A WHITE PAPER

GLOBAL INFRASTRUCTURE: THE POTENTIAL OF SRTM DATA TO BREAK NEW GROUND

Son Nghiem[1], Deborah Balk[2], Christopher Small[4], Uwe Deichmann[3], Antoinette Wannebo[2], Ronald Blom[1], Paul Sutton[5], Gregory Yetman[2], Robert Chen[2], Ernesto Rodriguez[1], Bijan Houshmand[1], and Greg Neumann[1]

[1]NASA/Jet Propulsion Laboratory, California Institute of Technology
[2]Center for International Earth Science Information Network, Columbia University
[3]The World Bank
[4]Lamont Doherty Earth Observatory of Columbia University
[5]University of Denver

28 NOVEMBER 2001

This paper evolved out of a Global Infrastructure Mapping workshop organized by CIESIN of the Columbia Earth Institute and by NASA/JPL of the California Institute of Technology, held at Columbia University, New York, on 4-5 October 2000. The research by the Jet Propulsion Laboratory, California Institute of Technology, was carried out under a contract with the National Aeronautics and Space Administration. Partial funding for the workshop was provided by the NASA Socioeconomic Data and Applications Center (SEDAC) under contract NAS5-98162 to Columbia University.

GLOBAL INFRASTRUCTURE: THE POTENTIAL OF SRTM DATA TO BREAK NEW GROUND

1. OBJECTIVE

There is general agreement across the social and physical scientific communities that there is an unmet need for a high-resolution, database indicating global infrastructure. It has not been possible to construct such a data set from long-time existing sources.

The Shuttle Radar Topography Mission (SRTM) data set presents a unique opportunity to obtain a global, cloud-transparent instantaneous snapshot of imagery from urban and suburban regions, together with collocated topographic information, which can be used to characterize building types, land use, and other key population variables. The SRTM data set in synergy with other global remote sensing data sets, such as Landsat 7, ASTER and DMSP-OLS nighttime imagery, can be used to derive a number of major (but not ALL) parameters constituting a significant part of the global infrastructure data set consistently at the time period during which the SRTM data set was collected (February 2000). The long-term goal is to create a database of global infrastructure which is useful for a multitude of physical and social scientific and operational applications. The general definition of infrastructure can be quite wide and includes all man-made structures and/or natural structures that are modified for human use.

The resulting product will ultimately present a unique resource which can be used as a global reference of the state of the world in the year 2000 for future studies of urbanization, infrastructure, population and land use change.

2. RATIONALE

A globally uniform, high-resolution data set is the critical unifying information for so many applications. In this regard, SRTM data set provides a new and unique opportunity to meld diverse space based data sets with human needs such as disaster mitigation, planning, and response. With economic development driving increasing concentration of population areas vulnerable to flood, fire, earthquakes, other natural phenomena, and man-made disasters, it is critical to improve procedures for hazard identification, mitigation, and response. With international response to major disasters becoming common, it is vital to have a uniform data base of infrastructure. Space-based remote sensing data can provide some of this, and can become a basis for national and international cooperation and collaboration.

3. RESOLUTIONS

There are two major classes of satellite sensors: (1) high spatial resolution and low temporal resolution, and (2) low spatial resolution and high temporal resolution. It is difficult and costly to have a sensor with both high spatial and high temporal resolutions.

Since infrastructures are predominantly at meters to hundred of meters, it is required to have a high spatial resolution. It takes time to build new infrastructures or to rebuild infrastructures that are destroyed by natural or man-made disasters, and thus a high temporal resolution is not necessarily required. Thus, the first class of sensor with high spatial resolution and low temporal resolution is appropriate for infrastructure mapping. SARs and narrow swath optical/infrared sensors belong to the first class. The second class of sensors including wide-swath optical sensors, microwave radiometers and scatterometers may provided additional information; however, they are not appropriate as the primary class of sensors for infrastructure mapping. Since the spatial resolution is important, it should be addressed for different parameters, data sets, and applications.

