Investigation of the Integration of AVIRIS and IFSAR for Urban Analysis

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Abstract

Most attempts at urban analysis using remotely sensed imagery lack the capabilities necessary to define the detailed geometry and differentiate the textures of the complex urban landscape. This paper presents a proof-of-concept study of the potential for integrative analysis of Interferometric Synthetic Aperture Radar (IFSAR) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral imagery for a study area in Los Angeles, California. Recent advances in the use of interferometric radar allow the definition of high resolution, three-dimensional (3D) geometry of surface features, topography, and impervious surfaces in urban areas. The radar analysis is enhanced using hyperspectral imagery to mask surfaces adjacent to structures in order to assist in the determination of baseline topography and segmentation of building footprints for improved geometric measurement of the complex urban area.

Introduction

The global tendency has been to locate cities in areas of sensitive environments, such as coastal zones, floodplains, and prime agricultural lands. Thus, the changing structure, size, and activity composition of cities has profound and disproportionate impacts on regional and global environmental change. With most of the Earth's population living in cities, there exists a great need for a means of rapidly and accurately inventorying and monitoring urban areas. This is especially true in developing nations, where the urban information infrastructure necessary for urban planning and management is not in place (IGBP, 1995).

The urban landscape is extraordinarily complex. It is the manifestation of both physical and human processes expressed in intricate structural geometry of roads, buildings, and land-cover mixtures in relatively unpredictable spatial patterns. Current theories on urban processes, which generate these geometric and land-use patterns evident in the urban landscape, are inadequate to explain, let alone predict, urban patterns of land use and land cover (Thrall, 1987).

Lacking a universal basis in theory to explain and predict the changing urban areas around the world, better methodologies and empirical tools must be developed to specify and analyze urban structure and processes. Improved methodologies and better analysis of these urban areas should provide the insights necessary for urban planning and management policies in the future.

Previous Research

Numerous studies have been undertaken to use remote sensing for analysis of urban areas (Haack *et al.*, 1987; Khorram *et al.*, 1987; Chavez and Bowell, 1988; Wang, 1993). In general, previous investigations have been plagued by these interrelated problems:

- limited analytical capabilities due to reliance on a single sensor;
- spectral and spatial resolution of sensors are too coarse for detailed analysis of urban geometry and texture;
- inability to discern detail of urban structure, while being extendible for regional scale analysis; for example, large-scale aerial photogrammetry can define detail, but can be cost prohibitive for large regions; and
- sensors/data products were not and cannot be optimized for characteristics of the urban environment, because urban analysis was not the primary objective in the sensor refinement.

Recent research has pointed towards the need for sensor data fusion using various available sensors and ancillary data sources to increase the accuracy of land-cover classification and the inference of human activity and land use.

Among the available sensors used for integrative urban analysis are SPOT High Resolution Visible (HRV) multispectral data, SPOT panchromatic imagery, Landsat TM, aerial photographs, and Synthetic Aperture Radar (SAR) (Henderson and Xia, 1997; Gouinaud *et al.*, 1996; Ridd, 1995; Weydahl *et al.*, 1995; Gong and Howarth, 1992; Webber and Hirsch, 1992; Haack *et al.*, 1987; Jensen, 1981; Jensen *et al.*, 1994).

While the combination of the above imagery data sources used with ancillary data has produced improved capabilities to inventory and map the urban system, research has identified a number of shortcomings in urban classification accuracy and the availability of synchronous ancillary data (Webber and Hirsch, 1992). Census data and existing maps — important information for urban area analysis — are unavailable in many cities, particularly in the developing world. Also, the above sensors have not been able to measure critical features accurately, such as surface roughness, topography, structural dimensions, and environmental variables (Xia and Henderson, 1997).

Topography, which includes the three-dimensional (3D) geometrical patterns of human structures, in addition to the natural topography, is valuable in the assessment of land cover/land use. Interferometric Synthetic Aperture Radar (IFSAR) data were used recently to classify general land covers in several areas of California and Oregon (Rodriguez *et al.*, 1998).

