are dimensionless, radiometric measures of vegetation exploiting the unique spectral signature and behaviour of canopy elements particularly in the red and NIR portions of the spectrum. The NDVI has been used as basic quantity for numerous applications. Satellite-derived vegetation indices are being integrated in interactive biosphere models as part of global climate modelling and production efficiency models. It is being also used extensively for operational studies in India like Crop Acreage and Production Estimate (CAPE) for production forecast (Dadhwal et al., 2002, Singh et al., 2002) or in monitoring cropping patterns (Rajak et al., 2002) and crop growth profiling, deriving regional LAI maps (Pandya et al., 2003), regional climate models etc. Studies utilizing NDVI have demonstrated that it is highly correlated to green-leaf density and can be viewed as a proxy for above-ground biomass (Justice et al. 1985, Tucker and Sellers 1986, Bannari et al.)
Because climate is one of the most important factors affecting vegetating condition, data from AVHRR-NDVI have been used to evaluate climatic and environmental changes at regional- and global-scales. For example, the index has been used for monitoring and investigating droughts (Gutman 1990, Kogan 1995, 1997, Unganai and Kogan 1998, Peters et al. 2002). El Niño/Southern Oscillation impacts (Anyamba and Eastman 1996, Li and Kafatos 2000, Gutman et al. 2000), arid ecosystems (Peters and Eve 1995), desertification (Tucker et al. 1991, Tucker and Newcomb 1994) and global climate changes (Potter and Brooks 1998, Kawabata et al. 2001).

Looking towards the various applications of NDVI and the unique capabilities of INSAT-3A CCD sensor, there was a need to develop a physical method to derive NDVI product from the geostationary platform. A study was carried out with the aim of developing an algorithm to derive partially atmospheric corrected (molecular scattering, ozone absorption) reflectance fields and generating NDVI fields from corrected reflectance over India.

5.2.2 DEVELOPMENT OF A PHYSICAL ALGORITHM FOR DERIVING NORMALIZED REFLECTANCE AND NDVI

The operational use of reflectances and VI require that these should be calculated in a uniform manner, and that the results are comparable over time and location. The subsequent sections intend to provide an outline for deriving normalized reflectances and NDVI by incorporating instrument characteristics and partial atmospheric correction (related to Rayleigh scattering and ozone absorption) in a form of algorithm.

5.2.2.1 Derivation of various atmospheric parameters

The processing flow for computing normalized reflectance and NDVI for INSAT 3A sensors is shown in the flowchart of figure 5.2.1. Two datasets of October 15, and December 1, 2004 were chosen for generating the product. The data was obtained in 10-bit digital number (DN). The DN image of each band was converted into radiance image. The atmospheric contribution in terms of Rayleigh scattering and ozone absorption (with ozone content of 0.3 cm NTP) was computed considering the viewing geometry pertaining to INSAT-3A CCD sensor and spectral response functions of each channel of CCD sensors. A sensor specific
number $E_0$ was also computed for the sensor. At-sensor radiance was corrected by incorporating atmospheric contribution to it and thus partially atmospheric corrected reflectance for red, NIR and SWIR were generated. The sequence of expressions (mainly for atmospheric transmittance, path radiance, diffuse irradiance etc) and coefficients used in this algorithm are reported in the following paragraphs.

The corrected surface reflectance ($\rho_s$) or normalized reflectance to be derived is,

$$\rho_s = \frac{\pi \cdot (L_s - L_p) \cdot d^2}{T_v \cdot (E_0 \cdot \cos \theta_s \cdot T_s + E_d)} \quad \ldots \quad (5.5)$$

**Computation of atmospheric path radiance $L_p$**

The atmospheric path radiance is the contribution from the scattered radiance from atmosphere due to molecules and aerosols. So the total path radiance is,

$$L_p = L_r + L_a$$

where, $L_r$ and $L_a$ are Rayleigh and aerosol contributions, respectively to the path radiance. Since we are considering Rayleigh atmosphere, $L_a=0$ so,

Figure 5.2.1. Flowchart showing steps for generating corrected reflectances and NDVI
\[ L_p = L_r \quad \text{(5.6)} \]

And the expression for Rayleigh path radiance is,

\[
L_r = \frac{E_0}{4\pi} \cdot \frac{\cos \theta_v}{\cos \theta_s + \cos \theta_v} \cdot P_r \left[ 1 - \exp \left( - \tau \left( \sec \theta_s + \sec \theta_v \right) \right) \right] T_{o3} T_{o3'} \quad \text{(5.7)}
\]

where, \( P_r = \text{Rayleigh phase function} = \frac{3}{4} \left( 1 + \cos^2 \psi \right) \) (pg: 178, Coulsom, 1988) ... (5.8),

\( \psi = \text{Scattering angle} = 180^\circ - \cos^{-1} (\cos \theta_s \cos \theta_v + \sin \theta_s \sin \theta_v \cos \phi) \) ... (5.9)

**Computation of viewing geometry components, \( \theta_v, \phi_v, \phi_s, \phi_u \)**

The components of the viewing geometry corresponding to the geosynchronous satellite INSAT-3A viewing from 93.5 deg E were computed by using method described in Pandya et al., 2000; Pandya and Dadhwal, 1999. Solar and viewing geometry is defined by \( \theta_v, \phi_v, \theta_s, \phi_s \) angles (Ranson et al. 1985). For geostationary platform viewing angles are fixed and can be estimated from latitude and longitude of the target \( (\delta_t, L_t) \) with respect to the latitude and longitude of subsatellite point \( (\delta_s, L_s) \), angular radius of the spherical Earth \( (\delta_r, \text{radian}) \), nadir angle measured at the spacecraft from the subsatellite point \( (\eta, \text{radian}) \) and Earth central angle \( (\lambda, \text{radian}) \) using following equations (Larsen and Wertz, 1992):

\[
\theta_v = \frac{\pi}{2} - \cos^{-1} \left( \frac{\sin \eta}{\sin \theta_v} \right) \quad \text{(5.10)}
\]

\[ \lambda = \cos^{-1} \left[ \sin \delta_r \cdot \sin \delta_s \cdot \cos \delta_r \cdot \cos \delta_s \cdot \cos \Delta L \right] \]

\[ R_e = \text{Radius of the Earth} = 6378.16 \text{ km and } H = \text{Altitude of satellite} \equiv 36000 \text{ km} \]

\[ \Delta L = |L_s - L_t| \]

