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Potential for global mapping of development via a nightsat mission

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Abstract Nightsat is a concept for a satellite system capable of global observation of the location, form and density of lighted infrastructure and development within human settlements. Nightsat's repeat cycle should be sufficient to produce an annual cloud-free composite of surface lighting to enable detection of growth rates. Airborne and satellite imagery have been used to define the range of spatial, spectral, and detection limit options for a future Nightsat mission. Our conclusion is that Nightsat should collect data from a near-synchronous orbit in the early evening with 50–100 m spatial resolution and have detection limits of $2.5E^{-8}$ W cm^{-2} sr^{-1} μm^{-1} or better. Multispectral low-light imaging data would be better than panchromatic data by providing valuable information on the type or character of lighting, a potentially stronger predictor of variables such as ambient population density and economic activity.

Keywords Urban · Exurban · Nighttime lights · Global mapping

Introduction

Artificial lighting is a unique indicator of human activity that can be measured from space. We propose a Nightsat mission, which could be used to map the extent and character of development more accurately and completely than most currently available tools. Improved global mapping of human settlements and their annual growth rates would address a variety of

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science and policy issues in the 21st century—an era in which human population numbers are expected grow substantially from the current 6+ billion mark.

The density of infrastructure—or 'urbanness'—can be viewed as a continuum ranging from wilderness at one extreme to central business districts at the other extreme (Weeks 2004). Human beings tend to cluster in spatially limited settlements with more than 50% of global population living in dense settlements occupying less than 3% of the world's land area (Small and Cohen 2004). Today more than half of the population lives in urban areas (United Nations 2006). Urban populations are growing rapidly in the developing countries of Latin America, Asia, and Africa. In Europe, North America, and Japan the population percent in urban populations are already near 80%. Sprawl on the urban fringe and exurban development are widespread. But structural change permeates urban areas through continuous redevelopment through the replacement of aging infrastructure. Over time urban areas are in a constant state of redevelopment and flux that reflect both growing urban populations and the evolution of technologies.

A recent report written by the Space Studies Board of the National Research Council had this to say regarding the observation of human impacts (Space Studies Board, National Research Council 2007):

> "Human influences on the Earth are apparent on all spatial and temporal scales. Thus, an effective Earth information system requires an enhanced focus on observing and understanding the impact of humans, the influence and evolution of the built environment, and the study of demographic and economic issues. For instance, space-derived information on urban areas can provide a platform for fruitful interdisciplinary collaboration among Earth scientists, social scientists (e.g., urban planners, demographers, and economic geographers), and other users in the applications community. Data on the geographic "footprint" of urban settlements, identification of intra-urban land-use classes, and changes in these characteristics over time are required to facilitate the study of urban population dynamics and composition, and thereby to improve the representation of human-modified landscapes in physical and ecological process models. Because of the rapid growth in urban areas, particularly in the developing world where there are few alternative sources of information on urban extent and land cover, these observations are needed to understand a growing source of anthropogenic forces on regional weather and climate, air and water quality, and ecosystems, and to apply this understanding to protect society and manage natural resources."

The potential value for satellite remote sensing of artificial lighting stems in part from the difficulty in global mapping of human settlements in a repeatable, timely manner from traditional sources. Although development features can be extracted from high spatial resolution (~1 m) satellite imagery, the production of annual maps of human settlements on a global basis from these data sources is not feasible (at this time) from either a collection or analysis perspective. Moderate resolution Landsat-style systems are capable of global collections on an annual basis and such data have been used effectively for mapping urban areas and tracking growth in local settings. However, recent comparative analyses of Landsat data from diverse urban areas worldwide indicate that the diversity of construction materials and construction types precludes the existence of any unique spectral signature for urban areas as a thematic class (Small 2005).

