Improved Urban Infrastructure Mapping and Forecasting for BellSouth Using Remote Sensing and GIS Technology

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Abstract

The results of a NASA-sponsored Earth Observations Commercial Applications Program (EOCAP) project conducted by BellSouth Telecommunications, the University of South Carolina, and NASA's Stennis Space Center are described. The goal of this EOCAP project is to incorporate remotely sensed data into a multi-purpose forecasting methodology that will assist BellSouth in its market forecasting activities. The research has concentrated on the evaluation of NASA's Calibrated Airborne Multispectral Scanner data (≤ 5- by 5-m spatial resolution) and SPOT 10- by 10-m panchromatic and 20- by 20-m multispectral data. SPOT 20- by 20-m data are sufficient to provide regional information on land-cover change. SPOT 10- by 10-m panchromatic data are useful for updating the urban transportation infrastructure. However, inventorying residential housing stock and estimating population characteristics requires imagery with a spatial resolution of ≤ 5 by 5 m. Several innovative methods based on remotely sensed information and ancillary data stored in geographic information systems are used to predict residential housing and commercial-industrial development. The technology is being tested in several wire centers in South Carolina and will be transferred to BellSouth, who will use the technology to perform more efficient forecasting, marketing, and planning.

Introduction

Since 1879, BellSouth has provided telephone service to the southeastern United States and currently serves over 15 million residences and 2 million business customers within a 200,000 square mile territory in nine southeastern states. BellSouth is a privately owned, government-regulated telephone company which had revenues of $15 billion in 1992.

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One of the most difficult annual planning functions in the regulated telephone industry is the identification of where capital investments are to be made. The capital investments include new and expanded buildings, network switching equipment, and cable (including fiber optic). Methods to improve the accuracy of the forecasts for capital equipment are constantly being pursued by the Strategic Market Planning Department, which assists in identifying where to allocate approximately $3 billion in capital equipment each year. The planning function centers around a geographical area known as a **wire center** which serves a specific neighborhood (i.e., the first three numbers of the seven-digit phone number). Customer phone lines terminate at the wire center and are connected to the world through cable and microwave relay facilities. There are 1700 BellSouth wire centers in the southeastern United States whose boundaries are constantly changing to meet residential and commercial-industrial growth. Each year the Strategic Market Planning Department must assist in producing growth forecasts for each of the 1700 wire centers. Knowing where, the extent, and when the customers will locate and their required phone services are some of the most difficult problems associated with forecasting at the wire center level.

Solution: Incorporate Remote Sensing and GIS into the Capital Investment Forecasting Process

Each wire center is responsible for producing its own forecast of capital expenditure. Critical information required to make accurate forecasts includes knowledge of the transportation network and the residential, commercial, industrial, and public buildings in various stages of development. BellSouth uses traditional forecasting to catalog these types of information. Aerial photography and satellite remote sensor data are not used operationally to identify these resources. Furthermore, because the traditional map resources are not geographically registered, it is not possible to "query" a database or conduct change detection between dates to identify where change is taking place.

This NASA-sponsored Earth Observations Commercial Applications Program (EOCAP) project has incorporated remote sensing and geographic information system (GIS) tech-

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nology into a **Digital Urban Infrastructure Capital Investment Forecasting Methodology** to improve BellSouth's wire center forecasting capability. The project was initiated in 1989 under NASA's Visiting Investigator Program (VIP) at the Stennis Space Center. The BellSouth VIP project demonstrated applications for Remote Sensing and GIS technologies critical to BellSouth's operations. BellSouth then competed on a national level to become an EOCAP II participant. This project was initiated in 1990 and continues through 1994. BellSouth and its Product Advisory Board are responsible for the day-to-day direction of the project, marketing, and implementation. NASA's Stennis Space Center personnel assist in database preparation, remote sensing data collection, and project evaluation. NASA and the University of South Carolina (USC) are responsible for achieving the technical objectives of the project.

