

# EARTH OBSERVATION FOR URBAN PLANNING AND MANAGEMENT

## State of the Art and Recommendations for Application of Earth Observation in Urban Planning

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### INTRODUCTION

In their report entitled 'State of the World Cities 2006/7' (United Nations, 2006) the United Nations predicts that globally, 2007 will see more people living in urban rather than rural areas. The number of urban dwellers is predicted to rise to almost 5 billion by 2030, which will be 62% of the estimated global population of 8.1 billion. Cities and urban areas will have to expand to accommodate such increases in population, resulting in a variety of social and environmental problems.

The key to successfully survive the rapid urbanization of our countryside is to provide accurate and timely spatial information that will assist decision makers in understanding, managing and planning the continuously changing environment. The synoptic view of cities afforded by Earth Observation (EO)<sup>1</sup> offers great potential for data collection over urban areas. With some major paradigm shifts in EO technology over the last 30 years it is appropriate to examine how EO can now be better harnessed to assist urban planners and managers, and what issues should be exploited by the research and academic community to further its practical application. To this end, a workshop on Earth Observation for Urban Planning and Management was held on 20-21<sup>st</sup> November 2006 in Hong Kong. Hong Kong's status as possibly the world's most densely built modern city, and thus being in need of the most innovative and efficient planning procedures available, provided the catalyst for this meeting. Critical issues were examined with Hong Kong being the point of reference. Delegates comprised an international group of researchers, and practitioners from Hong Kong government departments, providing a mixture of top-down demonstrations and case studies, with bottom-up feedback from user groups.

The workshop addressed four major application areas: *environmental monitoring, land use/land cover mapping, planning, and geotechnical monitoring*. Resulting from the workshop, observations were made on current and potential applications of EO technology, current data qualities and acquisition technologies, major impediments to their more widespread use, and recommendations for future development.

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<sup>1</sup>Earth Observation is defined for the purpose of this article as data collected by sensors mounted in aircraft or on spacecraft.

Image courtesy of [www.microsoft.com](http://www.microsoft.com)

### CURRENT STATUS OF EO IN URBAN PLANNING AND MANAGEMENT

The launch of the first earth observation satellites 35 years ago brought about a major paradigm shift from the use of film-based to digital data, and more recent technological developments have provided high resolution, multi-sensor systems. These are accompanied by other advances such as in computer speed and graphics capability (which, according to Moore's Law, doubles every 24 months (Moore, 1965)), developments in GPS and INS technology that enable the position and attitude of sensors to be fixed more accurately, improvements in communications and Spatial Data Infrastructure (SDI) that enable efficient handling and distribution of enormous volumes of data, and new software enabling faster and more reliable information extraction. These developments have allowed much more data from a greater range of sensors to be collected, and have significantly advanced the potential applications of EO data.

### AREAS OF CURRENT APPLICATION, AND TECHNOLOGIES USED

#### Environmental Monitoring

**Air Quality** — Aerosol Optical Depth (AOD) can be retrieved with acceptable accuracy at low resolution from multispectral sensors such as MODIS, and this is useful for depicting regional air quality affecting urban areas. However, the standard MODIS level II AOD product, at 10km resolution (Kaufman and Tanre, 1998) is too coarse to map aerosol variations over the 1000sq.km of Hong Kong, or to depict source areas. Current algorithms, which use dark vegetated or water surfaces, do not apply to heterogeneous urban areas. The contrast reduction algorithm (Tanre *et al.*, 1979; Sifakis and Deschamps, 1992) devised for application over heterogeneous surfaces, is the least accurate method for aerosol retrieval. Since it measures the blurring effect due to aerosol between pixels within a kernel, larger kernels give higher accuracy but with a corresponding loss of resolution eg. 450m using a 15 by 15 pixel kernel with Landsat data. Although it is unlikely that imaging sensors can ever provide air quality data at resolutions higher than 100m, as can be achieved by street-scale models, resolution improvements are desirable. This would also provide a better match with land cover data that are a major input to air quality models and which are now available from high resolution (HR) sensors.

