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Methods

3D Dynamic Representation for Urban Sprawl Modelling: Example of India's Delhi-Mumbai corridor

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Abstract

3D dynamic geo-visualisation models reflect changes in urban land areas and make a new contribution to the spatiotemporal representation of land use processes and the production of geographic knowledge. They facilitate understanding of the process of urbanisation and the resulting transformations of land use. The 3D dynamic visualisation model of the Delhi-Mumbai corridor in India illustrates how it is now possible to integrate the temporal, spatial dynamic and geographic dimensions of a process of land use transformation. Temporal methods of monitoring urbanisation are fundamental in anticipating future needs, and for land management and planning at national, regional or urban level. They can be used, for example, to highlight potential conflict zones that might result from the urbanisation of farmland or to monitor the environment and population. The limits of 2D/3D dynamic cartography are neither conceptual nor methodological. They consist in: (i) the size of geographic databases and the problems of management they entail, (ii) the quality of the data and the databases, which determines the accuracy of the representations and the potential for producing geographic knowledge. These models serve as decision aids in land development, forward planning or even geo-marketing and allow for better environment, population and land use management. Because they make it easy to read and understand the phenomena they represent, they provide excellent monitoring systems for non-geographers and the potential for their development is considerable.

Keywords: urban Geographic Information System, temporal GIS, geo-visualisation, dynamic modelling, India's Delhi-Mumbai corridor

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1. INTRODUCTION

Geographic Information Systems (GIS)[1] are used for 2D or 3D dynamic spatio-temporal modelling and analysis of the processes of urbanisation and metropolisation. 3D dynamic geo-visualisation[2] of urban growth is able to represent the intensity, spatial reach and impact of urbanisation on land area. It can be used to measure, characterise and model transformations of geographic space, taking into account both the global entirety and the local particularities of the urbanisation process on different geographic and temporal scales, to identify certain social consequences and even environmental impacts, or to anticipate possible changes in land use (Mitas et al, 1997).

2D/3D dynamic temporal Geographic Information Systems are created from satellite images, maps and geo-referenced databases. Because the volume of data to be integrated, processed, harmonized and modelled is so vast, and because so much computer time and processing power is still required[3], these systems are not as yet widespread. By making the representation of complex geographic phenomena more accessible and intelligible (Malinverni et al, 2002), however, geo-visualisation is of invaluable service and its potential for development is considerable.

This article analyses urbanisation along the Delhi-Mumbai development corridor to illustrate how the use of 2D and 3D dynamic geo-visualisation makes it easier to read, analyze and understand the processes of land transformation. The corridor in question has a population of over 500 million people and since the early 1990s has undergone massive urban growth characterised by diversified forms of land division. It is possible to geo-visualise urban growth along the entire Delhi-Mumbai corridor, at regional or urban level (figures 2, 5, 7, 8, 9) in either a static form (figure 5) or dynamic form (figures 8, 9), in 2D (figure 8) or in 3D (figure 9). These spatial models are used in planning to monitor spatial dynamics, analyse investment and infrastructure needs, implement planning policies at the federal, regional (transport system, land integration) and local level (urban planning). Figures 1, 6, 7, 8, 9 show that 2D/3D or true 3D representation renders intelligible the intensity, directions, structures and forms of growth of a developing city or urban region.

2. A MULTI-TEMPORAL, MULTI-LEVEL DYNAMIC 2/3D GEOGRAPHIC INFORMATION SYSTEM

2.1. GEOGRAPHIC INFORMATION SYSTEMS FOR URBAN GROWTH MONITORING

2.1.1. REMOTE SENSING APPROACHES TO URBAN SPRAWL

Satellite remote sensing offers a privileged gateway to the monitoring, modelling and analysis of urbanisation processes, particularly in developing countries, where it makes up for the scarcity of geographic data and up to date maps (Gadal, 2003).