Objectives

Objectives of the NASA BellSouth EOCAP II project include

- Developing a **Digital Urban Infrastructure Database Capital Investment Forecasting Methodology** based on the use of remotely sensed data and GIS technology that can be used to inventory and predict residential and commercial land-use development for capital investment forecasting. This is being implemented for selected South Carolina wire centers.
- Conducting a **Capital Investment Forecasting Test** in 1993-1994 for selected wire centers in South Carolina to assess the utility of the Digital Urban Infrastructure Database system and its cost effectiveness.
- If the Capital Investment Forecasting Test is successful, **transferring** the forecasting technology to the BellSouth Strategic Market Planning Department.
- **Implementing** the Digital Urban Infrastructure Database methodology in several of BellSouth's 1700 wire centers. If improvements in forecasting result in a savings of 1 percent in capital expenditures for all wire centers, this would yield approximately $30 million for BellSouth and its customers. There are also six more regions in the Bell System with forecasting problems similar to BellSouth Services. The nine-state BellSouth territory also has some 600 independent telephone companies to which this technology may be marketed.

The Digital Urban Infrastructure Capital Investment Forecasting Methodology

USC and NASA Stennis Space Center personnel conducted an intensive "user needs assessment" with the BellSouth Product Advisory Board. This assessment revealed that accurate capital investment forecasts require information on the following topics:

- *Transportation Network*
  - primary and secondary roads, railroads, and utility rights-of-way
- *Residential Housing*
  - number of single- and multiple-family residences in various stages of development and lot size
  - predictive models of the location of new residences
- *Commercial-Industrial Complexes*
  - number of complexes in various stages of development and lot size
  - predictive models of the location of new commercial-industrial complexes
- *Population Demographics*
  - number in household, age, sex, income, etc.
- *Existing BellSouth Facilities*
  - wire center buildings, major utility lines, and customer base.

The first three of these needs may be derived by visually or digitally interpreting remotely sensed data or by digitizing planimetrically accurate map information into a GIS for further analysis. Knowledge of the existing BellSouth facilities (the final item above) is currently found on diagrammatic, unrectified maps and statistical summaries within each wire center. A major objective of this project was to evaluate how remote sensing and GIS technology can be used to provide meaningful data on the first three items.

Deriving Transportation Network Information

Like many utilities, BellSouth uses highway department transportation maps, field diagrams, U.S. Geological Survey (USGS) Digital Line Graphs (DLG), and 1990 Bureau of the Census TIGER road network information to obtain transportation network information (Cowen and Jensen, 1988; Bennett, 1990; Cowen *et al.*, 1990). The TIGER data are of special interest to BellSouth because of their "address matching" capabilities (i.e., the roads contain address ranges). Unfortunately, many of these street "centerline" databases are out of date or geometrically inaccurate. Therefore, effort has gone into documenting how to update (a) the geometrically accurate but often *outdated* DLG transportation network, and/or (b) the geometrically *inaccurate* but more current TIGER data.

Previous research has demonstrated how SPOT 10- by 10-m panchromatic data may be used to update these very important transportation network files. For example, Figure 1a depicts TIGER transportation network data for a portion of the Dutch Fork Wire Center in Columbia, South Carolina superimposed on rectified 10- by 10-m SPOT panchromatic data (Cowen *et al.*, 1991). The TIGER data are geometrically inaccurate because the vectors were extracted by Bureau of the Census personnel from unrectified aerial photography and simply digitized into the TIGER file. It was possible to move misregistered TIGER roads to their proper planimetric position as shown in Figure 1b using "on-screen" digitization. It was also possible to update all new roads in the wire center since the last TIGER update (Figure 1b). Address matching along the TIGER vectors may now be scaled correctly. Similar procedures are used to update DLG transportation features.

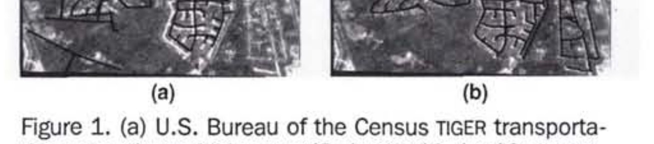

Figure 1. (a) U.S. Bureau of the Census TIGER transportation network overlaid on rectified SPOT 10- by 10-m panchromatic data. Note the geometric error in the TIGER transportation network data. (b) The TIGER road network was placed in its proper planimetric position using "on-screen" digitization. The file was also updated to include new residential subdivisions not present in the original TIGER file.