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**Urban Heat Islands** — The first few years of the 21<sup>st</sup> century have seen record summer temperatures in sub-tropical cities such as Hong Kong, and those of mid-temperate regions such as southern Europe and the southern USA; and the so-called "Oven Cities" of central and south China have recently grown in number. EO technology has been used to study the magnitude and extent of urban heat islands (Roth and Oke, 1989; Streutker, 2003; Voogt and Oke, 2003). However, most thermal image data that represent surface temperature are not collected at a suitable time for analysis of heat islands, which are based on air temperature, and which are greatest at night (Nichol, 2005). Thermal satellite images have however been used for analysis of urban microclimates, and can indicate heat mitigation measures such as appropriate building geometry, building materials, greening campaigns, parks and air flow corridors (Nichol, 1994, 1996, 2005). The resolutions of the only thermal sensors with assured continuity -- ASTER and MODIS (with 90 and 1000m respectively) -- are too low for microclimatic analysis. Furthermore, the resolution discrepancy is too great to permit fusion with high resolution (HR) visible wavelength sensors, to obtain some data quality improvements (Nichol, 1994).

**Planning of Green Space** — Planning of green space for cooling, amenity, recreation and ecology has until recently used air photos (Akbari *et al.*, 2003), due to the small size and fragmentation of urban biomass. However, it is now possible and cost effective for HR satellite images to replace air photos (eg. Pan, XS (06 – 2.5m, 2.5 - 10m)) (Stow *et al.*, 2003; Ehlers, 2004; Nichol and Lee, 2005).

### Land Use/Land Cover and Land Cover Change

Fully automated land use classification in urban areas is not yet operational, even with the development of knowledge-based classifiers, object recognition and feature extraction (Herold *et al.*, 2003; Myint, 2006), and manual interpretation of aerial photographs or HR imagery (eg. Pan, XS (06 – 2.5m, 2.5 - 10m)) is still the norm. Screen digitizing on HR images may give some cost reduction over air photos, but is not a desirable trend in the use of EO technology. To automate the procedures of urban mapping from HR images, integration of GIS information and remote sensing data (eg. Stow *et al.*, 2003) seems to offer great potential, and for the integration of very high resolution panchromatic images into lower resolution multispectral images data fusion methods are being developed (eg. Klonus and Ehlers, 2007). In Hong Kong, manual air photo interpretation and ground survey are used for mapping of the urban core and specialized features eg. industrial estates, airports, ports, expressways, whereas automated classification of medium resolution satellite images (Pan, XS (5 - 15m, 10 - 30m)) is used for land cover of the rural hinterland. Furthermore, since spatial data of the Chinese mainland are unavailable to Hong Kong authorities, satellite images are the only source of land cover information for regional strategic planning, and air quality modeling.

The role of EO sensors for rapidly archiving and documenting land cover change cannot be overestimated, since many cities update land cover annually, or as an on-going process. Therefore continuity of data sources is essential.

### Planning

**Structural and Strategic Planning** — Building of new roads, bridges, new towns etc. requires detailed topographic mapping of a site. Airborne digital cameras (ADCs) have had a significant impact

on image acquisition in many parts of the world with significant savings in the cost and timeliness of topographic mapping being observed. For example, the creation of a true color orthophoto mosaic at 0.3m resolution is said to cost \$140 km<sup>-2</sup> in the USA (Akbari *et al.*, 2003). Furthermore, digital airborne stereo sensors (Ehlers, 2006) are capable of producing automated surface models. Due to its well established film-based mapping program, Hong Kong is yet to benefit from such technological advances. However, in the UK aerial images, from both film and digital cameras, supplemented by lidar for height information, are the major sources of data for planning. Lidar is becoming increasingly important as costs are reduced and data quality increased.

