Land-cover Monitoring Using Time Series of Satellite Images
Based on Harmonic Analysis

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Abstract. Remote Sensing is a useful tool to monitor land covers observing the earth's surface. Multi-temporal approach based on the temporal profile allows us to get information about the earth and human activities from a long-term perspective. The goal of this study is to develop an efficient method for land-cover monitoring using time series of satellite images. A harmonic model can characterize the temporal variability with four components: mean level, frequency, phase and amplitude. The components of the harmonic function inherently contain temporal information about seasonal changes. Seasonal periodicity can be incorporates into multi-temporal classification. In this research, a classification method using harmonic model is proposed. The method is tested and evaluated with multi-temporal Moderate Resolution Imaging Spectroradiometer (MODIS) data, one of the most useful remotely-sensed imagery. Satellite data inevitably contain disturbances caused by atmospheric effects and surface anisotropy scattering, which impede the analysis of time series data. The quality of data streams is important for the sequential data analysis. A filtering method was applied to reconstruct high-quality data stream. Then the proposed classification method was performed over the Korean peninsula from 2012 to 2016, where land-cover types were classified both with the estimated harmonic components using an unsupervised classification approach. The results of the classification show that the new approach has a great potential for land-cover monitoring.

Introduction

Remote sensing is a useful and cheap tool for observing the earth's surface without making direct contact with the earth's surface. This provides a global perspective on the changes and interactions of complex biosphere components. Classification is an image processing technique to obtain the information on land cover types. Many land-cover classification techniques using remotely-sensed images have been developed such as statistical pattern recognition techniques [1-3]. The algorithm based on the spectral signatures at a single point in time has an inherent difficulty in discriminating between surface material types due to signal variability through time, which often cause classification errors. This is the motivation for the development of multi-temporal techniques. The statistical approaches for the analysis of multi-temporal remotely-sensed images are designed to characterize abundant and useful information in the sequence since the time-series data contains a mixture of seasonal, gradual and abrupt changes [4]. For this reason, the temporal patterns of land cover is better explored in the time domain than in the spatial and spectral domain [5].

In the analysis of multi-temporal image, the temporal trends are to be evaluated simultaneously with spatial trends. One approach is to transform multi-temporal data into representation of the area-under-the-curve or the integral of the temporal profile curve [6]. Then temporal trends in the processes are summarized by a feature that is associated with the temporal accumulation measure. A harmonic model characterizes the seasonal variations in a time series using four parameters: (1) level; (2) frequency; (3) amplitude; the harmonic components of the time series for an individual pixel represent the characterization of temporal variability of the local region corresponding to the pixel.
MODIS has a considerable potential to understand land covers at reasonable spatial resolution and high temporal resolution and to be utilized for land vegetation studies. Multi-temporal MODIS data has been applied to land-cover mapping and change detection, annual vegetation dynamics both at local and global spatial scales. Multi-spectral reflectance data have been transformed and combined into various vegetation indices. The most commonly used vegetation index for monitoring seasonal trends in phenological processes is the normalized difference vegetation index (NDVI). The NDVI versus time profile shows the vegetation’s seasonal development pattern. The shape of the seasonal profile may be used to discriminate the type of vegetation cover based on the magnitude and shape of the curve. NDVI is constructed using the band 1 and 2 of MODIS’s 36 bands. It provides consistent information on vegetation conditions and plant temporal growth cycling. Multi-temporal NDVI data have been successfully utilized for surface vegetation conditions and the related phenomena [7].

Satellite data inevitably contain disturbances caused by cloud presence, atmospheric variability, aerosol scattering, and instrument problems [8]. These error sources result in producing bad or missing observations and impede the analysis of the time series data. The availability of high-quality data is essential for accuracy and reliability of the analysis. There are a variety of correction models proposed including asymmetric Gaussian function fitting [9], Fourier and wavelet transformation filtering [10], maximum value composite (MVC), and so on. In our study, the filtering process is employed based on the first derivative of the temporal data to reconstruct the necessary high-quality data stream, where bad or missing observations are recovered based temporal oscillation statistics, while the original data are preserved as much as possible for further analysis.

