Title: High Spatial, Temporal, and Spectral Resolution Instrument for Modeling/Monitoring Land Cover, Biophysical, and Societal Changes in Urban Environments

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Description: There is critical need to adequately model, monitor land cover/land use, biophysical, and societal changes in the urban environment and assess climate change impacts on cities. The Hyperspectral Infrared Imager (HyspIRI) is a Decadal Survey tier 2 sensor that is well developed and can be used to satisfy this need.

With urbanization burgeoning around the world, there is a critical need to acquire data on urban environments at high spatial, temporal and spectral resolutions. A key feature of understanding the urbanization process is monitoring information on social, biological, and physical conditions of existing and transformed urban areas (Wentz et al., 2015). To this end, HyspIRI is a second tier 2007 Decadal Survey sensor that is ideally suited to gather data at high spatial, temporal, and spectral resolutions for quantifying and modeling land cover, biophysical, and societal characteristics of urbanization and its effects at local, regional, and even global scales. This whitepaper describes the rationale for deployment of the HyspIRI sensor as related to developing a better understanding of urbanization within the purview of two of the five Earth science themes defined in the Request for Information for ESAS2017: **(I) Weather and Air Quality: Minutes to Subseasonal; and (IV) and Climate Variability and Change: Seasonal to Centennial**,

Rationale:

For the first time ever, the majority of the world's population lives in cities and this proportion continues to grow. As of 2010, more than half of all people on the globe live in an urban area. By 2030, 6 out of every 10 people will live in a city, and by 2050, this proportion will increase to 7 out of 10 people. Almost all urban population growth in the next 30 years will occur in cities of developing countries, with most of this growth in “megacities” – those cities with 10 million inhabitants or more (UN, 2014). Thus, we are living in the first ‘urban century’ that will have profound impacts on the spatial ‘footprints’ of cities on planet Earth. Remote sensing data from orbital platforms are of key importance in the synthesis of these data along with other ancillary spatial data, to develop a better comprehension of the individual components of the urban ecosystem.

The Urban Ecosystem:

The urban ecosystem functions through the interaction of four separate but integrated constituents: the biotic complex; the physical complex; the social complex; and the built complex (Pickett et al., 1997). Overall, the interplay of these four constituents and assessing the causes and effects that drive or influence the outcomes from their interactions has multifaceted ramifications. Remote sensing data and GIS technology can be used synergistically to synthesize and model the real or potential interactions that occur as a function of urban ecosystem processes. Of particular importance is the synthesis of remote sensing data along with other ancillary spatial data to develop a better comprehension of the individual components of the urban ecosystem (Figure 1).

Each of the individual 'complexes' given in Figure 1 is in itself an ecosystem. The Biotic complex consists of the flora, fauna, and human entities that comprise the biological urban landscape. Here it is not only the land cover content that is extant such as forests, wetlands, or agricultural lands, but even more so the arrangement of these 'natural' land covers within and around urban areas that is of importance to the health of the biotic complex. As cities grow they extend into the periurban region – the area adjacent to the built environment that is subject to urbanization – and impact both the type and pattern of the biota around the city proper. Assessments of how much land cover change from 'natural' to impervious has occurred through time is important information that is used by decision makers and urban planners in assessing where urban expansion has taken place, and where growth will occur along the rural-urban interface. Remote sensing data have been used extensively to evaluate land cover changes associated with urban growth either in the direct temporal observation of these changes, or as integrated into a GIS with other ancillary data to show corresponding changes in urban infrastructure components (Weng and Quattrochi, 2007).

The urban physical complex consists of both the physical attributes and processes that interact to form the physical environment across or over cities. Attributes here include those related to the atmosphere (e.g., wind, precipitation, clouds) or land-atmosphere energy exchanges such as thermal energy fluxes or those related to plant oxygen-CO_2 exchanges with the atmosphere (Arnfield, 2003; Voogt and Oke, 2003). The physical complex also includes those elements related to the urban hydrosphere such as rivers, lakes, wetlands, watersheds, water runoff, and infiltration, and the impacts of rainfall over cities (e.g., flooding). It also includes the output from the built environment such as waste water, and the amount of water needed to maintain the overall structure of the city. (Weng, 2001).