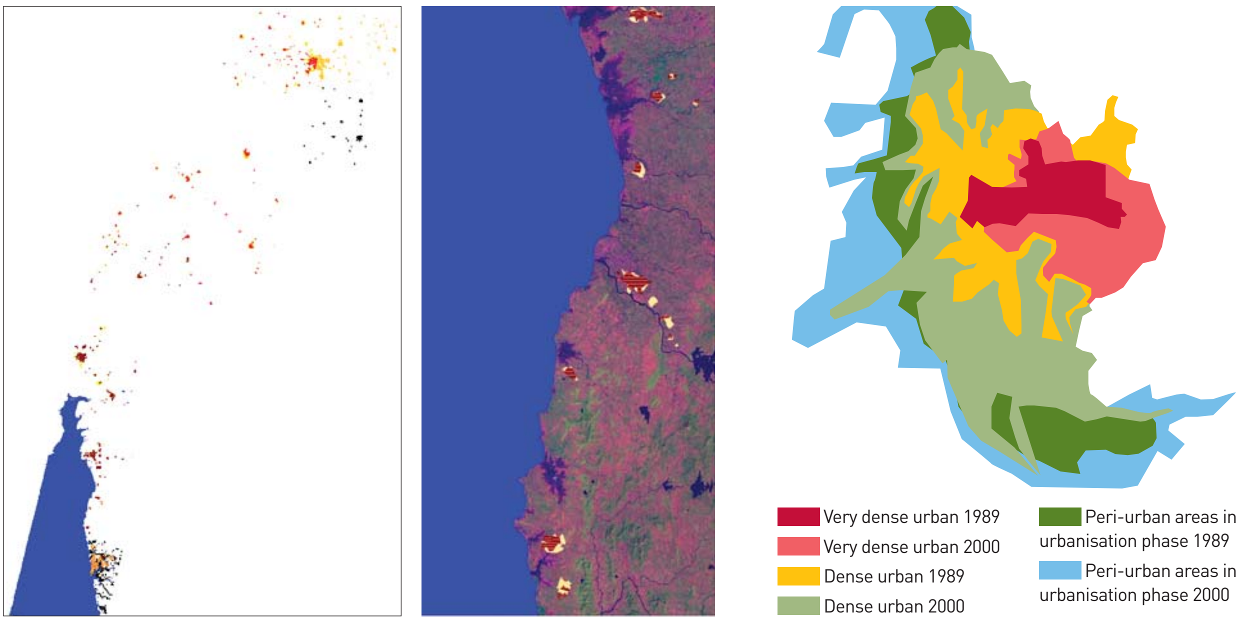

Figure 1. Urban growth along the Delhi-Mumbai corridor between 1990 and 2000: global, regional and urban scales.
The GIS provides geo-visualisation in cartographic form of the urban framework of the Delhi-Mumbai corridor and its development between 1990 and 2000 on different geographic scales: globally, over specific areas of land on regional and local scale in the form of geographic images or a spatial model of developing urbanisation. Global scale **(left)**: development of the Delhi-Mumbai corridor urban structure between 1990 (red) and 2000 (yellow) obtained from DMSP, Landsat 5 TM and Landsat 7 ETM+ images. (Note the lack of information on the northern part of the Delhi region in 1990.) Regional scale **(middle)**: coastal urban growth in the Navasari region over 185 km between 1990 (red) and 2000 (yellow) mapped from Landsat 5 TM and Landsat 7 ETM+ images. Urban scale **(right)**: modelling the expansion of Jaipur between 1989 and 2000 (Carton, Gadal, 2007).

1 See Glossary.
2 See Glossary.
3 (Abdul-Rahman et al, 2006; Cartwright et al, 2008; Cartwright et al, 2009; Cruz et al, 2009)