View azimuth angle can be estimated for a satellite position of 93.5 deg on equator by,

\[
\phi_v = \pi + \tan^{-1} \left( \frac{L_s - 93.5}{\delta_r - 0.0} \right) \quad \text{(5.11)}
\]

Solar zenith angle can be estimated by (List, 1984):

\[
\theta_z = \frac{\pi}{2} - \sin^{-1} \left[ \sin \delta \cdot \sin \delta_r + \cos \delta \cdot \cos \delta_r \cdot \cos H \right] \quad \text{(5.12)}
\]
Where, $\delta =$ Solar declination angle in radian and $H =$ Hour angle in radian

Sun azimuth angle can be estimated by (Mani, 1982),

$$\phi_s = \cos^{-1}\left(\frac{\cos \delta_t \cos \delta \cos H - \cos \delta_t \sin \delta}{\sin \theta_s}\right) \quad (5.13)$$

**Computation of atmospheric transmittance $T_s$ and $T_v$**

$$T_s = T_{rs} T_{wvs} T_{as} T_{oys} \quad (5.14a)$$

$$T_v = T_{rv} T_{wvv} T_{av} T_{ovv} \quad (5.14b)$$

where, $T_r$, $T_{wv}$, $T_a$, $T_o$ represent the transmittance corresponding to Rayleigh, WV, aerosol and ozone, respectively. Since in the present partial atmospheric correction scheme, aerosol and water vapour contributions are neglected, transmittances of these two quantities are 1. i.e. $T_{wvs}$, $T_{as}$, $T_{wvv}$, $T_{av}$ are assumed equal to 1. Thus equations 5.14a and 5.14b would reduce to following,

$$T_s = T_{rs} T_{oys} \quad (5.15a)$$

$$T_v = T_{rv} T_{ovv} \quad (5.15b)$$

The equations representing $T_{rx}$ and $T_{r0x}$ (where $x = s$ or $v$) are,

$$T_{rx} = e^{-\tau_r \sec \theta} \quad (5.16)$$

$$T_{r0x} = e^{-\tau_{0x} \sec \theta} \quad (5.17)$$

where, $\tau_r$ and $\tau_{0x}$ are the optical thickness of Rayleigh and ozone, respectively.

**Computation of Rayleigh optical thickness ($\tau_r$) and ozone optical thickness ($\tau_{0x}$)**

The computation of the ROT ($\tau_r$) can be carried out by knowing central wavelength ($\lambda$) in $\mu$m and height of the surface above sea level (h) in km, as described in section 4.3. The optical thickness of ozone is calculated by,

$$\tau_{o2} = a_{o2} c_{o2} \quad (5.18)$$

with $a_{o2}$ the ozone absorption coefficient per cm NTP and $c_{o2}$ the ozone content in the atmosphere in cm NTP. The $\tau_r$ and $\tau_{0x}$ can be computed as weighted by the solar irradiance and the sensor band relative spectral response as (Pandya et al., 2004),
Computation of diffuse irradiance $E_d$

$E_d$ is a part of global solar irradiance, $(E_g = E_b + E_d)$, where direct or beam irradiance $E_b$ is $E_0 \cos \theta_s T_s$ and is composed of two parts, diffuse irradiance due to Rayleigh scattering $(E_{dr})$ and diffuse irradiance due to aerosol scattering $(E_{da})$. The combined expression for $E_d$ is,

$$E_d = E_{dr} + E_{da}$$

$$E_d = \frac{1}{2} E_0 \cos \theta_s (1 - T_{rs}) T_{o3} T_{rs} + F_c(\theta_s) E_0 \cos \theta_s (1 - T_{rs}) T_{rs} T_{o3} \omega_0 \ldots (5.21)$$

The second term of right hand side of equation 5.21 is aerosol contribution, which is neglected in the present study. Taking $T_{rs}$=1, so the equation 5.21 reduces to,

$$E_d = \frac{1}{2} E_0 \cos \theta_s (1 - T_{rs}) T_{o3} \ldots (5.22)$$

Expressions 5.6 to 5.22 were used to compute terms appearing in the equation 5.5 and thus surface reflectance for red, NIR and SWIR bands were computed for INSAT 3A data. The NDVI was estimated using the corrected reflectance $(\rho_g)$ corresponding to red $(\rho_{red})$ and NIR $(\rho_{nir})$ using the following expression,

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \ldots (5.23)$$

**SPOT NDVI data for validation of INSAT derived NDVI**

In order to compare the INSAT derived NDVI, a standard ten-day composite SPOT VGT NDVI product was used covering the Indian landmass for the same time period. The data was obtained from the web site http://www.free.vito.be. The scaled digital number (DN) of SPOT-NDVI data was converted to the actual NDVI by the equation, $NDVI = (DN \times 0.004) - 0.1$.

5.2.3 RESULTS AND DISCUSSION

The sensor dependent quantities $E_0$, $\tau_r$ and $\tau_{o3}$ computed for INSAT-3A CCD sensor are summarized in the table 5.2.1a, b and c. The corresponding equations required for
converting the coefficients to the physical quantity is also provided in the table along with the coefficient of correlation and SEE.

Table 5.2.1a. Bandpass exo-atmospheric irradiance values $E_0$ for INSAT-3A CCD sensor

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>NIR</th>
<th>SWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (W/m$^2$/μm)</td>
<td>1553.57</td>
<td>1086.97</td>
<td>239.89</td>
</tr>
</tbody>
</table>

Table 5.2.1b. Coefficients for Rayleigh optical thickness $\tau_r$ for INSAT-3A CCD sensor

Where, $\tau_r = a + b \cdot h$, $h$ is altitude in km

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>NIR</th>
<th>SWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient, $a$</td>
<td>0.0451</td>
<td>0.0193</td>
<td>0.0012</td>
</tr>
<tr>
<td>Coefficient, $b$</td>
<td>-0.0045</td>
<td>-0.002</td>
<td>-0.0001</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>SEE</td>
<td>0.0003</td>
<td>0.0001</td>
<td>$8 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Table 5.2.1c. Coefficients for Ozone optical thickness $\tau_{O_3}$ for INSAT-3A CCD sensor

