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Mapping the City Landscape From Space: The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Urban Environmental Monitoring Program

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INTRODUCTION

As the global population expands, concentrating in the large urban centers of the world, the stress placed on these local environments will also magnify. It is estimated that in the next 25 years nearly two-thirds of the global population (over 5 billion) will come to live in cities [WRI, 1996]. Not since the Industrial Revolution has the world experienced such urbanization and human population expansion. Monitoring this growth and the subsequent land-use change can be a fundamental source of information for physical and social scientists intent on understanding the patterns of expansion, the impacts such growth will have on the local environment, and the demands it places on the population. An excellent synoptic means of gathering these data is by using repeat coverage remote sensing. In the past decade numerous new satellite instruments have been launched and many of these are being used to study earth science in urban settings. This paper describes one such satellite instrument and data collection program: the Urban Environmental Monitoring (UEM) project of the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) instrument. Detailed here is the algorithm development and testing—first using Landsat Thematic Mapper (TM) and NASA airborne sensor data, the UEM planning and implementation procedure, and the initial results utilizing ASTER.

Earth Sciences in the Cities

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BACKGROUND

In most countries, including the United States (US), a vast majority of the fastest-growing urban centers are vulnerable to natural hazards and ecological degradation because of their proximity to coastal and semi-arid environments [WRI, 1996; USCB, 2001]. The changes that occur to the urban core as well as the surrounding metropolitan area are significant and commonly detectable even with moderate to low spatial resolution satellite data [Anderson et al., 1976; Haack et al., 1987; Stefanov et al., 2001a]. Monitoring this urban population expansion by extension directly affects the largest percentage of a country's population and resources. Therefore, this activity on a global scale is seen as an important effort over the next two decades. Land cover mapping and monitoring provide input data into Geographical Information System (GIS)-derived models of infrastructure modifications, utility needs, economic development, and the potential vulnerability of the population to natural hazards and environmental damage [Lindgren, 1985; Martin et al., 1988; Treitz, 1992; Lyon et al., 1998; Balmford et al., 2002].

The current urban expansion and subsequent pressure on the fragile resources of highly-populated regions has given rise to new areas of urban science such as ecology, remote sensing, and geology relating to hazard mitigation. For example, the National Science Foundation (NSF) awarded the first ever urban Long-Term Ecological Research (LTER) projects to Phoenix, AZ and Baltimore, MD in 1997 [Grimm et al., 2000; Pickett et al., 2001]. The primary objective of the 21-site LTER network is to monitor and assess long-term ecological change in diverse ecosystems in the United States and elsewhere in the world. Whereas other LTER projects have focused on pristine locations well removed from the myriad effects brought about by extensive human modification and dominance of ecosystems, the two urban LTER programs are providing a unique opportunity to monitor human-induced ecological changes.

U.S. Growth

Urbanization of the semi-arid regions of the southwestern United States is a comparatively recent phenomenon in the history of the country, occurring largely in the last 50 years. The 1990 US Census identified eight of the ten fastest growing cities and six of the fastest growing metropolitan areas as being located in the west and southwest. For example, Arizona has been the second fastest-growing state in the US for the past six years, and the population of the Phoenix metropolitan area has doubled twice in the past 35 years. This growth has pushed the urban fringe into areas formerly occupied by agricultural land and pristine desert. Analysis of the official 2000 Census data show this trend continuing, with the largest increase in population occurring across the southern tier of the country and in the west (Table 1). This expansion is focused on both the central cities within each region as well as the surrounding area (metropolitan-region). The

TABLE 1. Data From The United States Census Showing
The Growth Rate Percentage Of U.S. Regions From 1990 To 1999

U.S. Region [a]	Central City Growth	Metro-Region Growth
Northeast	-2.4	4.1
Middle Atlantic	-2.2	4.2
South Atlantic	2.5	20.2
East North Central	-1.1	10.1
East South Central	1.9	18.0
West North Central	2.0	15.0
West South Central	9.5	23.8
Mountain	20.3	35.8
Pacific	8.1	14.9
United States (Total)	4.1	14.2

[a]Northeast: ME, NH, VT, MA, RI, CT; Middle Atlantic: NY, NJ, PA; South-Atlantic: DE, MD, DC, VA, WV, NC, SC, GA, FL; East-North Central: OH, MI, IN, IL, WI; East-South Central: KY, TN, AL, MS; West-North Central: MN, IA, MO, ND, SD, NE, KS; West-South Central: AR, LA, OK, TX; Mountain: MT, WY, CO, NM, ID, UT, AZ, NV; Pacific: WA, OR, CA, AK, HI.

dramatic growth of cities in the Mountain, West-Central and Pacific regions is at the expense of the urban populations in the Northeast, Middle-Atlantic, and East-North Central regions. However, despite many of those regions experiencing slow to negative growth, most still had positive growth in the metropolitan regions, indicating a trend toward suburbanization that began after World War II.

In order to carry out monitoring rapidly and efficiently, the LTER project in Arizona has relied heavily remote sensing. Described by Stefanov et al. [2001b], these products include vegetation, soil, and urban cover types (Figure 1). Because central Arizona is located at the major geographic and climatic transition zones between the Sonoran and Chihuahuan Deserts and the Sierra and Rocky Mountain ranges it has a unique ecosystem and climate. With less than 18 cm of annual rainfall, Phoenix is situated in a semi-arid landscape that provides excellent remote sensing opportunities due to minimal cloud and vegetation cover. However, this climate also produces a strong reliance on surface and groundwater sources, a high moisture evaporation rate, and a continual threat of drought. These same issues, faced by populations living in similar to more extreme environments around the world, makes the science and policy issues examined in Phoenix extremely relevant.