The urban built complex is familiar to us as the 'city' where the land surfaces ubiquitous to the urban environment such as buildings, houses, rooftops, roads, parking lots exist. The built complex may be thought of as the 'urban fabric' upon which the morphology of the city rests. It is extremely heterogeneous and where land surface types are juxtaposed and intertwined with one another to comprise this fabric. Although the built complex may be conceived of being comprised of primarily impervious surfaces, extensive 'patches' of pervious surfaces such as forested parks or grassy areas can also be present (Pickett and Cadenasso, 2008).

The urban social complex consists of the attributes that relate to human health, welfare, economics, and social interactions that occur within the urban environment. Here the inflows, outflows and exchanges of people, materials, and finances occur, and where segmentation of the social environment takes place through population migration (e.g., neighborhood gentrification, socio-economic class distinction). The social complex is perhaps the most complicated of all four of the complexes that comprise the overall urban ecosystem because of the vagaries of the human dimension and volatility to both internal and external forces that shape the socio-economic environment of the city. It is the capture of the attributes of the social complex within an integrated data environment that encapsulates the characteristics associated with 'socialization of the pixel' (Jensen and Cowen, 1999; Gatrell and Jensen, 2008).

Coupling of Urbanization with Urban Climate[1]

Because the urban surface regulates much of the urban climate, there is a tight coupling between land use and regional climate modeling. There is also mounting evidence that urbanization effects the cycling of water, carbon, aerosols and nitrogen in the climate system (Herold et al., 2005; Comarazamy et al., 2010; Comarazamy et al., 2013a; Comarazamy et al., 2013b). Urban climate modeling refers to micro and small-area estimates of temperature, wind speed and direction, atmospheric pressure, humidity, precipitation, energy fluxes, and atmospheric particulates in an urban area. Consistent among urban climate research is studying how urban surface features, such as the form, structure, and composition of buildings, trees, and asphalt, effect and alter these climate variables (Landsberg, 1981; Seto et al., 2009). Many studies show that the underlying land cover influences urban atmospheric and surface temperatures. For example, studies have found that simulated surface boundary conditions using data from remote sensing-derived land cover air temperatures predictions were close to observational values (Hirano et al., 2004; Shepherd et al., 2010). A particular challenge in urban climate analysis and modeling is acquiring data with requisite cell sizes to match thermal elements and fluxes and data collected at the time scales to effectively monitor diurnal temperature variations (Schmidt et al., 1991; Shepherd 2005, Liu and Weng, 2009; Chapin et al., 2010; Waide et al, 2013; Zhan et al., 2013) Day/night thermal differences related to characteristics of urban morphology, such as building size, orientation, and spacing and the availability of green space, show that the relative spatial location of land covers influences temperature more so than actual surface composition (Quattrochi et al., 2000). These findings are particularly interesting because they contradict the general perception that built-up areas are warmer during the daytime as well as at night because of their surface composition (see for example (Balling et al., 1998; Hirano et al., 2004; Nichol, 2005; Dousset et al., 2011).

Complementary to urban temperature, remotely sensed data are also being used in urban precipitation models. Two factors in the literature are: how convective forces that drive precipitation are altered due to urbanization and how aerosols, which are highly variable in urban areas, influence rainfall patterns. Rosenfeld et al., 1998 describe how multispectral satellite sensor images can be used to observe cloud particles as predictors of precipitation. Urban specific studies have reported regional increases and locational shifts in convective precipitation due to increases in surface temperatures (Grimm, et al., 2008; Rosenfeld, et al., 1998; Shepherd et al., 2010; Ashley et al., 2012). Using the precipitation radar on the Tropical Rainfall Measuring Mission (TRMM), Ashley et al., (2012) show that the regional position of the city influences the relative increase to rainfall. Depending on multiple factors such as climate zone, cloud type, time of year, type and amount of atmospheric particulates, aerosols are shown to either increase or decrease precipitation. This complexity is observed using both remotely sensed data sources as well as *in situ* measurements of atmospheric particulates.

