Review Article

Remote Sensing of Urban/Suburban Infrastructure and Socio-Economic Attributes*

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Abstract
Temporal and spatial resolution requirements for extracting urban/suburban infrastructure and socio-economic attributes from remote sensor data are presented. The goal is to relate the user information requirements with the current and proposed remote sensing systems to determine if there are substantive gaps in capability. Several remote sensing systems currently provide some of the desired urban/suburban infrastructure and socio-economic information when the required spatial resolution is poorer than 4 by 4 m and the temporal resolution is between 1 and 55 days (e.g., Landsat MSS and Thematic Mapper, SPOT1-4, Russian TK-350, RADARSAT, Indian IRS-1CD, NOAA AVHRR, GOES, Meteosat). Current high spatial resolution sensor systems such as the Russian SPIN-2 KVR-1000 (2- by 2-m panchromatic; when in orbit) and proposed sensor systems (EOSAT Space Imaging IKONOS 1- by 1-m panchromatic; EarthWatch Quickbird 0.82 by 0.82 m; OrbView-3 1 by 1 m) may provide additional capability. Large-scale metric aerial photography or digital camera imagery with spatial resolutions ranging from ≤ 0.25 to 1 m will still be required to satisfy several important urban/suburban information requirements.

Introduction
Urban landscapes are composed of diverse materials (concrete, asphalt, metal, plastic, glass, shingles, water, grass, shrubs, trees, and soil) arranged by humans in complex ways to build housing, transportation systems, utilities, commercial buildings, and recreational landscapes (Welch, 1982; Swerdlow, 1998). The goal of this construction is usually to improve the quality-of-life. A significant number of professional businessmen and women and public organizations require up-to-date information about the city and suburban infrastructure. For example, detailed urban information is required by (Cullingworth, 1997; American Planning Association, 1998):

- city, county, and regional planning agencies and councils of governments that legislate zoning regulations to improve the quality-of-life;
- city and state Departments of Commerce to stimulate development;
- Tax Assessor offices that maintain legal geographic descriptions of every parcel of land, assess its value, and levy a tax millage rate;
- Departments of Transportation that maintain existing facilities, build new facilities, and prepare for future transportation demand;
- private utility companies (water, sewer, gas, electricity, telephone, cable) that attempt to predict where new demand will occur and plan for the most efficient and cost-effective method of delivering services;
- Public Service Commissions that insure that utility services are available economically to the public;
- Departments of Parks, Recreation and Tourism who improve recreation facilities and promote tourism;
- Departments of Emergency Management and Preparedness who plan for and allocate resources in the event of a disaster;
- private real estate companies attempting to find the ideal location for industrial, commercial, and residential development; and
- residential, commercial, and industrial developers.

The urban/suburban land these professionals manage or develop is of significant monetary value. Therefore, it is not surprising that city, county, state, and federal agencies as well as private companies spend millions of dollars each year obtaining aerial photography and other forms of remotely sensed data to extract the required urban information. Much of the required information simply cannot be obtained through *in situ* site surveys.

Temporal, Spectral, and Spatial Characteristics of Urban Attributes and Remote Sensing Systems
Many of the detailed urban/suburban attributes that businesses and public agencies require are summarized in Table 1. This paper reviews how remotely sensed data may be of value for collecting information about these attributes. To remotely sense these urban phenomena, it is first necessary to appreciate the urban attributes' temporal, spectral, and spatial resolution characteristics.

Urban/Suburban Temporal Considerations
Three types of temporal resolution should be considered when monitoring urban environments using remote sensor data. First, urban/suburban phenomena progress through an identifiable developmental cycle much like vegetation progresses through a phenological cycle. For example, Jensen

* Preliminary versions were reported in J.R. Jensen and D.C. Cowen (1997), Remote Sensing of Urban/Suburban Socio-economic Attributes, *Proceedings, Land Satellite Information in the Next Decade II*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, compact disk, 19 p., and D.C. Cowen and J.R. Jensen (1998), Extraction and Modeling of Urban Attributes Using Remote Sensing Technology, *People and Pixels: Linking Remote Sensing and Social Science*, National Academy Press, Washington, D.C., pp. 164–188.

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Photogrammetric Engineering & Remote Sensing,
Vol. 65, No. 5, May 1999, pp. 611–622.

0099-1112/99/6505–611$3.00/0

TABLE 1. URBAN/SUBURBAN ATTRIBUTES AND THE MINIMUM REMOTE SENSING RESOLUTIONS REQUIRED TO PROVIDE SUCH INFORMATION

Attributes	Minimum Resolution Requirements		
	Temporal	Spatial	Spectral
Land Use/Land Cover			
L1-USGS Level I	5–10 years	20–100 m	V-NIR-MIR-Radar
L2-USGS Level II	5–10 years	5–20 m	V-NIR-MIR-Radar
L3-USGS Level III	3–5 years	1–5 m	Pan-V-NIR-MIR
L4-USGS Level IV	1–3 years	0.25–1 m	Panchromatic
Building and Property Infrastructure			
B1-building perimeter, area, height and cadastral information (property lines)	1–5 years	0.25–0.5 m	Pan-Visible
Transportation Infrastructure			
T1-general road centerline	1–5 years	1–30 m	Pan-V-NIR
T2-precise road width	1–2 years	0.25–0.5 m	Pan-V
T3-traffic count studies (cars, airplanes, etc.)	5–10 min	0.25–0.5 m	Pan-V
T4-parking studies	10–60 min	0.25–0.5 m	Pan-V
Utility Infrastructure			
U1-general utility line mapping and routing	1–5 years	1–30 m	Pan-V-NIR
U2-precise utility line width, right-of-way	1–2 years	0.25–0.6 m	Pan-Visible
U3-location of poles, manholes, substations	1–2 years	0.25–0.6 m	Panchromatic
Digital Elevation Model (DEM) Creation			
D1-large scale DEM	5–10 years	0.25–0.5 m	Pan-Visible
D2-large scale slope map	5–10 years	0.25–0.5 m	Pan-Visible
Socioeconomic Characteristcs			
S1-local population estimation	5–7 years	0.25–5 m	Pan-V-NIR
S2-regional/national population estimation	5–15 years	5–20 m	Pan-V-NIR
S3-quality of life indicators	5–10 years	0.25–30 m	Pan-V-NIR
Energy Demand and Conservation			
E1-energy demand and production potential	1–5 years	0.25–1 m	Pan-V-NIR
E2-building insulation surveys	1–5 years	1–5 m	TIR
Meteorological Data			
M1-weather prediction	3–25 min	1–8 km	V-NIR-TIR
M2-current temperature	3–25 min	1–8 km	TIR
M3-clear air and precipitation mode	6–10 min	1 km	WSR-88D Radar
M4-severe weather mode	5 min	1 km	WSR-88D Radar
M5-monitoring urban heat island effect	12–24 hr	5–30 m	TIR
Critical Environmental Area Assessment			
C1-stable sensitive environments	1–2 years	1–10 m	V-NIR-MIR
C2-dynamic sensitive environments	1–6 months	0.25–2 m	V-NIR-MIR-TIR
Disaster Emergency Response			
DE1-pre-emergency imagery	1–5 years	1–5 m	Pan-V-NIR
DE2-post-emergency imagery	12 hr–2 days	0.25–2 m	Pan-V-NIR-Radar
DE3-damaged housing stock	1–2 days	0.25–1 m	Pan-V-NIR
DE4-damaged transportation	1–2 days	0.25–1 m	Pan-V-NIR
DE5-damaged utilities, services	1–2 days	0.25–1 m	Pan-V-NIR

and Toll (1983) documented a ten-stage single-family residential housing development cycle at work in suburban Denver, Colorado that progressed from (1) rangeland to (10) fully-landscaped residential housing, often within one year. The image analyst must understand the temporal development cycle of the urban phenomena. If it is not understood, embarrassing and costly interpretation mistakes can be made.