Urban Science From Above

In addition to the NSF, NASA is also currently funding research into natural hazard mitigation within the urban environment using remote sensing, relying on

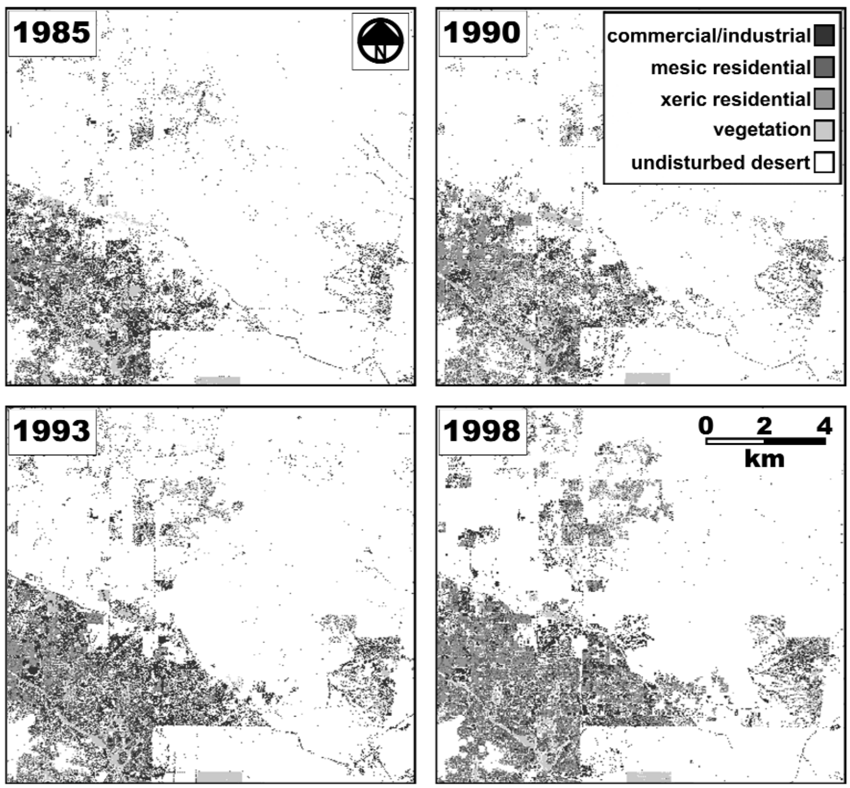

Figure 1. Land use/land cover supervised classification results of Landsat TM data for Scottsdale, AZ from 1985 - 1998. The expert-system derived classification procedure is detailed in Stefanov et al. [2001b]. This time series highlights the spread of urban land cover (residential, commercial/industrial) to the north and northeast, clearly defining the border with the non-developed Salt River Indian Reservation in the southeast. Explosive growth (sprawl) in such short time periods places high stress on the local environment and is a prime target for monitoring using data from ASTER.

both focused studies and global monitoring efforts [Pax-Lenney and Woodcock, 1997; Ridd and Liu, 1998; Quattrochi and Ridd, 1998; Ramsey and Lancaster, 1999; Stefanov et al., 2001b; Zhu and Blumberg, 2002]. However, remote sensing of cities has been limited in the past due to the low spatial resolution of most satellite-based instruments, as well as the lack of demand and use from city officials, planners, and scientists [Townshend, 1981; Harris and Ventura, 1995; Aplin et al., 1999]. This trend has changed with the advent of both innovative processing algorithms and inexpensive, higher spatial resolution data [Gong and Howarth, 1990; Aplin et al., 1997; Stefanov, 2002].

Among these new sensors is the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) instrument, launched in December 1999 on the NASA Terra satellite. Its nominal mapping phase, begun on 10 October 2000, is planned to continue until 2006. ASTER was designed by the Japanese Ministry of International Trade and Industry (MITI) and acquires repetitive, high spatial resolution, multi-spectral data. It is the first instrument to ever provide global data of this type in three wavelength regions from the visible/near infrared (VNIR) to the short-wave infrared (SWIR) to the thermal infrared (TIR), and it is the only high-resolution imager of the six instruments on board the Terra satellite [Kahle et al., 1991; Yamaguchi et al., 1998]. The spectral resolution varies between the three subsystems, with three channels in the VNIR, six channels in the SWIR and five channels in the TIR (Table 2). The high spatial resolution, multi-spectral coverage, and the ability to generate digital elevation models (DEMs) make it a critical tool for urban topographic and compositional analyses.

The Terra platform follows a sun-synchronous, polar orbit ~ 30 minutes behind the Landsat satellite providing ASTER with a nominal repeat time of 16 days (Table 2) and local overpass times of ~ 10:15 am/pm. However, with a cross-track pointing capability, the repeat time can be decreased to as low as five days with the added advantage of image collection up to 85º north/south latitude. ASTER has a 60km swath width and a ground instantaneous field of view that increases from 90 meters in the TIR to 30 meters in the SWIR to 15 meters in the VNIR (Figure 2). The instrument also has the ability to perform along-track stereo imaging by way of a 27.6º backward-pointing telescope in channel 3 (0.78 - 0.86µm) (Figure 3). This feature allows high-resolution digital elevation models (DEMs) to be created from the ASTER stereo pairs [Welsh, 1998]. Finally, ASTER data are acquired using one of several dynamic ranges in order to reduce data saturation (over highly reflective targets) and low signal to noise (over minimally reflective targets).

Unlike the previous and current Landsat TM instruments, ASTER is scheduled due to the large data volume it generates. It therefore operates on an 8% average

TABLE 2. ASTER Instrument Design Specifications

	VNIR	SWIR	TIR
Wavelength Range (µm)	0.52 - 0.86	1.60 - 2.43	8.13 - 11.65
Wavelength Channels	3 (+ 1 back-looking)	6	5
Spatial Resolution (m)	15	30	90
IFOV (µrad)	21.3	42.6	127.8
Repeat Time (days) [a]	5	16	16
Pointing Angle (degrees)	± 24	± 8.55	± 8.55

[a]Nominal repeat coverage can be substantially improved with the cross-track pointing capability.

Figure 2. Comparison of the spatial resolution for each of the three ASTER subsystems over a 2 km portion of São Paulo, Brazil. The ASTER L1B scene was acquired on 19 March 2002 (13:23:17 UT). All images have a 2% linear stretch applied. (top) 15 m/pixel VNIR band #2 (0.63-0.69 µm). (middle) 30 m/pixel SWIR band #7 (2.24-2.29 µm). (bottom) 90 m/pixel TIR bands #12 (8.93-9.28 µm).

duty cycle during the lifetime of the Terra mission. Scheduled targets are determined for each orbit from a priority function, which is calculated by including such variables as time of year, resource allocation, cloud coverage, the size of the data request, the presence of a ground campaign, etc. Small and potentially one-time only targets, known as data acquisition requests (DARs), comprise 25% of the total resource allocation of ASTER [Yamaguchi et al., 1998]. The remaining 75% is divided into the global map collection (50% of resource time) and the science team acquisition requests (STARs), which account for the remaining 25%. The global map is a primary goal of the data collection, designed to produce a cloud-free map of the entire land surface of the Earth in all spectral bands by the end of the mis-

