On the Blending of the Landsat and MODIS Surface Reflectance: Predicting Daily Landsat Surface Reflectance

Feng Gao, *Member, IEEE*, Jeff Masek, Matt Schwaller, and Forrest Hall

***Abstract*—The 16-day revisit cycle of Landsat has long limited its use for studying global biophysical processes, which evolve rapidly during the growing season. In cloudy areas of the Earth, the problem is compounded, and researchers are fortunate to get two to three clear images per year. At the same time, the coarse resolution of sensors such as the Advanced Very High Resolution Radiometer and Moderate Resolution Imaging Spectroradiometer (MODIS) limits the sensors' ability to quantify biophysical processes in heterogeneous landscapes. In this paper, the authors present a new spatial and temporal adaptive reflectance fusion model (STARFM) algorithm to blend Landsat and MODIS surface reflectance. Using this approach, high-frequency temporal information from MODIS and high-resolution spatial information from Landsat can be blended for applications that require high resolution in both time and space. The MODIS daily 500-m surface reflectance and the 16-day repeat cycle Landsat Enhanced Thematic Mapper Plus (ETM+) 30-m surface reflectance are used to produce a synthetic "daily" surface reflectance product at ETM+ spatial resolution. The authors present results both with simulated (model) data and actual Landsat/MODIS acquisitions. In general, the STARFM accurately predicts surface reflectance at an effective resolution close to that of the ETM+. However, the performance depends on the characteristic patch size of the landscape and degrades somewhat when used on extremely heterogeneous fine-grained landscapes.**

***Index Terms*—Data fusion, image enhancement, image processing, Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS), remote sensing, surface reflectance.**

I. Introduction

LANDSAT data have proven extremely useful in monitoring land cover and land-cover changes [1]–[3]. Recently, the Landsat ecosystem disturbance adaptive processing system (LEDAPS) was developed to create a Landsat-based surface reflectance product for North America to support the North American Carbon Program (NACP) [4]. Calibrated and atmospherically corrected surface reflectance is critical for the consistent retrieval of biophysical parameters and for detecting land-cover changes. However, the 16-day Landsat revisit cycle and frequent cloud contamination have limited the application of Landsat in detecting rapid surface changes that are crucial to some applications such as crop-growth monitoring and detecting intraseasonal ecosystem disturbance.

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F. Gao is with the Earth Resources Technology Inc., Jessup, MD 20794 USA (e-mail: Feng.Gao@nasa.gov).

J. Masek, M. Schwaller, and F. Hall are with the National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, MD 20771 USA.

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TABLE I
LANDSAT ETM+ BANDWIDTH AND MODIS BANDWIDTH

Landsat ETM+ Band	ETM+ Bandwidth (nm)	MODIS Land Band	MODIS Bandwidth (nm)
1	450-520	3	459-479
2	530-610	4	545-565
3	630-690	1	620-670
4	780-900	2	841-876
5	1550-1750	6	1628-1652
7	2090-2350	7	2105-2155

One solution is to combine the spatial resolution of Landsat with the temporal frequency of coarse-resolution sensors, such as Moderate Resolution Imaging Spectroradiometer (MODIS). The Terra platform crosses the equator at about 10:30 A.M. local solar time, roughly 30 min. later than Landsat-7. Their orbital parameters are equal, and as such the viewing (near-nadir) and solar geometries are close to those of the corresponding Landsat acquisition. The Terra/Aqua MODIS provides frequent coarse-resolution observations, revisiting the globe once to twice per day. The MODIS observations include 250-m spatial resolution for red (band 1) and near-infrared [(NIR) band 2] wavebands and 500-m spatial resolution for other five MODIS land bands (band 3–7). The MODIS land bands have corresponding bandwidths to the Landsat Enhanced Thematic Mapper Plus (ETM+) sensor except their bandwidths are narrower than ETM+ (see Table I). In this paper, we use the MODIS daily 500-m surface reflectance product (MOD09GHK) to blend Landsat and MODIS data in order to produce a synthetic "daily" Landsat image. Such a product could have considerable utility for applications that require both high spatial resolution and frequent coverage.

Many studies have focused on the fusing of a fine-resolution panchromatic band and coarse-resolution spectral bands from one or more instruments [5]–[7]. The major purpose of those studies has been to generate high-resolution multispectral imagery combining the spectral characteristics of low-resolution data with the high spatial resolution of the panchromatic imagery. However, the outputs from those techniques were not calibrated to spectral radiance or reflectance. The traditional data fusing approaches such as those using hue saturation value (HSV) transforms, principal component analysis [7], and wavelet transformation [5], [6] may not suitable for the problem considered here, since we wish to capture the quantitative changes in radiometry (surface reflectance) caused by phenology.