According to studies sponsored by the European Com-

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mission — DG XIII — Application of Remote Sensing to Urban Areas, a horizontal spatial resolution of 1 to 2 metres is required for extraction of urban geometrical patterns (Casciati *et al.*, 1996). This level of spatial resolution has only become available in recent SAR and IFSAR systems (Madsen *et al.*, 1993; Soumekh, 1995). Additionally, an important attribute of IFSAR is its orthorectification properties, which eliminates foreshortening of terrain found in conventional SAR imagery. These properties aid in the coregistration of the radar imagery to other sensor data and maps.

This paper will attempt to address some of the limitations of previous urban research using an integration of two sensor systems. Every urban area consists of a natural topography overlain by a human-created three-dimensional structure of buildings, roadways, and other features. The Interferometric Synthetic Aperture Radar (IFSAR) system is used to investigate an improved method for definition and measurement of the structural geometry of both the natural and the human-created topographies in the urban area.

However, accurate geometric measurement of these features requires knowledge of the textural components of the urban landscape. In addition, the urban area is more than simply the structural geometry of discrete features. The linkages, composition, and relative location of the mix of continuous natural and human phenomena expressed as land covers and land uses are essential to the inventorying and analysis of the urban area. The many spectral channels and the vertical viewing perspective of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) are used in this study to complement the use of IFSAR.

Objectives for Integrative Use of IFSAR and AVIRIS

The focus of this study is the acquisition of the 3D geometry of the urban area, not the development of a comprehensive land-cover classification for the study area. The objectives are to

- provide verification that the integration of AVIRIS and IFSAR data can assist in the delineation of urban features to allow more accurate measurement of both human and natural three-dimensional geometry;
- use the AVIRIS data to provide urban textural information corresponding to the geometric information obtained by the IFSAR; and
- assess the potential research requirements for future integrative use of the two sensors for more detailed and comprehensive urban analysis, inventory and monitoring.

Study Area/Sensor Data Used

The study area is in the Westwood section of the Los Angeles region, including the University of California, Los Angeles (UCLA) campus. The approximate area is shown in the AVIRIS natural color image and map insert displayed in Plate 1.

Corresponding coverages of the AVIRIS and IFSAR data were obtained from flights in 1994. AVIRIS data were extracted from the Santa Monica Mountains flight of 19 October 1994. The data range for the 1994 imagery was from Band 1, with a bandcenter of 373.40 nm (0.374 μm), to Band 224, with a bandcenter of 2503.26 nm (2.503 μm).

The IFSAR coverage of the study area was obtained on 5 August 1994. The IFSAR instrument was flown on a NASA/JPL DC-8 aircraft at an altitude of 11,000 metres. The flight path for the radar platform was from 33.97°N, 118.47°W to 33.97°N, 118.41°W. The center of the imaged scene is at 34.06°N, 118.44°W. The center frequency wavelength was 0.056689 metres with a transmit pulse length of 5 microseconds and a bandwidth of 40 MHz. The radar antenna separation was 2.5 metres. For this data acquisition, the IFSAR platform collected data over a 105-km path length with a 12.8-km swath width in one pass. The collected return signal for each antenna on the radar platform was 2.05 GBytes. The interferometric data were processed using the JPL standard processor to produce a topographic map of the imaged area, in addition to the orthorectified synthetic aperture radar intensity image. The data were reported on a regular grid of 5-metre posting with a vertical accuracy assessed at plus or minus 2.5 metres. The AVIRIS and IFSAR scenes were spatially subsetted to the match the study area boundaries.

Imagery Analysis of AVIRIS

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) has a spectral coverage of 224 channels, each 10 nm wide. This fineness of spectral resolution provides unparalleled ability to resolve absorption bands characteristic of the chemical composition of the Earth's surface materials and vegetation (Goetz *et al.*, 1985; Smith *et al.*, 1990). Most analyses of multispectral sensor data, such as Landsat TM or SPOT, concentrate on the limited number of relatively wide bands for characterization of the Earth's surface and features. The ability to resolve many more bands in hyperspectral data, such as AVIRIS, extends this characterization capability beyond that of conventional multispectral data.