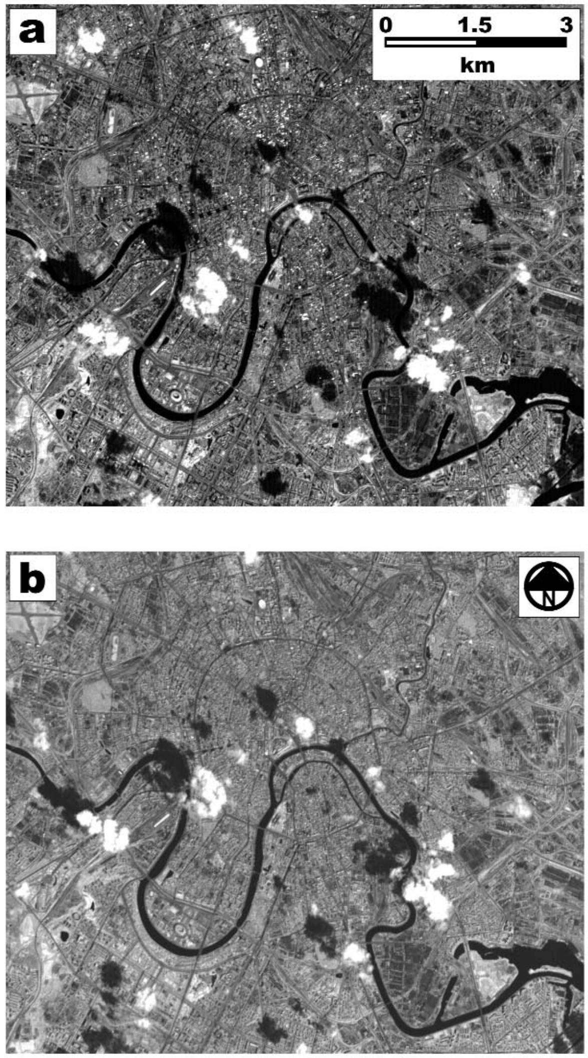

Figure 3. Band #3 (0.76-0.86 µm) ASTER L1A gray-scale images of Moscow, Russia collected on 28 August 2000. (a) Band #3n (nadir-looking telescope). (b) Band #3b (back-looking telescope). Band #3b is acquired with a different viewing geometry (note the cloud positions in each image with respect to their shadows). Images pairs such as this provide the ability to generate along-track digital elevation models (DEMs).

sion. The STARs, on the other hand, are dedicated to large global science objectives that demand larger resources from the instrument than DARs. There are numerous STAR objectives, including for example volcano observations, coral reef mapping, deforestation observations, the Global Land Ice Measurements from

Space (GLIMS) project [Raup et al., 2000, Wessels et al., 2000], the Arid Lands Monitoring project [Ramsey and Lancaster, 1999], as well as the UEM program described here [Ramsey, et al., 1999; Stefanov et al., 2000a]. The capability of ASTER to perform repeated global inventories of land-cover and land-use change from space make it ideal for assessing urban growth and change [Abrams, 2000; Ramsey et al., 1999]. The underlying philosophy of this strategy is to understand the consequences of human-induced change for continued provision of ecological goods and services. The planning, design and logistics for the UEM globally distributed data collection program are described below.

METHODOLOGY

UEM Planning

One of the core STARs of ASTER is the Urban Environmental Monitoring (UEM) program. The UEM project was conceived as means to capture data over the world's largest urban metropolitan areas (Figure 4). The emphasis is on those cities experiencing fast growth, facing potential environmental threats, and those concentrated in semi-arid environments (Figure 5). The data collection effort demands ded-

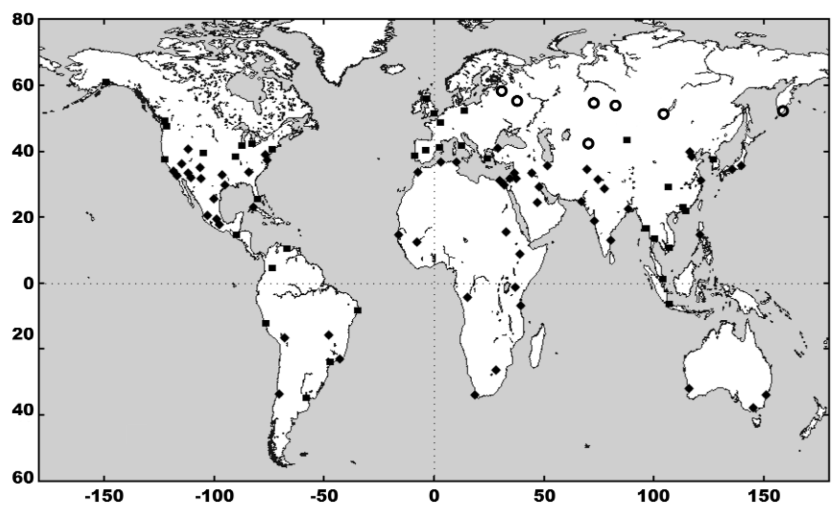

Figure 4. Urban targets of the UEM Science Team Acquisition Request (STAR). This project is divided in to high (solid diamonds) and low (solid squares) priority targets on the basis of specific criteria (see text). High priority targets comprise approximately two-thirds of the data request and are being monitored twice per year during the lifetime of the mission. The remaining low priority targets will imaged at least twice during the mission. The open circles denote the former Soviet Union (FSU) cities included as part of separate "spin-off" monitoring objective. See Table 3 for city names and exact locations.