The Urban Heat Island Effect:

The Urban Heat Island effect (UHI) results from elevated temperature over urban areas due to thermal energy characteristics of urban surface materials that absorb incoming shortwave solar radiation and re-emit this energy as longwave radiation from surfaces common to the city landscape (e.g., pavement, rooftops) (Dominguez, et al., 2011a). Studies modeling UHI have

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[1] The content in this section is taken from Wentz, E.A., S. Anderson, M. Fragkias, M. Netzband, V. Mezev, S.W. Myint, D. Quattrochi, A. Rhaman, and K.C. Seto, 2014. Supporting global environmental change research: A review of trends and knowledge gaps in urban remote sensing. *Remote Sensing*, 6: 3879-3905; doi: 10.3390/rs6053879.

been used to quantify the drivers of the UHI, to determine approaches to mitigate heat, and to analyze human, plant, and animal health, changes to rainfall patterns, and energy and water use (González et al., 2007; Grimm et al., 2008; Rosensweig et al., 2009; Weng, 2009; Zhou et al., 2011). The UHI may increase heat-related impacts by raising air temperatures in cities approximately 1–6 ^{o}C over the surrounding suburban and rural areas due to absorption of heat by dark paved surfaces and buildings; lack of vegetation and trees; heat emitted from buildings, vehicles; and air conditioners; and reduced air flow around buildings (USEPA, 2016). An example of the extent of the UHI in response to urban land covers is given in Figure 2. The figure shows Atlanta, Georgia's urban extent in gray (bottom) and corresponding thermal responses (top) as derived from Landsat TM data. Critical to understanding the extent, diurnal, and energy balance characteristics of the UHI requires having remote sensing data collected on a consistent basis at high spatial resolutions to enable modeling of the overall responses of the UHI in respect to the spatial form of the city landscape for different urban environments around the world (Figure 3). Unfortunately, current satellite systems do not have adequate revisit times, spatial resolution, or multiple thermal spectral bands to provide the information needed to model UHI dynamics and its impact on humans and the adjacent environment.

Partitioning of the urban thermal surface across the landscape is fundamental to understanding how the individual surface types that are ubiquitous to cities (e.g., rooftops, pavement) are vital to understanding urban land-atmosphere dynamics (Luvall, et al., 2015). The majority of research on the UHI has been focused on deriving land surface temperatures (LST) from thermal infrared (TIR) remote sensing data and their relationships with urban surface biophysical characteristics, especially with vegetation indices and land use and land cover types (Weng and Quattrochi, 2006; Weng, 2009; Dominguez et al., 2011b.)

Key Requirements:

The key requirements for a sensor capable of collecting high spatial, temporal, and spectral resolution data over urban areas are founded in two fundamental science questions: (1) How does urbanization affect the local, regional, and global environment?; and (2) Can we characterize this effect to mitigate its impact on human health and welfare? These basic science questions can in turn be broken down into three related sub-questions: (i) What are the relationships of land cover/land use change as they affect energy balances over the city?; (ii) What are the dynamics of the UHI on a spatial and temporal scale and what is the impact of the UHI on biophysical, climatic, and environmental processes?; and (iii) How can characteristics associated with human health such as factors influencing heat stress and surface temperatures, affect vector-borne diseases as a function of urbanization. An elaboration of these science sub-questions along with the measurement objectives, measurement requirements, instrument requirements, and instrument specifications is given in Figure 4 as a traceability matrix.

Affordability Achieving Required Measurements in the Decadal Timeframe:

To address scale issues, there are plans for obtaining finer spatial and spectral resolution data to improve remote sensing observation and analysis of urban areas. The Hyperspectral Infrared Imager (HyspIRI), which is currently a second tier 2007 decadal survey instrument, will have a hyperspectral Visible and ShortWave Infrared (VSWIR) spectrometer with bandwidths of 380 to 2500 nm in 10 nm band increments. It will also have a multispectral thermal infrared instrument with 8 bands in the 3.9–12.3 μm spectral bandwidth. HyspIRI will have a spatial resolution of 30 m for the VSWIR channels and 60 m for the thermal infrared channels, and a repeat cycle of 16 days, with the capability of acquiring both daytime and nighttime measurements. The VSWIR and thermal infrared data obtained by HyspIRI can be used to provide integrated higher level datasets for use in developing detailed quantitative information on spectral responses, surface temperatures, and albedo for the surface material types that comprise the heterogeneous urban landscape. An evaluation of the synergies between VSWIR and TIR data for the urban environment using the NASA AVIRIS and MASTER airborne sensors as HyspIRI surrogates, is given in Roberts et al., 2012. Results from this study illustrate that HyspIRI will provide accurate measurement of the differences between urban surfaces, given its high spatial, temporal, and spectral resolutions. Design and engineering specifications and mission architecture for HyspIRI are well documented via the HyspIRI study group (https://hyspiri.jpl.nasa.gov/) which has produced numerous comprehensive reports, white papers, workshop reports and articles in peer-reviewed journals (see the HyspIRI website as well as other references such as Hochberg et al., 2015; Lee, et al., 2015). The HyspIRI study group has also documented the estimated affordability of the mission concept within the lifespan of a sensor designed to meet 2017 decadal survey specifications (see the HyspIRI Concept and Mission Overview document on the HyspIRI website).