4. Background

4.1. The Shuttle Radar Topography Mission

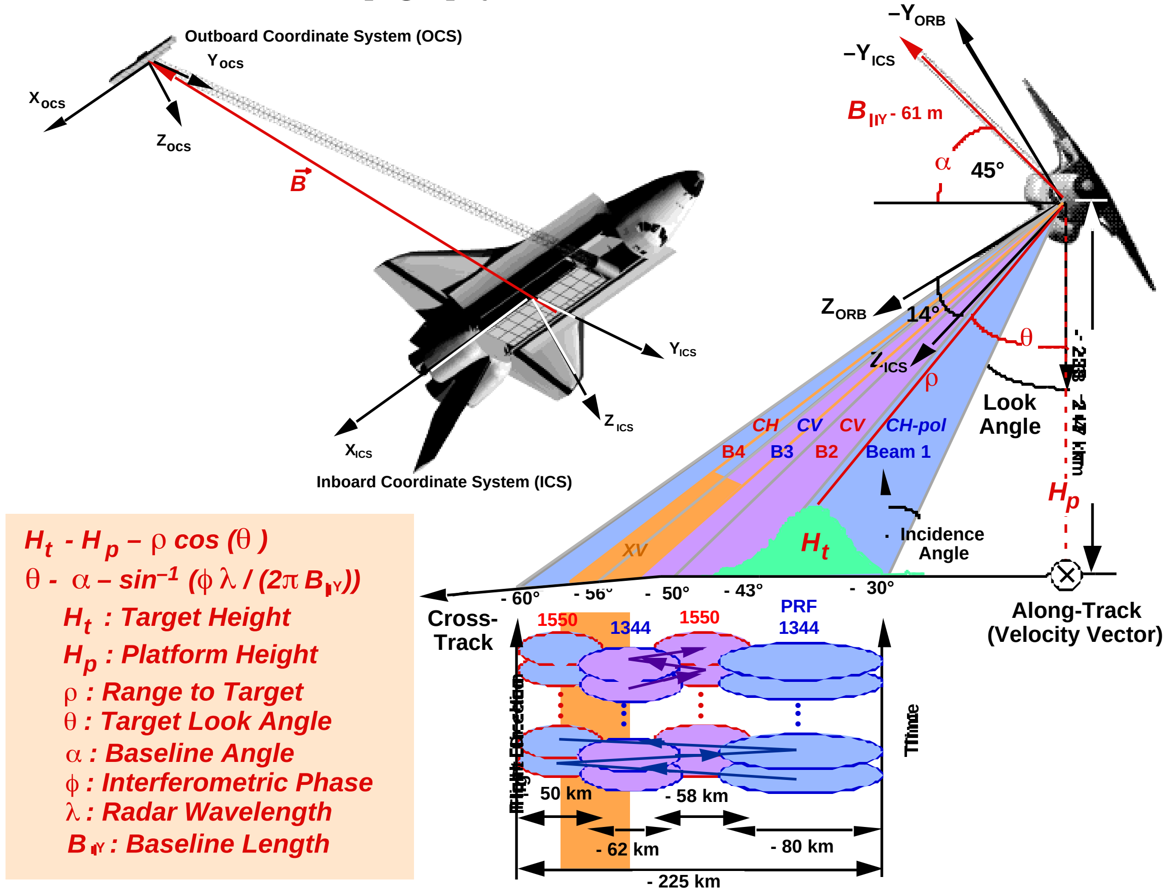

Figure 1.: SRTM system operation geometry

The Shuttle Radar Topography Mission (SRTM) (Jet Propulsion Laboratory, 2002a) aboard the Space Shuttle Endeavour was launched on February 11, 2000 to acquire terrain elevation data. SRTM used the same radar instrument that comprised the Spaceborne Imaging Radar-C/X-Band Synthetic Aperture Radar (SIR-C/X-SAR) that flew twice on the Space Shuttle Endeavour in 1994. SRTM was designed to collect three-dimensional measurements of the Earth's surface. To collect the 3-D data, engineers added a 60-meter-long (200-foot) mast, installed additional C-band and X-band antennas, and improved tracking and navigation devices. The system operation geometry of SRTM is illustrated in Figure 1. The mission is a cooperative project between the National Aeronautics and Space Administration (NASA), the National Imagery and Mapping Agency (NIMA) of the U.S. Department of Defense (DoD), and the German and Italian space agencies. It is managed by NASA's Jet Propulsion Laboratory, Pasadena, CA, for NASA's Earth Science Enterprise, Washington, DC. SRTM successfully completed the interferometric SAR collection. SRTM SAR data covers global land and coastal ocean between 60°S and 60°N with some regions having data coverage more than 4 times as illustrated in Figure 2 (Jet Propulsion Laboratory, 2002a). The data include backscatter at vertical and horizontal polarizations, correlation magnitude, interferometric phase, and derived topography at a nominal resolution of 30 m. Initial results show excellent three dimensional mapping capability of the radar over land covering almost the entire world urban and infrastuctures.

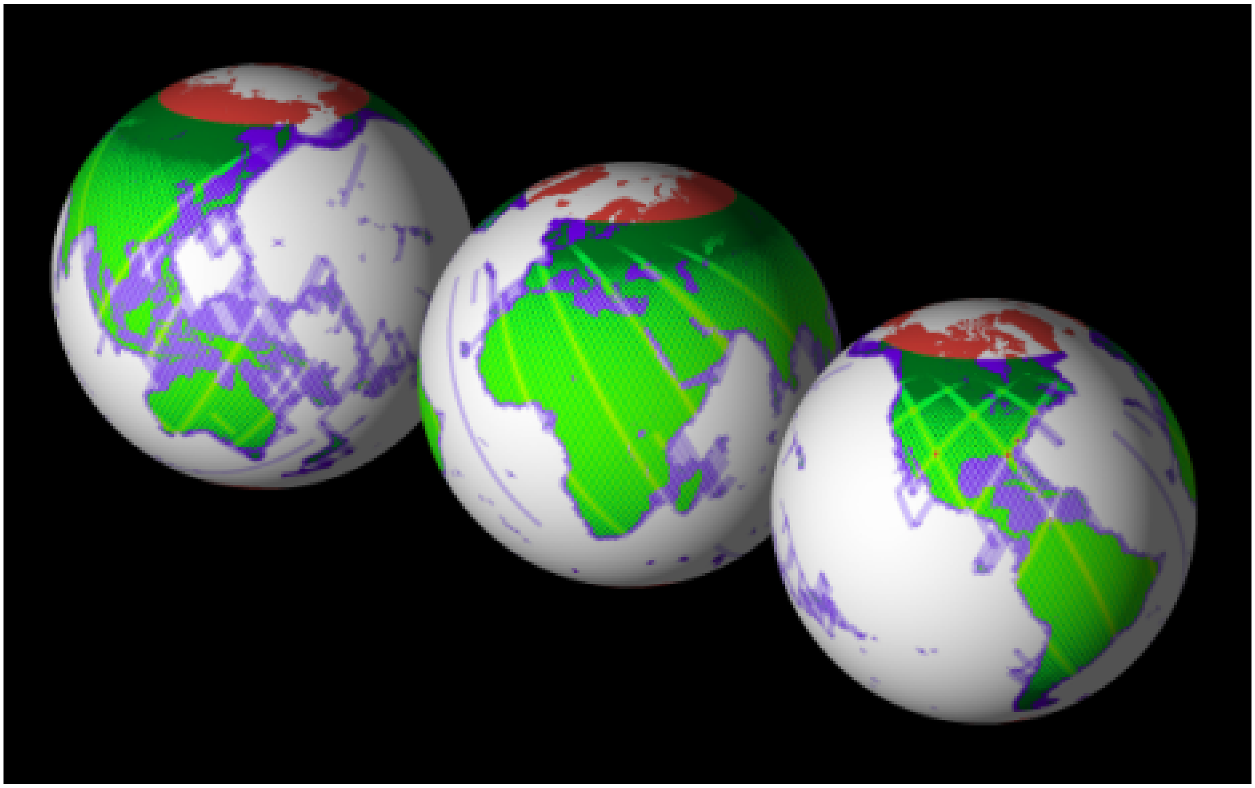

Figure 2: SRTM global coverage map. Times covered : LAND 0 1 2 3 4+ ? WATER 0 1 2 3 4+

As an example, Figure 3 (Jet Propulsion Laboratory, 2002a) shows perspective view of upstate New York shows Lake Ontario in the lower left, the Adirondack Mountains in the upper left, and the Catskill Mountains on the right. This image was generated using topographic data from SRTM and an enhanced true-color Landsat 5 satellite image. Topographic shading in the image was enhanced with false shading derived from the elevation model. Topographic expression is exaggerated 6 times. Fall foliage appears in a variety of colors, as expected for the mid-October Landsat data used here. Redder vegetation generally occurs at higher elevations and toward the north (left), especially in the Adirondack Mountains. The back edge of the data set forms a false skyline. Oneida Lake is just below the scene center. From the lake, Syracuse is toward the lower right, Rome is toward the upper left, and Utica is directly upward from the lake. Oswego is on the shore of Lake Ontario at the bottom edge of the image. All four cities appear whitish. The other whitish areas toward the north (left) are thin clouds in the satellite image. At Herkimer, just beyond Utica, the Mohawk River exits the Adirondacks and flows eastward into rugged terrain and onward toward Albany. Upon close inspection at full resolution, one can see the Erie Canal (dark blue line) running east from Oneida Lake to connect to the Mohawk River. Other parts of the canal connect to the Oswego River running north (left) to Lake Ontario, to Onandaga Lake next to Syracuse, and Cayuga Lake in the lower right corner of the image (just the edge of the lake). Parts of Owasco, Skaneateles, and Otisco Lakes are visible in the lower right (bottom to top). These are some of the Finger Lakes of central New York, with their narrow valleys (Otisco Lake is almost completely hidden by its valley walls). At the full image resolution, a thin white line marks the New York State Thruway from the bottom to the top of the image, passing north (left) of the Onandaga Lake next to Syracuse and through Utica and Herkimer. The valley between the Adirondacks to the left (north) and the Catskills to the right guides both the Erie Canal and New York State Thruway on their way to Albany and the Hudson River (both off the edge of the image), illustrating the importance of topography in transportation.