Two analytical approaches have been used in most AVIRIS applications (Goetz *et al.*, 1985; Roberts *et al.*, 1997). The classification of features and land cover is performed using statistical approaches for supervised and unsupervised classification and pattern recognition. The second approach employs the collection of a library of field spectra which are matched against spectral signals in the AVIRIS dataset. While the collection and comparison of field spectra for the urban landscape has several interesting possibilities, this research employs the first approach using statistical analysis of the image data to define land covers and features.

One of the initial problems encountered in interferometric measurement of the large buildings in urban areas is the effect of adjacent trees and smaller structures on the radar signal. The intensity of the radar reflection of the adjacent tree canopies, walkways, and concrete areas can be as bright as the SAR image of buildings. The corresponding IFSAR measurement of building geometry is confounded by the heterogeneous signals created around the perimeter. In the analysis, the large trees and other features adjacent to building structures can effectively alter the building footprint in the IFSAR measurements. To address this problem, the AVIRIS analysis required the segmentation of the imagery to delineate a footprint of the primary portions of each large structure. To this end, a vertical perspective mask is necessary to discriminate the vegetation and other materials adjacent to the buildings from the buildings to be measured.

The intent of the initial analysis using the AVIRIS data was to discover the combination of reflectance bands that could be used to identify and differentiate urban land covers adjacent to the buildings. Fieldwork and large-scale aerial photographs were used to define the regions of interest (ROI) or training sites for a supervised classification. Regions of interest (ROI) ranging from 30 to 50 pixels in size were taken from the imagery for each of five categories related to improving the IFSAR classification. These categories were grass, trees, mixed trees/concrete, roadways, and large buildings. The histograms for each of these regions of interest are shown in Figure 1. The centerline in each histogram is the average value. The lines above and below the mean indicate values two standard deviations from the mean, respectively. The average reflectance values for 224 bands across all five categories ranged from zero to a maximum of approximately 6500.

As might be expected, the shapes of the histograms for the buildings and roads are very similar. However, the mag-

Plate 1. Natural color AVIRIS image of the study area, indicating major features and structures to be measured.

nitude of the reflectance values trended higher for buildings than did the values for roads. The range for Band 10 (bandcenter 460 nm) for roads was 3553 to 5057, with a mean value of 4363.7. For buildings, the range was 3781 to 6464, with a mean value of 5203.7.

Likewise, the histograms for trees and grass exhibit a similar shape across the 224 bands. They are approximately equal in value in the region of bands 5 to 15 (411.75 to 509.3 nm). The average reflectance value for the grass ROI in Band 10 was 3249 and the value for the trees ROI was 3021.5. In the region of the near-infrared bands 42 to 50 (751.7 to 828.3 nm), the values are markedly different. Grass has a mean value of 6491.1 in Band 45 (780.4 nm). The mean value for trees is 4083.4 in Band 45. The bottom histogram (Figure 1) indicates a composite response of pixels of tree canopy over concrete walkways.

The potential to discriminate between the trees and grass adjacent to buildings and roadways is indicated in the histograms. The human-made urban features are quite distinctive across the respective histograms. Thus, the histogram analysis provided support for the hypothesis that the AVIRIS data can assist in the discrimination between urban features and land covers, particularly trees, necessary to create a vertical perspective mask.

The massive dimensionality and size of the AVIRIS data set makes coherent and consistent analysis and interpretation a challenge, even for a relatively small urban study area. Preliminary supervised and unsupervised land-cover classifications did not yield useful results to address the specific problems involved in the interferometric measurement. At this point, the approach was adapted to focus on the binary delineation of the shapes (footprints) of the large structures regardless of the surrounding land covers. In effect, the task was to create a mask over all land covers and nonprimary structural features adjacent to large buildings.

