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Moderate resolution remote sensing alternatives: a review of Landsat-like sensors and their applications

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Abstract. Earth observation with Landsat and other moderate resolution sensors is a vital component of a wide variety of applications across disciplines. Despite the widespread success of the Landsat program, recent problems with Landsat 5 and Landsat 7 create uncertainty about the future of moderate resolution remote sensing. Several other Landsat-like sensors have demonstrated applicability in key fields of earth observation research and could potentially complement or replace Landsat. The objective of this paper is to review the range of applications of 5 satellite suites and their Landsat-like sensors: SPOT, IRS, CBERS, ASTER, and ALI. We give a brief overview of each sensor, and review the documented applications in several earth observation domains, including land cover classification, forests and woodlands, agriculture and rangelands, and urban. We conclude with suggestions for further research into the fields of cross-sensor comparison and multi-sensor fusion. This paper is significant because it provides the remote sensing community a concise synthesis of Landsat-like sensors and research demonstrating their capabilities. It is also timely because it provides a framework for evaluating the range of Landsat alternatives, and strategies for minimizing the impact of a possible Landsat data gap.

Keywords: Landsat, SPOT, IRS, CBERS, ASTER, ALI.

1 INTRODUCTION

Moderate resolution remote sensing is integral to a wide variety of sectors including land use planning, agriculture, and forestry, at local, regional, and global scales [1]. Of the suite of moderate resolution satellites, Landsat is the most widely used for earth observation applications. A recent survey by the American Society for Photogrammetry and Remote Sensing [1] found that the majority of respondents (71%) use Landsat as their primary source of moderate resolution satellite data.

The popularity of Landsat data can be attributed to several key characteristics of the Landsat program, including a systematic data acquisition plan and archive that ensures global coverage and data availability. Further, low imagery costs and free data distribution facilitate widespread use. The keys to Landsat's popularity also include its data characteristics, namely its large footprint, and a spatial resolution fine enough to characterize typical land cover dynamics related to land management [2].

Landsat data have been collected and archived from six Landsat missions spanning nearly 35 years. The Landsat suite of satellites was initiated in 1972 with the launch of Landsat 1

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Multispectral Scanner (MSS), and continues to this day with the operation of Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+).

Despite the success of the Landsat program, the near future is uncertain. Landsat 5, launched in 1984, has greatly exceeded its engineered life cycle of three years, and will potentially run out of fuel by the end of this decade. In the meantime, the satellite recently began experiencing technical difficulties with its solar array drive and its onboard batteries, potentially threatening power generation and balance [3]. Landsat 7, launched in 1999, developed an intractable problem with the scan-line corrector in 2003, leading to a reduced data quality for many applications [4].

Implementation plans for a follow-on Landsat mission are currently in progress. In 2001, NASA and the USGS initiated the Landsat Data Continuity Mission (LDCM) to develop strategies for meeting the goal of the Land Remote Sensing Policy Act of 1992 [5] to maintain Landsat continuity. However, a follow-on Landsat launch cannot be expected before 2011 [4].

Given these uncertainties, the options for moderate resolution remote sensing in the near future are unclear. Many applications rely on continuous moderate resolution earth observation (e.g. LEDAPS [6]). In the event of a Landsat data gap, it is imperative that the remote sensing community understand the range of available options for data continuity and the potential trade-offs among them. A Landsat data gap notwithstanding, the demand for moderate resolution data is growing [1], and there is an increasing demand for up-to-date, intra-seasonal, cloud-free observations. A range of satellites could be used as complements or replacements to Landsat. Our objective for this paper, therefore, is to present a review of moderate resolution, "Landsat-like" sensors. We endeavor to provide the remote sensing community, and more specifically the Landsat user community, with a concise synthesis of Landsat-like sensors and research that documents their capabilities.

