APPENDIX A

The Changing Face of Remote Sensing

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EDITOR'S NOTE: A version of this paper with color graphics is posted at ftp://ellie.cla.sc.edu/pub/jensen.

One of the goals of this conference is to identify applications of remote-sensing and other information science technologies that might have significant value in transportation-related research. Before we begin to review the capabilities of new remote-sensing systems and the analog and digital methods used to extract information from the data, it is instructive to consider the economics of remote-sensing Earth observation.

REMOTE SENSING AS INFORMATION BUSINESS

Remote sensing is

> the measurement or acquisition of information of some property of an object or phenomenon, by a recording device that is not in physical or intimate contact with the object or phenomenon under study. (Colwell, 1983; 1997)

Remote-sensing Earth observation from aircraft or satellite may be considered an "information business." The goal of the business is to obtain Earth resource information by measuring and examining electromagnetic radiation reflected or emitted from the Earth's surface (and occasionally from subsurface materials) and supply the data or derived (value-added) information to users. Therefore, the first order of business is to acquire the remotely sensed data. There are currently three remote-sensing data-collection models: commercial, government, and a hybrid commercial-government model.

First, private commercial firms can underwrite the entire cost of designing, collecting, processing, and marketing the remotely sensed data (e.g., raw reflectance values) or value-added information extracted from the remotely sensed data. For example, commercial photogrammetric engineering firms routinely collect suborbital metric aerial photography and produce orthophotos, digital elevation models (DEMs), and so forth for transportation departments. In 1999, Space Imaging Inc. launched the IKONOS-2 satellite remote-sensing system and is marketing the 1×1-m panchromatic and 4×4-m multispectral data and value-added products.

Second, a government may underwrite the entire cost of the remote-sensing system at the taxpayer's expense. National Aeronautics and Space Administration's (NASA) Landsat 7 Enhanced Thematic Mapper Plus (ETM^+) satellite remote-sensing system, numerous National Oceanic and Atmospheric Administration (NOAA) weather satellites such as the Geostationary Operational Environmental Satellite (GOES) East and the GOES West, and the advanced very-high-resolution radiometer (AVHRR) are good examples. Finally, there is the hybrid model where the government financially subsidizes the risk taken by a commercial firm to provide the raw remote-sensing data and value-added information to the public. Good examples include the business relationship between the French government and SPOT Image, Inc., and the Canadian government and RADARSAT, Inc.

The commercial model has worked well for years based largely on private photogrammetric engineering companies obtaining suborbital aerial photography and the extraction of large-scale urban and rural infrastructure information. Conversely, if orbital satellite remote sensing of the Earth is to be operational so that transportation engineers and planners can count on a constant data flow, it must generate revenues sufficient to cover the costs of building and operating the systems that produce the information (MacDonald, 1999). Transportation engineers and planners do not want to develop useful applications of remote-sensing data only to find out that the data stream has ended or is easily interrupted for a variety of reasons (politics, cost, etc.). Thus, data continuity is a very real and important concern.

Creating Information from Remote-Sensing-Derived Data

Remote-sensing data alone are not a panacea for transportation planning or Earth resource management problems. Remote-sensing data and derived information are of most value when used in conjunction with other information in a well-conceived application. The general process of creating information from remote-sensing Earth observation is shown in Figure 1 (*1*; MacDonald, 2000). First and foremost, the remote-sensing "business customer" is an information consumer. In our case, the consumers are people with a need to obtain information that will have