In this paper, a spatial and temporal adaptive reflectance fusion model (STARFM) is presented to predict daily surface reflectance at Landsat spatial resolution and MODIS temporal frequency. The daily surface reflectance at Landsat spatial resolution is predicted from one or several pairs of Landsat and MODIS images acquired on the same day and one or more MODIS observations from the prediction date. The Landsat images can be "sparse" in time, letting the MODIS data capture temporal changes. Since Landsat surface reflectance is totally unknown for the predicted date, this approach works in an unsupervised style. The STARFM has been tested over forested areas, cropland regions, and heterogeneous mixtures of crop and forest. Results show that the STARFM can capture phenology changes precisely, although the accuracy depends on the characteristic patch size of the landscape.

Although MODIS and Landsat surface reflectances are used to test the STARFM algorithm, this approach is also applicable to other similar instruments in fusing fine spatial resolution and high-frequency temporal information. In particular, the next Landsat-like sensor [Operational Land Imager (OLI)] is slated to fly concurrently with the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Visible Infrared Imager/Radiometer Suite (VIIRS) global imager during the next decade. Algorithmic approaches such as those presented here will be especially valuable for obtaining the maximum value from both data streams.

II. Approaches

A. STARFM Theoretical Basis

Observations from different platforms first need to be calibrated and atmospherically corrected to surface reflectance so that they are comparable spatially and temporally. The LEDAPS has used the MODIS 6S approach for atmospheric correction of Landsat Thematic Mapper (TM) and ETM+ data, with the aerosol thickness derived from the imagery itself [4], [8]. Comparisons between MODIS and Landsat surface reflectance data reveal that they are very consistent [4]. However, due to the differences in data processing, acquisition time, bandwidth, and geolocation errors, small biases are expected.

Neglecting geolocation errors and differences in atmospheric correction, a heterogeneous coarse-resolution pixel at date t and surface reflectance (C_t) can be aggregated from finer resolution homogeneous pixels of surface reflectance F_t^i and percentage coverage A_t^i according to

$$C_t = \sum \left(F_t^i * A_t^i\right) \tag{1}$$

where i refers to the spatial index (location) of the fine-resolution pixel. Even under the situation that percentage area A_t^i does not change and can be retrieved from previous or next acquisitions, the problem is still ill posed mathematically, and a unique solution cannot be determined without additional information. If F_t^i can be obtained from neighboring homogeneous coarse-resolution pixels, results could be improved dramatically. Therefore, the key to finding an approximate solution is to find spectrally similar homogeneous neighboring pixels.

V. Conclusion and Discussion

Landsat 30-m-resolution observations have been widely used in regional land-cover mapping and change detection. Applications of Landsat imageries are unfortunately limited by 16-day repeat cycling and cloud contaminations. On the other hand, the Terra/Aqua MODIS observations cover the globe one or two times each day but lack fine spatial resolution. The STARFM algorithm that we developed in this paper uses spatial information from fine-resolution imagery and temporal information from coarse-resolution imagery to produce estimates of surface reflectance that are high resolution in both space and time. In essence, the collection of daily MODIS imagery and seasonal Landsat imagery allow the generation of synthetic "daily" Landsat-like views. This algorithm can be expanded to other similar data fusion applications given observations that can be corrected to comparable surface reflectance values.

The STARFM can produce extremely accurate estimates of high-resolution reflectance that preserve the high spatial resolution of Landsat and high temporal resolution of MODIS if "pure" coarse-resolution neighbor pixels can be found within the moving window. For complex mixtures of different land-cover types, the adjustment of algorithm parameters such as the size of the searching window and the weighting function (direct or logistic) can improve prediction. However, the algorithm ultimately requires daily data at a finer resolution than 500 m for these heterogeneous "fine grained" regions.

Although STARFM works with one input Landsat and MODIS pair, the prediction can be improved if more than one pair is used. For estimating the annual growing cycle, results are improved if Landsat imagery is available at the beginning (greenup), middle (maturity), and end (senescence) of the growing season. Thus, the Landsat data act as phenology "transition points" that bracket the temporal interpolation. The algorithm has proven very robust in capturing phenology and BRDF changes across large areas.

The simulation tests show that the STARFM can capture the initial and final states of changing shapes and thus can capture disturbance and land-cover change processes. If changes are "permanent" during the growing season (such as burn scars and land-cover conversion), the algorithm should be able to record the transition from one state to another as demonstrated in the simulation tests. However, if changes are transient and not recorded in any of the bracketing Landsat images (e.g., clouds), then it may not be possible to capture them in fine resolution. In addition, any changes that are too subtle to be observed by the MODIS observations are not predictable with this algorithm.

Although the work in this paper is based on the MODIS and Landsat surface reflectance, the STARFM approach is also applicable to future instrument suites, such as the Landsat Data Continuity Mission OLI and the NPOESS VIIRS. The former is slated to continue Landsat-type observations into the next decade, while the latter will provide operational continuity with MODIS. Although it may be scientifically desirable to have a constellation of high-resolution satellites giving Landsat-type observations every day or two, such a resource is unlikely in the immediate future. However, software approaches like STARFM may be able to blend aspects of coarse and fine-resolution sensors to accomplish many of the same observational goals at present.