Where, $\tau_{O_3} = a + b \cdot O_3\_content$, where $O_3\_content$ is ozone content in cm-NTP

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>NIR</th>
<th>SWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient, $a$</td>
<td>~0.0</td>
<td>~0.0</td>
<td>0</td>
</tr>
<tr>
<td>Coefficient, $b$</td>
<td>0.05806</td>
<td>0.00071</td>
<td>0</td>
</tr>
<tr>
<td>$R^2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>SEE</td>
<td>$9.1 \times 10^{-18}$</td>
<td>$8.04 \times 10^{-20}$</td>
<td>0</td>
</tr>
</tbody>
</table>

The viewing condition parameters for geosynchronous satellite positioned at equator on 93.5° E and on the 15th October 2004 are shown in figure 5.2.2. The possible range of values for each field is shown by a colour ramp between a minimum and maximum limit. The SZA at 10:30 hrs varies between 0-58 deg in the whole map, while it varies 29 to 52 deg for Indian landmass. The VZA increases gradually as latitude increases, while a systematic minor curvature is observed for longitudinal increase or decrease towards westward of satellite position. The VZA varies between 0 to 53 deg for the total map and 19-47 deg for Indian landmass. Similarly sun azimuth and view azimuth angles vary between 0 to 178 and 0 to 227 deg, respectively. These parameters are important for the deriving other quantities in subsequent computations.
Spatial maps of important atmospheric quantities derived over the Indian landmass during the study are shown in figure 5.2.3. The Rayleigh phase function ($P_r$) shows the angular distribution of the radiation scattered by a Rayleigh atmosphere. The pattern has axial symmetry in the forward direction (Coulson, 1988) and it varies from 0.75 to 1.50. The other atmospheric quantities for the red band are shown in the figure 5.2.3. The transmittance in Sun-target path ($T_s$) follows pattern of cosine of SZA and transmittance in target-sensor path ($T_v$) follows pattern of cosine of VZA, which is quite obvious because of their functional dependence on the respective zenith angle. As shown in the figure 5.2.3, Rayleigh atmosphere has transmittance value approximately from 0.90 to 0.94. The diffuse irradiance ($E_d$) is shown in the figure 5.2.3 and it also follows the pattern of SZA. It varies between 31.89 to 32.84 W/m²/μm. Atmospheric path radiance ($L_o$), which is equivalent to Rayleigh path radiance, shows linear patterns following axial patterns of $P_r$. As $P_r$ increases
scattering of radiation in the atmosphere increases and thus $L_p$ increases. Though values of $L_p$ are less than 9 W/m$^2$/sr/µm, it becomes important in case of low reflecting targets.

Figure 5.2.3. Variation in components of atmosphere in red band are shown over Indian landmass as $P_r$: Rayleigh phase function (0.75-1.50), $T_s$: transmittance in Sun-target path (0.90-0.94), $T_v$: transmittance in target-sensor path (0.91-0.94), $E_d$: diffuse irradiance (31.89-32.84 W/m$^2$/µm) and $L_p$: atmospheric path radiance (4.21-8.65 W/m$^2$/sr/µm).

Moreover it varies as a function of wavelength and thus affects differentially for red and NIR bands, thus producing deviations in NDVI value. The partially atmospheric corrected reflectance and NDVI products of October 15 and December 1, 2004 were generated using the processing flow described in the above section. Figure 5.2.4a and b show the red and NIR reflectance images, while 5.2.4c shows the FCC over India after performing the partial applying the method. NDVI derived from present algorithm is shown in the figure 5.2.4d. The influence of partial correction on INSAT-3A CCD data through the proposed algorithm was checked by comparing the NDVI images before and after the correction applied on selected vegetation classes of forest and crop targets. It showed a fair degree of improvement in the NDVI values due to the partial correction. The contrast of red and NIR
increased after the correction and thus atmospheric effects were reduced by a significant degree with the NDVI values increased up to as much as 0.2 on average.

Figure 5.2.4. (A) Red reflectance, (B) NIR reflectance, (C) colour composite (NIR, Red, Red) derived from INSAT-3A CCD, (D) INSAT-3A derived NDVI (0.07-0.60) and (E) SPOT derived NDVI (0.1-0.80) corresponding to same time period

The SPOT NDVI corresponding to same time period is also shown in the figure 5.2.4e. Visual comparison shows a good agreement between these two estimates, with the exception at the cloudy pixels in the INSAT data. INSAT being a single day image consists clouds, which is not seen in the SPOT NDVI because it is a ten-day composite and most of the cloudy pixels are avoided by the temporal compositing followed in the SPOT NDVI. A comparison between INSAT-NDVI and SPOT-NDVI was carried out at various cloud free locations as shown in the figure 5.2.5. It shows a good agreement between the two estimates, with a consistent underestimation in the INSAT-NDVI with respect to SPOT-NDVI. Amount of
underestimation in INSAT NDVI as compared to SPOT NDVI increases as NDVI value increases. This difference between SPOT-4 VGT and INSAT NDVI can be attributed the different scheme when performing atmospheric correction. The SPOT-4 VGT uses modified atmospheric correction scheme of Simple Method for Atmospheric Correction (SMAC, by Rahman and Dedieu, 1994). It corrects for molecular and aerosol scattering, for WV, ozone and other gas absorption based on the semi-empirical equations whose coefficients are determined on the basis of fitting reference computations performed with the 6S RT code (Vermote et al., 1997). It corrects effect of ozone based upon climatology, WV from numerical weather prediction analysis and aerosol from a fixed aerosol amount per band of latitude. Thus as compared to INSAT NDVI, SPOT NDVI is expected to give higher values because of the extra atmospheric correction steps involving WV and aerosol corrections.