Based on the results of the histogram analysis, a principal-components analysis was undertaken on the entire data set to reduce the dimensionality of the AVIRIS data. The intent was to extract a single component that reduced the information of the entire dataset to delineate the roof outlines and the building shapes (footprints) from the surrounding roadways, trees, and grass. The second principal component

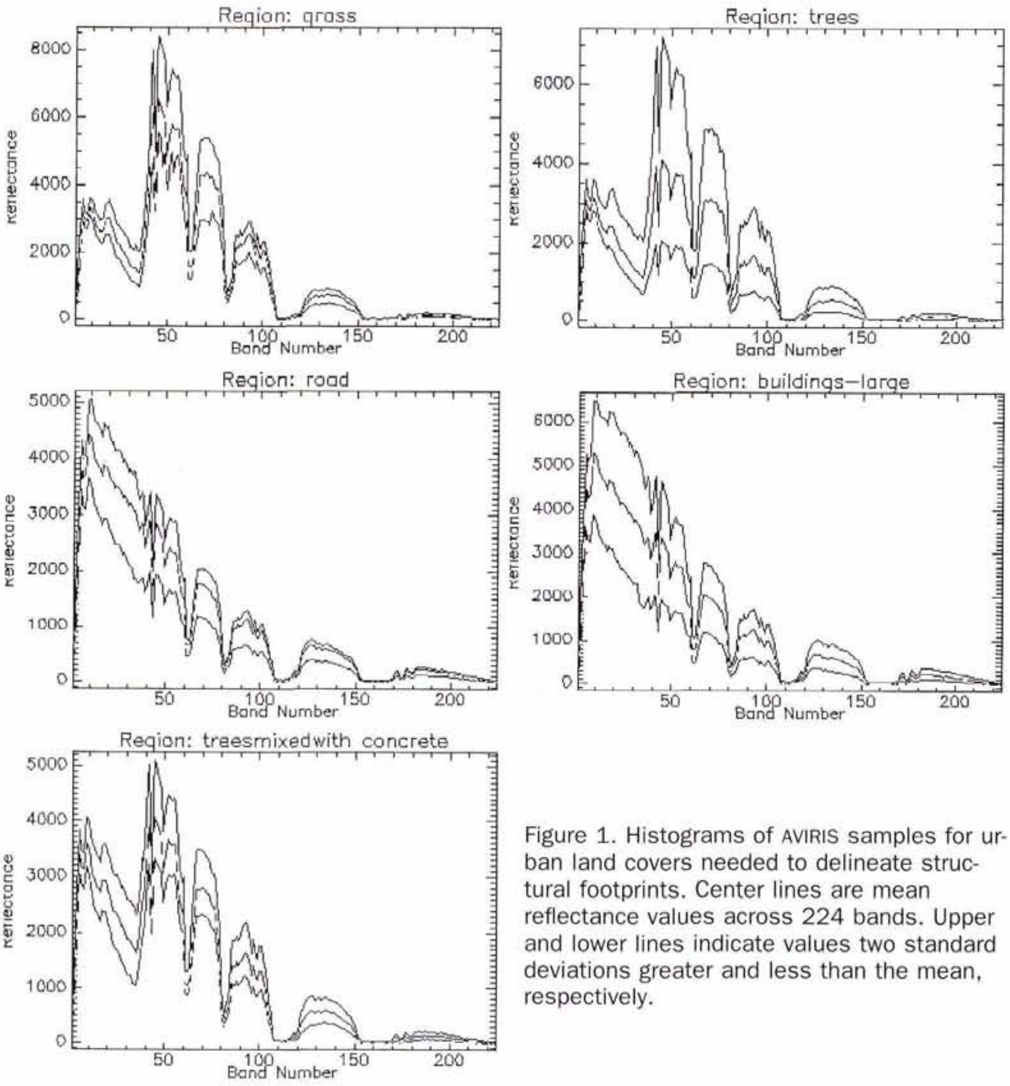

Figure 1. Histograms of AVIRIS samples for urban land covers needed to delineate structural footprints. Center lines are mean reflectance values across 224 bands. Upper and lower lines indicate values two standard deviations greater and less than the mean, respectively.

is portrayed in Figure 2. The individual housing units and single story commercial structures are indistinct, but the footprints of the larger structures on the UCLA campus and along Wilshire Blvd. are readily apparent. Note the footprints of the Pauley Pavilion on the UCLA campus, the Federal Building near the intersection of I-405 and Wilshire Blvd., and the Westside Pavilion Shopping Center east of I-405. These buildings were selected for detailed analysis because they varied in height, roof characteristics, and footprint geometry.