The second type of temporal resolution is how often it is possible for a remote sensor system to collect data of the urban landscape, e.g., every 8 days, every 16 days, or on-demand. Generally, satellite sensors that can be pointed off-nadir (e.g., SPOT HRV) have higher temporal resolution than sensors that only sense the terrain at nadir (e.g., Landsat Thematic Mapper). Orbital characteristics of the satellite platform and the latitude of the study area also impact the revisit schedule. Remote sensor data may be collected on demand from sub-orbital aircraft (airplanes, helicopters), weather conditions permitting. Up-to-date remote sensor data are critical for most urban/suburban applications.

Finally, temporal resolution may refer to how often land managers/planners need a specific type of information. For example, local planning agencies may require population estimates every 5 to 7 years in addition to the estimates provided by the decennial census. The managerial temporal resolution requirements for many important urban applications are summarized numerically in Table 1 and graphically in Figure 1.

Urban/Suburban Spectral Considerations

Most image analysts would agree that, when extracting urban/suburban information from remotely sensed data, it is more important to have high spatial resolution (often ≤ 5 by 5 m) than high spectral resolution (i.e., a large number of multispectral bands). For example, local population estimates based on building unit counts usually require a minimum spatial resolution of from ≤ 0.25 to 5 m (0.82 ft to 16.4 ft) to detect, distinguish between, and/or identify the type of individual buildings. Practically any visible band (e.g., green or red) or near-infrared spectral band at this spatial resolution will do. Of course, there must be sufficient spectral contrast between the object of interest (e.g., a building) and its background (e.g., the surrounding landscape) in order to detect, distinguish between, and identify the object from its background.

While high spectral resolution is not required, there are still optimum portions of the electromagnetic spectrum that

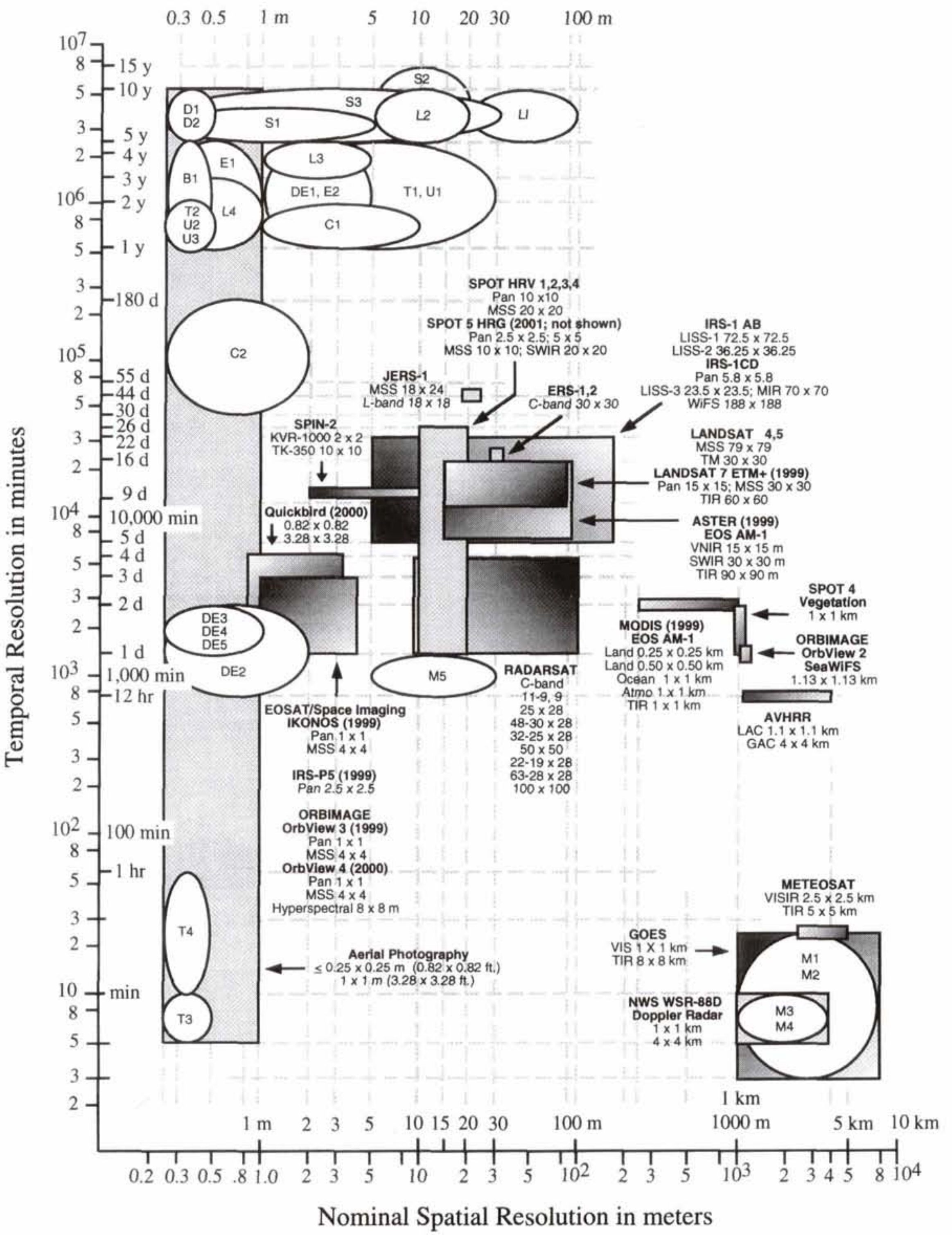

Figure 1. Subjective spatial and temporal resolution requirements for urban/suburban attributes overlaid on the spatial and temporal resolution capabilities of current and proposed remote sensor systems. Refer to Table 1 for urban/suburban codes. Information presented in this type of diagram will constantly change due to (a) the development of new remote sensing instruments and their associated temporal and spatial resolutions, and (b) the user community continuously redefines existing data requirements and identifies new attributes to be collected.

are especially useful for extracting certain types of urban/suburban information (Table 1). For example, USGS Level III land cover is best acquired using the visible color (0.4 to 0.7 μm; V), near-infrared (0.7 to 1.1 μm; NIR), middle-infrared

(1.5 to 2.5 μm; MIR), and/or panchromatic (0.5 to 0.7 μm) portions of the spectrum. Building perimeter, area, and height information is best acquired using black-and-white panchromatic (0.5 to 0.7 μm) or color imagery (0.4 to 0.7 μm). The thermal infrared portion of the spectrum (3 to 12 μm; TIR) may be used to obtain urban temperature measurements. Active microwave sensors may obtain imagery of cloud shrouded or tropical urban areas (e.g., Japanese JERS-1 L-band, Canadian RADARSAT C-band, and European Space Agency ERS-1, 2 C-band).