![Graph showing comparison of SPOT-NDVI with INSAT 3A CCD derived NDVI](image)

Figure 5.2.5. Comparison of SPOT-NDVI with the INSAT 3A CCD derived NDVI

However, the NDVI has been shown to be affected by variations in sun-target-sensor geometries specifically pertaining to INSAT (Pandya et al., 2000; Pandya and Dadhwal 1999), with sun angles varying with latitude and time of the day as well as year. The derivations of NDVI due to variable viewing geometry must be considered in the estimating VI products as it was proposed for SPOT NDVI products (Maisongrade et al., 2004). This variability is important for seasonal and intra-annual comparison of vegetative covers on a large scale. Therefore, some knowledge of the bi-directional reflectance distribution function (BRDF) is
needed for successful utilization of Vis, and the derivation of land cover-specific biophysical parameters (Cihlar et al., 1994). The influence of sun-target-sensor configurations pertaining to INSAT-3A will be investigated in future course of work by incorporating compositing based upon the BRDF, like bidirectional compositing (Maisongrade et al., 2004), where a BRDF model would be fitted on the 10-day cloud free observation set and normalizing all the observations to the nadir view angle and mean sun angle of 10-day. However present algorithm would enable to correct the INSAT 3A images partially and it could enhance the accuracy on using the coarse digital elevation model for height consideration in the computation of Rayleigh optical thickness and ozone content map in the computation of Ozone optical thickness.

5.2.4 CONCLUSIONS

An important surface parameter called NDVI was derived over India using a physics based algorithm developed to derive partially atmospheric corrected reflectance and NDVI fields from INSAT-3A CCD data. A significant improvement was observed in the derived products as compared to uncorrected product. This algorithm provides a major advantage to its derived fields over traditional reflectance or NDVI fields in a sense that it incorporates INSAT-3A CCD sensor characteristics such as, SRF in derivation of $E_0$, Rayleigh optical thickness, Ozone optical thickness and viewing geometry in deriving atmospheric contribution to radiance. The method will be useful in a number of applications especially at regional scale namely, inter and Intra-annual vegetation monitoring on a periodic basis, crop growth profile at regional scale, vegetation fraction for LSM, RCM, vegetation condition assessment (impact of drought, large scale crop damage), regional scale hydrological, Landuse/landcover applications and could form a major input to ongoing projects like EWBMS, CGMS and cropping system analysis. Moreover, physical units such as reflectances will be useful for quantitative inferences and inter-sensor/mission comparisons. The influence of sun-target-sensor configurations pertaining to INSAT-3A should also be investigated and incorporated in the algorithm.
5.3 Leaf area index retrieval using IRS LISS-III data and validation of the MODIS LAI product over central India

5.3.1 INTRODUCTION

Leaf area index (LAI) is one of the most important surface parameter characterizing a vegetation canopy. LAI is a dimensionless biophysical indicator used to quantify the single sided vegetation leaf area per unit of ground area in broadleaf canopies. It determines vegetation photosynthesis, transpiration and the energy balance of canopies (Bonan, 1993). LAI and fAPAR are important surface attributes controlling water, carbon and energy exchange between vegetation and atmosphere (Running et al., 1996). LAI is not only an important driver of most ecosystem productivity models operating at landscape to global scales (Turner et al., 1999), but also an interacting component of GCMs (Buermann et al., 2001). For effective use in such large-scale models, regional and global LAI must be available over a period of time. Field measurements of LAI however are cumbersome, time consuming and impossible to obtain at the global scale, in that respect satellite remote sensing is the most effective means of estimating LAI global fields on a regular basis.

As part of the US EOS, the Terra (launched in Dec. 1999) and Aqua (launched in May 2002) satellites, carry the MODIS along with a host of other advanced sensors. Algorithms have been developed to generate a number of land products from MODIS, including LAI/fAPAR (MODIS ATBD) that have been made available by the LP-DAAC for evaluation/validation and utilization. The MOD15 LAI and fAPAR are 1-km products provided on 8-day basis. The validation of LAI global fields, i.e., assessment of uncertainty of remote sensing derived products by analytical comparison with reference data assumed to represent the target values (Justice et al., 2000), is a strong requirement and has been carried out for many sites in the USA, Africa, Finland, France (Privette et al., 2002; Myneni et al., 2002; Wang et al., 2004, Tan et al., 2005) and elsewhere. No results are available for India however. A LAI Retrieval and Validation Experiment (LRVE) aiming at retrieval of LAI based on the site-specific vegetation index-LAI relationships and the validation of the MODIS LAI product was conducted at two sites of Central India during the wheat-growing season of 2001-02.
5.3.2 DATA AND METHODOLOGY

In this section we describe (1) field site description, (2) satellite data used in the study, (3) experimental measurements of LAI and atmospheric parameters, (4) LAI map generation procedure, and (5) remote sensing data analysis and generation of LAI maps.

5.3.2.1 Field sites

Two sites in the state of Madhya Pradesh of India, Indore (75°57'E, 22°53'N) and Bhopal (77°28'E, 23°10'N) were selected for LAI measurements. These sites are located in the Central India representing semi arid and semi humid zones respectively. Both the sites have soil type with little difference in their characteristics. Indore site has deep, moderately well drained, calcareous clayey soils on gently sloping undulating plain with mounds with moderate erosion (Fine, Montmorillonitic-calcareous, Hyperthermic, Typic Haplusterts). While Bhopal site has slightly deep, well drained, calcareous clayey soils on gently sloping plain with narrow valleys with moderate erosion (Fine, Montmorillonitic-calcareous, Hyperthermic, Vertic Ustochrepts). Indore has rainfed agriculture and Bhopal has an irrigated agricultural practice. Wheat (*Triticum aestivum*) was the major crop at the Indore site with a relative proportion of 65% while other 35% area was covered by gram (*Cicer arietinum*) and other very small proportion crops. The Bhopal site had 78% of wheat with 22% of gram, pea (*Pisum sativum*) and other crops. Well distributed sample plots (35 in the Indore site and 40 in the Bhopal site) were selected for LAI measurement, representing a good variability in terms of sowing dates and LAI range for a scene. The details on the study area and the remote sensing data used in the LRVE are shown in table 5.3.1.

5.3.2.2 Satellite data used in this study

*IRS LISS-III and PAN*

The data of the LISS-III and PAN onboard IRS-1D were used in the study. PAN has a 5.8 meter spatial resolution and it was used mainly for the demarcation of the fields and field-boundaries. IRS Images of three dates for each site were acquired (table 5.3.1).