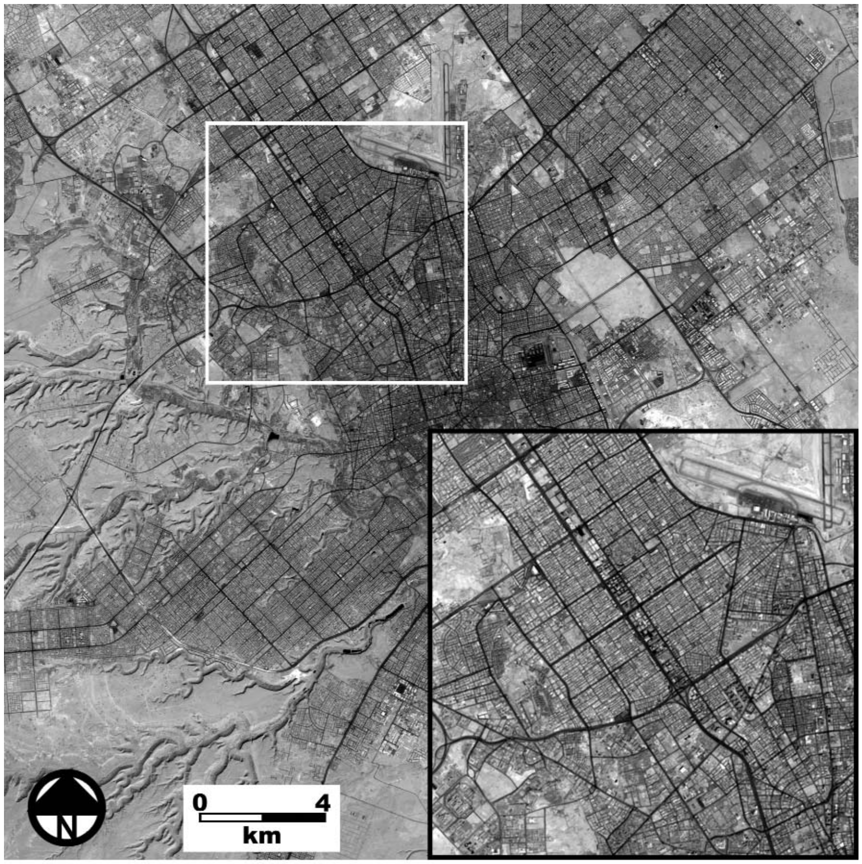

Figure 5. ASTER band #3n (0.76-0.86 µm) image of Riyadh, Saudi Arabia acquired on 23 November 2001 (07:46:23 UT). This scene has been processed to level 1B (L1B) with radiometric and geometric corrections applied. The imagery has a linear 2% stretch that highlights vegetation in white, desert soils in white to gray, and urban regions darker gray. The inset is displayed at full ASTER resolution and covers the central core of the city (denoted by the white rectangle).

icated processing and dissemination to local government officials and scientists. The primary goal of the UEM program is to ensure these data are acquired, processed and made available. The planned products are calibrated and geometrically accurate land use change, material identification, and heat island maps. As mentioned, these products form an integral part of the ecological modeling ongoing at locations such as the urban Long-Term Ecological Research (LTER) sites. In addition, these data form the geospatial context for studies that are examining urban hazard mitigation such as the detection of fire scars and their relationship to localized flooding, slope analyses and the spawning of landslides in connection to development, and soil identification pertaining to industrial “brown field” sites.

The Urban Environmental Monitoring STAR was originally conceived by P. Christensen as an extension of remote sensing pilot studies over portions of the Phoenix metropolitan area from 1992-1995 [P. Christensen, pers. comm., 1995]. The program as originally proposed consisted of 86 urban targets chosen somewhat arbitrarily, but based mainly on their location within semi-arid climates. Because all STAR proposals submitted prior to launch of the Terra spacecraft were reviewed and approved by the ASTER science team, feedback was provided on the UEM project, target selection, and science objectives. This process along with a nearly two-year delay in the launch of Terra resulted in significant revision and expansion of the urban monitoring program [Ramsey et al., 1999; Stefanov et al., 2001a]. The UEM project goals were expanded to include:

1. the infrastructure planning to ensure that all ASTER UEM targets are collected, processed and archived.
2. the production of certain derived data products including, but not limited to: calibrated surface reflectivity/emissivity; land use classification/change; surface heat flux maps.
3. the establishment of local contacts in regions/cities willing to work with the ASTER urban products and serve as points of contact for local research projects.
4. the dissemination of information and data to those contacts upon image acquisition.

Because of the enormous scale of this program, it was originally designed as a collaborative effort, as are most of the ASTER STAR projects. By including investigators worldwide, it is guaranteed that the data are disseminated and used for local science investigations. It also provides a point of contact to the ASTER team, and allows for future feedback, for example to add/delete entries in the database, and make changes to existing data collection parameters. During the launch delay, new collaborators were brought onto the project, the UEM parameters were finalized, and the list of cities was expanded to 100 targets (Table 3) using the following metrics:

1. a current metropolitan population near or in excess of one million people.
2. a predicted rapid growth in the next decade.
3. current or future environmental issues resulting from growth and/or land-use practices.
4. current or future geo-hazard potential due to location, environment and/or population.
5. a roughly even geographical distribution around the world thereby limiting the potential of focusing too heavily on one country/region.

TABLE 3. Global UEM Target List Showing The High And Low Priority Targets

City	Country	UEM Priority
Addis Ababa	Ethiopia	High
Albuquerque	United States	High
Alexandria	Egypt	High
Algiers	Algeria	High
Anchorage	United States	Low
Amman	Jordon	High
Athens	Greece	Low
Atlanta	United States	High
Baghdad	Iraq	High
Baltimore	United States	High
Bangkok	Thailand	Low
Bamako	Mali	High
Barcelona	Spain	Low
Beijing	China	High
Berlin	Germany	Low
Bogota	Colombia	Low
Bombay	India	High
Brasilla	Brazil	High
Buenos Aires	Argentina	Low
Cairo	Egypt	High
Calcutta	India	High
Cape Town	South Africa	High
Caracas	Venezuela	Low
Casablanca	Morocco	High
Chicago	United States	Low
Chongqing	China	Low
Dakar	Senegal	High
Dallas	United States	High
Damascus	Syria	High
Delhi	India	High
Denver	United States	Low
Der Es Salaam	Tanzania	High
Detroit	United States	Low
Edinburgh	Scotland	Low
El Paso	United States	High
Guadalajara	Mexico	High
Guangzhou	China	Low
Guatemala City	Guatemala	Low
Havana	Cuba	High
Ho Chi Minh City	Vietnam	Low
Houston	United States	High
Istanbul	Turkey	High
Jakarta	Indonesia	Low
Johannesburg	South Africa	High
Kabul	Afghanistan	High
Karachi	Pakistan	High
Khartoum	Sudan	High
Kinshasa	Zaire	High
Kuwait City	Kuwait	High
La Paz	Bolivia	High

TABLE 3. Global UEM Target List Showing The High And Low Priority Targets (Continued)

City	Country	UEM Priority
Lahore	Pakistan	High
Las Vegas	United States	High
Lima	Peru	Low
Lisbon	Portugal	Low
London	England	Low
Los Angeles	United States	High
Madras	India	High
Madrid	Spain	Low
Manila	Philippines	High
Melbourne	Australia	High
Mexico City	Mexico	High
Miami	United States	Low
Monterrey	Mexico	High
Moscow	Russia	Low
Nairobi	Kenya	High
New York	United States	Low
Novosibirsk	Russia	Low
Osaka	Japan	High
Paris	France	Low
Perth	Australia	High
Phoenix	United States	High
Puebla	Mexico	High
Rangoon	Myanmar	Low
Recife	Brazil	Low
Rio De Janeiro	Brazil	High
Riyadh	Saudi Arabia	High
Rome	Italy	Low
Salt Lake City	United States	High
San Francisco	United States	Low
San Diego	United States	High
San Paulo	Brazil	Low
Santiago	Chile	High
Seattle	United States	Low
Seoul	South Korea	Low
Shanghai	China	High
Singapore	Malaysia	Low
St. Louis	United States	Low
St. Petersburg	Russia	Low
Sydney	Australia	High
Tashkent	Uzbekistan	High
Tehran	Iran	High
Tel Aviv	Israel	High
Tianjin	China	High
Tokyo	Japan	High
Tucson	United States	High
Tunis	Tunisia	High
Urumqui	China	Low
Vancouver	Canada	Low
Washington D.C.	United States	High
Xianggang	China	Low