Urban/Suburban Spatial Considerations

Trained image analysts utilize the tone, color, texture, shape, size, orientation, pattern, shadow silhouette, site, and situation of objects in the urban landscape to identify and judge their significance (Jensen, 1996). The geometric elements of image interpretation (e.g., object shape, size, orientation, pattern, shadow silhouette) are especially useful when high spatial resolution imagery of urban environments are available. But should we judge the usefulness of a given type of imagery (e.g., aerial photography or Landsat Thematic Mapper imagery) for extracting very specific types of urban/suburban information based solely on its *spatial* characteristics? One solution might be to use the military and/or civilian versions of the National Image Interpretation Rating Scales (NIIRS) developed by the Image Resolution Assessment and Reporting Standards Committee (IRARS). The NIIRS is the metric used by the intelligence community to characterize the usefulness of imagery for intelligence purposes (Leachtenaurer, 1996; Leachtenaurer *et al.*, 1998; Logicon, 1995; Logicon, 1997; Pike, 1998). The NIIRS criteria consist of ten rating levels (0 to 9) for a given type of imagery arrived at through evaluation by trained image analysts. The IRARS committee makes it clear that spatial resolution (ground resolved distance) is only one of the measures of the interpretability of an image. Other factors such as film quality, atmospheric haze, contrast, angle of obliquity, and noise can reduce the ability of a well trained analyst to detect, distinguish between, and identify military and civilian objects in an image. While it would be useful to use the NIIRS criteria, it is not optimum for this review because (1) the civil NIIRS criteria were only recently made available (Hothem *et al.*, 1996; Leachtenauer *et al.*, 1998); (2) there has not been sufficient time for the civilian community to familiarize itself with the concept; and, consequently, (3) the civilian community has never reported their collective experiences in urban/suburban information extraction during the current and past decades in this context.

Fortunately, the civilian user community has often reported the utility of a given type of imagery for extracting urban information based on the comparatively easy to understand concept of nominal spatial resolution. When using satellite remote sensing systems, the nominal spatial resolution (ground resolved distance) of the sensor system is typically used such as the Landsat Thematic Mapper's six 30- by 30-m multispectral bands or SPOT Image's 10- by 10-m panchromatic band. Conversely, the figure of merit for measuring resolvability of a film camera system is the area weighted average resolution (AWAR) measured in line-pairs-per-millimeter (lp/mm) (Light, 1993). A line pair is the width of one black bar and one white space as contained on resolution targets in an aerial photograph. Together, they form a pair and serve as a measure of image quality for the aerial film camera industry. The five essential elements that make up the system AWAR are the lens, original film, image blur (smear) on the film due to aircraft forward velocity, angular motion, and the resolution of the duplicating film. Also, scene contrast of the Earth and atmosphere play a role in system resolution. Fortunately, scientists have studied the general relationship between aerial photography scale and AWAR. For example, Light (1993; 1996) documented that, if we assume that the Earth is a low contrast scene, the 1:40,000-scale National Aerial Photography Program (NAPP) photography exhibits approximately 39 lp/mm and yields approximately 25 μm for the size of 1 lp in the image. At 1:40,000 scale, 25 μm equates to a ground resolution of 1 by 1 m for low-contrast scenes. Therefore, a minimum of a 1-m ground resolution can be expected throughout the photographic mission. In fact, the USGS digital orthophoto quarter-quad files produced from 1:40,000-scale NAPP photography are provided at a 1- by 1-m (3.28- by 3.28-ft) spatial resolution by scanning the photography with a pixel size of 11 μm. Light (personal communication, 1998) suggests that there is a general linear relationship for larger scale aerial photography obtained using metric cameras, i.e., 1:20,000-scale aerial photography equates to approximately 0.5 by 0.5 m (1.64 by 1.64 ft), 1:10,000-scale photography to 0.25 by 0.25 m (0.82 by 0.82 ft), and 1:5,000-scale photography to 0.125 by 0.125 m (0.41 by 0.41 ft).

Another general spatial resolution rule is that there needs to be a *minimum* of four spatial observations (e.g., pixels) within an urban object to identify it. Stated another way, the sensor spatial resolution should be one-half the diameter of the smallest object-of-interest. For example, to identify mobile homes that are 5 m wide, the minimum spatial resolution of high quality imagery without haze or other problems is ≤ 2.5- by 2.5-m pixels (Cowen *et al.*, 1995).

The temporal, spectral, and spatial resolution requirements for the urban attributes summarized in Table 1 and Figure 1 were synthesized from subjective, practical experience reported in journal articles, symposia, chapters in books, and government and society manuals (Chisnell and Cole, 1958; Stone, 1964; Branch, 1971; Ford, 1979; Jensen, 1983; Avery and Berlin, 1993; Light, 1993; Light, 1996; Greve, 1996; Jensen, 1996; Philipson, 1997; Haack *et al.*, 1997; Keister, 1997; Cowen and Jensen, 1998; Pike, 1998; Ridley *et al.*, 1998; and others in the individual sections). Ideally, there would always be a remote sensing system that could obtain images of the terrain that satisfy the urban attributes' resolution requirements (Table 1). Practically, this is not always the case.

Evaluation of Urban/Suburban Attributes' Spatial and Temporal Requirements and the Availability of Remote Sensing Systems to Provide Such Information

The relationship between temporal and spatial data requirements for selected urban/suburban attributes and the temporal and spatial characteristics of available and proposed remote sensing systems is presented in Figure 1.

Land Use/Land Cover

The term *land use* refers to how the land is being used. *Land cover* refers to the biophysical materials found on the land. For example, a state park may be used for recreation but have a deciduous forest cover. One method of organizing land-use/land-cover information is to use a classification system. The most comprehensive hierarchical classification system for urban/suburban *land use* is the *Land-Based Classification Standard* (LBCS) under development by the American Planning Association (1998) that updates the 1965 Standard Land Use Coding Manual (Urban Renewal Administration, 1965) which is cross-referenced with the 1987 Standard Industrial Classification (SIC) Manual (Bureau of the Budget, 1987) and the updated North American Industrial Classification Standard (NAICS). The LBCS requires extensive input from *in situ* site surveys, aerial photography, and satellite remote sensor data to obtain information at the *parcel* level on the following five characteristics: activity, function,

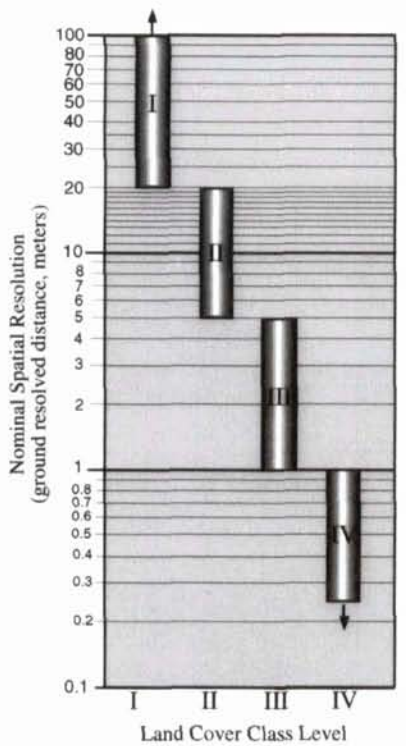

Figure 2. The general relationship between the U.S. Geological Survey Land Use and Land Cover Classification System class level and the nominal spatial resolution of the remote sensing system (often referred to as ground resolved distance in meters).

site development, structure, and ownership (American Planning Association, 1998). The system does not provide information on land cover or vegetation characteristics in the urban environment because it is relying on the Federal Geographic Data Committee "Standards" on these topics. The LBCS is not complete at this time. Therefore, the following discussion will focus on the use of the "land use and land cover classification system for use with remote sensor data" developed by the U.S. Geological Survey (Anderson *et al.*, 1976).