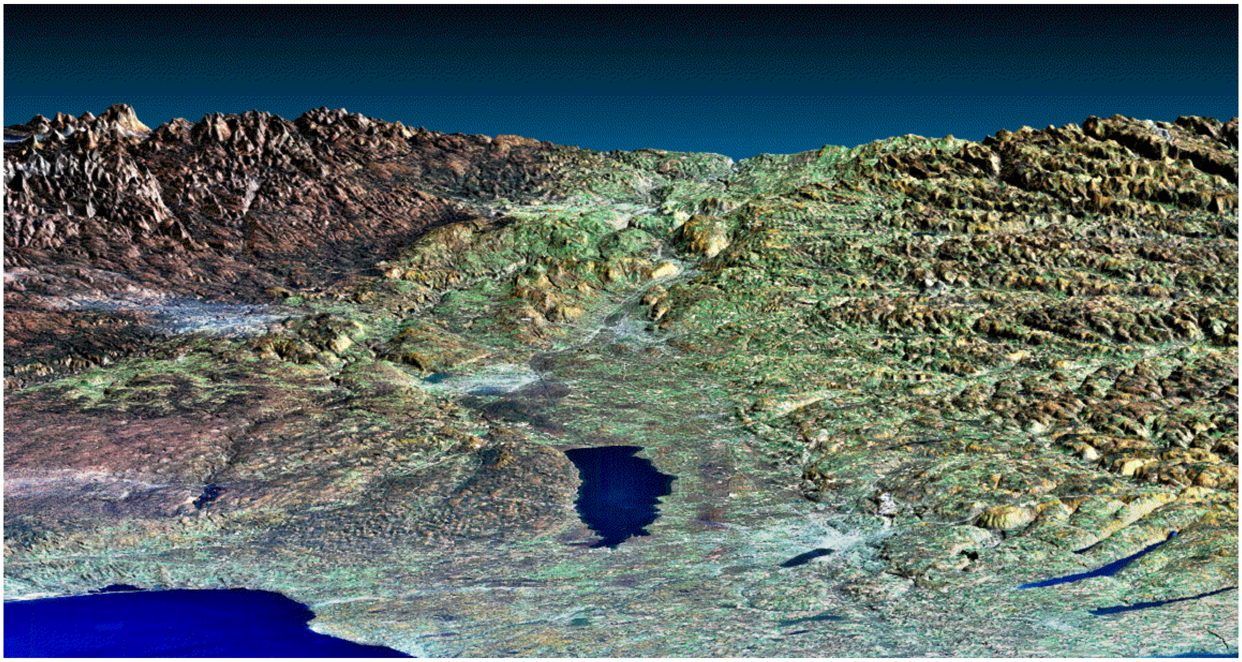

Figure 3: Perspective view of upstate New York shows Lake Ontario in the lower left, the Adirondack Mountains in the upper left, and the Catskill Mountains on the right.

The San Fernando Valley (lower right of center), shown in Figure 4 (Jet Propulsion Laboratory, 2002a) is part of Los Angeles and includes well over one million people. Two major disasters have occurred here in the last few decades: the 1971 Sylmar earthquake and the 1994 Northridge earthquake. Both quakes caused major damage to homes, freeways, and other structures and included major injuries and fatalities. The Northridge earthquake was the one of the costliest natural disasters in United States history. Understanding earthquake risks requires understanding a location's geophysical setting, and topographic data are of substantial benefit in that regard. Landforms are often characteristic of specific tectonic processes, such as ground movement along faults. Elevation models, such as those produced by the Shuttle Radar Topography Mission (SRTM), are particularly useful in visualizing regional scale landforms that are too large to be seen directly on-site. They can also be used to model the propagation of damaging seismic waves, which helps in urban planning. In recent years, elevation models have also been a critical input to radar interferometric studies, which reveal detailed patterns of ground deformation from earthquakes that had never before been seen. This perspective view was generated by draping a Landsat satellite image over a preliminary topographic map from SRTM. Landsat has been providing visible and infrared views of the Earth since 1972. SRTM elevation data matches the 30-meter resolution of most Landsat images and will substantially help in analyses of the large and growing Landsat image archive.

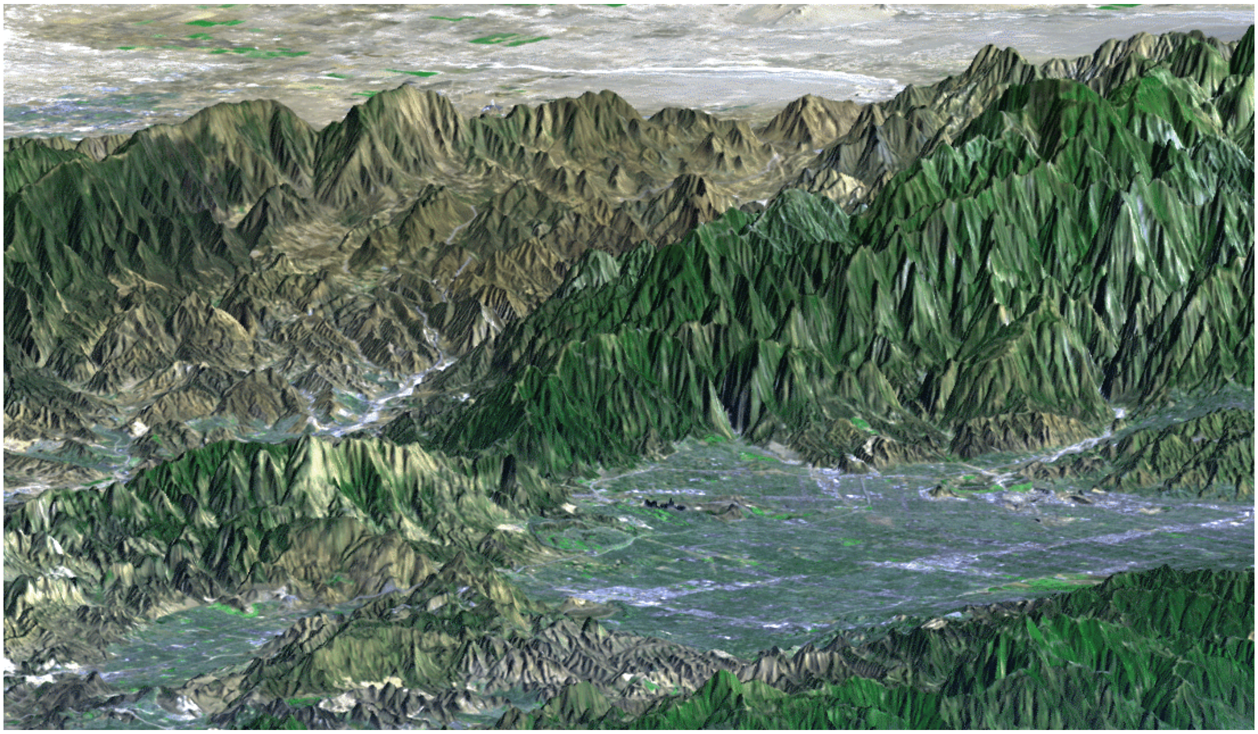

Figure 4: The San Fernando Valley (lower right of center) is part of Los Angeles and includes well over one million people.

4.2. SIR-C SAR, AIRSAR, and other SARs

The predecessor of SRTM SAR is the Spaceborne Imaging Radar – C / X-band Synthetic Aperture Radar (SIR-C/X-SAR). (SIR-C/X-SAR) is a joint U.S.-German-Italian project that uses SAR to capture images of Earth (Jet Propulsion Laboratory, 2002b). The radars illuminate Earth with microwaves allowing detailed observations at any time, regardless of darkness and cloud cover conditions. SIR-C/X-SAR instrument uses three microwave wavelengths: L-band (24 cm), C-band (6 cm) and X-band (3 cm). The instrument was flown on two flights in 1994. One was on space shuttle Endeavour on mission STS-59 April 9-20, 1994. The second flight was on shuttle Endeavour on STS-68 September 30-October 11, 1994. SIR-C polarimetric data at L and C bands were collected over many cities over the world with a resolution of 30 m matching that of SRTM. SIR-C data, having some common characteristics with SRTM, is an excellent complementary data set to SRTM for global infrastructure mapping applications.