The first two criteria in the above list were moderated by the remaining three. In other words, targets were not strictly chosen on the basis of overall population because a vast majority would be concentrated in China and India. Similarly, targets were no longer chosen simply because they were located in arid to semi-arid climates, even though it is clear that most of the fastest-growing urban centers are located in such environments. It was determined that some percentage of the target list would be modified to include: cities with declining or zero-growth populations (to serve as controls and examine land-cover issues unique to such cities), and more widely varying building materials and growth patterns (Tables 3, 4).

In order to conserve instrument resources, the ASTER science team placed further constraints on the individual DAR targets within a STAR request and the total area of each STAR. The new allotment of 400,000 km^2 per STAR included the total cumulative data collection are over the lifetime of the mission. This constraint in particular produced a limitation on data volume that would have made it impossible to meet the twice-yearly objective for each of the 100 cities. A solution to this limitation was derived by dividing the database in to high and low pri-

TABLE 4. United States Census 2000 Data For The US Metropolitan Regions That Are Part Of The UEM Acquisition Plan [a]

City Name	Size Ranking [b]	Urban Core	Metro Area
Albuquerque	62	420,578	678,820
Anchorage	138	257,808	257,808
Atlanta	11	401,726	3,857,097
Baltimore	4	632,681	7,359,044
Chicago	3	2,799,050	8,885,919
Dallas	9	1,076,214	4,909,523
Denver	19	499,775	2,417,908
Detroit	8	965,084	5,469,312
El Paso	60	612,770	701,908
Houston	10	1,845,967	4,493,741
Las Vegas	33	418,658	1,381,086
Los Angeles	2	3,633,591	16,036,587
Miami	12	369,253	3,711,102
New York	1	7,428,162	20,196,649
Phoenix	14	1,211,466	3,013,696
Pittsburgh	20	336,882	2,331,336
Salt Lake City	35	171,151	1,275,076
San Diego	17	1,238,974	2,820,844
San Francisco	5	746,777	6,873,645
Seattle	13	537,150	3,465,760
St. Louis	18	333,960	2,569,029
Tucson	57	466,591	803,618
Washington DC	4	519,000	7,359,044

[a] Census 2000 website.

[b] Rankings are out of the top 276 metropolitan regions in the United States.

ority targets. The high priority cities (~ 65% of the database) satisfy all the original UEM objectives, whereas the low priority cities have a limited coverage of only two observations over the lifetime of ASTER (Table 3).

Study Areas, Algorithm Testing & Development

The governing principle of the UEM program is that remote sensing and image processing techniques developed in other branches of the geosciences can be applied to urban regions in order to provide answers to problems facing their local populations. This foundation was formed during a series of NASA-sponsored pilot project from 1992-1995 in conjunction with the City of Scottsdale, AZ. As conceived, the project goal was to study the applicability of VNIR and TIR airborne data for the purposes of urban scene classification, environmental assessment, and change detection. These projects resulted in the collection of a large volume of data from numerous sources including space-based: Landsat Thematic Mapper (TM) and Shuttle Imaging Radar (SIR-C), as well as airborne: Thermal Infrared Multispectral Scanner (TIMS), airborne TM simulator (NS001) and color VNIR aerial photography. These data sets have been integrated into state and local activities to improve decision-making and planning. For example, the derived data products have been used in surface impermeability studies for storm runoff assessments; development versus preservation surrounding local mountain parks; soil identification to better understand hill slope processes [Stefanov et al., 1998], and brush fire hazards [Ramsey and Arrowsmith, 2001; Misner et al. 2002].

The urban landscape within the Phoenix metropolitan area provides a unique test and excellent ground truth for the validation of surface classification models [Harris and Ventura, 1995; Quattrochi and Ridd, 1998; Stefanov et al., 2001b]. Examination of multi-temporal scenes and identification of land-use patterns clearly show the "urban sprawl" commonly associated with large western US cities [Haack et al., 1987]. An example of this growth pattern monitoring of Phoenix, AZ is shown in Figure 1. Where available, instruments with multi-spectral TIR wavelength bands provide the means to produce very accurate temperature maps from which to study the spatial distribution of heat islands (Plate 1). These data are critical inputs into micro and regional climate models that attempt to predict variations over time with changing land use and urban growth [Stoll and Brazel, 1992; Hafner and Kidder, 1999].

Coinciding with the end of the pilot projects, the LTER program began and provided further resources for the expansion of the remote sensing analysis to the entire metropolitan area. This expansion included the acquisition of historic Landsat Multispectral Scanner (MSS) and TM data (for more complete temporal coverage), the Advanced Very High Resolution Radiometer (AVHRR) data (to examine the effects lower spatial scale), and the acquisition of new NASA data sets including the airborne ASTER simulator (MASTER) in 1999 and 2000.

Phoenix, AZ was chosen as the prime calibration target for the remaining 99 cities within the larger UEM project, because of the presence of the LTER, the man-years already invested, the ease of access to field calibration sites, and the unique growth issues facing the region. Studies are ongoing to monitor urban growth, land use change, impacts on the surrounding environment, and the development of urban heat islands (Figure 1, Plate 1).

As mentioned, a fundamental data set required to monitor these growth patterns and as input into the LTER ecosystem analyses is accurate land use/land cover change. This derived product consists of the major types of land cover and their areal percentages present in the study area. Land cover refers to the physical nature of the surficial materials present in a given area, whereas land use refers to the specific type and pattern of human development [Anderson et al., 1976; Sabins, 1997]. Collection of these data in a large urban environment is obviously very time-consuming and in some cases impossible. A more efficient approach is to use remotely sensed data with field verification to classify land cover types [Anderson et al., 1976; Hixson et al., 1980, Ridd, 1995]. Once the land cover classification is obtained it can be used as an input into a variety of ecological models, and land cover maps can be constructed to aid in planning field-sampling strategy. The land cover types can also be linked to different land use categories to investigate temporal and spatial changes in the urban ecosystem [Stefanov et al., 2001b; Zhu and Blumberg, 2002].