**Visual Impact Assessment by 3D City Modeling** — The data and techniques for generation of 3D city models from lidar and ADCs are available, but depend on manual processing and hence are expensive (eg. see Shan and Sampath, 2006). Models at three fundamental levels of detail (LOD) were identified (Figure 1):

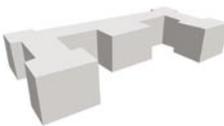
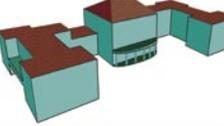
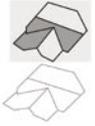
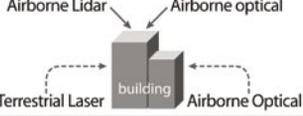
Level of Detail	Method of generation
 <p>1</p>	 <p>Map data plus LiDAR or stereo airborne imagery</p>
 <p>2</p>	 <p>As above plus roof detail from LiDAR and airborne imagery using edge and plane extraction</p>
 <p>3</p>	 <p>Airborne Lidar, Airborne optical, Terrestrial Laser, building, Airborne Optical</p>

Figure 1. Levels of detail for building reconstruction, showing methods of generation.

- **LOD1: Prismatic Models** — Buildings and other structures are represented by regular prisms based on footprints from observation or pre-existing maps, above the footprint, ignoring details of their actual shape.
- **LOD2: Geometrically detailed models** — Structures are represented by geometrically complex objects that show podiums, building shapes and roof structures. Textures may be applied from aerial imagery.
- **LOD 3: Accurately textured and geometrically detailed models** — Integration of aerial and terrestrial data from scanners and mobile mapping cameras.

In Hong Kong the impacts of new planning developments are usually presented in 3D, and building shapes are currently derived from extrusion of known building heights. For example, the Highways Department must present noise impacts of any new road using 3D noise models at LOD2 (Figure 2). Due to the structural complexity of the city, the Hong Kong Civil Engineering and Development Department is currently evaluating airborne laser scanning (ALS) for the greater detail and accuracy potentially obtainable.

**Facilities and Infrastructure Management** — Recent advances in imaging spectroscopy offer the potential for automatic recognition of specific urban surface materials such as roofing, or road type and condition (Herold and Roberts, 2005), but are limited by the low



Figure 2. Noise model in 3D for impact assessment of road traffic noise (Db) in Kwai Chung new town, Hong Kong. Noise levels shown in the model are for indicative purpose and do not relate to actual traffic noise levels on site (Source: Environmental Protection Department, Hong Kong SAR).

spatial resolution of current hyperspectral sensors. Developments in terrestrial based mobile mapping, making use of GPS and inertial navigation systems with image capture, have proved very effective for inventorying urban facilities and infrastructure such as street lights, traffic lights, railings and road signs. In Hong Kong, the Highways Department surveys road surface condition and street furniture by field observation, but The Leader Mobile Mapping System ([www.leador.com.cn](http://www.leador.com.cn)) has been collecting data for many Chinese cities.

## Geotechnical Monitoring

**Slope Monitoring for Landslide Hazard Assessment** — Landslides are the main urban hazard in Hong Kong. Since slopes are often vegetated, InSAR technology is ineffective for detection of slope movement or sub-meter features such as tension cracks, thus high resolution (<0.25m) air photos are extensively used. Lidar could also be used for this application as shown by the Highways Agency in the UK, (Duffel *et al.*, 2006)

**Stability Assessment** — Potential for the use of InSAR in non-vegetated areas is demonstrated by the case of subsidence monitoring on the reclaimed land site of Hong Kong's new airport (Ding *et al.*, 2004; Damoah-Afari *et al.*, 2005). Following reclamation, land undergoes a long period of subsidence, and monitoring of this and other ground deformations may be undertaken with InSAR with precision of a few centimeters (Figure 3). Currently most SAR sensors use C-band, which is not ideal for obtaining coherence over long time periods. The technique of permanent scatterers in urban areas has proven to be very effective where long time sequences of SAR data are available. The European TerraFirma project, for example, (<http://www.terrafirma.eu.com/>) provides a pan European Ground Motion Information Service.

**Urban Runoff and Flood Hazard Assessment by Terrain Modeling** — Lidar is now used in many developed cities such as those in the UK, where it has been extensively applied to mapping and monitoring of river flood plains, supplemented by SAR data to monitor actual flooding, but the techniques are not developed in Hong Kong.