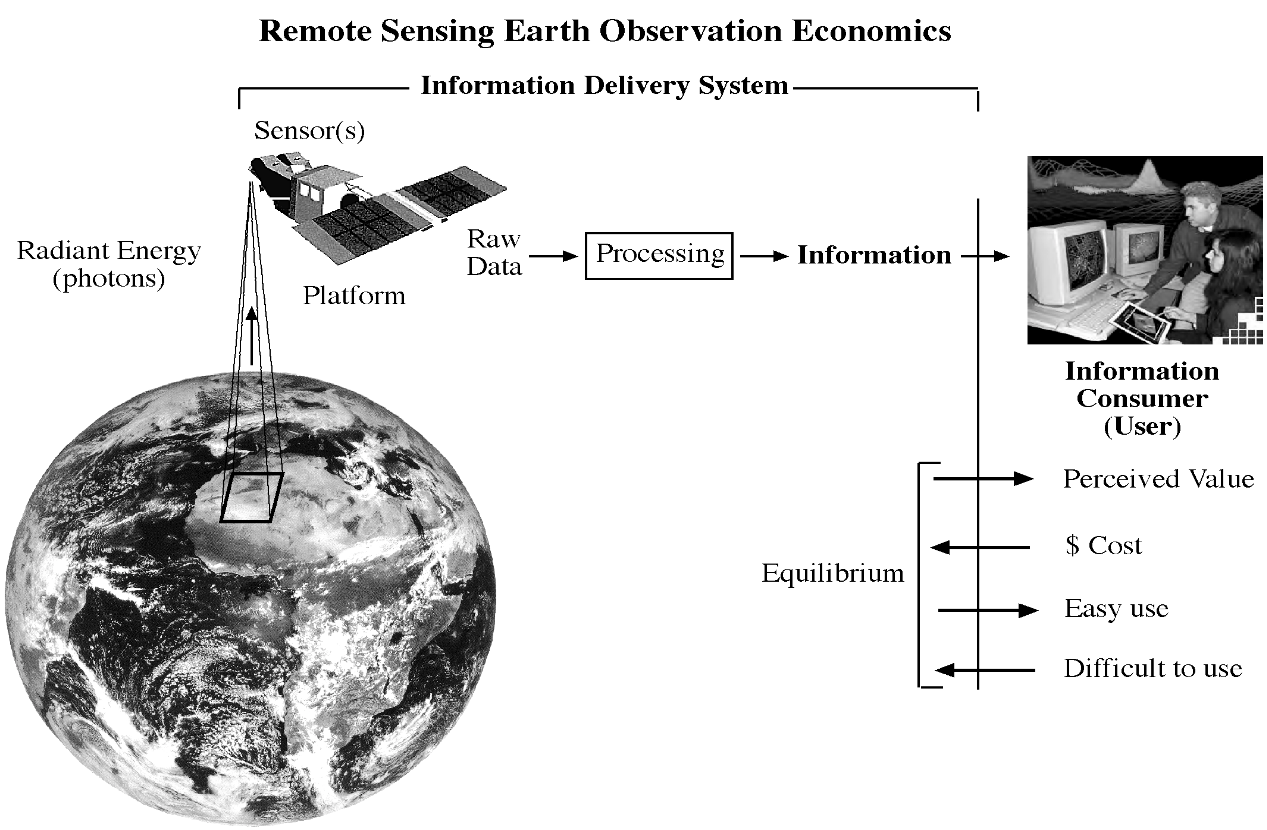


FIGURE 1 Characteristics of remote-sensing Earth observation economics.

value to transportation engineering or planning. These people generally need information of economic, social, strategic, environmental, or political value (*2*; MacDonald, 1999). In addition, the information must be relatively easy to use and understand.

For the revenues generated by the information delivery system to be sufficient to support the capital and operating costs of the system, there must be a balance (equilibrium) between the value of the information, as perceived by the consumer, and the revenue necessary to support the system (MacDonald, 2000). The equilibrium has been achieved for decades for several suborbital remote-sensing applications involving airborne photogrammetric mapping applications. Conversely, with the exception of the information produced by weather satellite systems and perhaps Space Imaging, Inc., with its new IKONOS-2 sensor system, the necessary balance between perceived value and cost has been difficult to achieve in the spaceborne case.

The general process of converting remotely sensed data to information is shown in Figure 2. It can be divided into two steps that must function in harmony:

Step 1. Remote sensor data preprocessing.
Step 2. Calibrated data-to-information conversion.

The first step involves relatively sophisticated digital (or analog) image processing to convert the raw remote-sensor data into calibrated, geocoded (accurate x, y, z location), reflectance, emittance, or backscattered data. The knowledge base associated with preprocessing remotely sensed data is relatively well developed, with many robust and workable algorithms (*1, 3*; Schott, 1998). Thus, the knowledge base symbolization in Figure 2 is relatively large. Unfortunately, the knowledge base is not always used correctly.