How do we define "Landsat-like" sensors? Landsat-like sensors are those with similar characteristics to Landsat sensors in terms of moderate spatial resolution (~30 m), multispectral coverage in the visible and near-infrared (VNIR), and shortwave-infrared (SWIR) ranges, large spatial coverage (~185 km swath), and multiple acquisitions over a year (Table 1). We limit our review to issues dealing with inherent sensor qualities, including spectral and spatial resolution, revisit time, and swath width. A thorough review of the programmatic issues related to data downlink, storage, archiving, access, and data cost is beyond the scope of this paper, and have been discussed elsewhere [7]. These logistical issues certainly play a large role in data selection, and it is important to note that the Landsat-like sensors fall short of Landsat in terms of global data acquisition or extent of and access to archived data. Despite these known limitations, it is instructive for users of moderate resolution remote sensing data to understand the key differences in the inherent data qualities that determine a sensor's merit for a particular application, where data are available. We describe five satellite suites (SPOT, IRS, CBERS, ASTER, and ALI) containing a total of 12 Landsat-like sensors, and review their published applications in several key earth observation domains. We conclude with a discussion of cross-sensor comparison and techniques that incorporate data from multiple sensors.

2 REVIEW OF LANDSAT-LIKE SENSORS AND APPLICATIONS

We begin with a description of the five satellite suites referred to above and their sensor characteristics (Table 2). Some of the sensors that we describe have long been in operation and may even exceed their proposed mission timelines. We limit our review to sensors with

Table 1. Landsat 5 and Landsat 7 specifications.

Satellite/Sensor	**Launch Date**	**Spectral Coverage (µm)**	**Spatial Resolution (m)**	**Revisit Time (days)**	**Swath Width (km)**
Landsat 5 /Thematic Mapper	1984	VNIR 0.45-0.52 0.52-0.60 0.63-0.69 0.76-0.90 1.55-1.75 2.08-2.35	30	16	185
		TIR 10.40-12.50	120		
Landsat 7 /Enhanced Thematic Mapper Plus	1999	PAN 0.52-0.90	15		
		VNIR 0.45-0.52 0.53-0.61 0.63-0.69 0.75-0.90 1.55-1.75 2.08-2.35	30		
		TIR 10.40-12.50	60		

comparable spectral, spatial, and temporal properties to Landsat. We do not review all sensor systems (from a particular satellite) if they are not comparable to Landsat.

For each sensor, we provide an overview of the range of published applications across several primary domains of earth observation research: land cover classification, forests and woodlands, agriculture and rangelands, and urban. While these sensors have been used for many other domains of earth observation research, we limit our review to these in an effort to be concise. The range of practical applications of Landsat has been well documented elsewhere [2,8]. Land cover classifications with Landsat are numerous [9,10]. Forest and woodland applications with Landsat include mapping gross and net primary production [11], leaf area index [12,13], forest disturbance [14,15], and carbon stores [16,17]. Agriculture and rangeland applications of Landsat include crop yield estimation [18,19], crop characterization [20], and mapping changes in irrigated crop area [21]. Urban applications of Landsat include estimating urban growth [22,23] and population density [24].

2.1 SPOT

SPOT (Satellite Pour l'Observation de la Terre) satellites are a suite of commercial earth observation satellites owned by the French Space Agency CNES (Centre National d'Etudes Spatiales). Currently SPOT 2, SPOT 4, and SPOT 5 are in orbit. The satellites carry two identical sensors to make them pointable in the cross-track direction, and also enable stereo

Table 2. Landsat-like sensors and their specifications.