Having up-to-date road network information is critical to the prediction of future growth and allocation of fiber optic telephone lines because new residential housing and commercial-industrial complexes are mostly located near major transportation arteries. Methods of automatically updating the road network using SPOT and higher spatial resolution remote sensor data are also under investigation (Wang and Newkirk, 1988; Moller-Jensen, 1990; Wang, 1992).

Deriving Residential Housing Information from Remotely Sensed Data

Housing Stock Inventory

BellSouth would like to know the location of each single-family home, multi-family residence (duplex, triplex), apartment complex, and trailer in each wire center. These data cannot be obtained accurately using Landsat 30- by 30-m Thematic Mapper data, SPOT HRV 20- by 20-m multispectral, or even SPOT 10- by 10-m panchromatic data (Jensen *et al.*, 1990; Haack and Jensen, 1994). Therefore, emphasis was placed on demonstrating if and how BellSouth will be able to use SPOT 5 (5- by 5-m) or Landsat *n* (5- by 5-m) data when they hopefully become commercially available in the last years of this century. In order to make this evaluation, Calibrated Airborne Multispectral Scanner (CAMS) data obtained at 5- by 5-m spatial resolution were acquired over the Dutch Fork Wire Center and functioned as a surrogate for the future high spatial resolution, satellite-derived remote sensor data. These data were rectified to a UTM projection using third-order polynomial equations.

Various transformations of the nine channels of CAMS data were used to extract individual dwelling units from the imagery (Cowen *et al.*, 1993). An example of a band-ratioed (near-infrared/red) image is shown in Figure 2. The dwelling units were obtained by ratioing the data, thresholding to identify house pixels, "clumping" the house pixels, and converting the raster clumps into polygons with their own area and perimeter.

The absence (or presence) of dwelling units extracted from the 5- by 5-m CAMS data were compared with the number of units summarized in the block group statistics of the 1990 U.S. Census of Population. The results were remarkably consistent with an r^2 of 0.97 (Pearson product moment correlation, $r = 0.987$). Satellite remote sensor data having $\leq$ 5- by 5-m spatial resolution will provide valuable housing stock information for BellSouth when they become available.

Digital National Aerial Photography Program (NAPP) data (Light, 1993) are also being investigated as a possible source of housing count information. However, is unlikely that NAPP 1:40,000-scale aerial photography obtained approximately every 5 years will meet BellSouth's yearly requirements.

In addition to documenting existing residential dwellings, it was also important to predict where future residential development might occur. Two approaches were investigated to predict such development. First, an empirical method was tested using selected land-use planning variables and Boolean logic. Second, two predictive models based on the use of 1980 and 1990 U.S. Census of Population, building permits, and county land-use information were used to develop analytical models of future growth.

An Empirical Model of Residential Development

The following spatial variables for a portion of the Dutch Fork Wire Center were placed in a raster GIS:

- 100 Year Flood Plain Map of Lexington County (Plate 1a),
- 1992 Lexington County Land Use Zoning Map file (Plate 1b),
- 1992 Lexington County Land Use Zoning file updated using remote sensing (Plate 1c),
- Lot size computed using remote sensing data (< ¼ ac; ¼ to ½ ac; ≥ ½ ac) (Plate 1d), and
- CAMS 5- by 5-m multispectral data (for planimetric detail).

Residential Housing Polygons Extracted from CAMS 5 x 5 m Data Using Band Ratioing Techniques

Figure 2. Individual dwelling units were extracted from the high spatial resolution CAMS 5- by 5-m data using band ratioing techniques. The house pixels were then "clumped" and converted into polygons for comparison with 1990 Bureau of the Census block group housing statistics.

These data were queried using Boolean logic to identify areas which have a high probability of becoming residential at specific housing densities. It is instructive to review how the variables were created and analyzed.

Few developers in South Carolina build residences in areas below the 100-year flood plain contour; therefore, these areas do not have a high probability of residential development and can be effectively removed from further analysis (Plate 1a). County land-use zoning maps are very important sources of future development information (Plate 1b). The zoning file identifies residential development (RS = single family; R1 = multiple family), commercial development (CG, CN, C1, and C2), and those areas not yet developed (D). This type of information is dynamic and rapidly becomes outdated. For example, the Lexington County Zoning Map shown in Plate 1b does not identify two major residential subdivisions already in existence. These subdivisions are easily identified on the CRT screen. "Heads-up" digitizing may be performed to update the land-use zoning file as demonstrated in Plate 1c.