The general relationship between USGS land-cover classification system levels (I to IV) and the nominal spatial resolution of the sensor system (ground resolved distance in meters) is presented in Figure 2. Generally, USGS Level I classes may be inventoried effectively using sensors with a nominal spatial resolution of ≥ 20 to 100 m such as the Landsat Multispectral Scanner (MSS) with 79- by 79-m ground resolution, the Thematic Mapper (TM) at 30 by 30 m, SPOT HRV (XS) at 20 by 20 m, and Indian LISS 1-3 (72.5 by 72.5 m, 36.25 by 36.25 m, 23.5 by 23.5 m, respectively). For example, Plate 1 depicts typical Level I urban vs. non-urban land-cover information for Charleston, South Carolina extracted from Landsat MSS data acquired on 26 March 1981 in red and any new urban development since 11 February 1979 in yellow.

Sensors with a minimum spatial resolution of approximately 5 to 20 m are generally required in order to obtain Level II information. The SPOT HRV and the Russian SPIN-2 TK-350 are the only operational satellite sensor systems providing 10- by 10-m panchromatic data. RADARSAT provides 11- by 9-m spatial resolution data for Level I and II land-cover inventories even in cloud-shrouded tropical landscapes. Landsat 7 with its 15- by 15-m panchromatic band may be launched in 1999.

More detailed Level III classes may be inventoried using a sensor with a spatial resolution of approximately 1 to 5 m (Welch, 1982; Forester, 1985) such as IRS-1CD pan (5.8- by 5.8-m data resampled to 5 by 5 m) or large scale aerial photography. Future sensors may include EOSAT/Space Imaging IKONOS (1- by 1-m pan and 4- by 4-m multispectral), EarthWatch Quickbird (0.8- by 0.8-m pan and 3.28- by 3.28-m multispectral), OrbView 3 and 4 (1- by 1-m pan and 4- by 4-m multispectral), and IRS P5 (2.5- by 2.5-m). The synergistic use of high spatial resolution panchromatic data (e.g., 1 by 1 m) merged with lower spatial resolution multispectral data (e.g., 4 by 4 m) will likely provide an image interpretation environment that is superior to using panchromatic data alone (Jensen, 1996).

Level IV classes and building and cadastral (property line) information are best monitored using high spatial resolution panchromatic sensors, including aerial photography (≤ 0.25 to 1 m) and, possibly, the proposed EOSAT Space Imaging IKONOS (1 by 1 m), EarthWatch Quickbird pan (0.8 by 0.8 m), and OrbView-3 (1 by 1 m) data.

Urban land-use/land-cover classes in Levels I through IV have temporal requirements ranging from 1 to 10 years (Table 1 and Figure 1). All the sensors mentioned have temporal resolutions of less than 55 days, so the temporal resolution of the land-use/land-cover attributes is satisfied by the current and proposed sensor systems.

Building and Cadastral (Property Line) Infrastructure

In addition to fundamental nominal scale land-use and land-cover information (i.e., identifying whether an object is a sin-

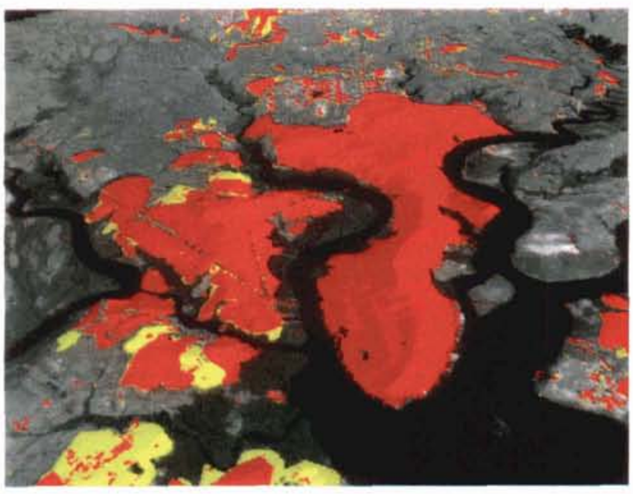

Plate 1. Typical Level I urban versus non-urban land cover information in red derived from a 26 March 1981 Landsat MSS image (79 by 79 m). The yellow areas represent new urbanization that has taken place since analysis of another MSS image acquired on 11 February 1979. Both the urban thematic information and the non-urban terrain (from the near-infrared band 4 MSS data) were draped over a USGS 1:100,000-scale digital elevation model and viewed from a position 3,000 m above the inlet to Charleston, South Carolina Harbor. The terrain was vertically exaggerated 100× for visual effect.

gle-family residence or a commercial building), transportation planners, utility companies, tax assessors, and others require more detailed information on building footprint perimeter, area, and height; driveways; patios; fences; pools; storage buildings; and the distribution of landscaping every 1 to 5 years. These building and property parameters are best obtained using stereoscopic (overlapping) panchromatic aerial photography or other remote sensor data with a spatial resolution of ≤ 0.25 to 0.5 m (Jensen, 1995; Warner, 1996). For example, panchromatic stereoscopic aerial photography with 0.3- by 0.3-m (1 ft) spatial resolution was used to extract the building perimeter and area information for the single-family residential area in Figure 3. With this type of data, each building footprint, patio, outbuilding, tree, pool, driveway, fence, and contour may be extracted. In many instances, the fence lines are the cadastral property lines. If the fence lines are not visible or are not truly on the property line, the property lines are located by a surveyor and the information is overlaid onto an orthophotograph or planimetric map database to represent the legal cadastral (property) map. Many municipalities in the United States use high spatial resolution imagery such as this as the source for some of the cadastral information and/or as an image back-drop upon which surveyed cadastral and tax information are portrayed.

Detailed building perimeter, area, and height data can be extracted from high spatial resolution (≤ 0.25- to 0.5-m) stereoscopic imagery (Jensen *et al.*, 1996). Such information can then be used to create three-dimensional displays of the urban terrain that we can walk through in a virtual reality environment if desired (Wolff and Yaeger, 1993; Barnell, 1998). For example, Figure 4 depicts (1) a large scale vertical aerial photograph of downtown Columbia, South Carolina, (2) a digital elevation model (DEM) of the same area extracted from the stereoscopic photography depicting the height of every building, and (3) the orthophotograph draped over the DEM creating a virtual reality representation of a major street. Architects, planners, engineers, and real estate personnel are beginning to use such information for a variety of purposes.