Satellite/Sensor	Launch Date	Spectral Coverage (µm)	Spatial Resolution (m)	Revisit Time (days)	Swath Width (km)
EO-1/ALI	2000	Pan 0.48-0.69	10	16	37
		VIR 0.43-0.45 0.45-0.51 0.53-0.61 0.63-0.69 0.78-0.81 0.85-0.89 1.20-1.30 1.55-1.75 2.08-2.35	30		
Terra/ASTER	1999	VNIR 0.52-0.60 0.63-0.69 0.76-0.86	15	16	60
		SWIR 1.60-1.70 2.15-2.19 2.19-2.23 2.24-2.29 2.30-2.37 2.36-2.43	30		
		TIR 8.13-8.48 8.48-8.83 8.93-9.28 10.25-10.95 10.95-11.65	90		
CBERS/CCD	CBERS-1: 1999 CBERS-2: 2003	PAN 0.51-0.73	20	26	113
		VNIR 0.45-0.52 0.52-0.59 0.63-0.69 0.77-0.89			
CBERS/IR-MSS		VIR 0.50-1.10 1.55-1.75 2.08-2.35	80	26	120
		TIR 10.40-12.50	160		
IRS-1C & 1D/Pan	IRS-1C: 1995	PAN 0.50-0.75	5.2	24	70

IRS-1C & 1D /LISS-III	IRS-1D: 1997	VNIR 0.52-0.59 0.62-0.68 0.77-0.86	23.5	24	141
		SWIR 1.55-1.70	70.5		148
IRS-P6 (RESOURCE-SAT-1) /LISS-III	2003	VIR 0.52-0.59 0.62-0.68 0.77-0.86 1.55-1.70	23.5	24	141
IRS-P6 (RESOURCE-SAT-1) /LISS-IV		VIR 0.52-0.59 0.62-0.68 0.77-0.86 1.55-1.70	5.8	5	23 70 (PAN)
IRS-P6 (RESOURCE-SAT-1) /AWIFS		VIR 0.52-0.59 0.62-0.68 0.77-0.86 1.55-1.70	56	5	740
SPOT 2/HRV	1990	PAN 0.50-0.73	10	26	60
		VNIR 0.50-0.59 0.61-0.68 0.78-0.89	20		
SPOT 4/HRVIR	1998	PAN 0.61-0.68	10	26	60
		VIR 0.50-0.59 0.61-0.68 0.79-0.89 1.58-1.75	20		
SPOT 5/HRG	2002	PAN 0.48-0.71	2.5 or 5	26	60
		VNIR 0.50-0.59 0.61-0.68 0.78-0.89	10		
		SWIR 1.58-1.75	20		

imaging. SPOT 2, launched in 1990, has two high resolution visible (HRV) sensors, and SPOT 4, launched in 1998, has two high resolution visible infrared (HRVIR) sensors, including sensitivity in SWIR wavelengths. SPOT 5, launched in 2002, also contains two high resolution geometric (HRG) sensors with 2.5 m panchromatic resolution, 10 m VNIR resolution, and 20 m SWIR resolution. The SPOT sensors, however, lack spectral coverage in the blue (0.45-0.52), SWIR (2.08-2.35), and thermal infrared (TIR) (10.40-12.50) regions, rendering specific applications that rely on these spectral regions (e.g. cloud detection or atmospheric correction) more challenging.

The suite of SPOT sensors is perhaps the most widely used Landsat-like alternative. Despite having a smaller swath width (60 km) than Landsat (185 km), the high spatial resolution (2.5 m to 20 m) makes it useful for a variety of applications. Moreover, while the typical revisit time (26 days) is longer than that of Landsat (16 days), the pointable optics potentially allow for more frequent image acquisition. For example, SPOT HRV was used to look at seasonal trajectories of NDVI in Japan, using the oblique viewing angle to increase observation frequency [25].

Several studies have shown SPOT to be at least as accurate as Landsat in direct comparisons of land cover classification accuracy. Land cover classifications with SPOT have been performed in a wide variety of regions, including Puerto Rico [26], Zambia [27], and Indonesia [28]. Clark et al. [29] demonstrated that Landsat 5 TM and SPOT 3 HRV had statistically similar accuracies for plant community classification in southwestern Idaho. Salajanu and Olson [30] found higher classification accuracy of forest species using SPOT XS (20 m VNIR) than Landsat TM. The improvement was attributed to the improved spatial resolution of SPOT XS versus Landsat TM.