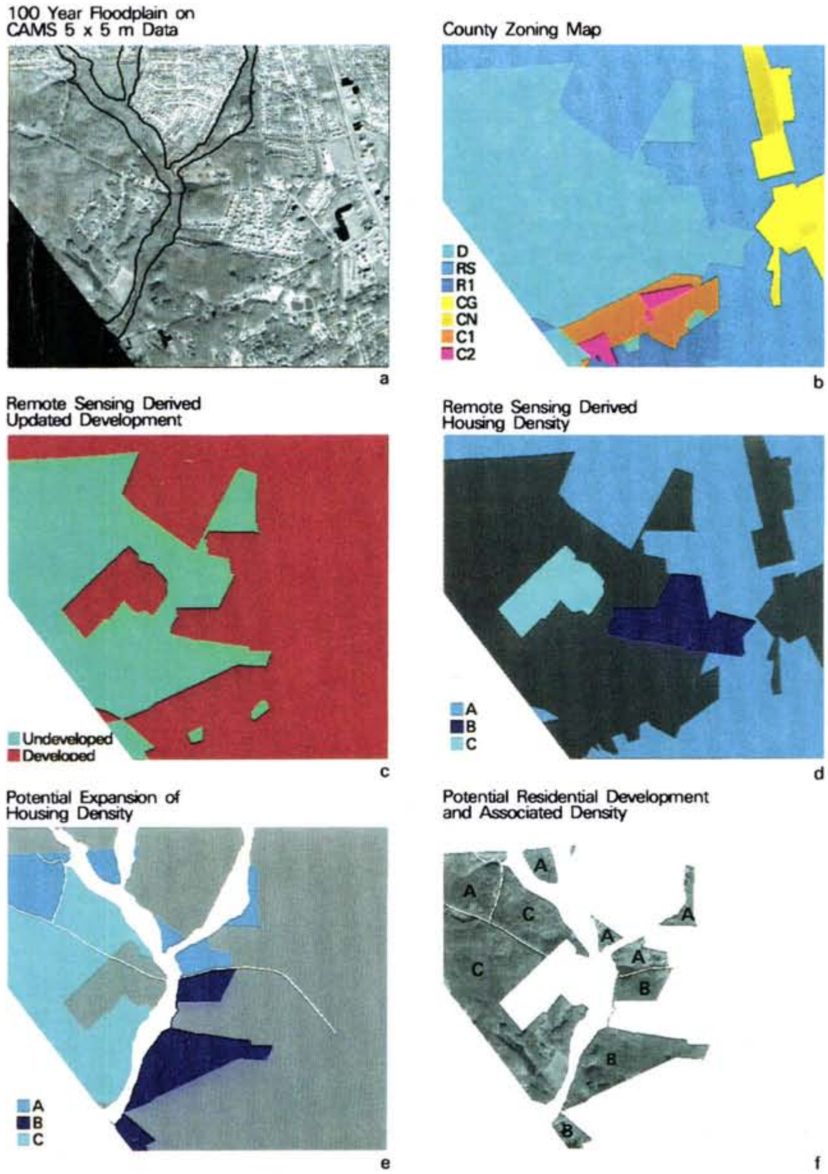

Plate 1. (a) The 100-year floodplain overlaid on rectified CAMS 5- by 5-m data. (b) Lexington County Zoning Map where RS = single family; R1 = multiple family; CG,CN,C1,C2 = commercial; and D = undeveloped. (c) The zoning map was updated using remote sensing to include new subdivisions and then recoded to two classes: developed and undeveloped. (d) Housing density per existing residential area was computed from the remotely sensed data: A = ≤ ¼ to ½ acre lots; B = ¼ to ½ acre lots; and C = ≥ ½ acre lots. (e) Land to be developed was assigned to one of the three density classes based on proximity to existing residential areas and their density. (f) Potential residential development and its predicted housing density.