Integration with IFSAR for Measurement of Urban Structures

Analysis of the orthorectified IFSAR data measures both the natural and human-created topography. In addition, the imagery contains the more conventional microwave reflectivity data for a scene. Interferometric processing uses either multiple passes of the radar platform over a study area, or multiple measurements of the study area using two antennas on the same platform in a single pass (Madsen *et al.*, 1993). In this study, the measurement is performed using two antennas situated on the same radar platform, but they are displaced perpendicular to the direction of the aircraft motion. The reflectivity response of the SAR image is composed of an intensity amplitude and a relative phase with respect to a reference. The intensity amplitude is a measure of the geometry of the illuminated area, the operating frequency of the SAR system, and the location of the illuminated area in terms of the radar position. The phase corresponds to the radar distance to the imaged area. Topography is generated by two SAR images with known displacement using their relative phase difference. The process of topography computation is automated and is currently operational (Madsen *et al.*, 1993).

The IFSAR output products are produced on a rectangular grid in a coordinate system that is defined by the direction of the platform motion (i.e., azimuth direction) and a perpendicular direction (i.e., ground range). This coordinate system is transformable to any other geographic coordinate system using a number of known ground control points. The resolution of the IFSAR measurement is dependent on the pulse bandwidth used for the range measurement, the radar antenna length, the length of the synthesized aperture, and the amount of averaging that is performed in the processing algorithms for reducing various noise sources. For a more detailed account on the intrinsic resolution of SAR measurements, and the effective resolution after processing, the reader should consult Elachi (1988). It must be pointed out that the IFSAR operates at wavelengths that penetrate through clouds and fog, and remains sensitive to the feature geometry of the imaged land surface.