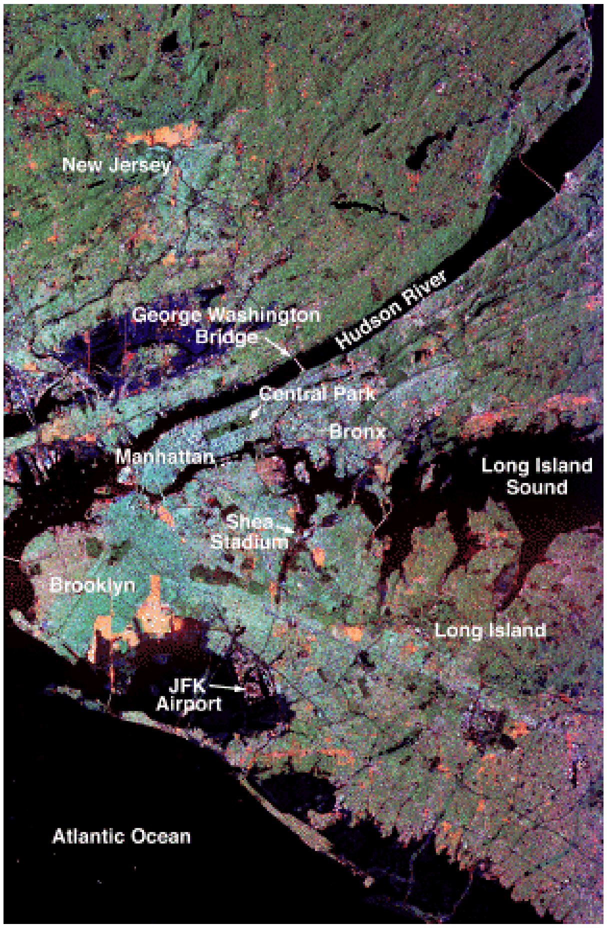

Figure 5: SIR-C image of New York

An example of SIR-C results using data acquired on 10 October 1994 over New York city metropolitan area is shown in Figure 5 (Jet Propulsion Laboratory, 2002b). The colors in this image were obtained by mixing the following radar channels: red represents the L-band (horizontally transmitted and received), green represents the L-band (horizontally transmitted, vertically received), and blue represents the C-band (horizontally transmitted, vertically received). The island of Manhattan appears in the center of the image. The green-colored rectangle on Manhattan is Central Park. The area shown is 75.0 km by 48.8 km (46.5 miles by 30.2 miles). The image is centered at 40.7°N and 73.8°W. In general, light blue areas correspond to dense urban development, green areas to moderately vegetated zones and black areas to bodies of water. The Hudson River is the black strip that runs from the left edge to the upper right corner of the image. It separates New Jersey, in the upper left of the image, from New York. The Atlantic Ocean is at the bottom of the image where two barrier islands along the southern shore of Long Island are also visible. John F. Kennedy International Airport is visible above these islands. Long Island Sound, separating Long Island from Connecticut, is the dark area right of the center of the image. Many bridges are visible in the image, including the Verrazano Narrows, George Washington and Brooklyn bridges. The radar illumination is from the left of the image. This causes some urban zones to appear red because the streets are at a perpendicular angle to the radar looking direction. Such radar images can be used as a tool for city planners and resource managers to map and monitor land use patterns. SIR-C system can detect the variety of landscapes, as well as the density of urban development.

Furthermore, the Jet Propulsion Laboratory AIRSAR system (Jet Propulsion Laboratory, 2002c) has been used to acquired polarimetric and interferometric SAR data over numerous urban, suburban, and rural areas at different times over the past decade. AIRSAR is an advanced airborne SAR system operated at P, L, and C bands with polarimetric and interferometric capability. Past, present, and future satellite SARs such as the Canadian RADARSAT SARs 1 and 2, the European ERS-1 and 2 and ENVISAT SARs, and the Japanese ALOS SAR will provide long-term SAR data to study changes in global infrastructure with respect to the fundamental reference of the global state in year 2000 provided by the SRTM data set.

4.3. Optical/infrared satellite data

There has been a strong interest in using Earth observation data in urban areas for several decades (Tuyahov, et al., 1973; Branch, 1971; Jensen, 1983; Haack, et al., 1997). Much of this effort has focused on the use of moderate to high resolution passive optical sensors. In an early attempt to relate remotely sensed reflectance to socioeconomic parameters, Forster (1983) devised a classification scheme for Landsat imagery that could be applied to urban areas to produce a residential quality index. Ormsby (1992) used Landsat TM to map nine classes of urban landcover in the Washington, DC metropolitan area. Remotely-sensed data have also been used in attempts to estimate population (Lo, 1995) and quantify urban growth (Morrisjones, 1988). More recently, Cowan and Jensen have identified eight urban/suburban attributes that can be measured using remote sensing data (Cowan and Jensen, 1998).

The spatial resolution of the sensor imposes a fundamental limitation on which components of the urban mosaic can be resolved. In a landmark study, Welch (1982) conducted a resolution analysis of satellite sensors and demonstrated that 0.5 to 10 m spatial resolution is necessary to adequately characterize urban infrastructure in most cities. This study also suggested that Asian cities tend to be more compact with a smaller characteristic structural scale than western cities. This increases the spatial resolution requirement for global mapping beyond what might be expected based on observation of U.S. cities alone. This observation also highlights the importance of using a diverse collection of cities when conducting pilot studies of infrastructure mapping. The current generation of high resolution (< 10 m) sensors (e.g. IKONOS) will begin to meet this need but the cost and data volumes associated with high resolution imagery may be prohibitive for a global study. For this reason, we focus on moderate resolution (10-30 m) imagery in this discussion. While it is not feasible to map details of individual structures with this resolution, it is reasonable to use this type of imagery to discriminate the built from the natural environment and to discriminate between different classes of built environment. Achieving these objectives on a global scale would represent a major advance in our understanding of the relationship between Earth's human population and the other components of the system.

The following sensors are discussed in order of importance towards these objectives. There is no clear role for AVHRR, so it is not included in this discussion.

- **Landsat 7 Enhanced Thematic Mapper (ETM+)**

  Landsat 7 provides the basis for passive optical mapping of global infrastructure. The global coverage and moderate spatial resolution (30 m) offered by Landsat 7 are a necessary complement to the SRTM imagery and the combined use of both systems would allow for greater accuracy than either could provide independently. Although earlier applications of previous Landsat missions have met with mixed success for urban mapping, more sophisticated methodologies combined with advances in the ETM+ sensor will facilitate the global infrastructure mapping objective. In addition to an improved signal/noise ratio in the multispectral bands and higher spatial resolution (60 m) in the thermal band, the ETM+ sensor also provides a panchromatic band with 15 m spatial resolution. Welch (1982) demonstrated that a significant portion of the structural characteristics of urban environments occur at spatial scales of 10-20 m so the 15 m panchromatic band will provide critical information necessary to characterize the built environment. The multispectral and panchromatic bands can be combined using pan-sharpening algorithms to provide a more detailed view of urban areas (see http://www.ldeo.columbia.edu/~small/NYC/NYCL7pancomp.html).

  The broadband multispectral imagery provided by Landsat can be used to classify and map the extent of the built environment. Urban areas are generally recognized in optical imagery by their geometric and textural characteristics. Spectral characteristics of urban landcover are less diagnostic than those of the rural periphery and unpopulated areas such as deserts and forests. There are significant differences between the spectral reflectance of urban surfaces and natural rock and soil surfaces but these differences may be difficult to detect with the limited spectral resolution provided by the Landsat TM sensor. The characteristic spatial scale and the spectral variability of urban landcover pose serious problems for traditional image classification algorithms that discriminate classes on the assumption of spectral homogeneity. In urban areas where the reflectance spectra of the landcover vary appreciably at scales comparable to or smaller than the Instantaneous Field Of View (IFOV), the spectral reflectance of an individual pixel will generally not resemble the reflectance of a single landcover class but rather a mixture of the reflectances of two or more classes present within the IFOV.