Forest and woodland applications with SPOT sensors abound in the literature. In some studies, the higher spatial resolution of SPOT was an advantage compared to Landsat, yet in other studies, the lack of a SWIR band on SPOT HRV was a potential disadvantage. For example, May et al. [31] compared the relative accuracy of Landsat TM and SPOT HRV multispectral data for mapping shrub and meadow vegetation in northern California. Despite the higher spatial resolution of SPOT, they found that TM was more accurate in separating shrubs from meadows. Salajanu and Olson [30] on the other hand found SPOT yielded higher accuracy than Landsat TM in predicting 19 forest cover types. In Pacific Northwest forests, both image texture and SWIR reflectance are important for characterizing forest structural attributes [32]. SPOT HRV 10 m panchromatic was highly correlated with tree size variability and mean size and density of trees in the upper canopy layers, as was Tasseled Cap wetness from Landsat TM [32]. Based on these results, it would appear that the higher spatial resolution of the SWIR band from SPOT HRVIR and SPOT HRG makes these sensors viable complements or alternatives to Landsat where these data are available. In another study, Donoghue et al. [33] developed models with SPOT HRVIR and Landsat ETM+ to predict mean height in two 17 year old Sitka spruce plantations, and found that both sensors yielded comparable accuracies. In a Finish study, SPOT XS (20 m) and PAN (10 m) spectral modes performed better than Landsat TM in estimating stand-wise stem volume and basal area [34]. Soudani et al. [35] computed NDVI and EVI in temperate coniferous and deciduous forest stands to compare SPOT HRVIR and Landsat ETM+, and found that both sensors showed the same predictive ability for stand LAI.

SPOT imagery has also been useful in urban settings to delineate core urbanized areas, such as the metropolitan region of Beirut [36]. Weber and Puissant [37] used SPOT imagery to map changes in six land cover classes in the southwestern part of metropolitan Tunis, Tunisia, and in South Auckland, New Zealand, SPOT imagery was used to map ten land cover classes at level II of the Anderson scheme [38].

2.2 IRS

The IRS (Indian Remote Sensing) satellites consist of a suite owned by the Indian National Remote Sensing Agency (NRSA). The IRS-1C (launched in 1995) and IRS-1D (launched in 1997) satellites each carry two Landsat-like sensors: the LISS-III multispectral and panchromatic sensors. The IRS-P6 satellite (RESOURCESAT-1), launched in 2003, carries three sensor systems: LISS-III, LISS-IV, and AWIFS, each with VIS, NIR, and SWIR bands at various spatial and temporal resolutions [39].

The IRS sensors have demonstrated the potential to support large-area remote sensing applications with comparable accuracy to Landsat. While the spectral resolution is less than Landsat on each IRS sensor, there is spectral coverage in the VIS, NIR, and SWIR portions of the electromagnetic spectrum. However, like SPOT, the IRS sensors lack spectral coverage in the blue, SWIR, and TIR regions. LISS-IV has four bands at 5.8 m spatial resolution, a five day revisit time, but a narrow 23 km swath width, rendering this sensor more practical for smaller area studies. The AWIFS sensor on the other hand, with a coarser spatial resolution (56 m) than Landsat has a swath width of 740 km, rendering this sensor potentially quite useful for large area applications. In fact, AWIFS was the imagery of choice for the USDA National Agricultural Statistics Service (NASS) development of their 2006 Cropland Data Layer [40].

The applications of IRS sensors have mainly been documented on the Indian sub-continent. Shalan et al. [41] used LISS imagery from IRS-IC in a fuzzy classification context to produce accurate land cover maps in West Bengal state, India. In the West Coast Western Ghats region of India, Nagendra and Gadgil [42] used LISS imagery for hierarchical land cover classifications in support of biodiversity assessments. In that study, they were able to discriminate approximately 30 distinctive ecotopes using supervised classification.