*The MODIS LAI product/algorithm*

The 8-day composites of the LAI/fAPAR products (MOD15A2) version 3 and 4 pertaining to
study sites were downloaded from the LP-DAAC Internet site. The product was selected in such a way that the 8-day compositing period would cover the acquisition dates of the IRS satellite data. Detailed information of the MODIS LAI products used in the present analysis is listed in Table 5.3.1. The MODIS LAI/fAPAR product is produced at the 1-km spatial resolution daily (MOD15A1) and composited over an 8-day period, where the selected value in a compositing period is that with the highest corresponding fAPAR. The version 3 and 4 products are projected on the Integerized Sinusoidal and Sinusoidal 10° grid, respectively. Where the globe is tiled into 36 tiles along the east-west axis, and 18 tiles along the north-south axis, are each approximately 1200X1200 km. A brief summary of the LAI algorithm is provided by Myneni (2002). The algorithm is based on rigorous three-dimensional RT theory (Myneni et al., 1990). A LUT method is used to achieve inversion of the three-dimensional RT problem. The 250 and/or 500 meter resolution bands are aggregated into normalized 1-km resolution grid cells prior to ingestion (Wolfe et al., 1998).

Table 5.3.1: LAI sites and details of satellite data/product acquisitions

<table>
<thead>
<tr>
<th>Description</th>
<th>Site: Indore</th>
<th>Site: Bhopal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site location</td>
<td>75° 57' E, 22° 53' N</td>
<td>77° 28' E, 23° 10' N</td>
</tr>
<tr>
<td>Date of IRS-1D LISS-III acquisitions</td>
<td>02 Dec 01, 27 Dec 01, 21 Jan 02</td>
<td>24 Dec 01, 18 Jan 02, 12 Feb 02</td>
</tr>
<tr>
<td>IRS-1D Path/Row</td>
<td>96/56</td>
<td>97/55</td>
</tr>
<tr>
<td>Date of MODIS LAI 8-day product</td>
<td>3Dec - 10Dec 2001, 27Dec 2001 - 3Jan 02</td>
<td>19Dec - 26Dec 2001, --</td>
</tr>
<tr>
<td>MODIS Tile Number</td>
<td>24H 6V</td>
<td>25H 6V</td>
</tr>
</tbody>
</table>

# Overcast conditions, hence not used in analysis

The LAI algorithm also requires a 1-km land cover map stratified in six major world biomes (grasses/cereal crops, shrubs, broadleaf crops, savannas, broadleaf forests and needleleaf forests) LUTs are generated for each biome by running the model for various combinations of LAI and fractional cover. During algorithm execution, the algorithm compares modeled
and observed reflectances for a suite of canopy structures and soil patterns that represent the range of expected natural conditions. All canopy/soil patterns for which modeled and observed reflectances show a predefined degree of correspondence are considered as acceptable solutions. A scale-independent test of energy conservation is also applied. The mean LAI for this solution set is reported as the MODIS LAI product value. When this method fails to provide a solution, a backup algorithm (Knyazikhin et al., 1998) based on relations between the NDVI and LAI is applied together with a biome classification map. The latest MODIS land cover product (MOD12Q1) version 3 was used (table 5.3.1) to investigate the biome assigned to the region of the study sites. The latest available MOD12Q1 product for our study period was October 15, 2000 and this product was used with the assumption that biome distribution does not change within a year.

5.3.2.3 Field measurements of LAI and atmospheric parameters
The objective was to make LAI measurements and to generate site-specific LAI maps. Therefore a suitable site of 30 km X 30 km representing the region was selected at two locations. The sites had adequate variability in terms of sowing date and variability in LAI. The LAI measurements were carried out using LAI-2000 plant canopy analyzer. The LAI-2000 (Licor, Inc., Nebraska) is a handheld instrument, which estimates LAI by measuring diffuse radiation above and below the canopy in five distinct zenith angle intervals of 0-13°, 16-28°, 32-43°, 47-58° and 61-74° (LI-COR, Jonckheere et al., 2004). The LAI-2000 was operated at a time of low solar zenith angles or under overcast conditions, to reduce the effect of multiple scattering on LAI measurements. All the measurements were taken by holding the sensors opposite to the direction of the sun. A 90° mask was used to prevent interference caused by the operator’s presence. A 270° mask was used in some fields of Bhopal because of heterogeneous distribution of trees around the fields. The LAI measurements were collected at eight locations within a field (with each observation being based on six point measurements) in order to obtain representative field LAI values. A total of 75 fields were sampled at various growth stages (monthly once, for three months at two sites) of the crops. The LAI measurements were carried out mainly for wheat crop with few observations on gram and pea. Special attention was paid in carrying out LAI measurements so that well
distributed sample plots were covered within a scene, representing a significant variability in sowing dates (approximately 7 to 30 days) and LAI range. The locations of fields were marked on FCC paper prints and also determined with a GPS. The atmospheric measurements of AOT and WV content were carried out concomitantly with the LAI measurements at the time of IRS-1D acquisitions using a Microtops-II Sun photometer.

5.3.2.4 LAI map generation and validation procedure
The field plots, in which LAI was measured, were generally 0.25-3.5 hectare area. Because of the surface heterogeneity (cover type and density changes), it was necessary to use fine-resolution images, in which field plots can be located accurately to validate the low-resolution product. The procedure for LAI map validation is:

1) Selection of representative areas in Central India and identification of IRS LISS-III scenes covering these areas;
2) Collection of LAI data in multiple (35-40) plots within each LISS-III scene using the same type of instruments and according to the same measurement protocol;
3) Identification of field plots in the scenes and extraction of the remote sensing data for each of the plots;
4) Development of a LAI-NDVI model for different sites using satellite and field data;
5) Generation of LAI maps for each site using the model developed;
6) Degradation of the LISS-III LAI maps to low resolution to compare and evaluate the MODIS LAI product.

5.3.2.5 Remote Sensing data analysis and generation of LAI maps

Generation of LISS-III LAI maps
LAI may be estimated at a variety of spatial scales and with different space-borne sensors (Chen & Cihlar, 1996) using techniques ranging from regression models to canopy reflectance model inversions with varying success, which includes (1) statistical models that relate LAI to band radiance (Badhwar et al., 1986) or development of LAI-vegetation index relationships (Chen & Cihlar, 1996; Myneni et al., 1997), (2) biophysical models like the Price model (Price, 1993), and (3) inversion of canopy reflectance using a numerical model or a LUT based models (Knyazikhin et al., 1998; Gao & Lesht, 1997; Qui et al., 1998). The
empirical approach is common in remote sensing of LAI estimation and is used in the present study. It is based on the idea that foliage reflectance is low in the red portion of the spectrum because most is absorbed by photosynthetic pigments, whereas much of the NIR is reflected by foliage. Then a vegetation index such as NDVI based upon a quantification of differences in image values in the red and NIR is used to estimate LAI.