Classification algorithms that accommodate spectral heterogeneity provide a way to discriminate heterogeneous built environments from more homogeneous natural environments as well as distinguish among different types of built environment. Spectral Mixture Analysis (SMA) classifies individual mixed pixels according to the distribution of spectrally pure end member fractions and provides a tool for discrimination and classification of urban areas. Preliminary attempts to classify spectrally heterogeneous urban areas on the basis of spectral heterogeneity has yielded promising results (Small, 2000a) and may allow Landsat 7 imagery to be combined with SRTM to areal extent of global infrastructure. In addition, SMA can be used to discriminate among different types of built environment on the basis of end member fraction distribution. The presence and abundance of vegetation is a fundamental component of the urban mosaic and plays a major role in the modulation of solar energy fluxes controlling the Urban Heat Island Effect. Intra-urban variations in vegetation fraction of several tens of percent have been mapped using Landsat TM imagery in the New York metropolitan area (Small, 2000b).

- **ASTER**

  Although ASTER is not expected to provide global coverage, its combination of spatial and spectral resolution at both reflected visible/IR and emitted thermal wavelengths could provide a valuable complement to Landsat and SRTM imagery for infrastructure mapping. ASTER imagery of several key cities would provide information about spectral reflectance and thermal emissivity that would help refine the methodology used to classify the Landsat imagery.

- **AVIRIS**

  The Airborne Airborne Visible Infrared Imaging Spectrometer (AVIRIS), could play a very important role in global infrastructure mapping. The AVIRIS sensor, developed by JPL scientists in the 1990's, provides a very detailed measurement of the radiance field at visible through reflected infrared wavelengths (~500-2500 nm), allowing much greater discrimination of target materials than is provided by broadband optical sensors or microwave systems. By imaging in 224 spectral bands, the AVIRIS sensor is able to resolve subtle differences in target reflectance resulting from different materials or physical conditions (e.g. moisture content). The spatial resolution of AVIRIS hyperspectral imagery is determined by the altitude of the aircraft so a fundamental trade-off exists between areal coverage and spatial resolution. Although usually deployed at altitudes giving spatial resolutions of ~20 m, recent low altitude deployments have allowed AVIRIS to acquire imagery with spatial resolutions of less than 10 m. High spatial resolution hyperspectral imagery of a range of urban targets would provide extremely valuable information about the spectral diversity of the built environment. This information would allow us to refine the classification methodology used for broadband optical sensors like Landsat and ASTER.

4.4. Derived parameters

From interferometric SAR data at different polarizations and looking angles, potentially derivable parameters include: (1) Topography which is the objective of SRTM, (2) Surface slope, (3) Topographic wetness index, (4) Urban extent and boundary, (5) Urban use segmentation by building types, (6) Urban/suburban vegetation height and distribution**,** (7) Terrain classification, (8) coast line, and (9) Building height and volume. It is necessary to investigate the possible use of the data for global infrastructure mapping applications, and to develop and validate appropriate algorithms to exploit the global SRTM data which have been collected and are being processed. Some of the parameters can be derived from conventional SAR data. The use of conventional SAR data at various frequencies, incidence angles, and polarizations may enhance the accuracy of parameters to be derived from SRTM data. For algorithm developments, synergy of various SAR data and optical data will help to determine the optimal approach and to define the advantages and limitations of SRTM. Optical/infrared sensors are sensitive to physical parameters different from those sensed by microwave interferometric and conventional SARs. Therefore, the two different types of data are certainly complimentary.

5. Applications

In the following sections, we discuss the overall requirement and use of parameters derived from SRTM in synergy with other SARs and sensor types for various social science applications. We identify several study areas where initial algorithms can be developed and demographic, geographic and socioeconomic applications can be demonstrated considering the advantages and limitations of SRTM and other data characteristics, data policy, and data schedules. The overall indication from various sciences and application is that SRTM data set can be used to derive a set of infrastructure parameters consistently at a fix time period (February 2000) serving as a common fundamental reference set. The extensive variety of topics provides a general picture and the interconnection among various fields, which can be used to determine and put specific near-term focus studies in the appropriate perspective.

5.1. Urban planning and development

Due to scale issues, SRTM data still have limitations for local planning; however, some data sets in synergy with other may have considerable value for state or regional applications. For example, eventually—assuming a time series were possible—SRTM would assist in evaluating the pace and nature of changes in urban areas, associated transportation networks, and related planning issues (e.g., impermeable surfaces and related water planning issues). Some of these thematic areas are discussed below.

5.2. Economic development and transportation infrastructure

Economic geography has recently experienced a resurgence of interest within mainstream economics (Fujita et al 1999). The "new economic geography" builds on advances in theoretical economic modeling to address questions of agglomeration economies, the location of economic activities and the interactions among interrelated regional economies. This theoretical work has influenced empirical research at the global scale that attempts to shed light on the fundamental question why some regions are rich and others remain poor. Increasingly, economic researchers use spatial data and GIS tools to model the role of natural endowments and man-made infrastructure in economic growth processes (e.g., Gallup and Sachs 1999). These studies, however, are often characterized by the use of fairly simplistic indicators to represent geographic features or concepts. This can partly be explained by the paucity of useful global GIS data layers that would be useful for socioeconomic analysis at small cartographic scales.

One of the main driving forces of economic growth in most parts of the world is urbanization—although Africa's *urbanization without growth* is somewhat of an exception. Economic activities in cities benefit from urbanization including access to a larger labor pool, availability of specialized services and increased innovation through improved information exchange. Empirical evidence on the interaction of urbanization and economic growth, however, is largely limited to analysis at the macro level using national level summary indicators. These studies also tend to be biased by the lack of standard definitions of what constitutes "urban". Definitions vary widely from country to country as documented in the UN Population Division's *World Urbanization Prospects* (UN 2000).

A consistent and accurate global database of the population and geographic extent of urban centers around the world over time is thus a primary requirement for empirical urbanization studies at the subnational level. While the UN and other agencies publish estimates of the population size of the world's largest cities, there is little information on medium size cities and towns and on the geographic area covered by built-up urban land. Despite recent attempts to estimated population totals using satellite data, the only reliable information source for population totals and other socioeconomic characteristics of urban population are censuses or data from population registration systems. Satellite information can, however, provide information on the extent of the built-up urban area, which can then be related to published population figures and other socioeconomic characteristics.

A number of studies have used Landsat, the Indian Remote Sensing Satellites, Ikonos and other high resolution, multi-spectral imagery to delineate urban extent. Landsat imagery over the last 20 years can be used to determine land use changes in the urban-rural fringe (see http://murbandy.sai.jrc.it for European examples). Lessons learned from studies of past land use conversion patterns can inform planning for future extension of urban areas in rapidly growing cities in developing countries. The limitation of these approaches is that the cost of the imagery and processing is too high to produce continental or global data layers. What is needed is a reliable and relatively inexpensive method to produce global high resolution information (1km and better) of urban areas. Candidate sensors are the DMSP nighttime lights data set and the SRTM brightness index. Multi-sensor case studies for a selected set of representative cities can generate information to validate the utility of these data sets for urban work.

An urban data layer will also benefit research and policy analysis in the rural sector. Cities serve as input and output markets for the rural sector and are important conduits for the transfer of agricultural technology. The analysis of urban-rural linkages by the global agricultural research community (e.g., the Consultative Group for International Agricultural Research centers) is so far hampered by the lack of reliable information on urban versus rural population sizes and their geographic distribution. An "urban mask" that indicates urban areas would be a first step towards addressing this data gap, and is currently being developed by collaborators at the Center for International Earth Science Information Network at Columbia University (CIESIN), the International Food Policy Research Institute (IFPRI) and the World Bank.