On a global scale, such a data analysis effort can only be accomplished with extensive testing and technique development. However, commonly used remote sensing and image processing approaches suffer from slow analyses techniques that would be impossible at the scale of the UEM project. The need exists for a robust method of identification and classification of the most common land cover types. In order to accomplish this task, an expert system approach to land cover/land use classification has been developed using TM data of Phoenix, AZ. This methodology, fully explained by Stefanov et al. [2001b], relies on well-calibrated data, the derivation of urban texture mapping, and the input of other land use data sets in a GIS hierarchical modeling approach to improve standard supervised classification results. Significant to the results of this study is the increased accuracy over other similar studies achieved with relatively poor resolution data (30m of Landsat TM). The authors were able to produce classifications with an overall accuracy of 85% and maintain twelve distinct land cover/land use classes. A large percentage of the data input into the classification model was derived directly from the data themselves (calibrated reflectance, vegetation indices, urban texture). Clearly, the need for extraneous GIS-based land cover data sets is a limiting factor for many remote cities of the world. However, testing of the model for other cities is now underway using ASTER data. It is being shown that even without the inclusion of non-image derived data sources, accuracy remains high due to the increased spatial and spectral resolution of the ASTER sensor [Stefanov, 2002; Zhu and Blumberg, 2002].

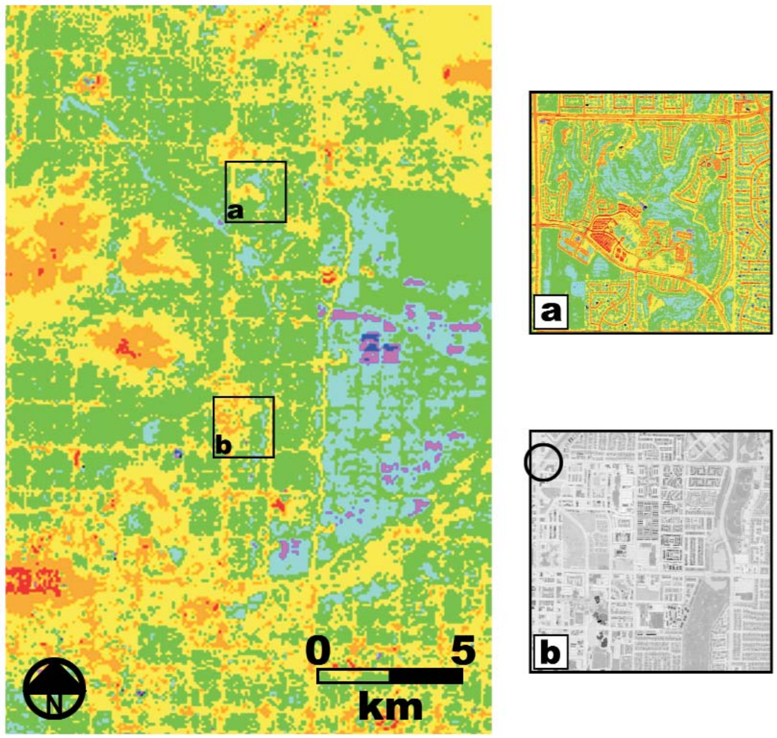

Plate 1. Ground surface brightness temperature images derived from both high spatial resolution airborne data as well as ASTER. The 90m/pixel spatial resolution ASTER TIR night time image (shown on the left) covers a large portion of the eastern Phoenix, AZ Valley. The data were acquired on 7 May 2001 and calibrated to a standard L2 product (atmospherically-corrected ground-leaving radiance). Brightness temperature was derived from the L2 product using an emissivity normalization approach and a maximum emissivity of 0.985. The color scale applied is as follows: 27-30°C (red), 24-27°C (orange), 24-27°C (yellow), 21-24°C (green), 18-21°C (cyan), 15-18°C (magenta), 12-15°C (blue), and < 12°C (black). Non-urbanized land use regions (Salt River Indian Reservation to the north and agricultural fields to the south) show a significantly cooler temperatures compared to the urbanized regions. Insets (a) and (b), denoted by the boxes, show regions covered by 4m/pixel Thermal Infrared Multispectral Scanner (TIMS) airborne data on 14 July 1995 at 02:45 LT. High resolution data such as these are used for calibration of the ASTER TIR products. (a) This region is dominated by commercial/industrial land use, and temperatures vary from 3-40°C, with cooler temperatures shown in darker gray (i.e., the Indian Bend Wash green way and the Central Arizona Project Canal). Note the 5°C cooling of Camelback and Scottsdale Roads as they pass over the canal (circled). (b) Color density slice of another portion of the same TIMS data set showing mesic and xeric residential land use. The cooler overall core of this block is caused by the presence of a golf course. Color scale: 36-40°C (red), 33-36°C (orange), 30-33°C (yellow), 27-30°C (green), 24-27°C (cyan), 21-24°C (magenta), 18-21°C (blue), and < 18°C (black).

This approach is continuing to be refined and updated as it is applied to new ASTER data (Plate 2). In order to produce meaningful land cover maps of all the UEM cities, the classification approach must be tested on numerous cities, which have been constructed in, and are subject to, a variety of conditions different than those of experienced at Phoenix. These include, but are not limited to, local/regional climate, development density, use of native building materials, different urban classes, and transportation patterns. Similar reasoning was the impetus for the selection of two fundamentally different LTER cities (Phoenix, AZ and Baltimore, MD).

Because of the author's relocation to Pittsburgh, PA from Phoenix, AZ, the former has also been selected as a UEM calibration target site and added to the UEM target database. The city of Pittsburgh differs from Phoenix, AZ in many ways and is represented by a declining population, urban decay/infill, denser development, and the presence of a higher percentage of surface water and vegetation. It is also the site of the some of the largest urban renewal projects in the United States producing significant land cover change in a short time period with the construction/demolition of sports stadiums, the growth of river-front retail zones at the sites of former steel mills, and the construction of new highways. Larger proposed projects include major redevelopment of the downtown and north shore of the Ohio River, and a high speed magnetic-levitation (maglev) train connecting the airport to the west and constructed through the urban core. The city therefore has the potential of being a unique test site combining the complications dense urban change in a region with less than ideal weather for remote sensing studies.