It is possible to perform specialized types of analyses on the preprocessed radiometrically and geometrically calibrated remote-sensor data and convert it into information that is useful to transportation planners and engineers. Good examples include (*a*) the creation of an accurate

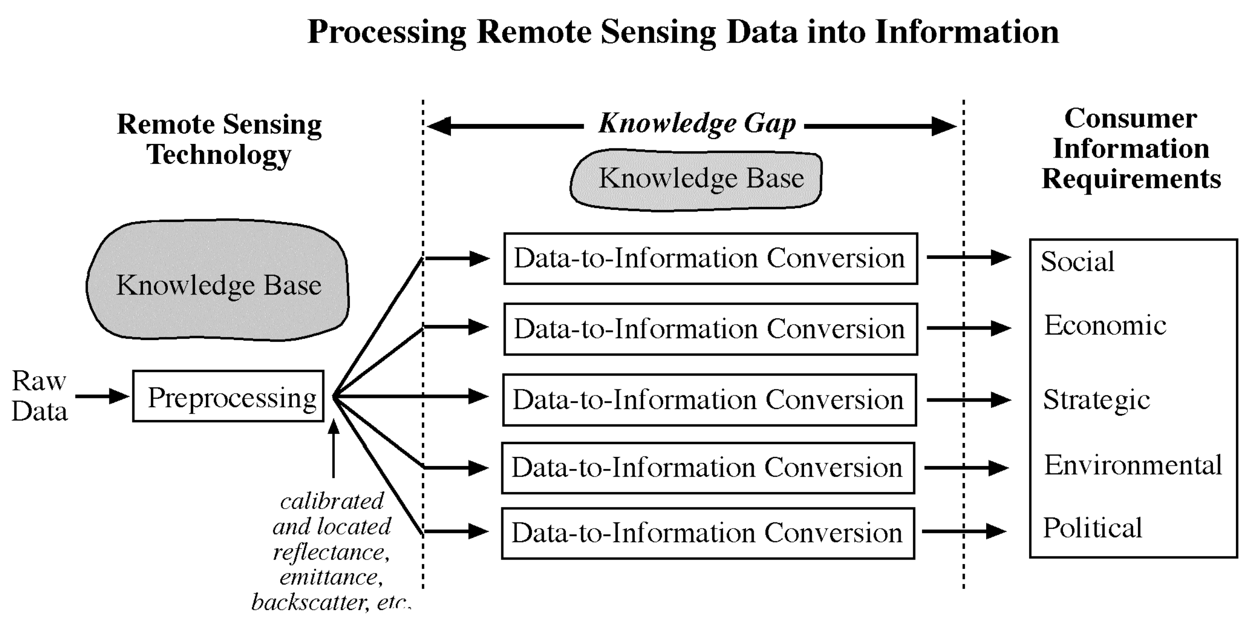


FIGURE 2 Knowledge gap associated with converting remote-sensing data into useable consumer information (adapted from MacDonald, 2000).

DEM using light detection and ranging (LIDAR) data and (*b*) the accurate mapping of building perimeter and height, sidewalks, and rights-of-way using stereoscopic vertical aerial photography and photogrammetric techniques. Unfortunately, such well-developed applications are not that commonly used for several reasons. First, the people on the left side of the diagram (the remote-sensing technology experts) generally do not have a good understanding of the specific information requirements of the user community on the right side of the diagram (see Figure 2). In this case, we are talking about the transportation community of users. Similarly, the consumers on the right side of the diagram have little, if any, knowledge of remote-sensing technology and of how it is used to derive information. The transportation engineer or planner is generally only interested in if the information is accurate, whether it can be delivered on time, and whether it is pertinent to the task at hand. Not surprisingly, the remote-sensing technology experts are often baffled as to why the consumers do not embrace the data and supposed information that can be generated using the remote-sensing technology. They fail to consider that the consumers generally have no motivation to use entirely new sources of information (e.g., remote sensing) just because these information sources may use an entirely different suite of technology to obtain information on economic, social, environmental, strategic, and political attributes.

MacDonald (1999) suggested that this creates a knowledge gap. Bridging the gap is mandatory if we are to use remote-sensing technology to wisely solve important transportation-related problems. It is unlikely that the transportation user community can devote the time to learn the physics of remote sensing and methods of analog or digital image processing and geographic information system (GIS) modeling necessary to produce useful information. Conversely, there is considerable interest on the technology side of the problem to build a communication bridge. Therefore, an effective way to decrease the size of the knowledge gap is for the remote-sensing technologists to work ever more closely with the transportation user community to understand its information requirements. This will lead to more useful remote-sensing-derived information of value to the transportation community.