In contrast, the remote sensing of artificial lighting provides an accurate, economical, and straightforward way to map the global distribution and density of developed areas. The widespread use of such lighting is a relatively recent phenomenon, tracing its roots back to the electric light bulb commercialized by Thomas Edison in the early 1880s. Artificial lighting has emerged as one of the hallmarks of modern development and provides a unique attribute for identifying the presence of development or human activity that can be sensed remotely. While there are some cultural variations in the quantity and quality of lighting in various countries, there is a remarkable level of similarity in lighting technology and lighting levels around the world.

The only satellite sensor currently collecting global low-light imaging data suitable for mapping urban lighting is the US Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). Results to date obtained from DMSP-OLS nighttime lights data indicate that this data source falls short of the science community's requirements for urban studies. The objective of this paper is to review the science community's requirements for global satellite observations of human settlements and to define a Nightsat mission concept to address an number of these requirements.

The DMSP-OLS

Beginning in the early 1970s the US Air Force Defense Meteorological Satellite Program (DMSP) has operated polar orbiting platforms carrying cloud imaging sensors with low light imaging capability. These sensors have two broad spectral bands: visible–near infrared (VNIR) and thermal infrared (TIR). The program began with a sensor known as the SAP (Sensor Aerospace Vehicle Electronics Package) flown from 1970 to 1976. The current generation of OLS sensors began flying in 1976 and are expected to continue flying until at least 2012. At night the visible band is intensified with a photomultiplier tube to permit detection of clouds illuminated by moonlight. The OLS detects radiances down to the $5E^{-10}$ W $cm^{-2}sr^{-1}$ range, which makes it possible to detect artificial sky brightness surrounding large cities and gas flares.

A digital archive for the DMSP-OLS data was established in mid-1992 at the NOAA National Geophysical Data Center. In 1994 NGDC began developing algorithms for producing annual global cloud-free composites of nighttime lights using OLS data (Elvidge et al. 1997a, 1999, 2001). These annual products have been used for a variety of applications, including:

- Spatial modeling of population density (Dobson et al. 2000; Sutton 1997, 2003; Sutton et al. 1997, 2001, 2003) and economic activity (Elvidge et al. 1997b; Doll et al. 2000; Ebener et al. 2005; Sutton et al. 2007).
- Quantifying both spatial and size distributions of urban land use for comparative analyses of the global scaling properties of settlement size distributions (Small et al. 2005) and discrimination of urban and rural population distributions (Balk et al. 2005; GRUMP 2006; Small 2004).
- Estimation of the density of infrastructure (Elvidge et al. 2004) for use in hydrologic modeling, flood prediction, the assessment of losses in agricultural land (Imhoff et al. 1997), terrestrial carbon dynamics (Milesi et al. 2003, 2005; Imhoff et al. 2004).
- Modeling of artificial sky brightness and its effect on the visibility of astronomical features (Cinzano et al. 2000, 2001a, b; Cinzano and Elvidge 2004).
- Spatial modeling of anthropogenic emissions to the atmosphere (Saxon et al. 1997; Toenges-Schuller et al. 2006).

From these and other studies the shortcomings of the OLS data for urban analyses have been defined: (1) coarse spatial resolution (2.7 km ground sample distance), (2) lack of on-board calibration, (3) lack of systematic recording of in-flight gain changes, (4) limited dynamic range, (5) six-bit quantitization, (6) signal saturation in urban centers resulting from standard operation at the high gain setting, (7) lack of a thermal band suitable for fire detection, (8) limited data recording and download capabilities (most OLS data are averaged on-board to enable download of global coverage), (9) lack of a well characterized Point Spread Function (PSF), (10) lack of a well characterized Field-of-View (FOV), and (11) lack of multiple spectral bands for discriminating lighting types.

The follow-on for the OLS is the Visible/Infrared Imager/Radiometer Suite (VIIRS) which will fly on the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The first VIIRS is currently being built and represents an improved, but still imperfect, instrument to measure nocturnal lighting (Lee et al. 2006). The NPOESS VIIRS instrument will provide low-light imaging data with improved spatial resolution (0.742 km), wider dynamic range, higher quantitization, on-board calibration, and simultaneous observation with a broader suite of bands for improved cloud and fire discrimination over the OLS. The VIIRS is not, however, designed with the objective of sensing nighttime lights. Rather, it has the objective of nighttime visible band imaging of moonlit clouds—the same mission objective of the OLS low-light imaging. While the VIIRS will acquire improved nighttime lighting data, it is not optimal for this application. In particular, the VIIRS low-light imaging spatial resolution will be too coarse to permit the observation of key nighttime lighting features within human settlements and the spectral band to be used for the low-light imaging is not tailored for nighttime lighting.