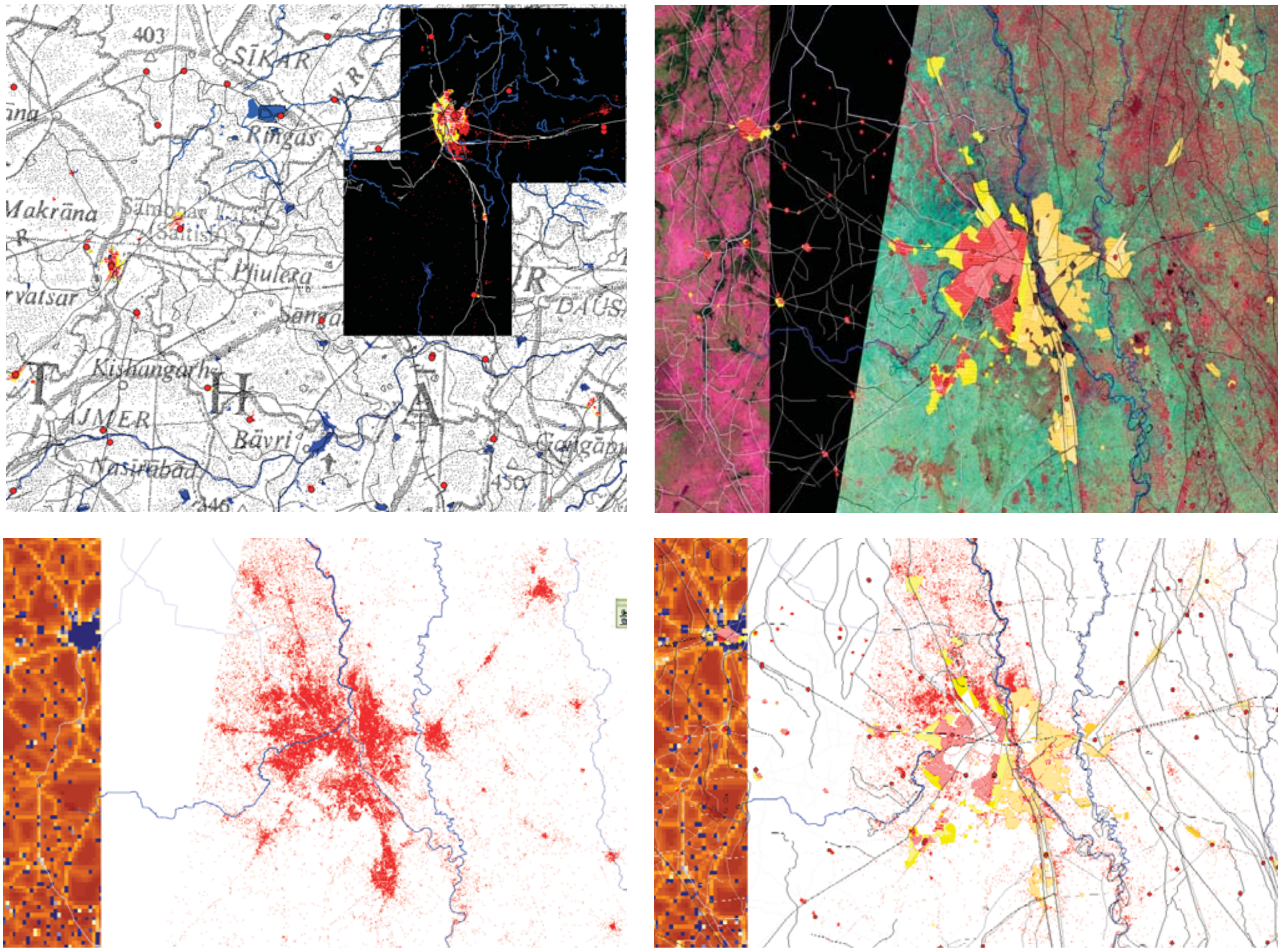

Figure 2. Geo-visualisation of "harmonised" hybrid databases.

Extracts from the GIS integrating geographic and cartographic information and images (produced by extracting urban spaces from satellite remote sensing or by merging images). The upper left panel shows a scanned topographic map of India associated with a map localising urbanised areas, and several spatio-maps of urban sprawl in 1990 and 2001, of hydrology and of road routes. These spatio-maps were generated from Landsat 5 TM and 7 ETM+ satellite images. The upper right panel represents the same spatio-maps superimposed on a colour composite (merging satellite images taken in different spectral bands). The lower left panel shows the results of extracting urbanised spaces in 2007 from Spot (red) and DMSP (blue) satellite images, associated with a hydrology spatio-map produced from a Landsat 7 ETM+ image. The lower right panel represents the same geographic information, onto which have been superimposed the map of urban area locations (villages, towns), and spatio-maps of the road network and of urban sprawl between 1990 and 2001.