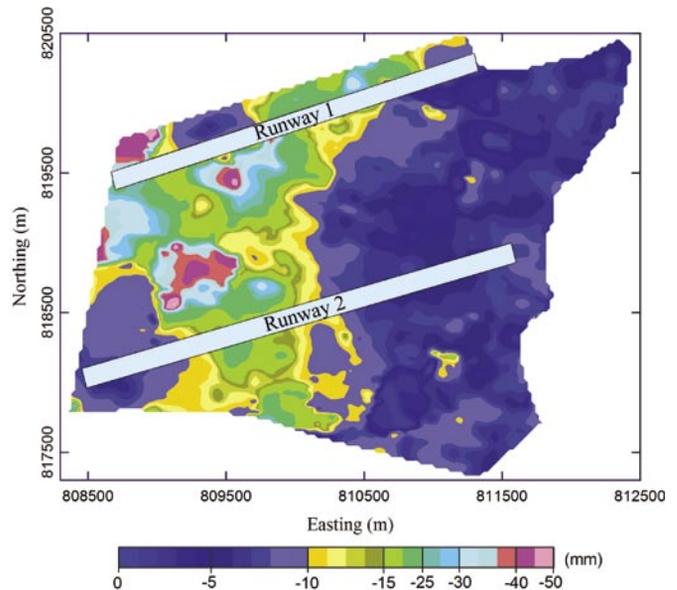


Figure 3. Interferogram from ERS-1's C-band SAR sensor, showing settlement of Hong Kong's Chek Lap Kok airport in the order of 50cms over a 315-day period.

## IDEAL DATA REQUIREMENTS

### Environmental Monitoring

**Air Quality** — The objective for aerosol retrieval over urban areas should be to integrate different methodologies to maximize the spatial resolution of the resulting aerosol product. To this end, provision of a medium resolution (eg. 15-20m) multispectral (or hyperspectral<sup>2</sup>) sensor having a middle infra-red band for the automated retrieval of surface reflectance over vegetation is needed (Kaufman and Tanre, 1998). This would also permit use of the contrast reduction method (Sifakis and Deschamps, 1992), without too much loss of spatial detail due to application of the kernel.

**Urban Heat Island** — The most essential requirement is continuity of a public thermal infrared sensor with at least the same quality as Landsat, since commercial data are too expensive. Optimally, a medium resolution (<30m) thermal infrared sensor combined with a multispectral imager is required. This would give better estimates of surface physical parameters for surface-atmosphere energy flux modeling. The workshop delegates noted that there are technical challenges in building such a sensor, which could be overcome if demand could be demonstrated. There is also a need to time data collection to avoid thermal crossover times and to include night-time images corresponding with heat island maxima.

### Land Use/Land Cover and Land Cover Change

For land use mapping in core urban areas, the spatial characteristics of current HR satellite sensors are adequate eg. 0.6 - 2.5m pan and 2.5 - 10m XS (and see Welch, 1982). Furthermore, urban land use/land cover mapping is not spectrally demanding and Herold *et al.* (2006) recommended the four multispectral IKONOS bands, with an additional two middle infra-red bands, as a suitable combination to distinguish between urban surface types.

For future land cover mapping and updating, the Landsat Data Continuity Mission (LDCM) will continue the medium spatial reso-

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lution (15-30m) multispectral format of the current Landsat ETM+ sensor, but without a thermal infrared band. ASTER will continue to collect data as part of the NASA Terra suite of Earth observation satellites, but ASTER is an “on-demand” sensor with no consistent coverage of any one spot on the globe. As part of the U.S. National Research Council’s (NRC) “Decadal Survey report” (NRC, 2007) that provides an integrated strategy for Earth science and applications from space for future NASA satellite platforms, a new sensor called the Hyperspectral Infrared Imager (HyspIRI) is planned to provide medium resolution data in hyperspectral bandwidths in the visible, near and middle reflective infrared, and thermal infrared wavelengths. Although the specifications for HyspIRI bandwidths, spatial resolution, and revisit time are currently in the planning stage, it is anticipated that data from this sensor will augment the capabilities for land cover mapping currently available.