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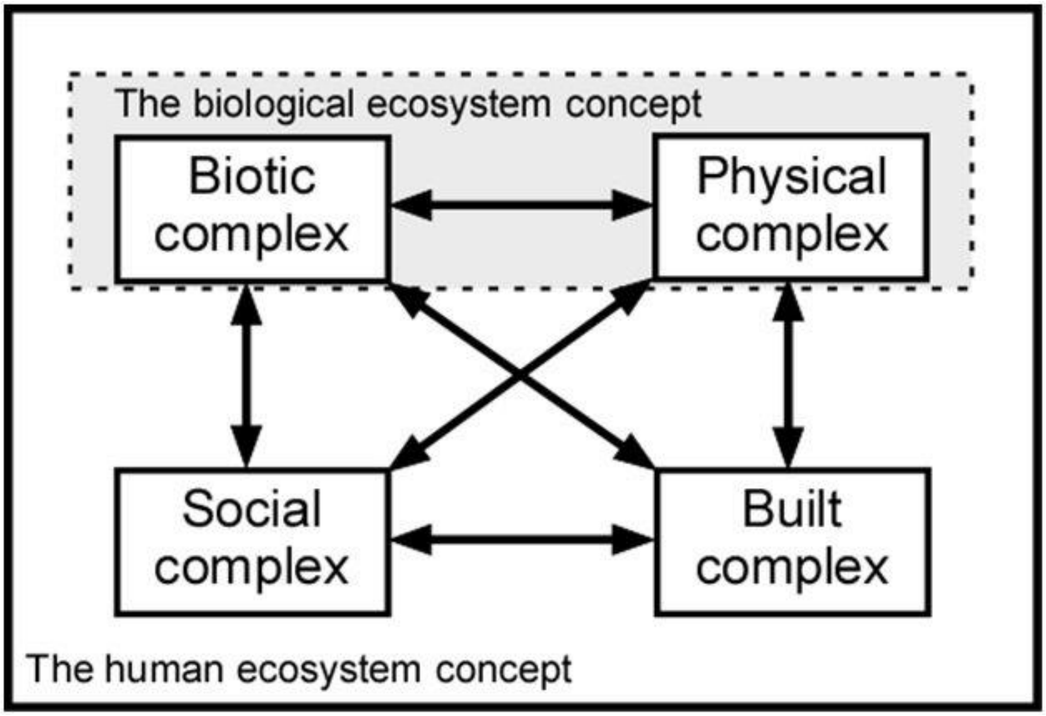


Figure 1. Diagram of the urban ecosystem concept. (Source: Baltimore Ecosystem Study: http://besurbanlexicon.blogspot.com/2011/12/human-ecosystem.html).