Satellite images, which are rapidly accessible and have been available for the past thirty years or so from the Landsat satellite serie and then from the Spot series[4], are used to monitor at regular intervals, annually or more frequently, the dynamics of urbanisation and land use transformation, particularly in countries like India which have very high rates of urbanisation (Sudhira et al, 2003). Maps and geographic databases, which rapidly become obsolete, can thus be updated. Satellite images can be used to monitor the development of urbanisation continuously over geographic areas of differing sizes[5]. Spatial modelling of urbanisation processes is carried out *ostensibly by* diachronic analysis of remote sensing, i.e. by comparison of images or spatio-maps between two or more dates (Sudhira et al, 2003; Sudhira et al, 2004; Gadal, 2006; Canty, 2007; Kumar Jat et al, 2008) (figures 1 and 4). The introduction of 2/3D representation for geo-visualisation of the structure[6] of urbanised areas, extracted from satellite images and modelled (Gadal, 2003; Niebergall et al, 2006), makes it easier to analyse and understand the organisation of land areas. Integrated into a Geographic Information System, structured and associated with other geographic information such as, for example, digital terrain models showing types of relief and roads, the geographic models produced give a spatialised representation of the urban development of land areas. There is a growing tendency to combine satellite remote sensing and GIS into a single system for analysing geographic space and its dynamics (Fedra, 1999; Mesev, 2007; Hasse, 2007; Yang, 2007), although it seems difficult to find a single definition for the approach (Mesev et al, 2007). The use of integrated approaches combining satellite remote sensing and GIS to monitor,

4 From the late 1980s, with the launch of the Spot 1 satellite in 1986.

5 60x60 km for images from the Spot satellites, 185x185 km from the Landsat 5 TM and 7 ETM+ satellites. 15x15km for images from the MSI sensor on the Kompsat-2 satellite.

6 The concept of urban space structure refers to the way in which land is used spatially, geographically and socially: communication corridors, infrastructure, habitat morphologies, localisation of services, open green spaces, social segregation, etc.

analyse, geographically model and spatially represent urbanisation is combined with two other approaches: the integration of 3D geo-visualisation and dynamic cartography/representation, i.e. the representation of urban growth in the form of a 3D animation (figure 9). Dynamic representation or cartography of geographic processes is used in physical geography to model and represent changes in relief, a watercourse, etc. (Drogue, 2002; Pilouk, 2007).

2.1.2. AN INTEGRATED MULTI-LEVEL GEOGRAPHIC INFORMATION SYSTEM

3D dynamic temporal geographic information systems result from the combination and then the merging of three GIS elements: time, dynamics and 3D representation, to which must be added the multi-scalar geographic dimension (scales of cartographic representations and images). Merging the content of the information layers or geographic data concerned[7] creates new and sometimes unprecedented geographic information. Time is modelled through the diachronic merging of spatio-maps of urbanised areas, themselves generated by a series of image processing operations based on satellite data[8]. Each spatial resolution refers to a specific level of geographic analysis and geo-visualisation of the dynamics of urbanisation, from the scale of the built environment (figure 3) to that of the Indian federation (figure 1).

By integrating the multi-scalar, multi-level dimension, it is possible simultaneously to visualise, model and analyse urbanisation processes from the local to the global level and to understand the different time scales. Each geographic level has its own time scales. The dynamic of change in urban objects, whether it be the building on the local scale, the urban area on the meso-urban or regional scale, or urbanised areas (conurbations, towns, villages) on the federal scale, is modelled in the form of a series of urban states at given times. 2D/3D representation is based on the construction of digital terrain models which are merged with states of urban sprawl at one or more dates and on a given

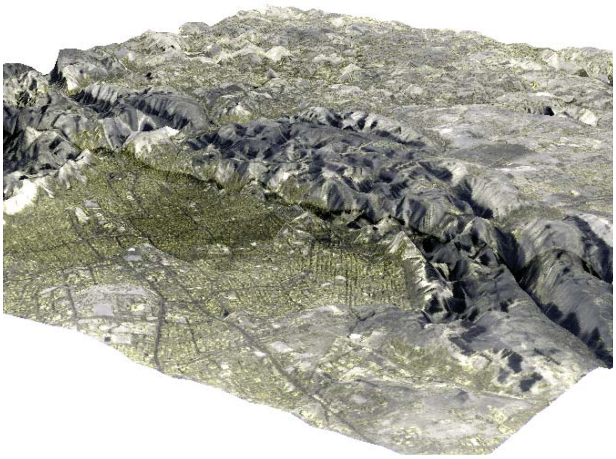

Figure 3. The Aravalli mountain barrier (Jaipur).
STRM WR-2 DTM merged with a colour composite generated from Kompsat-2 images of 16 December 2006.