A remote sensing product suite for human settlements

Below is a listing of a basic product suite for human settlements that could potentially be derived from satellite observations of lights. Because of the rapid changes ongoing in human settlements worldwide, these key global datasets would ideally be updated annually with a product latency of not more than one year for measurement of the rates of change and annual growth increments.

- Products depicting the geographic "footprints" of human settlements of all sizes. This includes the outline of the developed areas and estimates of the constructed area.
- Location and extent of sparse development in rural areas.
- Identification of intra-urban classes, such as residential areas, heavily lit commercial and industrial areas, and open lands with little or no development present.
- Vectors for streets and roads based on alignments of lights.

Our assessment is that a low-light imaging system optimized for deriving the listed human settlement products would generate data suitable for a wide range of urban, environmental and socio-economic applications. It is clear that having radiance calibrated data is a crucial requirement for the quantitative applications and change detection using nighttime lights data.

Data

To explore the remote sensing of nighttime lights we have examined high spatial resolution airborne and moderate resolution satellite data collected at night.

Airborne imagery

NASA acquired Cirrus Digital Camera System (DCS) data at night over Las Vegas, Nevada and Los Angeles, California on September 27, 2004 at 13.7 km above sea level. Digital photography was acquired using an 80 mm lens and a 1/60th second exposure. The Cirrus DCS is designed as a color camera. For the nighttime collections the infrared blocking filter was removed and the signal from each of the three bands were aggregated in post flight processing to form panchromatic imagery. The collections span desert areas devoid of lighting, cross a wide range of development types, and encounter the world's brightest light, emitted from the Luxor Hotel and Casino in Las Vegas. The Luxor lighting installation is composed of 39 7000-Watt xenon lamps, pointing straight up into the sky. The lighting installation intensity reaches 40 billion candelas. The spatial resolution of the Cirrus camera data was 1.5 m at 16-bit quantitization. The Cirrus camera was subsequently calibrated using an integrating sphere at the NASA Ames Research Center.

As seen in Fig. 1, it is possible to detect many individual light sources in the Cirrus imagery. Note that at this spatial resolution nighttime lights provide a very different view of development when compared to high resolution daytime imagery (Fig. 1). To analyze the spatial resolution limits that should be considered for a Nightsat, the high spatial resolution imagery was aggregated to 25, 50, 100, 200 and 742 m resolution (Fig. 2). The 742 m aggregation simulates the low light imagery that will be collected by the VIIRS instrument.

Space imagery

We investigated the feature content of moderate-resolution color imagery of lights at night from space with digital photography acquired from the International Space Station. Astronauts have long marveled at the shear beauty of cities at night. However, the features have been difficult to photograph due to mismatches between the optimal exposure times and the velocity of the spacecraft. During Expedition 6 (November 23, 2002 through May 3, 2003) to the International Space Station, a mechanized but manually driven image motion compensation mount was built from existing hardware and color images were acquired of cities at night all over the world through an optical-quality nadir-viewing window. Images were acquired with a Kodak-Nikon 760 digital

Fig. 1 (**a**) Nighttime lights observed for a section of Las Vegas, Nevada at 1.5 m resolution. The image has been co-registered to the Ikonos image shown in (**b**). (**b**) True color Ikonos imagery for a section of Las Vegas, Nevada