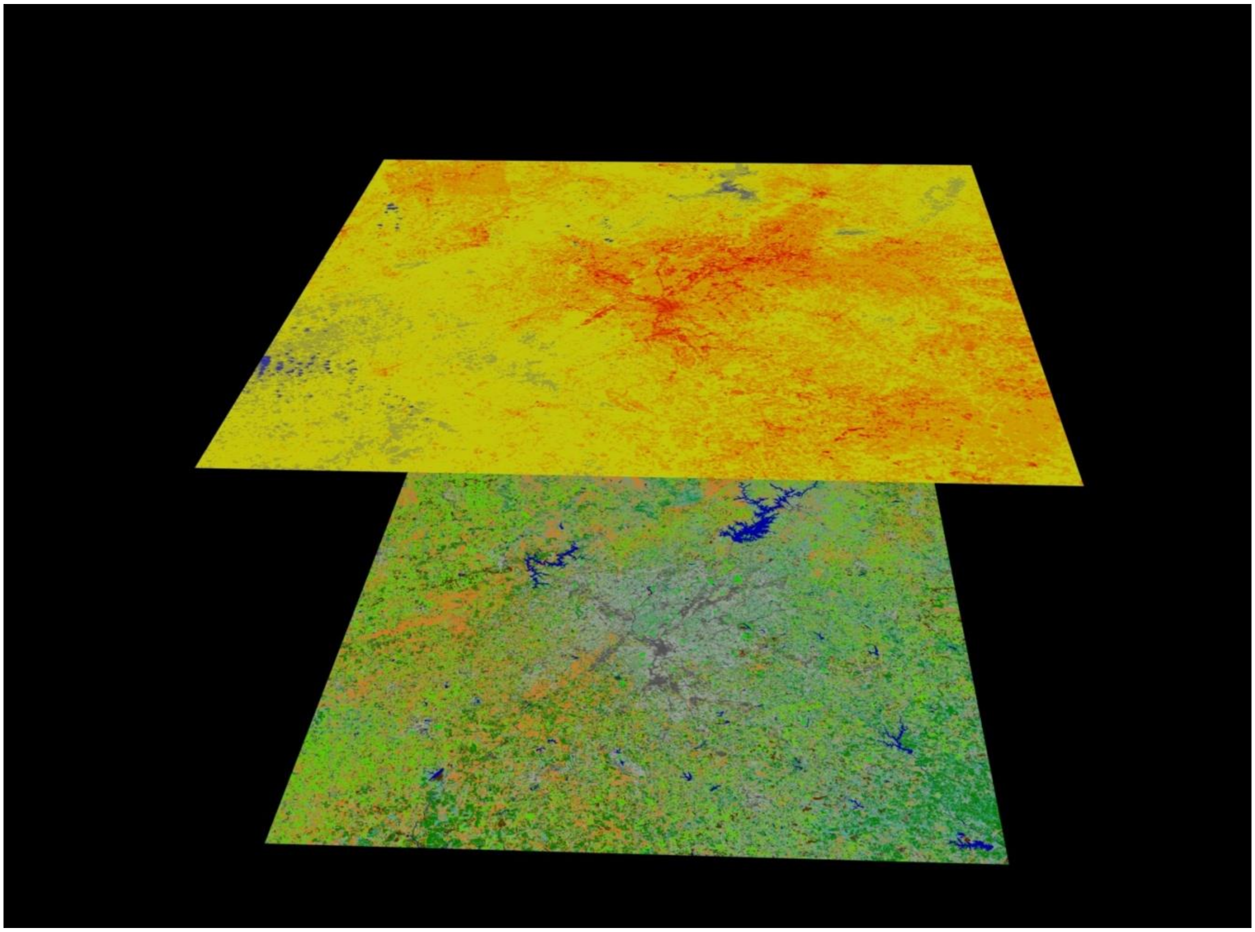


Figure 2. Atlanta Georgia’s urban extent in gray (bottom) and corresponding thermal responses (top) as derived from Landsat TM data, (Source: Quattrochi and Luvall, co-authors).