The interaction of the radar signal with the urban envi-

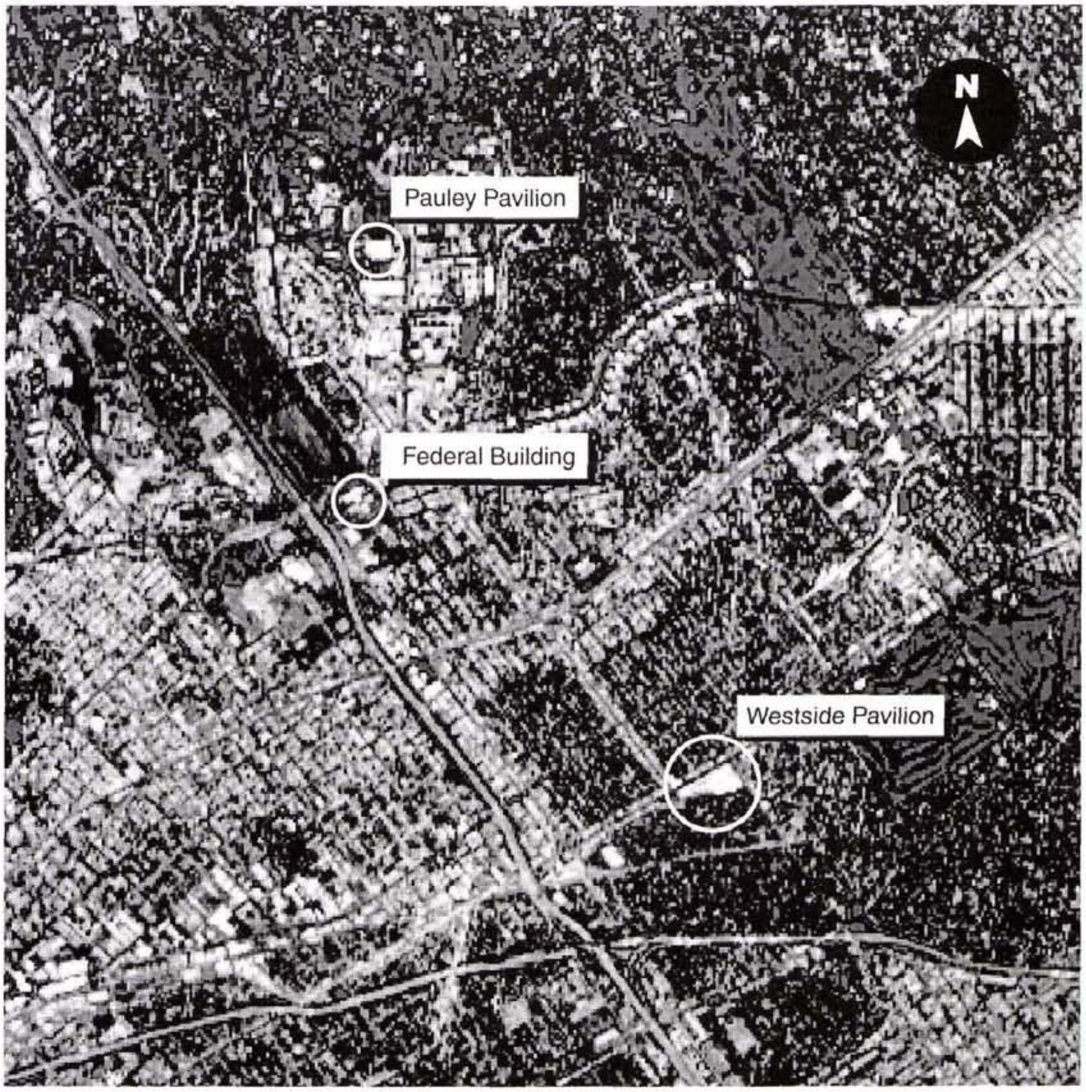

Figure 2. Image of large building footprints shown in white. Image results from a principal-components analysis of AVIRIS data.

ronment is complicated due to the presence, and the density, of the humanmade structures. As a result, the interpretation of the derived IFSAR topography and intensity images in the urban environment is different from that used for natural terrain (Houshmand, 1996).

In the complex urban environment, the vertical dimension has rapid changes in value. Large building structures appear as sharp topographic discontinuities over the natural terrain. For this study, IFSAR topographic data are available at a 5-metre horizontal posting, which captures the characteristics of larger structures.

In order to determine the height of a building, the vertical heights of all the pixels inside the building footprint are used to form a histogram of the distribution. The peak of this histogram corresponds to a height value which was most frequently reported (mode) by the IFSAR measurement over the building footprint, and is designated as the height of the building. This histogram analysis is performed so that the pixels with erroneous height values (due to various noise sources, such as multiple scattering from adjacent buildings, low signal level, and shadowing) will not bias the height estimate for the aggregate building. This procedure discards the height values for antenna towers, which are frequently placed on the roof of large structures. This algorithm can underestimate the height of a building where the roof is not predominately flat. For example, this algorithm underestimated the height of the Pauley Pavilion building, where the roof has a dome structure.

The IFSAR-derived topography is calculated with respect to a reference plane. For each pixel, the derived IFSAR height is the vertical location of the illuminated area with respect to this reference plane. For the natural terrain, this height can correspond to the ground level for open fields, or to the tree heights. For humanmade structures, this height corresponds to the ground level of urban surface areas. The vertical heights of structures are calculated by subtracting the height at the ground level from the structure height.

The topographic measurements produced by IFSAR contain the humanmade structures, in addition to the natural terrain. Integration of the AVIRIS mask enhances the IFSAR detection of building footprints. As discussed earlier, the presence of trees and adjacent buildings hinders this detection from the IFSAR measurements alone.