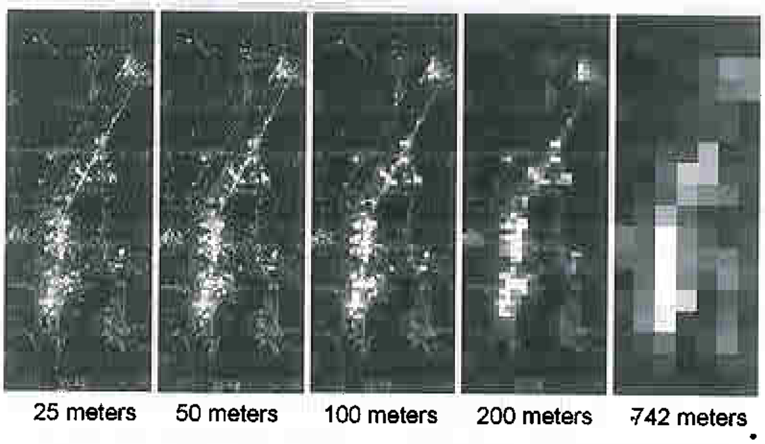

Fig. 2 Simulated nighttime lights data of Las Vegas, Nevada at 25, 50, 100, 200 and 742 m resolution. Source imagery was acquired at 1.5 m resolution from NASA's ER-2 flown at 13.7 km above the earth with a Cirrus DCS digital camera. Note that major buildings and many streets and roads can be discerned at 25–50 m resolution. Some of this detail is lost at 100 m resolution. At 200 m resolution it is still possible to map the urban form. At 742 m resolution (simulation of VIIRS low-light imagery) much of the detail in the urban form has been lost

camera with 58 mm, f1.2 nocto aspheric lens. The ground sample distance (GSD) of the imagery was generally near 60 m. Figures 3 and 4 show color images of Washington, DC and Abu Zaby, United Arab Emirates.

Discussion

The data in Fig. 2 can be used to establish the spatial resolution range for a future Nightsat sensor. Compared to the 1.5 m resolution source data there was very little degradation in spatial detail in the 25 m resolution aggregation. Lighting features associated with large buildings and roads are still discernable at resolutions of 50–100 m. When aggregated to 200 m the primary urban forms are clear. At 742 m resolution many of the urban form features have been lost. Our assessment is that a Nightsat should acquire low-light imaging data in the 50–100 m range.

In examining the Cirrus camera imagery we found that the dimmest detectable lighting had radiances in the range of 5E^{-5} W cm^{-2} sr^{-1} μm^{-1}. These areas were generally lit terrain closely surrounding shielded lights. The signal-to-noise ratio (SNR) for this lighting was about nine. Lighting from individual poorly shielded 100-Watt incandescent bulbs present on the exteriors of recently constructed homes produced measured radiances in the range of 1E^{-4} W cm^{-2} sr^{-1} μm^{-1} The Cirrus camera saturated at radiances above 3.83E^{-3} W cm^{-2} sr^{-1} µm^{-1}. The upward pointing light on the Luxor casino in Las Vegas produced a 37 m diameter circular zone of saturated pixels in the Cirrus imagery. Other small areas of saturated data were found on large casinos near the Luxor. Since the Luxor beacon is the brightest light on earth, this effectively defines the saturation radiance for a Nightsat at approximately 2.5E^{-2} W cm^{-2} sr^{-1} µm^{-1}, a level suitable for daylight imaging of the earth.

The Cirrus camera was unable to detect terrain lit by shielded lights—a key requirement for a Nightsat. It is estimated that detection of this type of lighting and sparse lighting in rural environments would require detection limits in the 2.5E^{-8} W cm^{-2} sr^{-1} µm^{-1} range for 50 m resolution imagery.

The 60 m resolution ISS imagery shown in Fig. 3 and Fig. 4 confirms that Nightsat imagery collected at 50–100 m resolution would provide a substantial level of detail on urban structures and urban forms. The camera used on the ISS acquired true color imagery and it is possible to discriminate orange, green and white lights in the images. For a Nightsat it would be possible to tailor the spectral bands more specifically artificial lighting. Using the photopic (0.51–0.61 µm) and scotopic (0.45–0.55 µm) bands, standards recognized in the lighting engineering community would make sense. A third low-light imaging band could be placed in the 0.6–0.9 µm range.