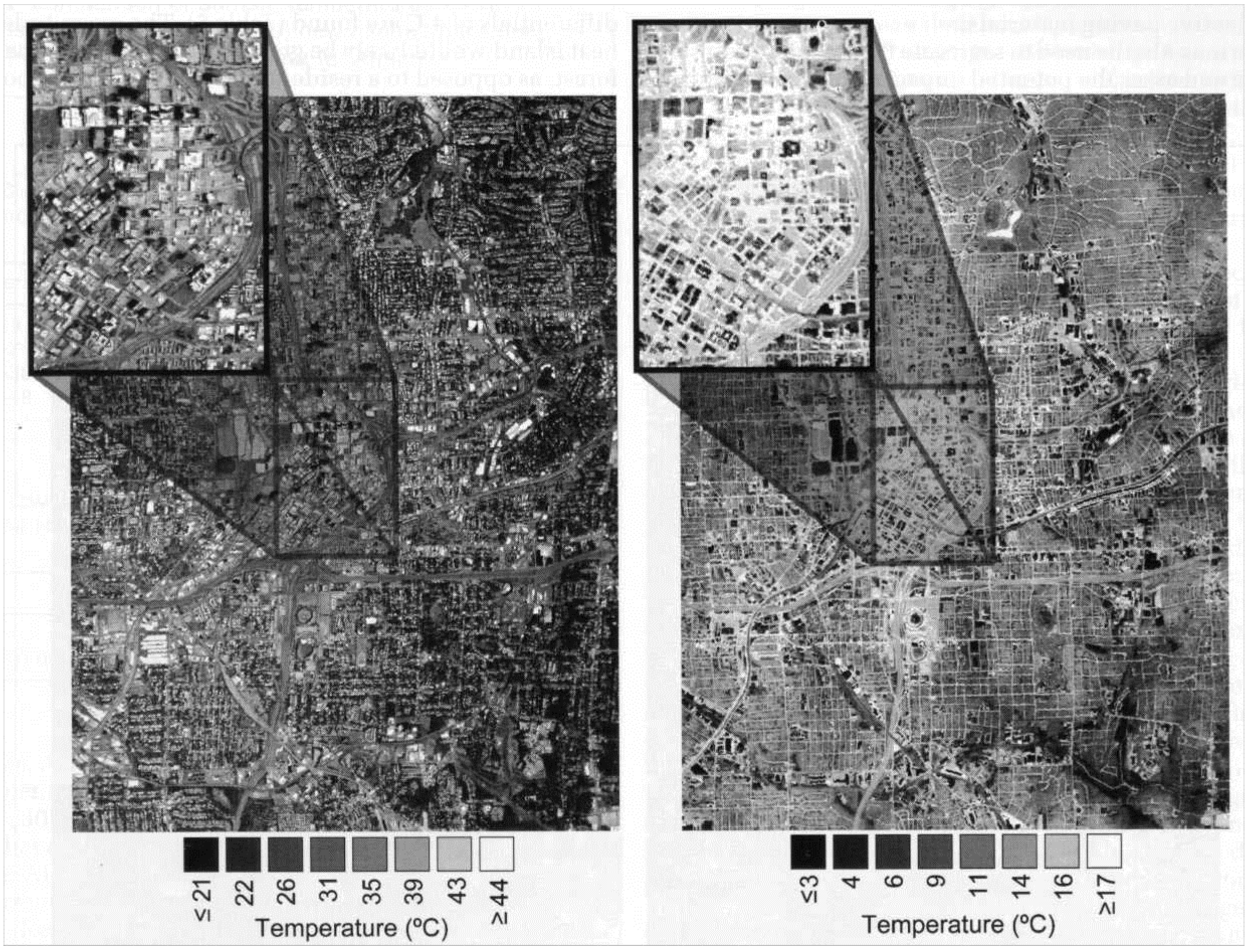
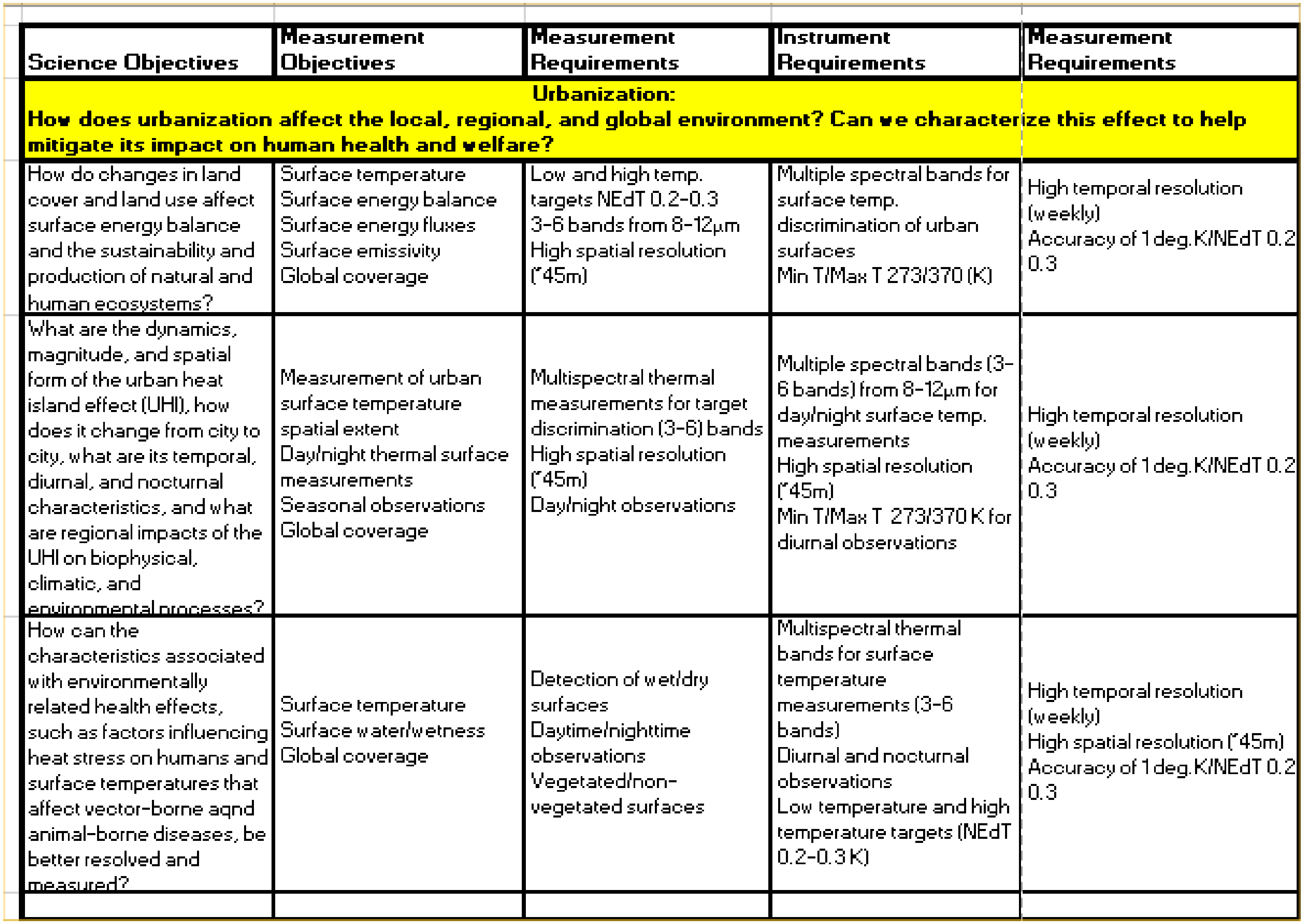