Developments in small satellites may also supplement, if not replace, large government funded platforms, even if operated on a commercial basis, due to lower costs of manufacturing and deployment. An example is the planned launch in 2009 of a hyperspectral satellite, EnMAP, a joint venture between the German government and the commercial sector. EnMAP will have a spatial resolution of 30 m, 216 spectral bands ranging from 430 – 2400 nm, a swath width of 30 km and repeat cycle of 3 days (Kaufmann *et al.*, 2006). Another German development by RapidEye AG for 2007/2008, is a constellation of 5 identical small satellites, having an effective one-day revisit cycle for the whole world (RapidEye, 2007). The RapidEye sensors are equipped with 5 spectral bands (blue, green red, red edge, near infrared) at 6.5 m resolution and a 77-km swath width.

## Planning

### **Structural and Strategic Planning and Visual Impact Assessment —**

The 3D topographic models and building models generally required for major engineering projects can be semi-automated if lidar/ADC data can be made more cost-effective.

**Facilities and Infrastructure Management —** Automated mapping of urban surface materials eg. roofing materials, asphalt and concrete is possible if high resolution hyperspectral sensors are made available. However, these are not urgent requirements and neither hyperspectral data nor higher resolution are considered a priority for urban mapping.

## Geotechnical Monitoring

**Slope Monitoring and Stability Assessment —** It is desirable to supplement the current high resolution SAR sensors, with more frequencies and longer wavelengths such as the L-band SAR sensor on the current Japanese ALOS satellite, and the X band on the forthcoming German TerraSAR X satellite, to be followed later by TanDEM X as well as the provision of imagery with short time intervals. More research on data processing is also required to improve the general performance of InSAR techniques.

**Inundation —** Data from InSAR and lidar are able to supply the requisite extensive scale terrain models but, for any project, cost effectiveness must be established.

## RECOMMENDATIONS

Workshop participants made the following recommendations for the use of earth observation in urban areas such as Hong Kong.

## Software improvements

- Existing thermal and air quality models are outdated and cannot exploit current HR land cover data; therefore, larger scale and multi-scale models for both thermal and air quality analysis are required.
- Current aerosol retrieval algorithms are least accurate over heterogeneous urban areas and resolution is low. More research is required to integrate models which operate over dark vegetation and water surfaces with those developed for urban areas.
- Improvements in automated recognition of complex objects on high resolution image data are required to avoid the analysis of large quantities of HR imagery by “computer-assisted photo-interpretation”, which is a euphemism for screen-digitizing.
- Development of automatic 3D segmentation algorithms for conversion of lidar images to accurate 3D building models is the main requirement for visual impact assessment.

## Cost Reductions

Lower image costs are required to promote greater usage, but this may be difficult in the short term as current HR commercial satellites such as IKONOS are supported by bulk orders from military budgets (Vaughan, 2004). Although in the medium term, cost reductions may result from greater demand due to increased awareness, small satellites such as ESA’s PROBA, China’s Beijing 1 and Nigeria’s NigeriaSat are a welcome development.

## Promotion of Data Sharing Policies and Practices

The use of data would be increased and costs lowered if data were more easily shared. Currently in Hong Kong, government departments share government-flown aerial photography at no cost. The inability to share satellite images purchased from one department’s budget due to copyright restrictions imposed by space agencies mitigates against increased use of EO data, and reinforces existing workplace practices.

## Better definition of data quality standards

Universally recognizable spatial data infrastructures (SDI) with standard formats, definitions and metadata, permitting understanding of data quality, would also promote increased acceptance of EO data by end users. The problems of radiometric degradation due to satellite sensor ageing, processing at ground stations, sensor calibration factors and geometric accuracy are often not readily available or understandable to end users.