Photogrammetrically derived length and width measurements of the residential subdivisions in conjunction with housing information (previously discussed) can be used to compute a housing density statistic per residential area. For example, Plate 1d identifies three classes of residential density: A = ≤ ¼ acre lots (0.62 ha), B = ¼ to ½ acre lots, and C = ½ acre lots.

Land tracts within the wire center, which were not within the floodplain and were zoned "ready for development," were assigned to the housing density category closest

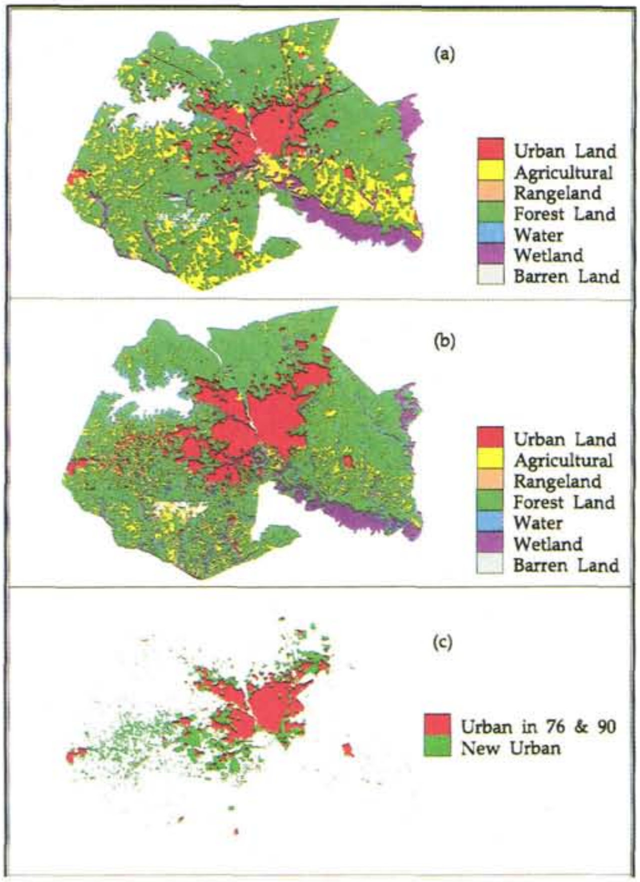

Plate 2. (a) U.S. Geological Survey 1976 GIRAS land-use and land-cover data of Richland and Lexington counties in South Carolina. (b) Land-use and land-cover data extracted from a 1990 SPOT HRV multispectral dataset. (c) The growth in urban area from 1976 to 1990.

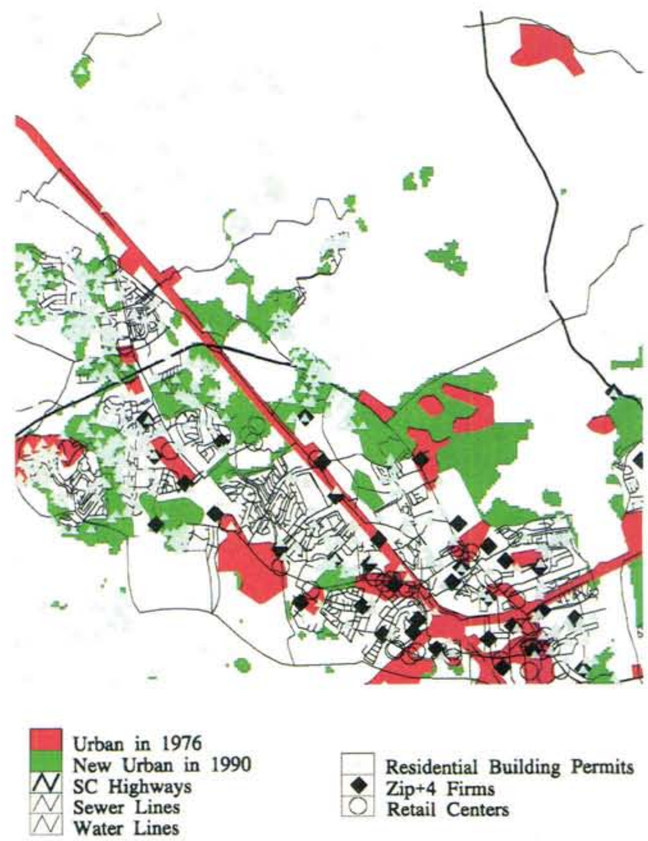

Plate 3. An example of the spatial variables which may be present in the final *Digital Urban Infrastructure Capital Investment Forecasting* database. The data may be derived from remote sensing sources (e.g., new urban areas in 1990 and updated transportation network), county files (residential and commercial building permits, and water and sewer lines), plus geocoding from proprietary address-matching.