Figure 3. High spatial resolution (20 m) thermal infrared aircraft data collected over Atlanta, GA for daytime (left) and nighttime (right). The images demonstrate the detail that can be discerned about surface temperatures thermal energy fluxes from different urban surfaces from high spatial resolution data. (Source: Quattrochi, D.A., J.C. Luvall, D.L. Rickman, M.G. Estes, Jr., C.A. Laymon, and B.F. Howell, 2000. A decision support information system for urban landscape management using thermal infrared data. *Photogrammetric Eng. and Remote Sensing,* 66(10):1195-1207).



Science Objectives	Measurement Objectives	Measurement Requirements	Instrument Requirements	Measurement Requirements
Urbanization: How does urbanization affect the local, regional, and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?				
How do changes in land cover and land use affect surface energy balance and the sustainability and production of natural and human ecosystems?	Surface temperature Surface energy balance Surface energy fluxes Surface emissivity Global coverage	Low and high temp. targets NEdT 0.2-0.3 3-6 bands from 8-12µm High spatial resolution (~45m)	Multiple spectral bands for surface temp. discrimination of urban surfaces Min T/Max T 273/370 (K)	High temporal resolution (weekly) Accuracy of 1 deg. K/NEdT 0.2 0.3
What are the dynamics, magnitude, and spatial form of the urban heat island effect (UHI), how does it change from city to city, what are its temporal, diurnal, and nocturnal characteristics, and what are regional impacts of the UHI on biophysical, climatic, and environmental processes?	Measurement of urban surface temperature spatial extent Day/night thermal surface measurements Seasonal observations Global coverage	Multispectral thermal measurements for target discrimination (3-6) bands High spatial resolution (~45m) Day/night observations	Multiple spectral bands (3-6 bands) from 8-12µm for day/night surface temp. measurements High spatial resolution (~45m) Min T/Max T 273/370 K for diurnal observations	High temporal resolution (weekly) Accuracy of 1 deg. K/NEdT 0.2 0.3
How can the characteristics associated with environmentally related health effects, such as factors influencing heat stress on humans and surface temperatures that affect vector-borne aqnd animal-borne diseases, be better resolved and measured?	Surface temperature Surface water/wetness Global coverage	Detection of wet/dry surfaces Daytime/nighttime observations Vegetated/non-vegetated surfaces	Multispectral thermal bands for surface temperature measurements (3-6 bands) Diurnal and nocturnal observations Low temperature and high temperature targets (NEdT 0.2-0.3 K)	High temporal resolution (weekly) High spatial resolution (~45m) Accuracy of 1 deg. K/NEdT 0.2 0.3

Figure 2. Urbanization traceability matrix.