The first cloud-free ASTER scene of Pittsburgh, PA was acquired on November 24, 2000 (16:35:04 UT) and since then nine other scenes have been acquired, including a cloud-free summer scene on August 19, 2002 (16:17:23 UT) shown in Plate 2. The data reveal a higher density urban environment with large rivers, and dominated at this time of year by the presence of large amounts actively photosynthesizing vegetation (tree canopy). In contrast to semi-arid cities such as Phoenix, urban land cover in cities like Pittsburgh will change markedly during other seasons with the appearance of snow cover and loss of tree canopies (Plate 2). Such change will clearly impact the classification of natural land cover types, but also has the benefit of revealing more of the urban classes previously masked by vegetation. Application of a modified version of the land cover classification model has been performed on the data. Qualitative estimates of this preliminary analysis show very good agreement to current land cover in the region. More quantitative estimates of the model accuracy are expected to include the amount of change detected from the winter to summer seasons. Modifications in the urban classification model developed at the Phoenix site will be implemented and tested at the other non-desert UEM cities in addition.

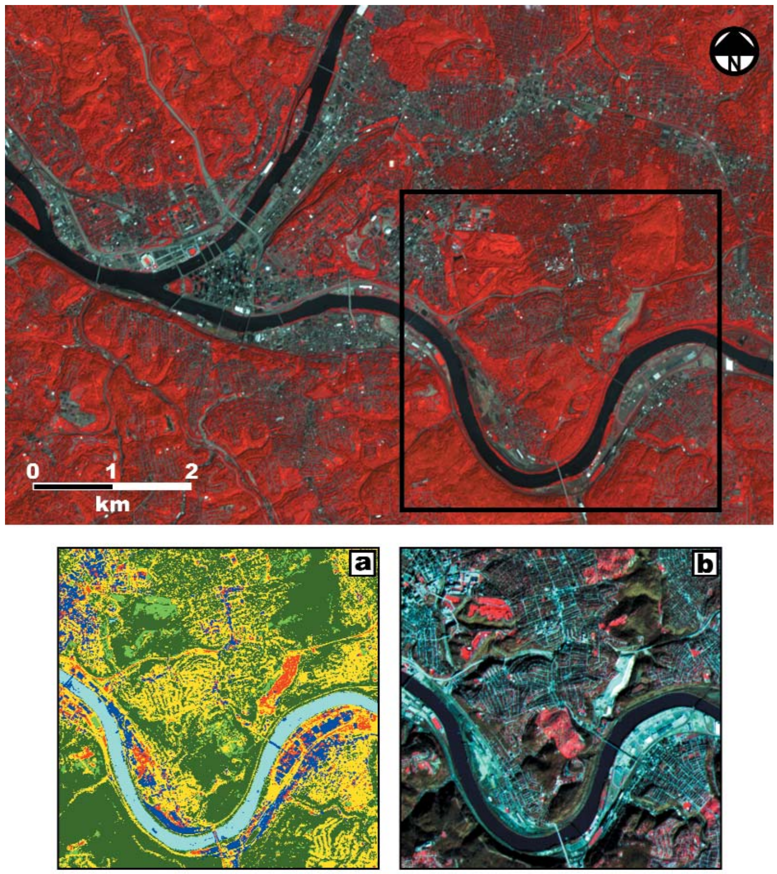

Plate 2. Subset of an ASTER L1B scene of Pittsburgh, PA and surrounding regions acquired on 19 August 2002 (16:17:23 UT). Growth rates, construction materials and patterns, vegetation, and environmental issues in industrial cities of the northern US such as Pittsburgh are dramatically different than those in high growth cities such as Phoenix, AZ. The visible/near infrared (VNIR) color composite (bands 3n, 2, 1 in red, green, blue, respectively) shows vegetation in red and clearly denotes the urban regions in blue-green, with the black box indicating the areas covered by the insets below. (a) Supervised classification of the VNIR and SWIR data highlighting the dominant land use classes: tree canopy (dark green), grass (light green), commercial/industrial (blue) residential (yellow), disturbed surfaces (red) and water (cyan). The large commercial/industrial regions along the river were both sites of former steel mills that have been demolished and replaced by retail and office complexes in the past decade. (b) Difference in the land cover appearance in the winter months (24 November 2000, 16:35:04 UT). Classification results such as these are being compared to similar products derived for other cities in the UEM program.

DISCUSSION

The UEM program has already served as a catalyst for a variety of "spin-off" projects that either use currently available UEM data or seek to expand the list of cities to include new areas. One example of this process is the data analyses ongoing in Pittsburgh, PA and the inclusion of it into the UEM database. Other active projects include the monitoring of the cities of the former Soviet Union (FSU), the study of brush fire and flooding hazards at the urban-wilderness interface, and the impact of rapid urban sprawl on the vulnerability of people living in the mega-city of São Paulo, Brazil.

UEM "Spin-off" Projects

Former Soviet Union cities For a decade, the region that included the former Soviet Union and the states of Central and Eastern Europe has been undergoing fundamental and, at times, tumultuous change. Societies are being transformed, and economic and political systems are being rebuilt under a variety of models and conditions. With the current fiscal condition of Russia and the other FSU countries, both ecological and environmental problems within the urban population centers are commonly overlooked. ASTER data are important in addressing these problems because of the reasons mentioned previously. The principal goals of this particular study are to develop urban scene classifications, environmental assessments and begin a program of change detection of these major urban centers.

In order to accomplish that task, a DAR was submitted to the ASTER science team that augmented the current UEM STAR, which already contained the Russian urban centers of St. Petersburg, Novosibirsk and Moscow (Figure 3). As part of the new request, these cities were increased to high priority (collection of scenes twice/year) and four new urban centers were added (Tashkent in Uzbekistan, and Omsk, Irkutsk, and Petropavlovsk in Russia). Scientific collaborations have already been established with government and academic institutes in England and Moscow. Plans are also underway for field visits and verification of the ASTER data in these cities. This program also has the potential of being both a scientific and political outreach tool over the next several years.

Urban brush fire research The summers of 2000 and 2002 were the worst fire seasons in the past 50 years for the western United States. As of early September, 2000 over 6.5 million acres were burned and the cost of fighting the fires is exceeded $1 billion US dollars. Much of the damage was concentrated in the remote, high elevation pine forests of the western states. However, a large percentage of the Los Alamos, NM fire in May, 2000 and the Rodeo-Chediski fire in July, 2002 attest to hazards of desert brush fires. Where these fires impinge on rural and urban fringe development, the potential cost to lives and property becomes considerable. Further, these burned regions have the potential to facilitate flash flooding and soil erosion during the monsoon rainy seasons over the next few years [Ramsey and Arrowsmith, 2001]. As people expand into these environments and their exposure to hazards increases, the ability to predict and control fires becomes increasingly important. Remote sensing together with detailed field data has been used to characterize areas scarred by past fires with the goal of assessing the risk for burning in the future [Misner et al., 2002].