Recent Innovations in Remote-Sensing Systems and Information-Extraction Methods

The previous discussion suggests that the remote-sensing technology side of the data-to-information conversion process is fairly well developed (Figure 2). It would be ideal if MacDonald knew all about the transportation community side of the calibrated data-to-information conversion process. Unfortunately, this is not the case. All the author can do is build on what he knows and help to educate the community of transportation users about new developments in remote-sensing science. In particular, during the past few years, there have been significant improvements in

- The quantity and quality of orbital and suborbital sensor systems that collect a variety of remotely sensed data, and
- Methods for analyzing these data and turning them into information that have the potential for transportation applications and research.

Of course, to be truly useful the remote-sensing-derived information must be developed in conjunction with experts in transportation science. Nevertheless, it is useful to identify briefly some of the major advances so that we might begin to bridge the knowledge gap previously discussed.

The remainder of this paper identifies several new or innovative remote-sensing systems that appear to be particularly useful to transportation-related research. This paper does not review all of the current or proposed remote-sensing systems. Recent books by Jensen (*4*) and Lillesand and Kiefer (*5*) provide detailed information about most of the major analog and digital remote-sensing systems. The sensor systems are not presented in a vacuum. In most cases, new image-processing methods have been developed to more accurately extract useful information from the remote-sensor data. Thus, whenever possible, the nature of the innovative image-processing methods used to transform data into information are also introduced, often with a brief example. Unfortunately, all the new methods of processing remotely sensed data to extract information cannot be reviewed in this paper. The following texts contain much of this information: Jensen (*1*), Schowengerdt (*3*), and Lillesand and Kiefer (*5*).

High-Spatial-Resolution Digital Stereoscopic Imagery

Jensen and Cowen (*6*) reviewed many urban and suburban data-collection applications that are required by a variety of planners, engineers, and so forth to manage a city, county, or council of governments. How often the data or information must be collected (i.e., its temporal resolution) and the range of remote-sensing spatial resolutions (e.g., 1×1-m, 1×1-ft ground-resolved distance) necessary to extract the desired information are summarized in Table 1 and as ellipses in Figure 3. The temporal and spatial resolution of existing and proposed remote-sensing systems that might be able to provide the desired information are shown as shaded rectangles in Figure 3.

As shown in Table 1 and Figure 3, the vast majority of urban-suburban applications requires very-high-spatial-resolution remote-sensor data, often ≤1×1 m. Traditionally, large-scale (>1:10,000) vertical, analog stereoscopic aerial photography obtained by photogrammetric engineering firms has been analyzed to obtain useful information (topographic, planimetric, cadastral, tax, road centerlines, orthophotos, etc.). The characteristics of a typical aerial photograph are shown in Figure 4*a*. An example of planimetric detail extracted from large-scale vertical aerial photography is shown in Figure 5.

Suborbital Airborne Digital Area-Array Camera Imagery and Soft-Copy Photogrammetry Information-Extraction Techniques

Recently, digital frame cameras that are based on area-array charge-coupled-device (CCD) technology have become available (*7*). The characteristics of a typical digital frame camera are shown in Figure 4*b*. It is composed of multiple arrays (matrices) of detectors, which are set up to be sensitive to specific regions of the electromagnetic spectrum. Numerous private commercial firms—such as Emerge & Landcare Aviation, Inc.; Positive Systems, Inc.; and Image America, Inc.—have developed specialized digital camera remote-sensing systems that obtain digital data (*7*, *8*). The most significant improvement is that on-board kinematic Ground Positioning System (GPS) and inertial measurement units obtain positional x, y, z information at the exact instant that each pixel is recorded. It is then possible to mosaic many flightlines of these digital images into accurate, seamless mosaics of orthophotography, using very few ground control points and a DEM. A 1×1-ft digital metric camera image of Harbor Town on Hilton Head Island (S.C.), obtained using an area-array sensor with 3,072×2,048 pixels per frame, is shown in Figure 6. A church in Missouri is recorded at a 3×3-in. spatial resolution using a digital frame camera with 32,000×8,000 pixels per frame (see Figure 7).