The Forest Survey of India used LISS to map forest types and distinguish between dense and open forests [43,44]. LISS data has also been used to study species richness of different altitudinal zones [45] and to identify conservation priority sites [46]. Chandrashekhar et al. [47] used a hybrid-approach of supervised and unsupervised classification to evaluate biodiversity in the western Himalayas. Similarly, Behera et al. [48] mapped forests types to prospect for *Taxus* species in a temperate forest in north-eastern India. Shanmugam et al. [49] tested the capabilities of LISS-III and Landsat TM sensors to map the distribution of wetlands at three coastal sites using spectral mixture analysis.

In agricultural settings, IRS-1B LISS-II and IRS-1C LISS-III have been used to identify mango orchards and estimate crop yield in India [50]. The results showed that LISS-III yielded higher accuracy over LISS-II, likely because of improved spatial resolution. Singh et al. [51] used IRS-1B LISS-II, and Patel et al. [52] used AWIFS to accurately estimate crop yield in agricultural regions of India.

The IRS satellite has also been useful in urban settings. Raghavswamy et al. [53] used LISS-III to map land use classes up to information level III. The enhanced spatial resolution of LISS has been found to be very useful in the identification of boundaries of polygon features and road intersections [54].

2.3 CBERS

CBERS (China-Brazil Earth Resources Satellite) is owned by the joint China-Brazil Earth Resources Satellite Program. The two satellites each contain two relevant sensors with different spatial resolutions and data collection frequencies: a high resolution Charge Coupled Device (CCD) camera, and an Infrared Multispectral Scanner (IR-MSS). The CCD camera, with five bands, is pointable up to 32 degrees, and capable of providing stereoscopic images. The Infrared Multispectral Scanner (IR-MSS) extends the CBERS spectral coverage to the shortwave and thermal infrared ranges. Currently CBERS-1 (launched in 1999) and CBERS-2 (launched in 2003) are in orbit, and two additional satellites (CBERS-3 and CBERS-4) are planned for future launch (in 2008 and 2010 respectively) with technologically improved sensors [55].

The CBERS-1 and CBERS-2 have higher spatial resolution (20 m) than Landsat in the visible and near-infrared bands, yet the shortwave- and thermal-infrared bands are much coarser spatial resolution (80 m and 160 m respectively). Therefore, for applications that can rely solely on visible and near-infrared bands, such as NDVI-based analyses, CBERS is a potentially viable alternative. However, for applications necessitating the use of SWIR, CBERS is inferior to Landsat in terms of spatial resolution.

Documented applications of CBERS imagery are difficult to find in the primary literature, though it has been utilized for several large-area land cover mapping projects. For example, in Hebei Province, China, land cover was classified at 20 m resolution with CBERS-2 imagery, and then used to derive land surface heat flux [56]. In China's Loess Plateau, CBERS-1 and Landsat TM imagery were used for forest change classification [57]. CBERS has also been used to compare NDVI derivations from the CCD versus the IR-MSS sensors [58], and to estimate biomass of pine plantations [59].

2.4 ASTER

ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) is one of five sensors aboard NASA's Terra satellite, launched in 1999. The sensor consists of three separate instrument subsystems; the visual and near infrared (VNIR) with three bands at 15 m (but lacking coverage in the blue region), the shortwave infrared (SWIR) with six bands at 30 m, and the thermal infrared (TIR) with five bands at 90 m. The sensor's VNIR subsystem is pointable up to 24 degrees [39].