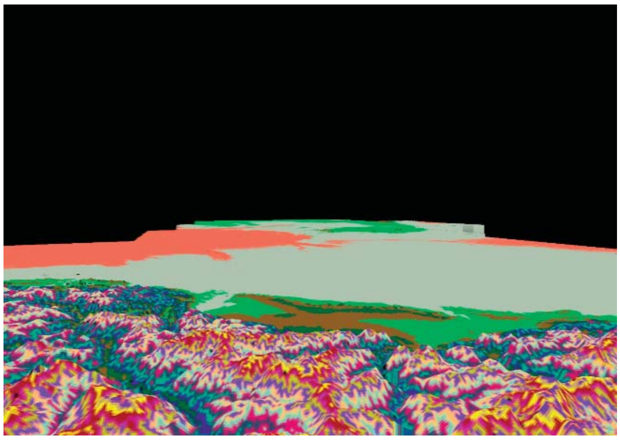

Figure 4. SRTM 2-generated DTM.
Geo-visualisation of the DTM generated from the Himalaya along a North-South axis.

geographic scale: local, regional or global. Multi-scalar 2D and 3D dynamic characterisation of urbanisation reinforces the level of understanding of the geographic processes at work on the global, regional and local scales. The 2D/3D dynamic GIS covers the entire urban development corridor between Delhi and Mumbai over an area 1,500 kilometres in length by 400 kilometres wide. It is structured around a hybrid geographic database of over 280 GB containing topographic and thematic maps, plans, geo-referenced databases of urban centres, demographics, digital terrain models and satellite images at different spatial resolutions. It is harmonised by a geo-referenced meta-file model.

The layers of geographic information generated that are shown here are: the scanned topographic map, the vector format spatio-maps of Delhi's urbanisation between 1990 and 2001, those of the hydrographic and communication networks, the map localising urban centres, the maps of urban sprawl in 2008 (produced by processing Landsat, Spot and DMSP images), and colour composites.

2.2. DIGITAL TERRAIN MODELS IN URBAN DYNAMIC ANALYSIS

2.2.1. TOWARDS A DEMOCRATISATION OF DEM – DTM USES

Digital Terrain Models (DTM) are a three-dimensional representation of a portion of geographic space representing digitised altimetric values in the form of a matrix of pixels or dots (Podobnikar, 2009). DTM production and use was long the preserve of the military. In just a few decades, acquisition techniques have developed considerably, along with altimetric accuracy and geographic coverage. In the past, the high cost of acquisition limited the use of DTM to certain areas. Nowadays, over three quarters of the earth's land mass has been digitised. The Endeavor shuttle mission of February 2000 produced DTMs with a resolution of 3 arc seconds (90x90 metres) and 1 arc second (30x30 metres) for the entire United States, using radar interferometry. In September 2003, the USA made the data public, ending the military

7 Merging data in raster format relies on arithmetic models (addition, multiplication, division, etc.). Merging information in vector format requires the use of topological or set models (Venn diagram, Boolean logic).

8 Satellite data cover the very near infrared (VNIR) spectrum at different spatial resolutions: 16m² for Kompsat-2 multi-spectral images, 100 m² for Spot 5 and Spot 3 resampled multi-spectral images, 900 m² for Landsat 5 TM and Landsat 7 ETM multi-spectral images and 9 km² for DMSP images.

monopoly on DTM, even if some of the data were deliberately altered for reasons of national security. Free access to this data makes foreign users directly dependent on the USA in terms of acquisition, circulation, quality and possible applications.

Thanks to the ongoing development of higher quality, lower cost information processing, DTM production and use is becoming much more widespread, particularly in the modelling of urban dynamics and metropolisation processes.

2.2.2. INTEREST OF DIGITAL TERRAIN MODELS IN URBAN DYNAMIC MODELLING

The use of DTM for spatial analysis and geo-visualisation of urbanisation processes is relatively rare. The forms of relief modelled as a DTM in geomatics are often interpreted in geography as (topological) morphological/physical constraints on urban growth, structuring the development, morphology and shapes of towns. Relief is perceived as a geographic constraint factor on an idealised form of urban growth, and is rarely seen as a geographic element explaining the location of an urban structure, but rather as an obstacle, a physical barrier limiting the development of a town.

The use of DTM in geomatics takes relief into account as a major explanatory geographic factor for the location, presence and forms of urban development. GIS-generated 3D dynamic geo-visualisation makes it possible to model and consider urban growth in its physical, environmental and territorial context and in its geographic continuum. The association of DTM with dynamic modelling and 3D representation defines the description and analysis of land and urban transformation processes and allows for a better geographic understanding of the phenomena.