in geometric space (Plate 1e). The final map depicts the actual land available for residential development and its predicted density (Plate 1f). The area of each potential tract can be computed and used to determine the average number of homes which can be located in it. Such predictive information is very important to BellSouth and can be obtained using relatively straightforward remote sensing and GIS technology.

An Analytical Model of Residential Development

The decennial national census provides a wealth of residential information. Typically, the longer the time from the last census, the greater the amount of error in population estimates. The fundamental need is to generate accurate intercensus inventories of urban development and to estimate where new development will occur. In order to meet these needs, an analytical study is underway to develop an integrated GIS and remote sensing environment that can be used to monitor urban expansion between census periods over large geographic areas. It addresses the need to capture and analyze systematically a wide range of data sources that are *surrogates* of urban development. A study area centered on the Columbia, South Carolina Metropolitan Statistical Area (MSA), consisting of Lexington and Richland counties, was used to test the methodology. Although there are 20 incorporated cities in the MSA, 85 percent of the land within these counties is undeveloped.

The most important indicator of residential development is the change in the number of housing units. These data are tabulated by the Bureau of the Census every ten years. Therefore, it is possible to use the change in number of houses between 1980 and 1990 as a benchmark for examining other indicators of urban change. The 1980 and 1990 census tract polygons were chosen as the unit of measure because the two dates had similar boundaries and geographic extent. Once there was a geographic correspondence in tract polygons and tract number, the 1990 housing counts were linked to the 1980 tract polygons. The total population change from 1980 to 1990 in Richland and Lexington Counties was +40,221 and the total housing change was +34,017. Twenty-four census tracts lost housing between 1980 and 1990, mainly in the downtown area of Columbia. The areas with the greatest increase in housing units were located in the suburbs in northeast, northwest, and west Columbia. The goal of the research was to compare surrogate measures of urban change that could be used to estimate the rate of change in number of houses and the spatial distribution of these changes. The first surrogate was based on the use of remotely sensed data.

Forecasting Residential Land-Use Change Using Satellite Remote Sensor Data

Because no 1980 land-cover information derived from satellite data existed, 1976 USGS land-use and land-cover data derived from 1:60,000-scale aerial photography were used as the initial baseline. These data represent an inexpensive source of land-cover data available for the entire United States (U.S. Geological Survey, 1986). The polygonal land-cover data are summarized in seven Level II classes (Plate 2a).

Previous research has shown that SPOT imagery can be used in detecting urban fringe growth (Colwell, 1985; de Brouwer *et al.*, 1990; Jensen *et al.*, 1990; Wang, 1993). A 1990 SPOT image was analyzed using traditional unsupervised classification techniques (Jensen, 1986) to identify the same seven land-cover classes (Plate 2b). The algorithm used to convert the 1990 raster data to polygonal data was an edge stepping algorithm (Piwowar *et al.*, 1990; Vander Knapp, 1992). To determine the amount of change from 1976 to 1990, the two classifications were intersected (Jensen *et al.*, 1993) to create a composite land-cover change file (Plate 2c). The composite layer was intersected with the 1980 census tract polygons to determine the land-cover change by tract. The amount of change from rural to urban was obtained by performing a polygon overlay analysis. This operation identified all polygons which were undeveloped land in 1976 and developed in 1990. These data were moderately correlated with housing change at the Census tract level ($r = 0.68$). The model

Percent Change in Housing = 0.005 + 0.538 (Percent Change in Developed Land)

provides a useful initial analytical model for forecasting future housing. Using this model, it is possible to estimate housing by monitoring land-cover changes from remote sensing sources.