It is important to recognize some of the caveats related to the distinction between lighted area and population density. Comparisons of the OLS lights with higher resolution imagery shown here indicates that stable lights detected from space are related primarily to outdoor lighting rather than leakage of indoor lighting. At fine spatial scales, the lights are actually a proxy for the presence of lighted infrastructure rather than population density. While the presence of lighted infrastructure usually indicates the presence of population at global scales, the spatial scales differ such that many lighted areas are actually not inhabited at spatial scales approaching the dimension of the area lit by an individual light (e.g. parking lots). At coarser spatial scales larger lighted complexes may be sparsely populated (e.g. oil production facilities). At still coarser scales, approaching the dimensions of small cities, scattering of light in the atmosphere results in an overglow that extends beyond the actual built area (Imhoff et al. 1997; Small et al. 2005). The extent to which area and intensity of lighting corresponds to population density, or even infrastructure extent, depends on a variety of historical, political and socioeconomic factors. At global scales there is some correspondence between lighted area and population density but there is considerable variance in the relationship (Sutton et al. 1997, 2001, 2003). At the finer spatial scales advocated for Nightsat, the most brightly

Fig. 3 Abu Zaby (United Arab Emirates) imaged at night from the International Space Station (ISS). The resolution of the imagery is approximately 60 m. Note that orange, green and white lighting can be discerned. It is likely that the orange lights are from sodium vapor lamps. The linear features are roads lit by string of streetlights. The ISS cities at night digital photography demonstrates the feasibility of collecting moderate resolution multispectral low-light imaging data globally from a satellite platform

Fig. 4 Washington, DC imaged at night

lighted areas would not necessary correspond to the most densely populated regions but the data could be aggregated to spatial scales where lighted infrastructure would generally be a reasonable proxy for population density above some threshold level.

Conclusion

Nighttime lights provide a useful proxy for development and have great potential for recording humanity's presence on the earth's surface and for measuring important variables such as annual growth rates for development. Current and planned systems for global low-light imaging from space lack the spatial resolution to meet primary objective in the urban and socio-economic sciences. Therefore, we propose a Nightsat mission capable of acquiring sufficient data in a year to form a global map the spatial distribution, size and brightness of artificial lighting. Moderate resolution low-light imaging sensor data would be an important complement to the mapping capacity of moderate resolution daytime imaging sensors such as Aster and Landsat because it would provide an unambiguous indication of the presence of development and growth in development.

To be effective in delineating primary nighttime lighting patterns, Nightsat low-light imaging data must be acquired in the range of 50–100 m spatial resolution and achieve minimal detectable radiances in the range of $2.5E^{-8}$ W cm^{-2} sr^{-1} μm^{-1} (or better) with a SNR of 10. While panchromatic low-light imaging data would be useful, multispectral low-lighting imaging data acquired with three to five spectral bands would enable more quantitative applications and enable the detection of lighting type conversions. Cloud and fire screening of the low light imaging data would be accomplished using simultaneously acquired thermal band data. The thermal band data could come from VIIRS if Nightsat were flown on an NPOESS satellite. The system would use a combination of methods to produce radiance-calibrated data. Geolocation accuracy would be ~50 m, comparable to that of Landsat. The system objective would be to collect a sufficient quantity of imagery to construct annual global cloud-free composites of nighttime lights. A near-sun-synchronous polar orbit, with an early evening overpass, would provide temporal consistency important for change detection.

The weight of scientific evidence increasingly points to human activity as the primary driver for environmental and biological change on the planet. While other satellite missions focus on observing the changes in the environment, the Nightsat mission will focus on mapping the spatial distribution and intensity of an indicator of human activity—nocturnal lighting. The Nightsat sensor requirements have been set to cover a wide range in brightness levels and lighting types, providing detection of sparse development in rural areas and detailed mapping of forms present in urban areas. The ability to track the growth in lighting globally, in a consistent manner on an annual basis would enable a synoptic understanding of the human footprint on natural systems and socioeconomic processes.

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