TABLE 1 Urban-Suburban Attributes and Minimum Remote-Sensing Resolutions Required to Provide Such Information (*6*)

	Minimum Resolution Requirements		
Attributes	**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	Pan
Building and Property Infrastructure			
B1—Building perimeter, area, height and cadastral information (property lines)	1–5 years	0.25–0.5 m	Pan-V
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 and right-of-way	1–2 years	0.25–0.6 m	Pan-V
U3—Location of poles, manholes, substations	1–2 years	0.25–0.6 m	Pan
DEM Creation			
D1—Large-scale DEM	5–10 years	0.25–0.5 m	Pan-V
D2—Large-scale slope map	5–10 years	0.25–0.5 m	Pan-V
Socioeconomic Characteristics			
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 h	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—Postemergency imagery	12 h–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 and services	1–2 days	0.25–1 m	Pan-V-NIR

NOTE: USGS = U.S. Geographical Survey; NIR = near infrared; MIR = middle infrared; TIR = thermal infrared; Pan-V = panchromatic visible.

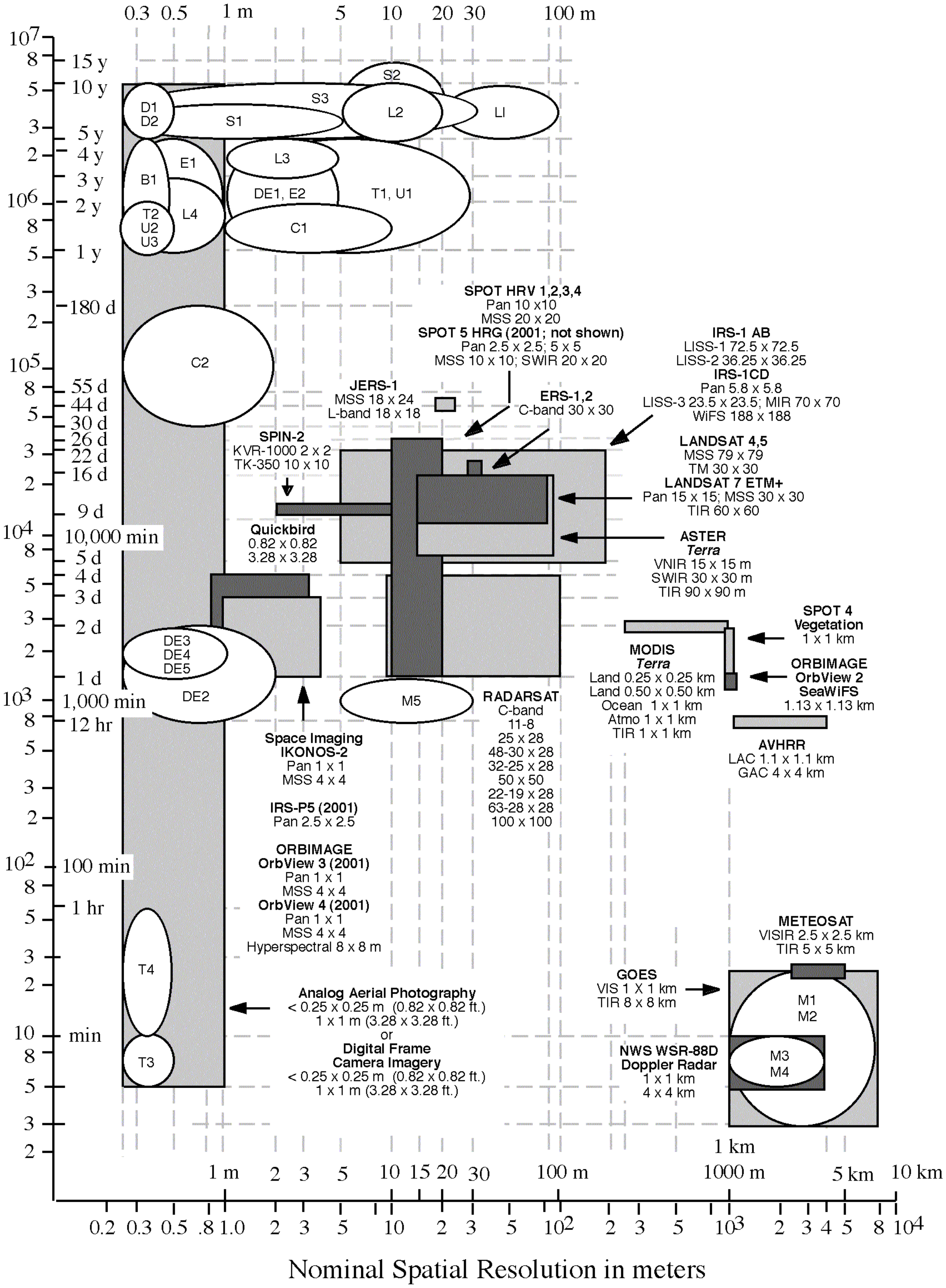


FIGURE 3 Clear polygons represent spatial and temporal requirements for selected urban attributes listed in Table 1. Gray boxes depict spatial and temporal characteristics of major remote-sensing systems, which may be used to extract required urban information (*4, 6*).

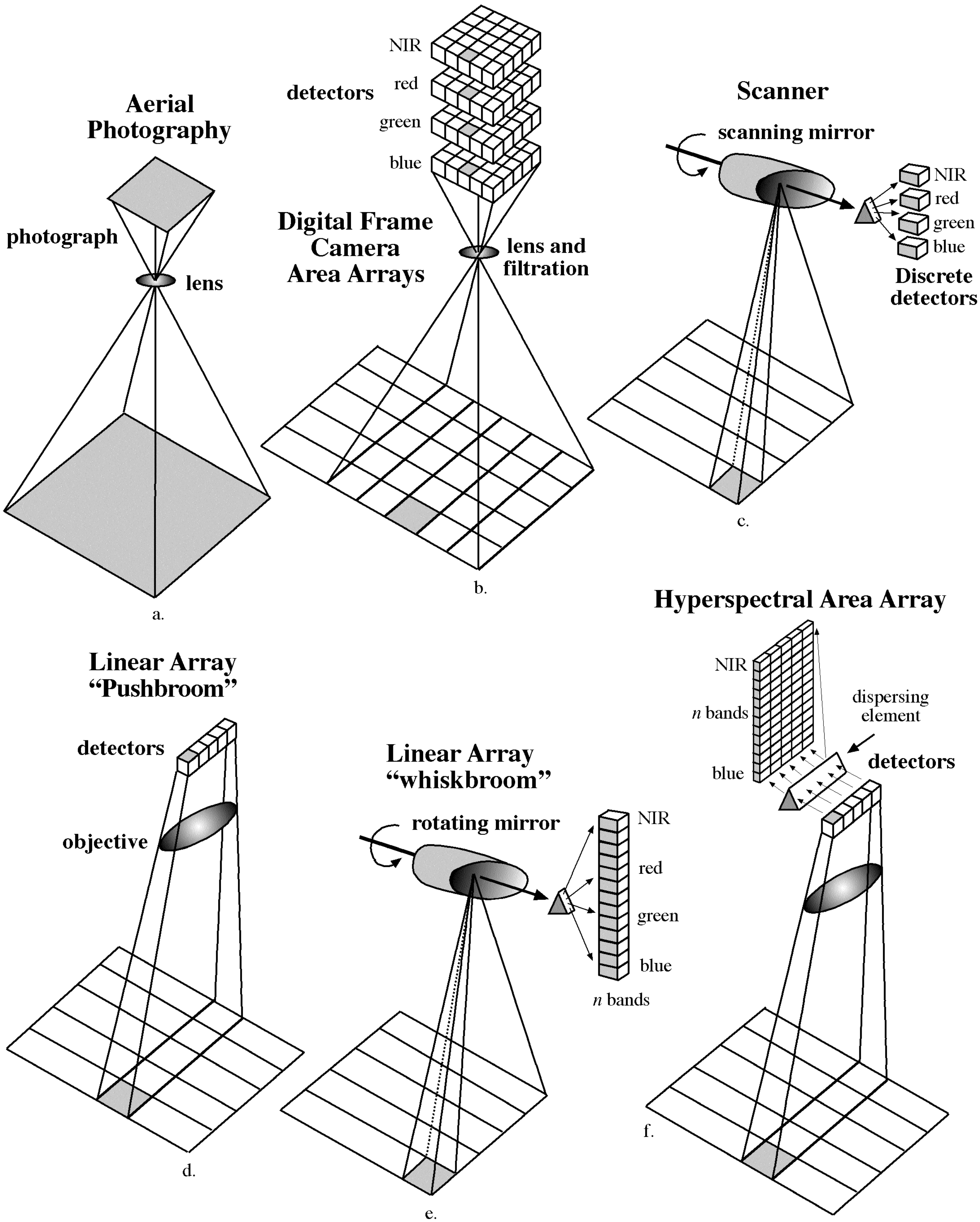
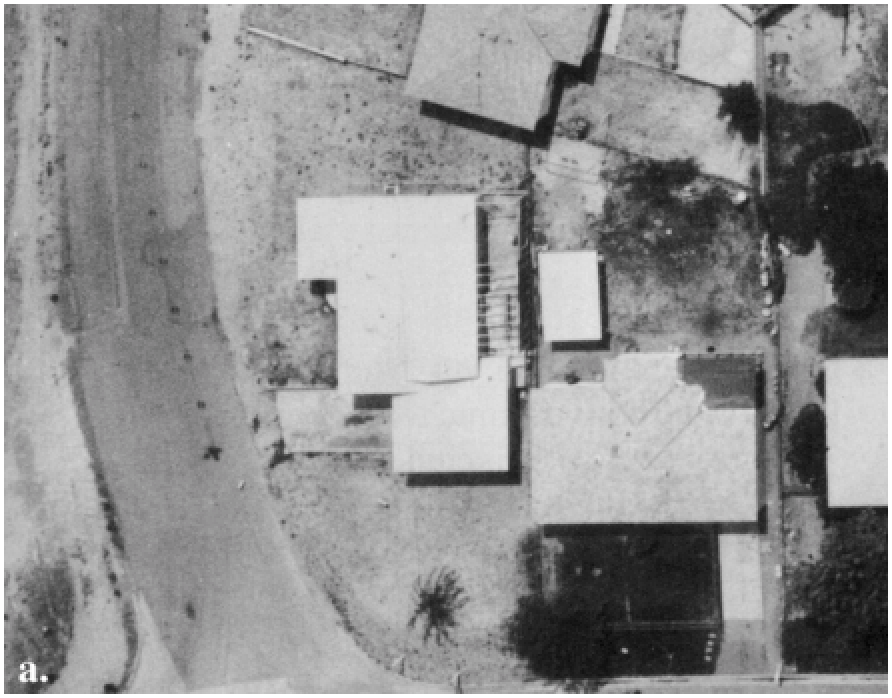