EOSAT Space Imaging (1999), OrbView (1999), and EarthWatch (2000) plan to provide fore-aft stereoscopic images from satellite-based platforms with approximately 0.8- to 1-m spatial resolution. Ridley *et al.* (1998) conducted a feasibility study and found that simulated 1- by 1-m satellite stereoscopic data could "have potential for creating a national 3D building model if the processes were automated, which would produce a much cheaper source of building heights." The accuracy of the building maximum heights (z) ranged between 1.5 and 3 m RMSE. Thus, the use of such imagery may not obtain the detailed planimetric (perimeter, area) and topographic detail and accuracy (building height and volume) that can be extracted from high spatial resolution stereoscopic aerial photography (≤ 0.25 to 0.5 m). Research is required using real 1- by 1-m stereoscopic data obtained from satellite platforms (Ridley *et al.*, 1998).

Transportation Infrastructure

Engineers often use remote sensor data to (1) update transportation network maps; (2) evaluate road, railroad, and airport runway and tarmac condition; (3) study urban traffic patterns at choke points such as tunnels, bridges, shopping malls, and airports; and (4) conduct parking studies (Mintzer, 1983; Haack *et al.*, 1997). One of the more prevalent forms of transportation data are the street centerline spatial data (SCSD). Three decades of practice have proven the value of differentiating between the left and right sides of each street segment and encoding attributes to them such as street names, address ranges, ZIP codes, census and political boundaries, and congressional districts. SCSD provide a good example of

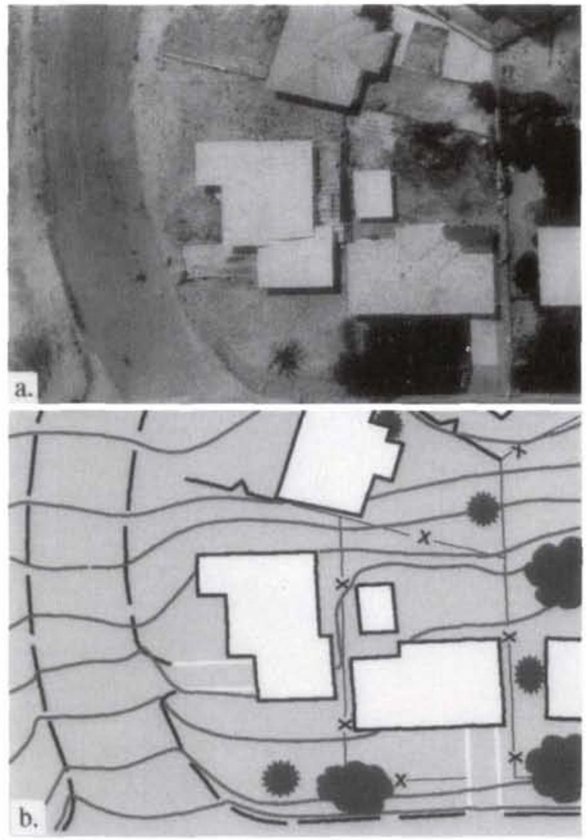

Figure 3. Planimetric cadastral information of a single-family residential area extracted photogrammetrically from panchromatic stereoscopic vertical aerial photography. Building footprints are in black, fence lines with *x*'s in black, driveways in white, shrubs and trees in black, 2-ft contours in continuous black lines, and highway right-of-way in dashed lines.

a national framework spatial data theme by virtue of their extensive current use in facility site selection, census operations, socio-economic planning studies, and legislative redistricting (NRC, 1995; FGDC, 1997a).

Road network centerline updating in rapidly developing areas may be performed every 1 to 5 years and, in areas with minimum tree density (or during the leaf-off season), can be accomplished using imagery with a spatial resolution of 1 to 30 m (Lacy, 1992). If more precise road dimensions are required such as the exact center of the road and the width of the road and sidewalks, then a spatial resolution of ≤ 0.2 to 0.5 m is required (Jensen *et al.*, 1994). Currently, only aerial photography can provide such planimetric information (refer to Figure 3).

Road, railroad, and bridge conditions (cracks, potholes, etc.) are routinely monitored both *in situ* and using high spatial resolution remote sensor data. For example, Figure 5 presents a vertical panchromatic image of railroad and road bridges. Careful inspection of high spatial resolution imagery (≤ 0.25 to 0.5 m) by a trained analyst can provide significant information about the condition of the road and railroad (Stoeckeler, 1979; Haack *et al.*, 1997).

Traffic count studies of automobiles, airplanes, boats, pedestrians, and people in groups require very high temporal resolution data ranging from 5 to 10 minutes. Even when