In this study, the coregistered AVIRIS data are used to de-

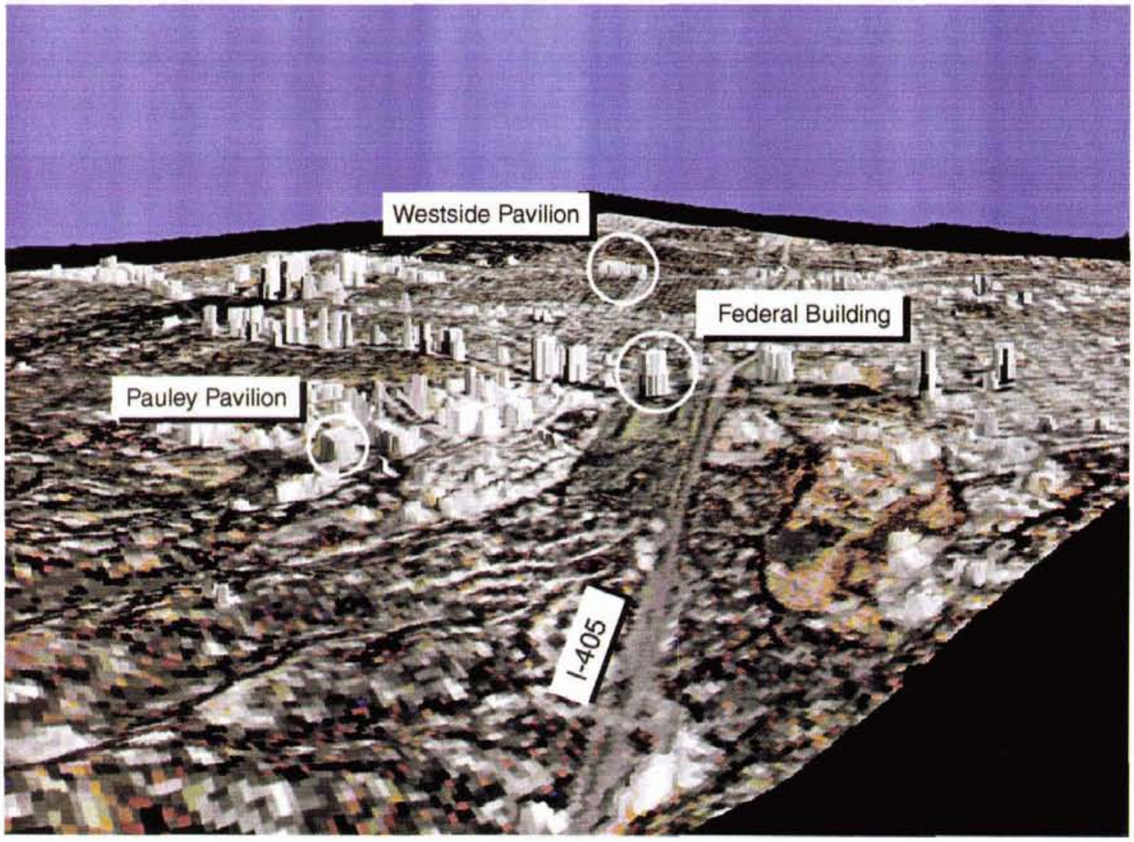

Plate 2. Oblique perspective created using IFSAR measured structures superimposed upon the AVIRIS image of the study area. The image shows the general natural topographic surface with over 400 larger measured structures.

lineate large building structures in the IFSAR data and to aid in establishing the ground reference. For each structure, the vertical dimension is the difference between the IFSAR topography and the ground level height. In addition to the building geometry, a background topography of the urban area is created by removing large structures and smoothing the remaining topography.

An oblique perspective of the study area is shown in Plate 2. The image is a product of combining the AVIRIS visible bands and the IFSAR background topography along with the large building structures which were detected with AVIRIS data. There are 440 structures shown in this image with footprints of larger than 1000 square metres. The scene is viewed from the northwest, where the look direction is toward the southeast. The buildings in the foreground are on the UCLA campus, and the linear arrangement of taller buildings follows Wilshire Boulevard.