FIGURE 4 Remote-sensing instruments.



(a)

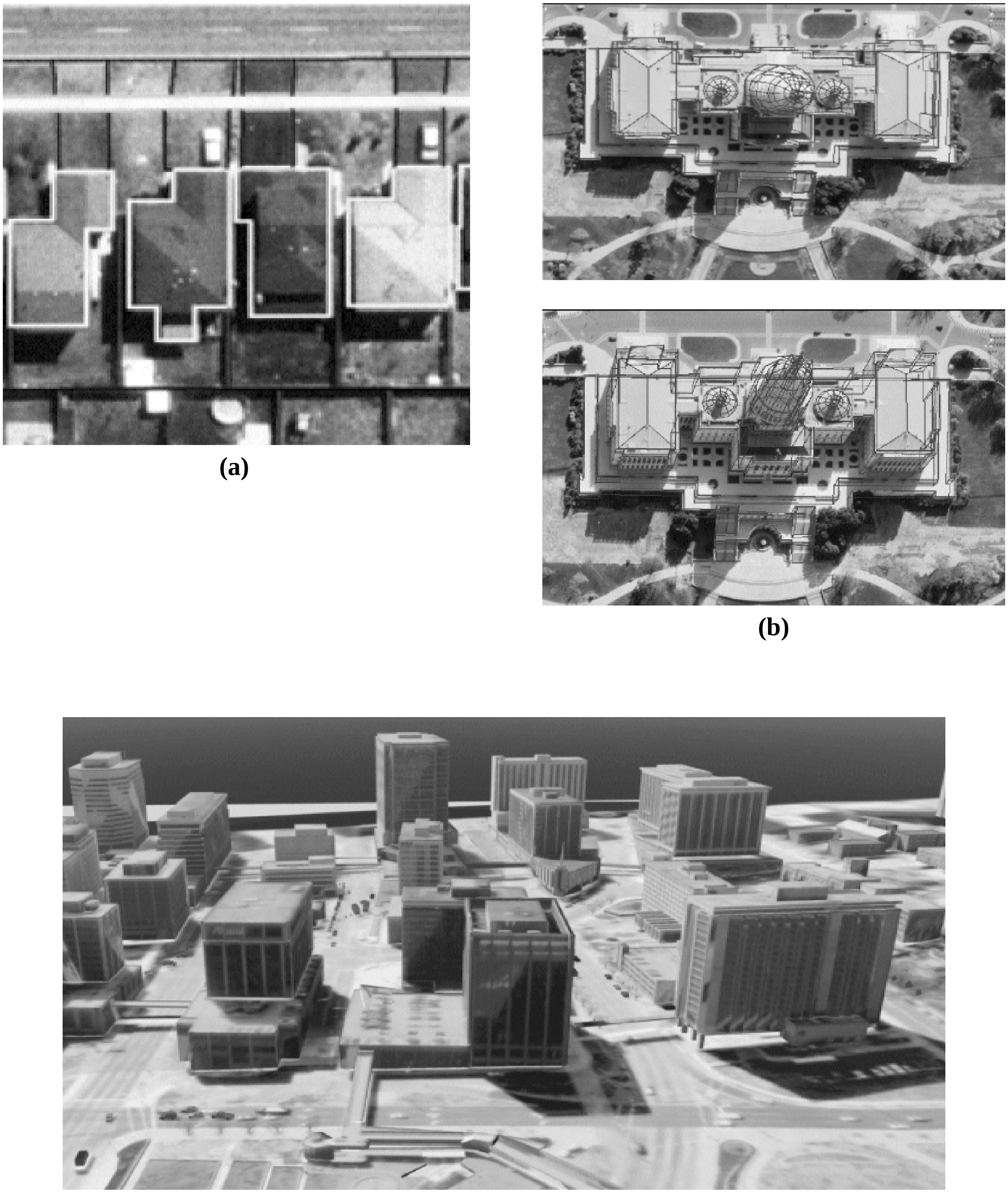
(b)

FIGURE 5 (a) Portion of vertical aerial photography of Covina, Calif., transformed into orthophoto using photogrammetric techniques and (b) planimetric and topographic information (1-ft contours) extracted using photogrammetric techniques (*4*).

FIGURE 6 Orthophoto of Harbor Town on Hilton Head Island, S.C., obtained using digital frame camera (courtesy of Emerge and Landcare Aviation, Inc., and Don L. Light).

The actual processing of the data is innovative because it is based on soft-copy photogrammetry. This means that the individual frames of digital imagery are processed on personal computers using specialized photogrammetric software. The user can work interactively with the stereoscopic three-dimensional (3-D) models viewed on the CRT screen or conduct batch processing to achieve the desired result. Whereas the majority of the functions are complex, the new soft-copy photogrammetry visual analysis software is relatively easy to use by novice interpreters. For example, Figure 8*a* depicts a fundamental 2-D planimetric building and street infrastructure detail. Figure 8*b* displays a 3-D capitol building infrastructure information derived from stereoscopic digital imagery. Digital imagery may also be overlaid onto DEMs to create unique 3-D landscapes, which can be navigated using virtual reality techniques. For example, Figure 8*c* depicts a 3-D image of a portion of Rosslyn, Va., draped over a DEM and viewed from an oblique perspective. This 3-D soft-copy photogrammetry visualization environment is becoming very important for (*a*) extracting useful x, y, and z 3-D urban-suburban infrastructure information and (*b*) communicating concepts and proposed changes to groups of people in a 3-D environment.

FIGURE 7 High-spatial-resolution panchromatic digital imagery of Poplar Bluff, Missouri, obtained on Feb. 15, 2000, using 32,000×8,000 area array of detectors (courtesy of Image America, Inc.).



(a)

(b)

(c)

FIGURE 8 Various types of information extraction and visualization using soft-copy photogrammetric techniques: (*a*) building perimeter information extracted from vertical aerial photography using soft-copy photogrammetric techniques; (*b*) perimeter, height, and volume information extracted from stereoscopic aerial photography of capitol using soft-copy photogrammetric techniques; and (*c*) orthophoto of Rosslyn, Va., overlaid on DEM and viewed from oblique perspective.