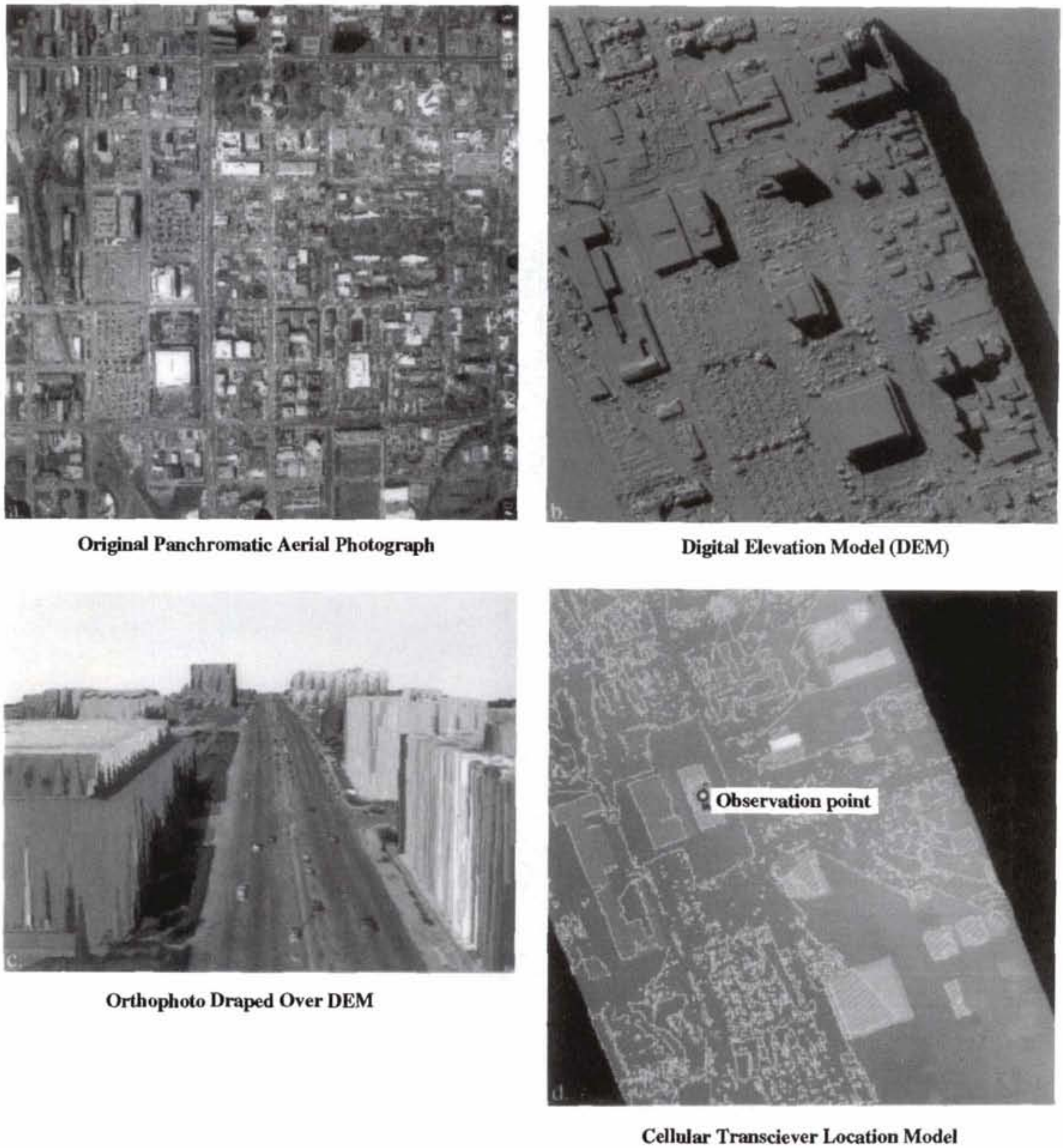

Figure 4. (a) Panchromatic aerial photograph of Columbia, South Carolina (original at 1:6,000 scale). (b) Digital elevation model (DEM) derived from a stereopair and portrayed as a shaded-relief model. (c) An orthophotograph of the area draped over the DEM and displayed in a three-dimensional perspective projection. (d) The DEM and a viewshed model were used to identify the optimum building on which to place a cellular phone transceiver.

such timely data are available, it is difficult to resolve a car or boat using even 1- by 1-m data. This requires high spatial resolution imagery from ≤ 0.25 to 0.5 m. Such information can only be acquired using aerial photography, digital cameras, or video sensors that are (1) located on the top edges of buildings looking obliquely at the terrain, or (2) placed in aircraft or helicopters and flown repetitively over the study areas. When such information is collected at an optimum time of day, future parking and traffic movement decisions can be made. Parking studies require the same high spatial resolution (≤ 0.25 to 0.5 m) but slightly lower temporal resolution (10 to 60 minutes). Doppler radar has demonstrated some potential for monitoring traffic flow and volume.

Utility Infrastructure

Urban/suburban environments are enormous consumers of electrical power, natural gas, telephone service, and potable water (Haack *et al.*, 1997). In addition, they create great quantities of refuse, waste water, and sewage. The removal of storm water from urban impervious surfaces is also a serious problem (Schultz, 1988). Automated mapping/facilities management (AM/FM) and geographic information systems (GIS) have been developed to manage extensive right-of-way corridors for various utilities, especially pipelines (Jadkowski *et al.*, 1994; Jensen *et al.*, 1998). The most fundamental task is to update maps to show a general centerline of the utility of interest such as a powerline right-of-way. This is relatively

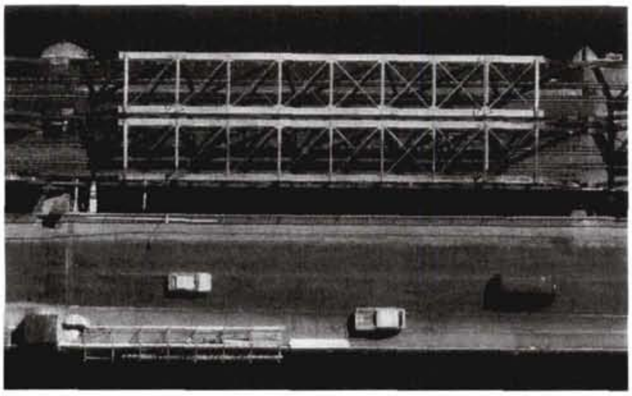

Figure 5. High resolution vertical panchromatic imagery of railroad and highway bridges. Road and railroad condition as well as bridge condition can be monitored using such imagery.

straightforward if the utility is not buried or obscured by trees and if 1- to 30-m spatial resolution remote sensor data are available. It is also often necessary to identify prototype utility (e.g., pipeline) routes (Feldman *et al.*, 1995). Such studies require geographically extensive imagery such as SPOT (20 by 20 m) or Landsat Thematic Mapper data (30 by 30 m) that have relatively large scene dimensions. The majority of the actual and proposed rights-of-way may be observed well on imagery with 1 to 30 m spatial resolution obtained once every 1 to 5 years. But, when it is necessary to inventory the exact location of transmission tower footpads, utility poles, and manhole covers; the true centerline of the utility; the width of the utility right-of-way; and the dimensions of buildings, pumphouses, and substations, then it is necessary to have a spatial resolution of from ≤ 0.25 to 0.6 m (Jadkowski *et al.*, 1994). Ideally, new facilities are inventoried every 1 to 2 years.

Digital Elevation Model (DEM) Creation

Most GIS used for socio-economic or environmental planning include a digital elevation model (DEM) (Cowen *et al.*, 1995). The public often forgets that digital elevation models are derived primarily from analysis of stereoscopic remote sensor data (Jensen, 1995). It is also possible to extract relatively coarse z-elevation information using SPOT 10- by 10-m data, SPIN-2 data (Lavrov, 1997), and Landsat Thematic Mapper 30- by 30-m data (Gugan and Dowman, 1988). Any DEM to be used in an urban/suburban application should ideally have z-elevation and *x, y* coordinates that meet Geospatial Positioning Accuracy Standards (FGDC, 1997b). A sensor that can provide such information at the present time is stereoscopic large-scale metric aerial photography with a spatial resolution of ≤ 0.25 to 0.5 m. A DEM of downtown Columbia, South Carolina, derived from aerial photography, was previously shown in Figure 4. The DEM data can be modeled to compute slope and aspect statistical surfaces for a variety of applications. It can also be used to identify the optimum location for placing various utilities as shown in Figure 4d.

Ridley *et al.* (1998) found that simulated 1- by 1-m stereoscopic satellite data when processed using standard off-the-shelf DEM generation packages, yielded a z-elevation RMSE ranging from 1.5 to 2 m after editing and showed considerable potential for creating DEMs for use in national mapping. Digital desktop softcopy photogrammetry is revolutionizing the creation and availability of DEMs (Petrie and Kennie, 1990; Jensen, 1995) and should be of significant value when applied to the commercial high spatial resolution remote sensor data.

Terrain elevation does not change very rapidly. Therefore, a DEM of an urbanized area need only be acquired once ever 5 to 10 years unless there is significant development and the analyst desires to compare two different date DEMs to determine change in terrain elevation, identify unpermitted additions to buildings, or determine changes in building heights.

Socio-Economic Characteristics

Selected socio-economic characteristics may be extracted directly from remote sensor data or by using surrogate information derived from the imagery. Two of the most important attributes are *population estimation* and *quality-of-life indicators*.

Population Estimation

Knowing how many people live within a specific geographic area or administrative unit (e.g., city, county, state, country) is very powerful information. In fact, it has been suggested that the global effects of increased population density on ecosystem land-cover conversion and human well-being may be much more significant than those arising from climate change (Skole, 1994). Population estimation can be performed at the local, regional, and national level based on (1) counts of individual dwelling units, (2) measurement of urbanized land areas (often referred to as settlement size), and (3) estimates derived from land-use/land-cover classification (Lo, 1995; Sutton *et al.*, 1997).