5. 3. Transportation infrastructure

Related to the study of urban-rural linkages is the role of transport infrastructure in facilitating economic interaction. Lack of access to urban markets limits the possibilities for the rural population to market their surplus to urban consumers and to benefit from urban amenities. Areas that have limited linkages to the urban sector can become "spatial poverty traps" (Jalan and Ravallion 1997). Up-to-date information on rural roads in the vicinity of urban centers is absent in many parts of the developing world. High resolution satellite data could fill this data gap. Roads typically appear as linear features in radar imagery. While automatic detection of roads from radar imagery has not been completely successful, semi-automatic, and manual road extraction is possible. For the purposes our application, we propose to use a semi-automatic procedure to detect roads from SRTM radar imagery, and to create road network topography using the SRTM DEM data product. This procedure allows the extraction of road features such as road grade (slope). The above procedure has been applied to the JPL AIRSAR interferometric data, and the results are reported in (Gamba and Houshmand, 1999). While 30-m resolution SRTM data are likely too coarse to allow identification of rural roads, higher resolution SAR and optical data could be used to update existing map bases. An investigation of the use of SRTM data capability and limitation to detect different types of transportation infrastructure is necessary. The long-term goal should be the development of much improved transportation infrastructure data layers that support research and regional planning applications.

5.4. Population growth and dynamics

The measurement of population dynamics in urban areas has historically been one of the weaker areas of demographic inquiry, owing in part to the fluidity of urban environments, boundaries, infrastructures and associated behavioral characteristics. The definition of an urban population varies from country to country, thus urban statistics need to be interpreted with caution (Brockerhoff, 2000). Demographers do a good job of estimating the population size and composition of urban areas, within each nation's given construction of urban, but pay little attention to the spatial distribution and extent of those changes, in large part because spatial data (e.g., boundaries) and demographic data are rarely integrated. Thus the UN population division accepts each country's own definition of urban in its calculation of urban population estimates and projections (UN 2000). This is problematic when one is interested in making comparisons across countries. Uniformly and globally collected data, like STRM, could be used in an effort to standardize degrees of urbanization or urban extent which would assist in the spatial estimation of population.

Another area of weakness in demography is in understanding the rate of change and variation in urban population statistics. Conventional population censuses—used to estimate population size and composition—tend to be taken decennially at a designated time of year with no intent or ability to estimate the population of a given area at particular times of day, month or season. Nevertheless, numerous issues (e.g., relating to infrastructure, transportation, hazards) require data that estimate population size or composition (e.g., age or gender) that vary by time of day or year. Thus, new technology that would facilitate more frequent measurement of population-related factors (e.g., building type or capacity, comminuting zones) would be highly valuable to understanding population-related dynamics of urban areas.

Further, several studies have used satellite data, primarily, NOAA's Operational LineScan or "lights at night" (DMSP-OLS) data set, in combination with conventional estimates of population or other socioeconomic attributes to model population size or dynamics of urban areas or associated socioeconomic characteristics (Elvidge et al. 1997a, Elvidge et al. 1997b, Sutton et al. 2000; Doll and Muller, 2000). DMSP-OLS imagery alone can measure both the areal extent of urban clusters and the light-intensity volume of those urban clusters, albeit with error. Nevertheless, these quantities have shown strong linear relationships with population, electricity consumption, metropolitan GDP, and CO2 emissions. Such estimates would be improved and validated by incorporating SRTM which can considerably improve the estimates of urban extent and clusters. To the extent that these new techniques will then be used in modeling the spatial distribution of population, they will require substantial validation within the demographic or population geographic community. Both communities would welcome input from satellite-based data to improve their own estimation techniques.

5.5. Housing and other building stock

The history, nature, and quality of urban building stock around the world vary dramatically. Many cities are experiencing dramatic expansion, often informal, on their periphery (Pezzoli 1997: Human Settlements and Planning for Ecological Sustainability MIT Press). This settlement is often haphazard and results in many conflicts between the settlers and city governments. Assessing poverty levels in growing urban areas and documenting change in these areas would assist urban planners in the provision of basic services and infrastructure. By using SRTM data in conjunction with other remotely sensed data , such as the night-lights data, along with traditional census data on population and housing, there is the potential to improve measurement and monitoring of building stock in the urban environment. While local non-image based information is vital for appropriate local planning responses, the speed and scale at which these changes are taking place warrants the use of remotely sensed information also.

5.6. Natural and man-made hazards

5.6.1. Flood risk mapping

Floods are transient surface events and can occur at the same time over widely separated geographical locations (even on different continents). To record such events, information on flooding with a high resolution and a frequent and large-scale coverage is necessary. Even within the United States, where in-situ data are abundant, events such as the Great Flood of the Upper Mississippi Valley in 1993 destroyed many gauging stations, and it was so geographically extensive that assembling a comprehensive survey of affected rivers and tributary systems took the U.S. government several years. Conventional methods to compile flood information involve manual collection and collation of point data. These processes are time consuming and final report output often takes years to complete. Aircraft reconnaissance for synoptic coverage of flood inundation is dependent on weather and operational conditions, and is limited in areal coverage. The thick and widespread cloud cover accompanying the wet phase of the monsoon cycle and storm systems persistently impairs visible and infrared sensors such AVHRR for flood boundary delineation and limits surface observations (Imhoff et al., 1986, 1987).

Spaceborne microwave passive sensors such as the Special Sensor Microwave/Imager (SSM/I) are applicable to surface observations under various cloudy conditions. SSM/I measures brightness temperatures at 19, 22, 37, and 85 GHz. Brightness measurements have been used to indicate the surface wetness with a parameter called the Bassist wetness index (BWI), a product of emissivity change and surface temperature (Bassist et al., 1998). However, BWI requires data at 19, 37, and 85 GHz, and thus limits the results to the low resolution at 19 GHz (69 km x 43 km) and to higher atmospheric effects at 85 GHz. Mean monthly BWI is derived with a 1^{o} by 1^{o} resolution in latitude and longitude (Bassist et al., 1998) which is approximately 100 km x 100 km in the tropical regions. The low resolution is inherent to the one-way antenna gain in the passive measurements. Preliminary tests of this and similar SSM/I-derived wetness indices by the Dartmouth Flood Observatory (DFO) to date also show little correlation of wetness anomalies to river flooding, and major river floods are not apparently recorded by the wetness index. Satellite scatterometer such as SeaWinds on QuikCAT satellite can be used for early detection of wet land and inundated areas, but at the valley scale due to the limitation in spatial resolution (Nghiem et al., 1998, 2000).

Spaceborne synthetic aperture radars (SAR) have very high resolutions (10 m to 100 m). Space-shuttle SAR data such as SIR-B and SIR-C data have been used to study flood mapping (Imhoff et al., 1987; Hess et al., 1995). Flood applications with satellite SARs, such as ERS-1, ERS-2, RADARSAT, and JERS-1, have been investigated. A common technique is to use multi-temporal data by comparing images taken at different times. Gineste et al. (1998) argue that the whole temporal backscatter profile should be considered for the remote sensing of saturated areas. Townsend and Walsh (1998) have combined multitemporal JERS-1 and ERS-1 SAR data, a Landsat Thematic Mapper (TM) time-series, and GIS coverages to model the potential of flood inundation within the lower Roanoke River floodplain. While the high resolution makes SAR appropriate to study detailed flood areas, it limits results to small geographic coverages. Thus, multiple SARs are necessary to have better coverages.

Given the resolution of SRTM at 30 m, the data set can be used to determine a reference set of flood-hydrology related parameters. The topographic wetness index (TWI) is determined by catchment area and topographic slope, which can be used as a flood risk index. Within the accuracy and resolution of SRTM, TWI can be derived and its use as a flood risk index need to be investigated. A complementary data set is Hydro 1K at 1 km resolution can be used to compare and verify SRTM results. In the near term, candidate study areas with different flood types are: (1)

Monsoon region such as India, Bangladesh, SE Asia, and Australia, (2) Snowmelt/flood area such as Midwest US and Canada, and (3) flash flood areas which may need higher resolution data. Furthermore, data of urban infrastructure, population, road network, cement surfaces should be combined to determine impermeable surface areas, which is important urban flood hydrology.