The high spatial and spectral resolution of ASTER is useful for a variety of moderate resolution applications. Muukkonen and Heiskanen [60] tested the suitability of ASTER satellite data for estimating biomass and carbon stocks in the boreal forest of Finland. The study found all ASTER bands to be sensitive to tree biomass, but in particular the green and SWIR bands. Broadbent et al. [61] investigated forest structure after selective logging in Bolivia using a time-series of ASTER images. Falkowski et al. [62] estimated crown closure and crown bulk density for forest fire fuel monitoring with ASTER. Heiskanen [63] used ASTER to estimate LAI and aboveground tree biomass with a variety of vegetation indices and found that the Simple Ratio and NDVI were the most strongly correlated. Toomey and Vierling [64] compared ASTER with Landsat TM to predict foliar moisture content and found that both sensors showed similar results. In Germany, high classification accuracy was obtained around flux measurement sites using both ASTER and Landsat ETM+ imagery [65].

ASTER has also been used extensively for urban applications. The spatial, spectral and radiometric resolution of this sensor makes it useful in the urban environment. The Urban Environmental Monitoring Program (UEM) was initiated to collect daytime and nighttime ASTER data over 100 urban centers [66]. Stefanov et al. [67] used ASTER to develop a landcover map consisting of 11 urban classes in Phoenix, Arizona. Netzband [68] used ASTER to calculate a number of land cover metrics for ten cities. In Beer Sheva, Israel, Zhu and Blumberg [69] acquired ASTER data to test its utility in urban studies and found that only the three 15 m bands were needed.

2.5 ALI

ALI (Advanced Land Imager), aboard NASA's Earth Observer (EO-1), was launched in 2000, and was designed to be comparable with Landsat's spatial and spectral resolution, all the while reducing mass, volume, and cost [70]. EO-1 initially flew just one minute behind Landsat 7, thereby observing the same ground location through a nearly identical atmosphere [39]. The push-broom ALI sensor has wide-angle optics and an integrated multispectral and panchromatic spectrometer. Intended to inform the LDCM, ALI's spectral bands were designed to mimic six Landsat bands (excluding TIR) with three additional bands covering 0.43-1.30 μm [70].

The ALI sensor has shown improved capability versus Landsat ETM+ for a variety of environmental applications [71]. ALI has comparable spatial resolution (30 m) to Landsat, with improved spectral resolution (9 bands, but lacking TIR), and identical revisit time (16 days). A limitation to the use of ALI is its narrow swath width (37 km), which potentially renders the task of large area coverage more challenging and costly.

Several studies have shown improved land cover classification accuracy with ALI versus Landsat. In the Okavango Delta of Botswana, large-scale mapping of riparian features was consistently improved with ALI, likely as a result of a higher signal-to-noise ratio and an improved dynamic range [72]. In western Canada, forest type classification was nearly 10% more accurate overall using ALI than Landsat ETM+ [73]. In southern Cameroon, ALI yielded slightly higher accuracy for tropical rainforest classification than ETM+ [20].

ALI also outperformed ETM+ in separating several types of conifer and hardwood forest in Canada [73]. ALI has shown higher performance in retrieving crown closure information and leaf area index in a semi-arid environment in Northern California [74]. Elmore and Mustard [75], however, found that ALI did not yield higher accuracy for estimating vegetation cover in the Great Basin. In the agricultural domain, ALI yielded equal or higher accuracies than ETM+ for crop discrimination in northwestern Mexico [19]. ALI's extra spectral bands proved useful for atmospheric correction and prediction of albedo and LAI at two sites in Maryland and Australia [76].

2.6 Other Landsat-like sensors

In addition to the five satellite suites reviewed here, three other satellite suites carry Landsat-like sensors that may become relevant to the moderate resolution remote sensing community in the near future. Our review of these sensors is limited because at the time of writing they were not yet operational or they lacked published applications in the primary literature.

ALOS (Advanced Land Observing Satellite), owned by the Japanese Aerospace Exploration Agency (JAXA), carries two relevant remote sensing instruments: the Panchromatic Remote sensing Instrument for Stereo Mapping (PRISM) and the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) [77]. The satellite was launched in early 2006; therefore, we expect published applications are forthcoming.