Remote sensing techniques may provide population estimates that approach the accuracy of traditional census methods if sufficiently accurate *in situ* data are available to calibrate the remote sensing model. Unfortunately, ground-based population estimations may be inaccurate (Clayton and Estes, 1979). In many instances in developing countries, remote sensing methods may be superior to ground-based methods.

The most accurate remote sensing method for estimating the population of a local area is to count individual dwelling units based on the following assumptions (Forester, 1985; Lindgren, 1985; Lo, 1986; Lo, 1995; Holz, 1988; Haack *et al.*, 1997):

- the imagery must be of sufficient spatial resolution to identify individual structures even through tree cover and whether they are residential, commercial, or industrial buildings;
- some estimation of the average number of persons per dwelling unit must be available;
- some estimate of the number of homeless, seasonal, and migratory workers is required; and
- it is assumed that all dwelling units are occupied, and that only *n* families live in each unit (calibrated using *in situ* investigation).

This is usually performed every 5 to 7 years and requires high spatial resolution remotely sensed data (≤ 0.25 to 5 m). For example, individual dwelling units in a section of Irmo, South Carolina were extracted from 2.5- by 2.5-m aircraft multispectral data (Cowen *et al.*, 1995). Correlation of the remote sensing derived dwelling unit data with U.S. Bureau of the Census dwelling unit data for the 32 census block area yielded an $r^2 = 0.81$ (correlation coefficient of 0.91). These findings suggest that the new high spatial resolution panchromatic sensors may provide a good source of information for monitoring the housing stock of a community on a routine basis. This will enable local governments to anticipate and plan for schools and other services with data that have a much more frequent temporal resolution than does the decennial census. These data will also be of value for real estate, marketing, and other business applications (Lo, 1995). Unfortunately, the dwelling unit approach is not suit-

Table 2. Urban/Suburban Attributes that May Be Extracted from Remote Sensor Data Using the Fundamental Elements of Image Interpretation and Used to Assess Housing Quality and/or Quality-of-Life

	Attributes
Site	Building
	single or multiple-family
	size (sq. ft.)
	height (ft.)
	carport or garage (attached, detached)
	age (derived by convergence of evidence)
	Lot
	size (sq. ft.)
	front yard (sq. ft.)
	back yard (sq. ft.)
	street frontage (ft.)
	driveway (paved, unpaved)
	fenced
	pool (in-ground, above-ground)
	patio, deck
	out-buildings (sheds)
	density of buildings per lot
	percent landscaped
	health of vegetation (e.g. NDVI greenness)
	property fronts paved or unpaved road
	abandoned autos
	refuse
Situation	Adjacency to Community Amenities
	schools
	churches
	hospitals
	fire station
	library
	shopping
	open space, parks, golf courses
	Adjacency to Nuisances and Hazards
	heavy street traffic
	railroad or switchyard
	airports and/or flightpath
	freeway
	located on a floodplain
	sewage treatment plant
	industrial area
	power plant or substation
	overhead utility lines
	swamps and marsh
	steep terrain

able for a regional/national census of population because it is too time consuming and costly (Sutton *et al.*, 1997). Broome (personal communication, 1998) suggests that this method requires so much *in situ* data to calibrate the remote sensor data that it can become operationally impractical. Research is required to document the utility of the method in a variety of cultures and population densities.

Scientists have known for some time that there is a relationship between the simple urbanized built-up area (settlement size) extracted from a remotely sensed image and settlement population (Tobler, 1969; Olorunfemi, 1984), where $r = a \times P^b$ and r is the radius of the populated area circle, a is an empirically derived constant of proportionality, P is the population, and b is an empirically derived exponent. Estimates of these parameters are fairly consistent at regional scales but the estimate of the a parameter varies between regions. For example, Sutton *et al.* (1997) used Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) visible near-infrared nighttime 1- by 1-km imagery to inventory urban extent for the entire United States. When the data were aggregated to the state or county level, spatial analysis of the clusters of the saturated pixels predicted population with an $r^2 = 0.81$. Unfortunately, "DMSP imagery underestimates the population density of urban centers and overestimates the population density of suburban areas" (Sutton *et al.*, 1997).

Another widely adopted population estimation technique is based on the use of the Level I through III land-use information previously described. This approach assumes that land use in an urban area is closely correlated with population density. Researchers establish a population density for each land use by field survey or census data. Then, by measuring the total area for each land-use category, they estimate the total population for that category. Summing the estimated totals for each land-use category provides the total population projection (Lo, 1995). The urban built-up area and land-use data method can be based on more coarse spatial resolution multispectral remote sensor data (5 to 20 m) every 5 to 15 years.

Quality-of-Life Indicators

Lo and Faber (1998) suggest that adequate income, decent housing, education and health services, and good physical environment are important indicators of social well-being and quality-of-life. Evaluating the quality-of-life of a population on a continuing basis is important because it helps planners and government agencies involved with the delivery of human services to be aware of problem areas.

In the past, most quality-of-life studies made use of census data to extract socio-economic indicators. Only recently have factor analytic studies documented how quality-of-life indicators (such as house value, median family income, average number of rooms, average rent, and education) can be estimated by extracting the urban attributes summarized in Table 2 from relatively high spatial resolution (≤ 0.25 to 30 m) imagery (Monier and Green, 1953; Green, 1957; McCoy and Metivier, 1973; Tuyahov *et al.*, 1973; Henderson and Utano, 1975; Jensen, 1983; Lindgren, 1985; Holz, 1988; Avery and Berlin, 1993; Haack *et al.*, 1997; Lo and Faber, 1998). Note that the attributes in Table 2 are arranged by *site* (building and lot) and *situation*. The site may be situated in positive and negative surroundings.

Onsrud *et al.* (1994), Curry (1997), and Slonecker *et al.* (1998) point out that scientists must exercise wise judgment when using remotely sensed data to extract socio-economic and/or quality-of-life information so that they do not infringe on an individual's right to privacy. The misuse of the high spatial resolution remote sensor data will likely be the impetus for future restrictive legislation.

Energy Demand and Production Potential

Local urban/suburban energy demand may be estimated using remotely sensed data. First, the square footage of individual buildings is determined. Local ground reference information about energy consumption is then obtained for a representative sample of dwellings in the area. Regression relationships are derived to predict the energy consumption anticipated for the region. This requires imagery with a spatial resolution of from ≤ 0.25 to 1 m. Regional and national energy consumption may be predicted using DMSP imagery (Welch, 1980). Unfortunately, DMSP imagery of urbanized areas are recorded at 6-bits radiometric resolution (0 to 63), causing most of the urban, energy consuming areas to saturate at a brightness value of 63 (Elvidge *et al.*, 1997; Sutton *et al.*, 1997).

It is also possible to predict how much solar photovoltaic energy potential a geographic region has by modeling the individual rooftop square footage, slope, and orientation (e.g., north or south) with known photovoltaic generation constraints. This requires very high spatial resolution imagery (≤ 0.25 to 0.5 m) (Clayton and Estes, 1979; Angelici *et al.*, 1980).