The temporal profile of NDVI processes can be featured by reducing dimensionality for the analysis. In this study, it is represented with a harmonic model characterized by four components: mean level, frequency, amplitude and phase, where the parameterization provides physically interpretable values to characterize the seasonal development of a vegetated pixel. Seasonal periodicity can be incorporated into multi-temporal classification. The resulting classification is based on the components which reflect temporal variation.

The NDVI data were obtained from MODIS imagery over the Korean Peninsula for 2012 and 2160, and the harmonic components for the five-year sequence were estimated. Then land-cover types were classified using the multistage classification algorithm that makes use of hierarchical clustering [4].

**Classification Procedure**

**Data Reconstruction**

The erroneous observations caused by atmospheric effects and surface anisotropy scattering are usually presented as anomalous high (spikes) and low (drops) values in temporal data stream. The monotonic properties of a data stream can be examined by the first derivatives. The monotonic oscillation observed from the time series data statistically shows a pattern of normal distribution as follows,

\[
\text{diff}_i(t) = |\text{NDVI}_i(t) - \frac{\text{NDVI}_i(t) + \text{NDVI}_i(t+1)}{2}|
\]  

\[
\text{diff}_i(t) \sim N(\mu_{\text{diff}}, \sigma_{\text{diff}}^2)
\]

where \(\text{NDVI}(t)\) be the value at time \(t\) in the temporal NDVI profile. The points located outside of the normal distribution are likely to have noise occurrence. Then the threshold for the anomalousness can be statistically defined using confidence interval such as 99.8% confidence interval limits [11]. A bad-quality observed value at time \(t\) in the \(i\)th pixel can be estimated using the following,

\[
\text{NDVI}_i(t) = \frac{\text{NDVI}_i(t) + \text{NDVI}_i(t+1)}{2} + \text{diff}_i(t)
\]

The resulting reconstructed data stream has a significant implication to a more accurate analysis for classification.
**Harmonic Model**

All tables and figures you insert in your document are only to help you gauge the size of your paper, for the convenience of the referees, and to make it easy for you to distribute preprints. Harmonic analysis is a mathematical procedure to break complex waveforms into sum of comparatively simple sinusoidal components [12]. The sequence of each pixel is represented with a harmonic model according to the temporal variance of its class. Given time series of size $n$, $\{x_0, x_1, x_2, \ldots, x_n\}$ the observed value at time $t$ can be defined as follows,

$$X_t = \mu_t(c) + \epsilon_t,$$

where $\mu_t$ is original intensity value, and $\epsilon_t$ is the random noise at time $t$.

$$\mu_t(c) = \{\mu_t, c(\cdot), \alpha_{c(i)} + R_{c(i)} \sin(\omega_{c(i)} t + \theta_{c(i)}), i \in I_n\} $$

(4)

where $I_n = \{1, 2, \ldots, n\}$ is a set of pixel indices, $c = \{c(i), i \in I_n\}$ is an integer valued random vector related to a particular configuration of classes. The constant mean $\alpha_{c(i)}$ frequency $\omega_{c(i)}$ amplitude $R_{c(i)}$ and phase $\theta_{c(i)}$ are the harmonic components associated with class $c(i)$ of the $i$th pixel. a sinusoidal variation is represented with $\{\alpha_{c(i)}, \omega_{c(i)}, R_{c(i)}, \theta_{c(i)}\}$. The parameters of the harmonic model are estimated from the temporal trajectory of each pixel’s intensity [13, 14]. The classification is performed by comparison with the estimates of the harmonic components.

For unsupervised classification, a multi-stage hierarchical clustering technique was employed [4]. In the hierarchical structure, more than one sub-regions in the lower levels can be merged into large homogeneous regions in the higher levels and this process is repeated at successively higher levels. Under the assumption of the hierarchical structure, it is possible to determine natural image segments by combining hierarchical clustering.