Forecasting Change Using Building Permit Applications

Another analytical approach to monitoring urban change was based on building permit transactions. The Central Midlands Regional Planning Council maintains a tabular database of all building permits issued by Richland and Lexington County, including number, street, city, county, month, year, school district, demolition, tract number, cost, type of construction, number of units, subdivision name, tax map number, and number of permits. To convert the building permit data into a GIS database, it was necessary to locate each permit geographically and link the attributes to the location. This geocoding process utilized a new BellSouth proprietary "address-matching" tool.

Between 1981 to 1990 there were 15,975 building permits issued in the study area. Using the proprietary geocoding methodology, 67 percent of these were successfully address matched. These points were then aggregated at the census tract level and compared with the estimated housing change over the past decade. From these data a regression procedure was used to generate a predictive analytical model for the period from 1980 to 1990:

Percent Change in Housing = 0.002 + 0.883 (Change in Building Permits).

A high correlation ($r = 0.84$) suggests that tracking building permit data provides a good way to monitor housing changes. The EOCAP II project research is now focusing on the relationship between the satellite-based residential change detection and the building permit activities.

Data Integration

The benefits of these approaches to monitoring and modeling urban changes are evident when the various types of data are integrated into a GIS database. While the census provides indispensable data for urban forecasting, of necessity it is aggregated both spatially and temporally. Both the remotely sensed data and the building permit information can be examined on a continuous basis at a much finer level of spatial detail than census areas. The power of this type of data integration is readily apparent when individual neighborhoods are examined (Plate 3). This example demonstrates how it is possible to integrate point level data (building permits, commercial firm and retail center locations), linear features (highways, water and sewer lines), various areal features including census polygons, and change in urban land use. The EOCAP II project is now concentrating on the creation of a robust housing model that incorporates these data sources into an improved wire center forecast.

Commercial-Industrial Inventorying and Modeling

Commercial shopping centers, business parks, and industrial parks contain large amounts of expensive telephone equipment, often exceeding that found in residential areas. Therefore, BellSouth desires to know where potential commercial-industrial development may take place. They currently obtain such information by windshield surveys and anecdotal information known by local forecasters. To date, only an empirical model of industrial-commercial development in the southwest portion of Columbia, South Carolina has been implemented.

Empirical Model Prediction of Commercial-Industrial Development

Current information on proposed commercial and industrial complexes are not always found in the county zoning files. For this reason, the following industrial location constraint criteria (Jensen and Christensen, 1986) were used to identify prospective commercial-industrial development sites:

- CAMS 5- by 5-m multispectral data to obtain planimetric detail and identify existing residential development (Figure 3a),
- must be within 300 m of an adjacent highway or railroad (Figures 3b and 3c),
- must be within 300 m of an adjacent railroad,
- 100-Year Floodplain (Figure 3d),
- 1992 Lexington County Land Use Zoning file of proposed residential development (Figure 3e), and
- must be ≥ 150 contiguous acres.

The application of these Boolean logic constraints resulted in a map showing the optimal sites for commercial-industrial development in this portion of Columbia, South Carolina (Figure 3f). Since this study was completed, the area under the star in Figure 3f has become the largest U.S. Postal Service Center in South Carolina. The area is outside the 100-year floodplain, was not zoned residential, is within 300 m of a highway and railroad, and is greater than 150 acres in dimension. In this case it was possible to view the optimal sites overlaid onto the 5- by 5-m CAMS data. How-