Studies have documented how high spatial resolution (1

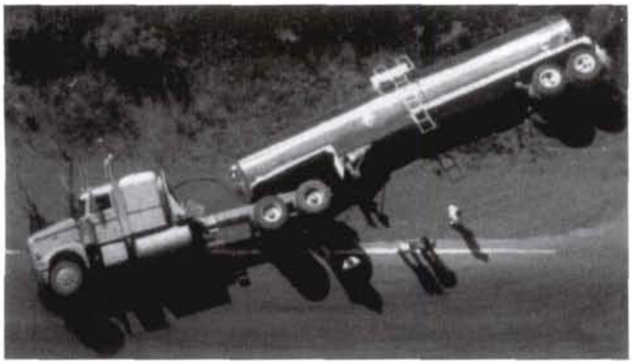

Figure 6. Overturned tanker and associated spill in Anchorage, Alaska. The high spatial resolution panchromatic vertical aerial photograph was obtained shortly after the accident (courtesy of AeroMap U.S.; Schweitzer and McLeod, 1997).

to 5 m) pre-dawn thermal infrared imagery (8 to 12 μm) can be used to inventory the relative quality of housing insulation if (1) the rooftop material is known (e.g., asphalt versus wood shingles), (2) moisture is not present on the roof, and (3) the orientation and slope of the roof are known (Colcord, 1981; Eliasson, 1992). If energy conservation or the generation of solar photovoltaic power were important, these variables would probably be collected every 1 to 5 years.

Meteorological Data

Daily weather in urban environments affects people, schools, businesses, and telecommunication and transportation systems. Great expense has gone into the development of near-real-time monitoring of frontal systems, temperature, precipitation, and severe storm warning systems. These important meteorological parameters are monitored almost exclusively by sophisticated airborne and ground-based remote sensing systems. For example, two Geostationary Operational Environmental Satellites (GOES) are positioned at 35,800 km above the equator in geo-synchronous orbits. GOES West obtains information about the western United States and is parked at 135° west longitude. GOES East obtains information about the Caribbean and eastern United States and is parked at 75° west longitude. Every day millions of people watch the progress of frontal systems that sometimes generate deadly tornadoes and hurricanes. Full hemispheric disk images may be obtained every 25 minutes. Intense storms in relatively smaller regions (3000 by 3000 km) may be imaged every 3.1 minutes. The spatial resolution is 1 by 1 km for the visible band and 4 to 8 km for the thermal infrared bands (Kidder and Haar, 1995). European nations use Meteosat with visible near-infrared bands obtained at 2.5 by 2.5 km and thermal infrared data collected at 5 by 5 km every 25 minutes. Early hurricane monitoring and modeling based on these data have saved thousands of lives in recent history. For example, in 1989 Hurricane Hugo caused approximately one billion dollars in damage to residential, commercial, and industrial facilities but no lives were lost because of remote-sensing assisted early warning and evacuation.

The public also relies on ground-based National Weather Service Weather Surveillance Radar (WSR-88D) for precipitation mapping and timely severe storm warning. The Doppler radar "composite reflectivity" product is projected onto a Cartesian geographical map with a 1- by 1-km resolution out to 230 km or at a 4- by 4-km resolution out to 460 km (Crum and Alberty, 1993). The data are obtained every 5 minutes in severe weather mode, every 6 minutes in precipitation mode, and every 10 minutes in clear air mode.

High spatial resolution (5 to 30 m) day- and night-time thermal-infrared data may be used to obtain detailed quantitative spatial information on the urban heat island effect (Lo *et al.*, 1997). Some have used AVHRR thermal-infrared data for this application with mixed results (e.g., Roth *et al.*, 1989).

Critical Environmental Area Assessment

Urban/suburban environments often include very sensitive areas such as wetlands, endangered specie habitat, parks, land surrounding treatment plants, and the land in urbanized watersheds that provides the runoff for potable drinking water. Relatively stable sensitive environments only need to be monitored every 1 to 2 years using a multispectral remote sensor collecting 1- to 10-m data. For extremely critical areas that could change rapidly, multispectral remote sensors (including a thermal infrared band) should obtain ≤ 0.25- to 2-m spatial resolution data every 1 to 6 months.

Disaster Emergency Response

Recent floods (Mississippi River in 1993; Albany, Georgia in 1994), hurricanes (Hugo in 1989, Andrew in 1991, Fran in 1996), tornadoes (every year), fires, tanker spills, and earthquakes (Northridge, California in 1994) demonstrated that a rectified, pre-disaster image database is indispensable. The pre-disaster data only need to be updated every 1 to 5 years. It should be high spatial resolution (1- to 5-m) multispectral data if possible.

When disaster strikes, high resolution (≤ 0.25- to 2-m) panchromatic and/or near-infrared data should be acquired within 12 hours to 2 days (e.g., Figure 6; Schweitzer and McLeod, 1997). If the terrain is shrouded in clouds, imaging radar might provide the most useful information. Post-disaster images are registered to the pre-disaster images, and manual and digital change detection takes place (Jensen, 1996). If precise, quantitative information about damaged housing stock, disrupted transportation arteries, the flow of spilled materials, and damage to above-ground utilities are required, it is advisable to acquire post-disaster ≤ 0.25- to 1-m panchromatic and near-infrared data within 1 to 2 days (Jensen *et al.*, 1998). Such information was indispensable in assessing damages and allocating scarce clean-up resources during Hurricane Hugo, Hurricane Andrew (Davis, 1993), Hurricane Fran (Wagman, 1997), and the recent Northridge earthquake.

Observations

Table 1 and Figure 1 reveal that there are a number of remote sensing systems that currently provide some of the desired urban infrastructure and socio-economic information when the required spatial resolution is poorer than 4 by 4 m and the temporal resolution is between 1 and 55 days. However, very high spatial resolution data (≤ 1 by 1 m) is required to satisfy several of the data requirements. In fact, as shown in Figure 1, the only sensor that currently provides such data on-demand is aerial photography (≤ 0.25 to 0.5 m). EOSAT/Space Imaging IKONOS (1999) with its 1- by 1-m panchromatic data, OrbView 3 (1999) with its 1- by 1-m panchromatic data, and EarthWatch Quickbird with its 0.8- by 0.8-m panchromatic data (2000) may satisfy some of these urban data requirements, but not all. It may be necessary to develop higher spatial resolution (≤ 0.25- to 0.5-m) satellite remote sensor data to provide some of the detailed urban/suburban infrastructure and socio-economic information, or utilize aerial photography. None of the sensors can provide the 5- to 60-minute temporal resolution necessary for traffic and parking studies except for (1) repetitive aerial photography (very costly), or (2) the placement of digital or video cameras on the top edge of buildings to obtain an oblique view. The GOES satellite constellation (east and west) and the European Meteosat provide sufficient national and regional weather information at reasonable temporal resolution (3 to 25 minutes) and spatial resolutions (1 to 8 km and 2.5 to 5 km, respectively). Ground-based National Weather Service Weather Surveillance Radar provides sufficient spatial resolution (1 by 1°) and temporal resolution (5 to 10 minutes) for precipitation and intense storm tracking in urban environments.

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(Received 03 March 1998; accepted 29 April 1998; revised 13 August 1998)