5.6.2. Earthquake/volcano vulnerability assessment

Earthquakes and volcano eruptions have been the cause of severe disasters throughout mankind history. The use of SAR for earthquake and volcano has been intensively investigated recently (Massonnet and Feigl, 1998). Over seismic and volcanic risk areas, it is important to assess building infrastructure and road network. These parameters are necessary to evaluate the potential loss, to develop appropriate mitigation plan, and to facilitate the allocation of relief personnel and resource in the aftermath of earthquake or volcano eruption. Based on SRTM data, the potential capability to derive key parameters such as building density, type, height, and volume and roads need to be investigated. For this purpose, useful complementary data sets include Landsat (or high resolution visible and infrared data), ASTER, and seismicity and related geophysical data. Candidate study areas are should cover two cases: cities with existing building inventories and cities without building inventories in active seismic and volcanic areas. For both cases, the hazard vulnerability needs to be assessed or developed and developing countries where there can be differences in infrastructure characteristics and resources for hazard mitigation. The relationship between infrastructure and road network with population distribution and population dynamics should be studied in the assessment of earthquake and volcano vulnerability.

5.6.3. Land slide risk and lahar

Land slide and lahar are important applications of satellite SAR data (Kimura and Yamaguchi, 2000; Chorowicz et al., 1997). Land slide and lahar risk areas needs to be identified. Useful parameters based on SRTM data are topographic slope and area. Furthermore, soil and rock type and orientation are necessary in the assessment of land slide and lahar risk. The risk factor needs to be studied for different failure scenarios such as earthquake, volcanic eruption, heavy rain, and snowmelt. Suggested candidate study areas include California, Philippines, Indonesia, and Venezuela. The results should be connected to other applications by overlaying the land slide and lahar risk factor with infrastructure, population, and road network data.

5.6.4. Coastal Hazard and Sea Level Rise

Hurricane, storm surge, and tsunami are natural hazards that pose serious thread to coastal communities. Water level change has been accurately measured with SAR data (Alsdorf et al., 2001). To assess the coastal hazard and sea level rise, important parameters include proximity of building type and volume to coast, and altitude on building infrastructure above the normal local marine water level. For this application, key parameters based on SRTM data are the distribution, type, and volume of buildings, elevation and slope data, and coastline identification. Complementary data includes existing DEMs and elevation datasets for selected coastal cities, existing building inventories together with coastal GIS data, and SLOSH model. Candidate study areas should covers both developed and developing countries. The results should be overlaid with infrastructure, road network, and population data in the overall assessment of coastal hazard risk.

5.6.5. Building vulnerability

A consistent identification of large buildings, factories, or commercial centers to determine their location, distance to airport and other risk facility, surrounding road network is important for the overall assessment of risk factor or vulnerability to natural hazard (earthquake, volcano, land slide, flood, …) and man-made hazard (terrorist, toxin release, chemical explosion, …) and the potential socio-economics impact at the national/federal level. The advantage of SRTM data set is that it can provide the basis to obtain a consistent national data set representing large building conditions at the SRTM reference time.

6.7. Habitat fragmentation

Habitat loss or fragmentation due to urban development in rural areas ranks among the principal causes of species endangerment. Our proposed research focuses on the study of anthropogenic dynamics behind habitat fragmentation as opposed to natural fragmentation resulting from such events as fires or avalanches. The parameters derived from the STRM data enable the identification of intensive anthropogenic activity ranging from agriculture to the built environment. The spatial pattern of these activities is important to understanding the socio-economic drivers of habitat fragmentation and predicting potential future impacts on biodiversity should existing trends continue.

Environmental modification, such as habitat fragmentation, results in species composition and abundance changes. In Latin America the pace of environmental modification is related to anthropogenic factors, including economic and population growth (FAO, 1996). Agriculture-related activities were ranked second in order of importance of environmental modifications. Fifth on this list were roads, human settlements and urbanization. The relevance of these factors varies by country and locality, emphasizing the need to study landscape level dynamics along the rural-urban corridor.

The STRM parameters of topography, surface slope, urban extent and boundary, urban/suburban vegetation height and distribution and terrain classification are all candidates for this study. Terrain classification is the most obvious variable of import, enabling the identification of habitat fragmentation types in combination with urban extent delineation. The addition of topographic and surface slope information is important in understanding the relationship between fragmented areas and the natural landscape. Such physical barriers as mountain ranges and changes in elevation often define species composition and distribution ranges.

The contribution of STRM data is greatest in regions were current relatively high-resolution maps (topographic, land use and land cover) are not easily available, and anthropogenic pressures on the natural habitat are severe. Such regions include the Pantanal and the Atlantic forest region of Brazil. The Pantanal (the largest wetland in the world) is an area of key biological diversity currently facing many anthropogenic pressures as the increasing and non-planned development in the up-streams highlands surroundings. For this study, increased fragmentation of natural biotic corridors and the expansion of roads are most relevant. Brazil's Atlantic forest region is considered a priority threatened "hotspots" for terrestrial biodiversity on Earth, on par with Madagascar, the Philippines and the Tropical Andes. Only 2 to 5% remain of an estimated original area of 2 million kilometers. Today it has among the highest human population density in the Western Hemisphere, including both Rio de Janeiro and Sao Paulo, the second largest city in the world. The Pantanal itself does not currently have megacities, but its urban areas in the highlands surroundings, as Cuiabá and others are rapidly expanding, decreasing habitat and species diversity in the terrestrial and aquatic environment which in turn impacts the Pantanal downstream.

A study of habitat fragmentation along the rural-urban corridor integrating ecological and socioeconomic data could help local land use planners evaluate potential threats of land use change on native biodiversity. The most important contribution of this study is the integration of socio-economic drivers underlying habitat fragmentation with local ecological studies. Predictive patterns of future urban growth can then be used to develop a biodiversity-fragmentation risk map. Thus, areas of potential conflict between expanding urban areas and biodiversity conservation needs could be identified.

6.8. Other

There are numerous other applications for which an infrastructure dataset might prove invaluable. Some of these include integration into standard geographic information system, particularly by improving information on elevation. Other example application areas would include health planning and management and pollution modeling and assessment.

7. POTENTIAL USERS

The list of potential users is wide ranging. A few of the key institutions that would make use of these data are listed below. Representatives of several of the key organizations (e.g., the United Nations) have already demonstrated their need for these data, and several have projects underway that would substantially benefit from the creation of a global infrastructure database and map.

7.1. US agencies/departments

NASA, NOAA, NSF, EPA, FEMA, USAID, Census Bureau,
DoD, DoE, DoC,
States/Local governments.

7.2. Mapping organizations

National and international mapping organizations.

7.3. International organizations

United Nations, World Bank, World Health Organization,
World Resources Institute, International Federation of
Red Cross, Conservation International, Wetlands International, BCIS.

7.4. Educational/R&D organizations

Universities, National Laboratories, Data Centers,
Disaster Centers, Socio-economic Research Centers.

7.5. Industries

Economics consulting firms, shipping industry, telecommunication, insurance companies.

REFERENCES

Alsdorf, D.E., L.C. Smith, and J.M. Melack (2001). "Amazon floodplain water level changes measured with interferometric SIR-C radar," IEEE Transactions on Geoscience and Remote Sensing, 39 (2), 423-431.