The complete procedure is shown in figure 5.3.1. Keeping the study area (30 km X 30 km) in center where LAI measurements were carried out, an image covering a little larger area (approximately 47 km X 30 km for the Indore site and 30 km X 36 km for the Bhopal site) was extracted from IRS-1D LISS-III. The DN was converted to TOA reflectance using the sensor gain, offset, sun-angle and $E_0$ (Pandya et al., 2002). Surface reflectance was calculated from TOA reflectance using the 6S-code (Vermote et al., 1997a) using measured AOT and WV at the time of satellite pass and climatological value of ozone thickness as input. Out of six IRS-1D LISS-III acquisitions (table 5.3.1), two were cloudy and not used in

![Figure 5.3.1. Procedure describing retrieval of LAI from the IRS LISS-III data and its comparison with the MODIS LAI product](image)
the analysis. The reflectance images for different sites/dates were registered to corresponding geo-rectified reference images using nearest neighbour resampling with less than 0.5 pixels RMSE. The fields with LAI measurements were identified and carefully demarcated on the corresponding LISS-III and PAN merged (5.8 m spatial resolution) data and GPS readings. The mean NDVI is computed for each field. Site-specific non-linear NDVI-LAI relations are developed for each site and acquisition. The logarithmic and polynomial fits were found to have higher $R^2$ (0.58-0.73) than the linear fits (0.3-0.52). The logarithmic form of models was used to generate the fine resolution LAI maps from LISS-III data for each site and date (e.g. figure 5.3.2). These LAI images were degraded to 1-km spatial resolution using averaging for comparison with the MODIS LAI product.

**MODIS LAI product processing**

The MODIS LAI product, tile 24H6V for the Indore site and 25H6V for the Bhopal site of 1-km spatial resolution and composited over an 8-day period in HDF EOS format were acquired from LP-DAAC (table 5.3.1). These data were reprojected from the original Integered Sinusoidal (version 3) or Sinusoidal (version 4) projection to the UTM projection. The values are stored in digital form with a scale-factor and offset, which is applied to transform the stored values to their biophysical counterparts for analysis (table 5.3.2).

<table>
<thead>
<tr>
<th>SDS variable</th>
<th>Data type</th>
<th>Fill value</th>
<th>Scale factor</th>
<th>Offset</th>
<th>Valid range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAI_1km</td>
<td>Uint8</td>
<td>255</td>
<td>0.1</td>
<td>0.0</td>
<td>0-100</td>
</tr>
<tr>
<td>FparLai_QC</td>
<td>Uint8</td>
<td>255</td>
<td>N/A</td>
<td>0.0</td>
<td>0-254</td>
</tr>
</tbody>
</table>

The LAI were generated by applying a scaling factor after masking out water and urban pixels. Quality flags supplied with MODIS LAI products were studied and inter-comparison between LISS-III LAI and MODIS LAI was restricted to pixels pertaining to the class of overall best/good quality (cloud free pixels and LAI retrieval through RT model/empirical method).

5.3.3 RESULTS AND DISCUSSION

5.3.3.1 Variability in LAI and atmospheric measurements across sites

Information on sites, date of LAI measurements, crops covered, range of LAI, AOT and WV measured are summarized in table 5.3.3. The LAI for crops considered, spans a wide range
corresponding with crop emergence to the peak vegetative stage (LAI: 0.14 to 5.6 across sites/season). The range of AOT measurements collected at the time of satellite pass across the sites was 0.16 to 0.32 at 500 nm and the range of WV was 0.71 to 1.28 cm. Atmospheric measurements could not be carried out when the day of satellite overpass had overcast conditions and hence the data pertaining to these days were not used for analysis.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date of Field Observation</th>
<th>Crop</th>
<th>LAI Range</th>
<th>AOT at 500 nm</th>
<th>Water vapour (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indore</td>
<td>02 Dec 01 wheat, gram</td>
<td>0.17-3.30</td>
<td>0.16</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 Dec 01 wheat, gram</td>
<td>0.69-4.63</td>
<td>0.26</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>21 Jan 02 wheat, gram</td>
<td>0.64-3.26</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Bhopal</td>
<td>24 Dec 01 wheat, gram, pea</td>
<td>0.14-3.80</td>
<td>0.2</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18 Jan 02 wheat, gram, pea</td>
<td>1.05-5.6</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 Feb 02 wheat, gram, pea</td>
<td>1.25-4.48</td>
<td>0.32</td>
<td>1.28</td>
<td></td>
</tr>
</tbody>
</table>

5.3.3.2 Relationship between vegetation index and field-based LAI

LAI-NDVI models based on empirical relationships were developed for the LISS-III sensor and LAI images of the study sites were produced. The relationship between LAI and NDVI before and after employing atmospheric correction of the study sites is shown in fig. 5.3.2.

Figure 5.3.2. Relationship of field-measured LAI for crop fields with IRS-LISS-III-derived NDVI for Indore and Bhopal sites, shown with 95% confidence band.

The exponential form of the models was used to generate the fine resolution LAI maps from atmospherically corrected LISS-III derived NDVI. The model coefficients for different...
sites/dates are summarized in table 5.3.4. The $R^2$ values are in the range from 0.58 to 0.73. The 95% confidence band for the relationship was obtained and shown in figure 5.3.2. The results pertaining to one date analysis for the Indore and Bhopal sites are shown here as examples, similar plots for other dates were also prepared but not presented here.