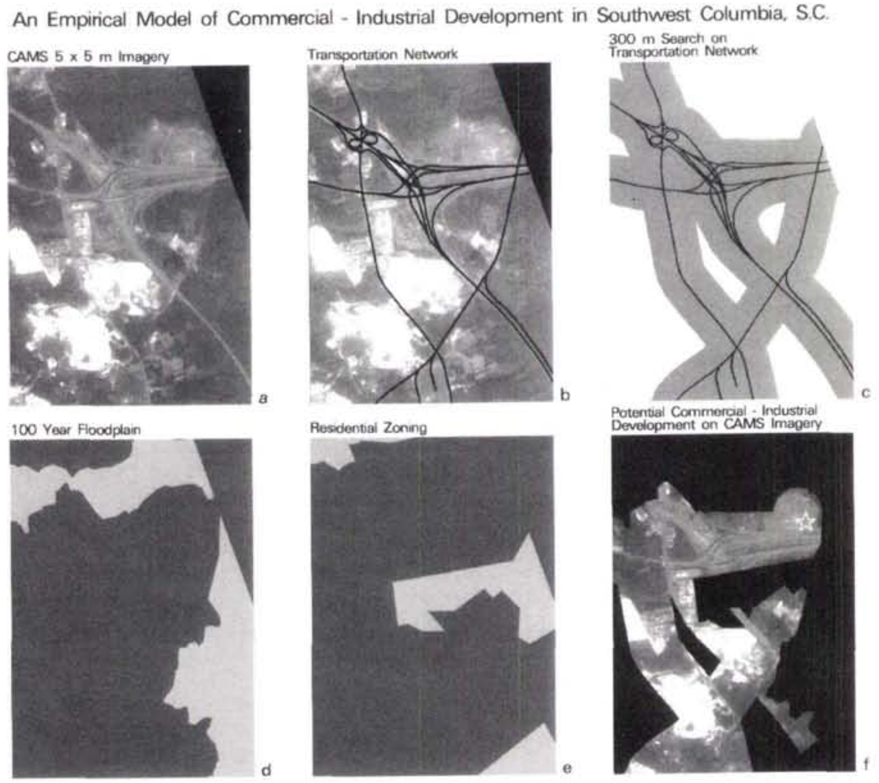

Figure 3. (a) CAMS 5- by 5-m imagery of an area in southwest Columbia, South Carolina. (b) Highways and railroads transportation network overlaid on the CAMS imagery. (c) 300-m buffer around the transportation network. (d) The 100-Year Floodplain. (e) Proposed residential development derived from Lexington County Land Use Zoning map. (f) Potential commercial-industrial developments which meet the constraint criteria. The area with a "*" became the largest U.S. Postal Service Center in South Carolina in 1993.

ever, SPOT 10- by 10-m data would be sufficient. Boolean logic, industrial-commercial development models such as this can be applied to entire wire centers once the appropriate datasets are in place.

BellSouth EOCAP Forecasting Strategy

Forecasting the demand and location of telephone services is so important to BellSouth and the other six regional Bell holding companies that a *National Telecommunications Forecasting Conference* (NTFC) is held each year to discuss the latest methods of compiling accurate capital expenditure forecasts. Results from this EOCAP II project have been reported twice at the NTFC, once receiving the meritorious paper award. Why is BellSouth so concerned with the accuracy of the forecasts? An inaccurate forecast will result in (1) too much material or switching facilities being ordered, which can produce substantial inventory control and cash flow problems, or (2) too few materials being ordered, resulting in not enough of the correct equipment or facilities available upon demand. These forecasting problems translate directly into dollars saved or lost on a very large scale. Therefore, the BellSouth business strategy plan has two major objectives:

- to incorporate the *digital urban infrastructure database forecasting methodology* (product) into BellSouth's *internal* area forecasting methodology to produce a 1 percent savings, and
- to market the improved methodology (product) *externally* to other telephone companies that have similar forecasting problems.

These two objectives represent both near- and long-term business strategies. BellSouth intends to accomplish the first objective and then review the potential for marketing outside its corporate limits. *BellSouth will consider the EOCAP II project a success if considerable progress can be made to realize the first objective.*

BellSouth recognizes the risk of relying on just a few commercial sources of remote sensor data (e.g., EOSAT or SPOT). If the improved method of forecasting is compromised due to data unavailability, or if the risk of using existing commercial data is considered too high, BellSouth may consider funding its own remote sensing data acquisition system to support its forecasting requirements. One of the outcomes of this EOCAP II project would be specific sensor system recommendations that could be used in this regard.

Conclusions

Knowledge concerning BellSouth's customer base is critical to the effective delivery of telecommunications service. Traditional techniques for acquiring information are inadequate in an era of rapidly changing demographics. Results to date demonstrate the utility of remote sensing and GIS techniques to predict customer location. The efficiency and organization achieved through a geographically registered, multivariate database allow BellSouth to perform queries and track patterns in customer behavior not possible with traditional techniques. The NASA/BellSouth EOCAP II project is entering its third year and is focusing on completing the forecasting model and integrating the derived techniques into several wire centers within the BellSouth service district. As with most new technologies, BellSouth will continue to discover new ways to use remotely sensed and other spatial data.

Acknowledgment

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