Basist, A., N. C. Grody, T. C. Peterson, and C. N. Williams, (1998), "Using the Special Sensor Microwave/Imager to monitor land surface temperatures, wetness, and snow cover," *J. Appl. Meteorol.*, *37*(9), 888-911.

Brockerhoff, Martin. 2000. "An Urbanizing World," *Population Bulletin* 55(3): 1-44.

Brockerhoff, Martin. 1999. "Urban growth in developing countries: a review of projections and predictions," *Population and Development Review*, 25 (4): 757-78.

Chorowicz, J., E. Lopez, F. Garcia, J.F. Parrot, J.P. Rudant, and R. Vinluan (1997). "Keys to analyze active lahars from Pinatubo on SAR ERS imagery," *Remote Sensing of Environment, 62*(1), 20-29.

Doll, Christopher & Muller, Jan-Peter (2000). "A comparison of different techniques applied to the UK to map socio-economic parameters: Implications for modelling the human dimensions of global change," International Society of Photogrammetry and Remote Sensing Congress 2000, July 2000, Amsterdam.

Elvidge, C., K. Baugh, et al. (1997a). "Relationship between satellite observed visible-near infrared emissions, population, economic activity, and electric power consumption." *International Journal of Remote Sensing* 18: 1373-1379.

Elvidge, C. D., K. E. Baugh, et al. (1997b). "Satellite inventory of human settlements using nocturnal radiation emissions: A contribution for the global toolchest." *Global Change Biology* 3: 387-395.

Fujita, M., Krugman, P., and Venables, A. (1999). *The spatial economy: cities, regions and international trade*. Cambridge, Mass.: MIT Press.

Gallup, J.L. and J. Sachs (1999), "Geography and Economic Development," Consulting Assistance on Economic Reform (CAER II) Discussion Paper No 39, Harvard Institute for International Development, www.hiid.harvard.edu/projects/caer/papers/paper39/paper39.html

Gamba, P., and Houshmand, B. (1999). "Three-Dimensional urban characterization by means of IFSAR measurements," *Proc. of IGARSS*, Vol. V, 2401-2403.

Gineste, P., C Puech, and P. Merot, (1998). "Radar remote sensing of the source areas from the Coet-Dan catchment," *Hydrol. Process.*, *12*(2), 267-284.

Hess, L. L., J. M. Melack, S. Filoso, and Y. Wang, (1995), "Delineation of inundated area and vegetation along the Amazon floodplain with the SIR-C synthetic-aperture radar," *IEEE Trans. Geosci. Remote Sens.*, *33* (4), 896-904.

Imhoff, M. L., C. H. Vermillion, M. Story, and F. Polcyn, (1986), "Flood-control planning in Bangladesh - A result of the Shuttle Imaging Radar-B program," *The Sci. of the Total Environ.*, *56*, 277-286.

Imhoff, M. L., C. Vermillion, M. H. Story, A. M. Choudhury, A. Gafoor, F. Polcyn, (1987), "Monsoon flood boundary delineation and damage assessment using spaceborne imaging radar and Landsat data," *Photo. Eng. Remote Sens*., 53(4), 405-413.

Jalan, J. and M. Ravallion (1997), "Spatial poverty traps?," World Bank Policy Research Working paper 1862.

Jet Propulsion Laboratory (2002a). *Shuttle Radar Topography Mission – The Mission to Map the World*. Internet at http://www.jpl.nasa.gov/srtm/.

Jet Propulsion Laboratory (2002b). *Shuttle Imaging Radar (SIR-C).* Internet at http://southport.jpl.nasa.gov/sirc-c/.

Jet Propulsion Laboratory (2002c). *AIRSAR Airborne Synthetic Aperture Radar*. Internet at http://airsar.jpl.nasa.gov/.

Kimura, H., and Y. Yamaguchi (2000). "Detection of landslide areas using satellite radar interferometry," *Photogrammetric Engineering and Remote Sensing*, *66*(3), 337-344.

Lo, C. P. (1995). "Automated population and dwelling unit estimation from high-resolution satellite images –A GIS approach." *International Journal of Remote Sensing, 16*(1), 17-34.

Massonnet D., and K.L. Feigl (1998). "Radar interferometry and its application to changes in the earth's surface," *Reviews of Geophysics*, *36*(4), 441-500.

Morrisjones, D. R. (1988). "Satellite remote-sensing monitors urban-growth," Laser Focus Electro-Optics," 24(3):136.

Nghiem, S. V., W. T. Liu, and X. Xie, (1998), "Flood detection and mapping with spaceborne Ku-band scatterometer," *Int. Geosci. Remote Sens. Symp*., Hamburg, Germany.

Nghiem, S. V., W. T. Liu, W.-Y. Tsai, and X. Xie, (2000), "Flood mapping over the Asian continent during the 1999 summer monsoon season," *Int. Geosci. Remote Sens. Symp.*, Honolulu, Hawaii.

Sutton, P. C., D. Roberts, et al. (2000). "Census From Heaven: An estimate of the global population using nighttime satellite imagery." *International Journal of Remote Sensing*, In Press.

Townsend, P. A., and S. J. Walsh, (1998), "Modeling floodplain inundation using an integrated GIS with radar and optical remote sensing," *Geomorph*., *21*(3-4), 295-312.

United Nations (2000). *World Urbanization Prospects: The 1999 Revision* United Nations Department of Economic and Social Affairs (ESA/P/WP/161) UN: New York.

WORKSHOP PARTICIPANTS AND CONTACT S

1. NASA

- Dr. John L. LaBrecque, Manager
- Solid Earth and Natural Hazards Program
- Codes YS/YO
- Office of Earth Science
- National Aeronautics and Space Administration
- Washington, DC 20546-0001
- Tel: 202-358-1373
- Cell: 917-825-7141
- Fax: 202-358-2770
- E-mail: jlabrecq@hq.nasa.gov
-
- Dr. Earnest D. Paylor, II

  At the time of workshop:
- Solid Earth and Natural Hazards Program Scientist
- Pacific Disaster Center Program Manager (OASD(C3I))
- Applications and Outreach Division
- Office of Earth Science
- NASA Headquarters
- 300 E. St. SW
- Washington, DC 20546
- Tel: 202-358-0851
- Fax: 202-358-2770
- E-mail: epaylor@hq.nasa.gov

2. Columbia University

- Dr. Deborah Balk
- Dr. Robert Chen
- Dr. Sig Grava
- Dr. Roberta Miller
- Dr. Christopher Small
- Ms. Antoinette Wannebo
- Ms. Christine Williams
- Mr. Gregory Yetman

Contact point:
Dr. Deborah Balk
CIESIN
Columbia University
P.O. Box 1000
Palisades, NY 10964
Tel: 914-365-8965
Fax: 914-365-8922
E-mail: deborah.balk@ciesin.columbia.edu

3. Jet Propulsion Laboratory

- Dr. Ronald Blom
- Dr. Bijan Houshmand

- Dr. Yunjin Kim
- Mr. Gregory Neumann
- Dr. Son Nghiem
- Dr. Ernesto Rodriguez
- Dr. Jakob van Zyl

Contact point:
Dr. Son V. Nghiem
Mail Stop 300-235
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
Tel: 818-354-2982
Fax: 818-393-3077
E-mail: nghiem@solar.jpl.nasa.gov

4. The World Bank

- Dr. Uwe Deichman
- Development Research Group
- The World Bank, Room MC2-560
- Washington, DC 20433
- Tel: 202-473-6400
- Fax: 202-522-3230
- E-mail: udeichmann@worldbank.org

5. University of Denver

- Dr. Paul C. Sutton
- Department of Geography and Environmental Science
- University of Denver
- Denver, Colorado 80208
- Tel: 303-871-2399
- Fax: 303-871-2201
- E-mail: psutton@du.edu