Remote sensing of the urban environment and surrounding region of several southwestern US cities has revealed the presence of old brush fire scars dating back 30-50 years. Depending on the wavelength region examined, the age and surface properties of the scars can be determined. A NASA-sponsored research study now underway in Phoenix, AZ and Los Angeles, CA, is examining the linkage between the fire scar age, vegetation type/recovery, soil type, and local topography, using data from the Landsat ETM, SIR-C radar, and airborne MASTER [Ramsey and Arrowsmith, 2001; Misner et al., 2002]. Once burned, it is hypothesized that the removal of vegetation may facilitate rapid flood run-off and erosion during intense periods of precipitation. By examining the spatial variability of numerous scars in one location, and given the potential to evaluate their relative ages automatically, it should be possible to establish fire recurrence intervals around any urban area. This can be compared with lightning frequency, climate, vegetation, and terrain characteristics to vastly improve the characterization of hazards associated with semi-arid environment brush fires.

Urban sprawl and vulnerability in São Paulo, Brazil The urban core of São Paulo has experienced some of the fastest growth of any city in the world over the past 75 years. It has expanding from a modest-size agriculturally dominated urban center to become a mega-city with a population in excess of 20 million people. This extreme growth coupled with poor to non-existent laws and enforcement of land-use has produced chaotic urban sprawl conditions that impact on the physical and economic vulnerability of the city's inhabitants. The settlement patterns are a result of direct and indirect public policies that drive populations from the more densely populated urban cores to the less densely settled periphery. Sprawl is a complex socio-economic process and policies to address sprawl are even more complicated and controversial.

The dominant concern about rapid urban growth that results in sprawl is a function of economic costs versus quality of life. It is also more or less of a concern depending on the country in which the urban sprawl is occurring. Prosperous nations have the technology, resources and interest to limit, or at the very least, debate the issue of sprawl. However, the quality of life of people in every large and rapidly expanding city around the world is impacted by this problem. Left unchecked, ecological assets and their services, such as water storage values of forested hillsides or the landscape value of natural hilltops, are either unrecognized or unwittingly sacrificed [Balmford et al., 2002].

The application of ASTER data to the growth issues faced by people of São Paulo and surrounding regions is intended to develop and implement a method for predicting what the economic, quality of life and ecological costs of sprawl processes will be. These predicted costs can be contrasted to alternative development patterns designed to be more conscious of these costs. For example, these data are being used to perform an urban risk analysis, a hydrological/geological assessment of the region, and urban change detection. Included are "point hazards" such as landslides, ground collapse and fire, as well as "distributed hazards" such as flooding, waterway pollution/health, and severe weather impacts. This collaborative project with three universities in the São Paulo region was initiated in the summer of 2002 and discussions and data analyses are in their initial stages.

ASTER data structure and sources

The ASTER science team has developed and tested numerous software packages designed to derive higher-level data products from the calibrated ASTER radiance [Yamaguchi et al., 1998; Abrams, 2000]. The complete description of these products can be found at the ASTER web site [http://asterweb.jpl.nasa.gov/] or within the Algorithm Theoretical Basis Documents (ATBD) located at the Earth Observing System web site [http://eospso.gsfc.nasa.gov/eos_homepage/for_scientists/publications.php]. The products derived from radiance at sensor (Level 1A) or calibrated radiance at sensor (Level 1B) data have the designation of level 2 and include surface emissivity, kinetic temperature, reflectance, DEMs, and several others. Any data that ASTER has acquired are available at the Earth Observing System Data Gateway (EDG) site [http://edcimswww.cr.usgs.gov/pub/imswelcome/], which is coordinated by the USGS land processes Distributed Active Archive Center (DAAC) in Sioux Falls, SD. These data sets (including the UEM targets) will continue to be archived at the DAAC and available at the aforementioned web site. However, a limited number of Level 1A and 1B scenes (mostly those of high priority calibration cities) and all the derived urban data products (such as land cover classifications) for the UEM targets will be available at the project web site [http://elwood.la.asu.edu/grsl/UEM/cities/]. Groups at both the University of Pittsburgh and Arizona State University are monitoring the progress of the UEM collection, examining the data, and refining classification algorithms for the targets already acquired.

ASTER data has began to arrive in earnest as of early 2001. As an example, during the first ten months of data collection (May, 2000 - February, 2001) over 65,000 scenes were processed and made available. Even more amazing is the fact that during most of those ten months, ASTER was engaged in minimal data collection as it underwent calibration and validation tests. Only a small fraction of those scenes comprised urban-focused data. However, since ASTER has been returning data there now exist approximately 650 city scenes in the UEM database. Managing the large volumes of images and meta-data is a challenge where dealing with a globally distributed, multi-temporal program like the UEM. Research groups that are leading such programs must be ready to ingest, process, and disseminate global data sets. Automated routines to produce for example land cover/land use maps are critical. However, the outcome of such an effort provides a valuable resource for urban science as a historical record and as near real-time hazard monitoring tool.

CONCLUSIONS

The primary application of remote sensing data to examine urban regions is to provide a synoptic means for extrapolating local detailed measurements to a regional context. Specifically, multi-spectral image classification can be used to identify land cover types, such as different grasses, crops, trees, soils, man-made materials, water, and native vegetation. Where used with field validation, these data provide accurate identification and estimates of the areal distribution of these different units [Martin, 1988; Treitz, 1992; Stefanov et al., 2001a,b]. These data can then be used to create regional land use thematic maps that depict different processes. For example, urban versus native materials, permeable versus impermeable surfaces, and transportation systems (asphalt and concrete materials) can all be mapped. Over time, the monitoring of surface units allows for the detection of change. Temporal analysis of Landsat TM data has proven critical in identifying ecosystem loss, monitoring growth-related issues, and as input into governmental policy.

During the early stages of the ASTER mission, fine-tuning occurred on the UEM database and the process is still ongoing. In addition, work continues on such items as the dissemination of data sets to the investigators in near-real time, ensuring they have the tools to analyze those data, creating a rapid search tool by way of the world wide web, and continuing to test and refine land cover mapping algorithms. However, it is expected that these issues will not present any major obstacles to the overall success of the program. The field of urban remote sensing is ever expanding and many of the tools used by remote sensing geologists, ecologists and social scientists are directly applicable to these types of analyses. The ASTER UEM project provides important new data for many cities around the world, and the future of the project depends on the availability of calibrated ASTER data and the continued collaboration with investigators worldwide.

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