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indore</td>
<td>02 Dec.2001</td>
<td>0.5156</td>
<td>0.1341</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>27 Dec.2001</td>
<td>0.4776</td>
<td>0.1425</td>
<td>0.60</td>
</tr>
<tr>
<td>Bhopal</td>
<td>24 Dec.2001</td>
<td>0.5847</td>
<td>0.1225</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>12 Feb.2002</td>
<td>0.5197</td>
<td>0.1634</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 5.3.4(b). Regression models to estimate LAI from LISS-III derived NDVI, Equation: $y=a*exp(bx)$, $y=LAI$, $x=NDVI$

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>$a$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indore</td>
<td>02 Dec.2001</td>
<td>0.0837</td>
<td>4.9181</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>27 Dec.2001</td>
<td>0.1678</td>
<td>4.2534</td>
<td>0.60</td>
</tr>
<tr>
<td>Bhopal</td>
<td>24 Dec.2001</td>
<td>0.036</td>
<td>5.9722</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>12 Feb.2002</td>
<td>0.235</td>
<td>3.5588</td>
<td>0.58</td>
</tr>
</tbody>
</table>

5.3.3.3 Validation of MODIS LAI products

The validation of version 3 and 4 MODIS LAI fields with LISS-III derived LAI fields were carried out by performing regression analysis between LAI from the MODIS product (dependent) and LAI derived from LISS-III (independent). The detailed results obtained from this validation are summarized in the following sections.

Validation of version 3 MODIS LAI

The results on the MODIS LAI product version 3 analyses are presented in table 5.3.5 and illustrated in figures 5.3.3(a-d). Figures 5.3.3(a-b) show the comparison of two LAI estimates for the Bhopal site and figures 5.3.3(c-d) for the Indore site. The comparison indicates a significant positive correlation between LISS-III derived LAI and MODIS LAI ($r=0.78$ for Bhopal and $r=0.72$ for Indore). A slope of 1 and 0 intercept indicates a full match, while deviations show over/under estimation. The analysis indicates an overestimation in the
MODIS LAI product compared to LISS-III LAI for both sites. The magnitude of overestimation is quite high for Bhopal (slope: 1.98 and 2.49) compared to Indore (slope: 0.74 and 1.16). Overestimation by LAI is higher, for higher LAI estimates by LISS-III, especially in Bhopal (figure 5.3.3a-b). The overall RMSE of MODIS LAI is higher for Bhopal (0.92 and 1.26) compared to Indore (0.20 and 0.33), however Bhopal has a higher range of LAI (0.1 to 3.28 in LISS-III LAI, 0.3 to 6.9 in MODIS LAI). During the analysis, many pixels of the MODIS LAI product are observed to have LAI (5-6.9), which seems to be unrealistically high and opposite to the field observations.

<table>
<thead>
<tr>
<th>Site</th>
<th>MODIS LAI product version</th>
<th>Date</th>
<th>a*</th>
<th>b*</th>
<th>R²</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indore</td>
<td>Version 3</td>
<td>02 Dec.2001</td>
<td>0.57 (0.01)</td>
<td>1.16 (0.04)</td>
<td>0.52</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27 Dec.2001</td>
<td>0.68 (0.02)</td>
<td>0.75 (0.03)</td>
<td>0.51</td>
<td>0.33</td>
</tr>
<tr>
<td>Bhopal</td>
<td>Version 3</td>
<td>24 Dec.2001</td>
<td>0.43 (0.05)</td>
<td>2.50 (0.07)</td>
<td>0.61</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 Feb.2002</td>
<td>0.42 (0.09)</td>
<td>1.99 (0.06)</td>
<td>0.61</td>
<td>1.26</td>
</tr>
<tr>
<td>Bhopal</td>
<td>Version 4</td>
<td>24 Dec.2001</td>
<td>0.49 (0.03)</td>
<td>1.29 (0.04)</td>
<td>0.54</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12 Feb.2002</td>
<td>0.71 (0.05)</td>
<td>0.82 (0.03)</td>
<td>0.38</td>
<td>0.82</td>
</tr>
</tbody>
</table>

*Numbers in brackets show root mean square error of individual coefficients

Validation of version 4 MODIS LAI

The results of analysis using version 4 data of MODIS LAI products carried out for the Bhopal site are summarized in table 5.3.5 and illustrated in figures 5.3.4(a-b). A positive correlation between LISS derived LAI and MODIS LAI (r=0.62 to 0.73) was observed and a significant reduction in LAI values was found in version 4 in comparison to version 3. It was observed that the MODIS LAI version 4 values with slope of 1.29 and 0.82 were in close agreement to LISS-III LAI as compared to MODIS LAI version 3 (slope: 1.98 and 2.49). The slope reduced for version 4 products in comparison to version 3 products by 50% and RMSE reduced from 0.92 to 0.55 (40%) for 24 December 2001 and 1.26 to 0.82 (35%) for 12 February. The improvement in the performance of the MODIS LAI version 4 products was associated with the apparent change in proportion of pixels belonging to different quality control (QC) flags, which is discussed in the following section.
Figure 5.3.3. Comparison of the LISS-III LAI and MODIS LAI (Version 3) for Bhopal site: (a) Dec. 24, 2001 and (b) Feb. 12, 2002. For Indore site: (c) Dec. 2, 2001 and (d) Dec. 27, 2001

5.3.3.4 Issues associated with validation of MODIS LAI

Algorithm path (RT based or empirical) used for MODIS LAI retrieval

Comparison of MODIS LAI and LISS-III derived LAI is restricted to the MODIS-pixels labeled with best quality (RT-model/empirically derived pixels, cloud free) and good quality (flagged...
as good, but not the best, cloud free) flags. An analysis to infer the proportion of pixels pertaining to different quality flags was carried out for the MODIS LAI version 3 products of both the sites and version 4 products for the Bhopal site (figure 5.3.5a-c) considering QC variables supplied in QC files accompanying the products. For the version 3 MODIS LAI products, it was observed that maximum pixels (approximately 80 to 90%) were retrieved by RT method only for the Bhopal site as compared to the Indore site (53 to 60%).