## Education

The research and scientific community can encourage increased usage of EO technology by case studies to increase awareness of EO technologies. For example, there are many applications of 3D city models, but the benefits of these are not always known to decision makers. The development of “Virtual London” by the Centre for Advanced Spatial Analysis (CASA) at University College, London University (<http://www.casa.ucl.ac.uk/projects/projectDetail.asp?ID=55>) and the European Organisation for Experimental Photogrammetric Research’s (OEEPE) studies of 3D city models (Fuchs *et al.*, 1998) provide examples that can be targeted at a wide range of user groups, from visual impact and noise analysis, to flood hazard assessment and air quality in urban canyons. To this end, more research and communication of costs and benefits to decision-makers is recommended.

## SUMMARY

Overall, eight recommendations for researchers, space agencies and decision makers resulted from the workshop, as summarised below:

### For Researchers

- Collect and distribute case studies demonstrating cost effective benefits of EO data.
- Continue development of algorithms for:
  - ♦ automated feature extraction for land use mapping from HR images,
  - ♦ automated 3D feature extraction from lidar data,
  - ♦ estimates of data quality and uncertainty, and
  - ♦ aerosol retrieval in urban areas.
- Promote data sharing policies and technologies by working with the Open Geospatial Consortium (OGC: [www.opengeospatial.org](http://www.opengeospatial.org)) and the Global Spatial Data Infrastructure Association (GSDI: [www.gsdi.org](http://www.gsdi.org)).

### For Space Agencies (in order of priority)

- Ensure continuity of Landsat type data for land cover mapping.
- Provide a high resolution thermal imager for urban climatology.
- Provide a new multispectral sensor with 10 – 20m resolution and a short-wave infra-red band for air quality analysis.
- As above, but substitute "hyperspectral" for "multispectral".

### For Decision Makers

- Provide funding for further research into use of EO data for local requirements and work with local research organisations to achieve local objectives.

## CONCLUSION

The workshop concluded that, with the exception of thermal modeling, the impediments to wider use of EO data in urban planning and management are educational and institutional, not technical. The technology for image data acquisition is available and its wider utilisation is mainly dependent on increased awareness of its availability among practitioners, cost reductions, and easier integration into existing work procedures. In practice, action at the local level is likely to be more effective and the use of case studies is recommended. In order to optimise such initiatives, further research is essential to increase automation in 3D city modeling and land use mapping from HR images. However, since every city is unique, the development of "black box" algorithms, implying complete automation, is probably neither possible nor desirable and researchers are encouraged to work with end users to develop realistic local solutions. For example, Hong Kong planners require 3D city models at LOD3 due to the layered complexity of the city. Thus, semi-automation of data processing algorithms that use knowledge-based models and permit end-user interaction is more realistic. This entails a degree of change in workplace methodologies, which can best be facilitated by demonstrations of how EO technology can make peoples' jobs more efficient and productive.

Over the last 35 years, EO technology has developed the ability to capture urban areas at higher levels of spatial and spectral detail than are actually required for effective urban planning and management. Indeed, frequent use of the terms "multi-" and "hyper-" suggest an imminent shortage of superlatives. For dynamic cities

such as Hong Kong, where even 25-year-old buildings are considered obsolete, and neighbouring cities on the Chinese mainland are growing at lightning speed, environmental monitoring, automated land use mapping and VRML modeling for planning decisions, are the most immediate needs. The challenge now is for the research and scientific community to develop and demonstrate these applications.

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Sustainable urban planning and management demand innovative concepts and techniques to obtain up-to-date and area-wide information on the characteristics and development of the urban system. The increasing availability of Earth Observation (EO) technologies has provided new opportunities for a wide range of urban applications, such as mapping and monitoring of the urban environment, socio-economic estimations, characterization of urban climate, analysis of regional and global impacts and urbanâ€™ Earth Observation (EO) can play a valuable role in sustainable urban development and planning, since it represents a powerful data source with the potential to provide a number of relevant urban sustainability indicators. To this end, in this paper we propose a conceptual list of EO-based indicators capable of supporting urban planning and management. Three cities with different typologies, namely Basel, Switzerland; Tel Aviv, Israel; and Tyumen, Russia were selected as case studies. The EO-based indicators are defined to effectively record the physical properties of the urban environment in a