**Results and Discussion**

The MODIS image data analyzed in this study were obtained over the Korean Peninsula for five years from 2012 to 2016, each having $2590 \times 4380$ pixels with the special resolution of $250m \times 250m$. Since a large number of observations in the images are unobserved or contain inaccurate information, the data stream is to be reconstructed to estimate an accurate harmonic model for a certain period of time. Conventional compositing schemes are based on the maximum of NDVI to minimize atmospheric optical depth and select the clearest pixel. In this approach, it is difficult to completely produce cloud-free surface measurements. It also has a possibility of the subtle surface changes between the scenes. Here, bad-quality observations were restored based on the statistics of observed oscillations of the time series with 99.8% confidence interval limits as described previously. Figure 1 explains the importance of high-quality time series in NDVI analysis. A harmonic model was applied to the original data and the restored data and the its harmonic fit results are compared in Figure 1(a) and (b), which shows that the spectral measurements deteriorated by atmospheric changes are corrected and the harmonic fit for the time series is improved.

We applied the harmonics analysis to the reconstructed MODIS NDVI time series data stream at the end of each year. The harmonic components, mean level, amplitude and phase, were estimated for one year period. For the classification analysis the feature vector of the $i$th pixel are composed of the estimated harmonic components as follows:

$$f_i = \begin{bmatrix} \mu \\ R_1 \\ \varphi_1 \\ R_2 \end{bmatrix}$$

where $\mu$ is an mean level, $R_1$ a amplitude index, $\varphi_1$ a phase index of one year, respectively and $R_2$ is an amplitude index of a half year. Figure 2 shows the images of the estimated values of the harmonic components in year 2016.

The multi-temporal images of the MODIS NDVI were classified into seven classes separately.
using the multistage algorithm [13]. The classification results of MODIS data for 5 years from 2012 to 2016 is shown in Figure 3. The percentage shown in the legend represents the area occupied by each class. Figure 4 shows the harmonic patterns of vegetation for each class, and Table 1 contains the estimated values of the elements of each pattern in year 2016. In this classification, the first class (Class 1) corresponds to the urban area, and the northern part of the peninsula has the second, third and fourth classes (Class 2, 3 and 4). The vegetation types of the fifth, sixth and seventh classes (Class 5, 6, 7) are mainly distributed in the southern part of the Korean peninsula. The annual-average values of NDVI are higher in the southern region and in the mountain region than in the northern region, but the northern region has a higher amplitude range. The northern mountain area of the peninsula exhibits great seasonal variation in vegetation processes, but difference between the seasons is relatively small in the southern area.

Figure 1. Data reconstruction effect: blue- original data, red- harmonic model fitting after data reconstruction by the proposed method, black- harmonic model fitting after data reconstruction by a wavelet-based method.

Figure 2. Estimated parameter Image for MODIS of Year 2016.

Figure 3. Classification Map using Harmonic modeling for MODIS for 5 years from 2012 to 2016.
Conclusion

Time series of satellite images have been effectively utilized in monitoring land-use and land-cover change for better management and use of Earth’s resources. The harmonic modeling has a great potential for analysis of multi-temporal data that exhibit seasonal trends such as vegetation activity. Fortunately, most of vegetation processes show one year cyclic behavior. In many researches, it is shown that the variability observed in the NDVI time series data is usually due to inter-seasonal variability. The harmonic analysis is consistent with this type of variability.

In harmonic modeling of the NDVI sequential processes, temporal pattern is integrated with its components. Especially, three component indices explain the temporal dynamics, which are the mean index representing the overall mean level of vegetation activity measured by NDVI, the amplitude and phase indices characterizing the shape of the seasonal spectral profile. Each land-cover type has a unique temporal profile according to the development cycles, which are reflected in the harmonic parameters. Therefore these indices can be employed as a feature for classification of land covers. The proposed method was applied to the MODIS time series data over the Korean Peninsula for test and the classification results show that the proposed method can be usefully employed for monitoring land covers.

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