For the Indore site a significant number of pixels (35%) were also retrieved by empirical method. For both the sites, 6 to 16% pixels were labeled cloudy or not usable due to various reasons. A significant change in the proportion of pixels was observed in quality labels (from best quality to good quality), when MODIS LAI products of version 3 and version 4 were compared for the Bhopal site. The proportion of best quality pixels decreased from 90 % to 40% for 24 December 2001 acquisition and 80% to 36% for 12 February 2002 acquisition when version 3 products were compared to version 4 products. While good quality pixels
increased from 0.2% to 53% and 4% to 52% for 24 December 2001 and 12 February 2002 acquisitions respectively. A significant improvement in the comparative analysis between MODIS LAI and IRS derived LAI was observed for version 4 products (figure 5.3.4a-b) as compared to version 3 products (figure 5.3.3a-b) mainly due to change in the retrieval algorithm. Comparison of the MODIS LAI products give more resemblance to the IRS derived LAI when the MODIS LAI was retrieved through the combination of RT model as well as empirical method for most of the pixels. The retrieval accuracy reduced when only RT model was used for retrieving the MODIS LAI, as it was seen in the case of Bhopal-site results using version 3 LAI products where factor of overestimation and RMSE are high significantly in version 3 as compared to version 4 (table 5.3.5). A preliminary analysis using all pixels including partially/totally cloudy pixels and pixels labelled with not usable flag indicated a much higher scatter between MODIS LAI and LISS-III estimated LAI. For example, version 3 LAI product of the Indore site (27 December, 2001 data) showed a reduction in $R^2$ (from 0.51 to 0.44) and an increase in RMSE (from 0.33 to 0.45).

**MODIS LAI product composite period**

The choice of 8-day composite period of the MODIS LAI products to match the acquisition date of IRS LISS-III overpasses was found to be a crucial factor when the crop is in an early growth stage for the Indore site. The 8-day composite period of the MODIS LAI products used in our analysis was chosen such that it covers the date of IRS LISS-III overpasses, except for Dec. 2, 2001 acquisition of IRS LISS-III for Indore, where the composite period of 3-10 Dec., 2001 was considered instead of 25 Nov.-2 Dec., 2001. When the IRS derived LAI for this acquisition was compared with the MODIS LAI of two different neighbouring composite periods, the MODIS LAI product of 3-10 December 2001 (representing 26-33 day-crop) showed more resemblance ($R^2=0.52$) with IRS derived LAI as compared to the MODIS LAI product of 25 Nov.-2 Dec. 2001 (representing approximately 18-25 day-crop) ($R^2=0.17$) and thus this product was considered in the analysis. The reason for considering the closest composite period is that the acquisition of LISS-III (Dec. 2, 2001) was aimed to address the crown root initiation stage of wheat crop (25 days after sowing) in this region, an 8-day composite period is susceptible to soil and vegetation changes during this growth stage.
Misclassification of biome type for study area

The overestimation in MODIS LAI can arise from a number of factors such as (Tan et al., 2005; Jonckheere et al. 2004) wrong biome type classification, multiband reflectance retrievals, mixed cover types, spatial scaling, reflectance saturation etc. We made an attempt to understand the reason for the overestimation by investigating the validity of biome classification for the study areas. Analysis of the MODIS land cover product (MOD12Q1) indicated errors in assigning land cover classes for the study sites. The study regions were assigned the broadleaf crop biome class (biome-3) instead of the grasses-cereal biome class (biome-1). Myneni et al. (2002) have shown when misclassification of land cover takes place between such classes, LAI retrieval indicated overestimation of approximately 20%. Such order of overestimation has been found for the Indore site, while the Bhopal site has a very high overestimation, which cannot be explained by the error caused by misclassification. Argão et al., (2005) have also reported that the overgeneralization of land cover layer can be a source of uncertainties for the LUT parameterization in version 4 MODIS LAI for broadleaf forest site.

Chen et al. (2002) have reported that LAI values derived from coarse resolution image (derived from AVHRR) were always lower than the LAI estimated from fine resolution images (derived from Landsat TM) and indicated several sources of errors such as coregistration-errors, effects of surface heterogeneity and mixed pixels, difference in land cover classification for two images etc. Tan et al., (2005) have reported that several issues arise when field measurements and high resolution satellite data are used to produce fine-resolution reference LAI maps to use them as reference to validate MODIS products. Uncertainty in field measurements, spatial heterogeneity in field LAI, especially in the case of sparse vegetation canopies, lower the measurement accuracy. Moreover, imperfect atmospheric correction, calibration and geolocation errors also reduce the retrieval accuracy. Such errors in field and satellite data propagating through extrapolation procedures can result in a reference LAI map of lower quality. Tan et al., (2005) have indicated that small variations in input due to observation errors result in a very low precision of desired parameter and thus the retrieval of LAI from satellite data is an ill-
posed problem and one has to understand and use information on input errors in the retrieval technique to generate stable retrievals. However, significant correlations between LISS-III derived LAI and MODIS LAI give an indication of encouraging performance of the MODIS LAI product, additional studies are needed before using the MODIS LAI product operationally.

5.3.4 CONCLUSIONS

A study on retrieval of LAI from IRS LISS-III data and validation of the MODIS LAI product is presented for two sites in Central India. The retrieval of LAI was carried out using empirical models between field measured LAI and satellite derived NDVI. Comparison of the version 3 and 4 MODIS LAI product with LISS-III derived LAI showed a significant positive correlation ($r=0.62$ to 0.78), indicating a good performance of the MODIS LAI product. However, an overestimation was observed for the version 3 MODIS LAI product (by a factor of 1.16 to 2.5) when compared with the LISS-III derived LAI with an RMSE of 0.20 to 1.26. The factor of overestimation decreases significantly by 50% and RMSE reduces by 40% when version 4 was analyzed and compared to LISS derived LAI. Efforts have been made to understand the cause of overestimation in the MODIS LAI product in terms of algorithm applied in different versions (or inferring the proportion of pixels with different quality flags in two different versions), choice of compositing period and land cover used for the classification of the study area. In this study the retrieval accuracy was found to be higher when the MODIS LAI was retrieved through the combination of a RT model as well as empirical method (with dominance of LAI retrieval by the empirical method i.e. backup algorithm) as compared to the retrieval only through RT model. Based upon the analysis of the MODIS land cover product, it was found that an erroneous biome classification is assigned to the study regions. It can be pointed out that LAI is spatially a very heterogeneous variable, and is measured with a high uncertainty in field observations and other procedures. However, additional studies, covering more sites and vegetation types should be carried out before using the product operationally. Since the observations were made primarily for wheat-gram-pea crops, observations for other crops and natural vegetation are essential for a broad scale validation of the LAI product.