A limited comparative sample of building heights to IFSAR-derived estimates was gathered to confirm the basic approach. The height of the Pauley Pavilion was measured at 17 metres using IFSAR. The actual height of Pauley Pavilion is 21 metres. The actual height is underestimated slightly due to the domed shape of the building roof. The Federal Building at the intersection of I-405 and Wilshire Blvd. is 16 stories. It was measured by the IFSAR analysis to be 75 metres. Assuming an average of 5 metres per floor, the IFSAR estimate is 5 metres less than the 80-metre vertical dimension of the structure. The last structure is the Westside Pavilion (three-story shopping mall) in the southern portion of the study area. Its height was measured at 15 metres using IFSAR. The roof is not flat, with portions of this structure as high as 25 metres. The discrepancy among the actual building heights and the IFSAR measurements are due to the errors in determining the ground level reference base, as well as the assignment of a height value to the non-uniform, aggregate pixels within the structure footprint.

Implications and Future Research

This study has undertaken a limited integration of IFSAR and AVIRIS for urban analysis. Our investigation has indicated that measurement with moderate accuracy is feasible in complex urban areas. However limited, this is the first study in the published literature to use IFSAR for urban 3D measurement. Furthermore, the study has illuminated areas of future research necessary to enhance the capabilities of interferometric radar and hyperspectral sensors for urban analysis.

This study confirms that the interferometric radar can be used to define the three-dimensional (3D) geometry of the features and topography of an urban area. The next step in this research is to perform an assessment of the accuracy of IFSAR measurement for a large sample of structures. This will validate further the approach, as well as assist in specifying the factors contributing to the variability in measurement.

Very significant measurement problems in urban areas involve the shadowing of features by other features. This problem is manifested in the imagery by mixed reflectance signals from a building or area being shadowed by another. Also, one feature may actually block the active radar signal or impede or bounce the reflected signal from that blocked feature. This shadowing and the resultant signal distortion is a significant problem for the use of both AVIRIS and IFSAR in urban areas. Computational and data acquisition approaches to minimize multiple reflection effects within the urban area are prime research areas.

While it is believed that increased spatial resolution will yield better measurements, it seems apparent that higher resolution may create signal distortion tradeoffs. A systematic assessment of the effectiveness of increasing the ground resolution of the imaging on our ability to make accurate measurements is necessary as higher resolution data become available. It is anticipated that meeting these research needs will yield the parameters necessary to tune the radar instrument and the analytical methodology specifically for detailed urban analysis.

AVIRIS hyperspectral data were used to enhance the capability to measure urban surface characteristics with the IFSAR. There are other sensors available to create the building footprint mask, such as aerial photography. However, hyperspectral imagery provides the spectral range and differentiation for the development of a comprehensive analysis and mapping of urban surface materials. It is believed that additional features can be measured using IFSAR/AVIRIS integration, such as impervious surfaces and vegetation canopies. Using radar, these measurements can be accomplished through clouds and urban air pollutants. Unlike large-scale photography, high-altitude airborne and satellite sensors, such as AVIRIS, are extendible to regional analysis in a cost-effective manner.

The 20-metre spatial resolution of AVIRIS is a relative limitation in its use with IFSAR. Pixels comprised of portions of both large buildings and adjacent land covers are shown in gray and black in the footprint edge pixels (Figure 2). These mixed pixels complicate classification and delineation of building footprints and other features potentially resolvable by integrative analysis. Although dependent on the shape of the building or feature, very large structures are affected less by the 20-metre resolution, because the ratio of perimeter pixel edges to interior pixels is less as the building size increases.

The creation of spectral libraries for urban surface materials and land covers to aid in the performance of subpixel analysis has the potential to diminish some of the limitations of the spatial resolution of AVIRIS data for urban analysis. Other hyperspectral sensors, which have a finer spatial resolution, will be available in the future. In order to establish that this integrative methodology is accurate and robust over differing urban landscapes, it needs to be applied to a variety of urban settings.

The integration of IFSAR and AVIRIS provides information regarding the vertical size and the spatial extent for the natural topography and humanmade structures in an urban area. Three-dimensional measurements merged with the radar intensity and hyperspectral classification of the extended scene has the capability to provide a powerful regional information base. In addition, the extended image provides orthorectified positioning and relative locational and contextual information necessary for the creation of a more comprehensive geographic information systems (GIS) approach. In this regard, our future efforts will be directed toward automating these measurement procedures and data fusion activities for use in a near-real-time GIS development.

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