DMC (Disaster Monitoring Constellation) consists of five satellites owned by the Algerian, Nigerian, Turkish, British, and Chinese governments [78]. Spain plans to join the consortium by launching the sixth DMC in 2008. The satellites work together to achieve global coverage, with a temporal resolution of one day at most latitudes. Like ALOS, published applications of DMC data were not readily available in the primary remote sensing literature.

RapidEye is a German constellation of five satellites planned for launch in 2007. The satellites will provide a daily coverage of high resolution, multispectral data over a large area. The satellites will be pointable at several look angles to the earth's surface on a 24-hour revisit cycle [79]. The RapidEye sensors will have five optical bands in the VIR range, with 5 m spatial resolution at nadir.

3 RESEARCH NEEDS

While each of the sensors that we reviewed has the potential to complement or replace Landsat for some applications, no single sensor encapsulates the full suite of characteristics (data qualities plus programmatic considerations) that make it as practical as Landsat. For that reason, it’s likely that near-future moderate resolution remote sensing will rely on approaches that incorporate data from multiple sensor sources.

Many moderate resolution remote sensing programs and applications rely upon the continuation of historical Landsat-like observations (e.g. LEDAPS [6]). In the event of a Landsat data gap, alternatives will need to be identified. The use of imagery from other sensors in comparison to the Landsat archive, therefore, hinges upon accurate cross-normalization. Wulder et al. [80] demonstrated how an ordinal-rank normalization procedure using multi-temporal imagery from four different sensors (Landsat 5, Landsat 7, ASTER, and SPOT 4) could be used to perform cross-sensor change detection with accurate results. Another approach is premised on the use of normalized vegetation indices. Given somewhat different spectral resolutions among sensors, the use of vegetation indices like NDVI and the Tasseled-Cap permit some degree of intercomparability, if accurate radiometric normalization can be achieved. Steven et al. [81] were able to demonstrate accurate calibration of NDVI across numerous simulated sensor platforms to within +/- 2% precision. Even across Landsat sensors, techniques have been described to deal with radiometric normalization, and these offer potential guidance to other cross-sensor applications. For example, Multivariate Alteration and Detection (MAD) has been successfully implemented to find invariant targets for accurate normalization of surface reflectance across long time series of Landsat TM and ETM+ data [82].

Another potential approach for utilization of Landsat-like data is data fusion techniques that integrate imagery across sensors, effectively leveraging the most desirable characteristics from multiple sensors. The spatial, spectral, and temporal resolution of any given sensor can potentially be enhanced by merging bands within or across sensors [83], using a variety of techniques including wavelet transformations [84] and edge enhancement intensity modulation (EEIM) [83]. Fusion of high spatial resolution PAN bands with high spectral resolution VNIR bands has been demonstrated to improve both spatial and spectral information content [84]. Aguena and Mascarenhas [85] fused Landsat ETM+ panchromatic and CBERS-1 using a technique called Projection Onto Convex Sets (POCS). High temporal resolution sensors like MODIS and AVHRR have been fused with higher spatial resolution sensors like Landsat and SPOT to increase the information content [86]. Likewise, Gao et al. [87] predicted daily Landsat surface reflectance by fusion with MODIS.

Given the likelihood of a Landsat data gap, and the increased demand for moderate resolution remote sensing data, moderate resolution data users might consider the full suite of available Landsat-like imagery for any given location and date. While image availability, cost, and other programmatic issues are not equal across sensors, where available, Landsat-like data has the potential to complement or even replace Landsat data for some applications. Our review of the literature demonstrates that Landsat-like sensors have been used extensively for earth observation research across key earth observation domains. While our objective for this review was not to prove that Landsat-like sensors are superior or inferior to Landsat itself, in many of the papers that we reviewed, researchers found comparable results to Landsat. This suggests that where data are available for Landsat-like sensors, they warrant consideration for relevant applications seeking to augment or replace Landsat coverage. However, more research is needed across other earth observation domains to better understand the tradeoffs between Landsat and these Landsat-like sensors.

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