Topography modelling is widely used in urban planning and development, and in particular in evaluating and managing natural risks such as flooding or landslides (Rashed et al, 2007).

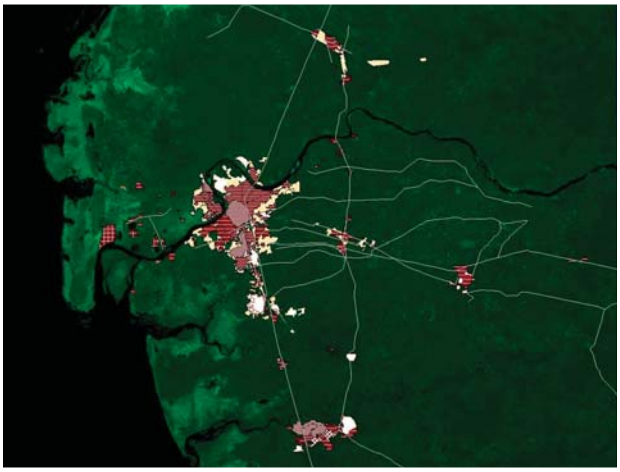

Figure 5. Urban growth of Surat (merger of two vector format spatio-maps). Urban growth between 1990 (red) and 2001 (yellow) merged with a processed Landsat 7 ETM+ image.

Gradients calculated using DTMs can be associated with permeability coefficients modelled from land use spatio-maps to indicate the locations of water run-off and collection in the event of flooding, and the possible intensities. Reconstitutions of relief generated from DTM associated with maps of the geological and pedological substratum can be used to identify zones of geomorphological risk and to map their possible impacts on habitat, for example. Dynamic representation is also used in physical geography to model the changing morphology of a relief or the trajectory of a shock wave capable of triggering a tsunami (Arcas, 2006).

2.2.3. CHARACTERISTICS OF SRTM

DTMs represent the geomorphology of the surface of the earth and of land areas. Two altimetric data storage formats are used. Vector format DTMs, developed in the 1970s, model the surfaces of the relief in the form of polygons. Raster format DTMs are digital matrices in which each pixel represents an altitude. The 3D dynamic cartography of urbanisation between Delhi and Jaipur uses raster format. The size of the pixel (spatial resolution) determines the precision of the DTM used: 8,100 m² (90x90 metres) in our study. Each DTM covers an area of 34,225 km². The DTMs used are produced by the National Geospatial Agency (NGA) and the National Aeronautic and Space Administration (NASA) based on the Shuttle Radar Topography Mission (SRTM) carried out by the space shuttle Endeavor in February 2000.

3. DYNAMIC REPRESENTATION OF URBAN GROWTH MODELLING

3.1. SPATIO-TEMPORAL MODELLING OF URBAN DEVELOPMENT

The first cartographic representation of spatio-temporal processes consisted of a series of maps or spatial representations of urban area states at different dates. It was followed, between the late 1990s and the early 2000s, by the development of *Land Cover Change Models* (LCCM), the result of arithmetic merging of two raster format images at two different dates.

Integrating the dynamic dimension into the modelling of urbanisation and metropolisation processes is an attempt to present the "non-static" character of the land use transformations under way. Integrating the different urban time stages into a dynamic form provides a continuous representation of land use transformations present and past. Dynamic cartography, both 2D and 3D, of urbanisation gives a better visual understanding of the urban geographic processes which are by nature complex, given the number of geographic objects in movement and interacting. With cartographic dynamic modelling of the urban geographic area, time merges with the concept of movement, of transformation. When land use is perceived in visual and temporal movement, time and the concept of dynamic become one. The dynamic is not time itself, but is defined as the series of maps and images of urbanisation created at different stages in time. Spatio-temporal modellings of the urban space make up the component elements of the model for geo-visualisation of the dynamics of land use transformation, relying particularly on animations. 2D or 3D dynamic geo-visualisation of urbanisation is a model for representing urbanisation and metropolisation processes.

3.2. TIME, DYNAMICS AND CHANGES IN TERRITORIAL STRUCTURE

While all three forms of spatial and temporal representation model the transformations of urban landscapes, the change from statistical cartography to a dynamic representation of land use changes transforms the way in which geographic space is analysed, modelled and represented. Yet does it also contribute to greater intelligibility of land use processes? The ease of reading provided by 2D or 3D dynamic geo-visualisation makes it easier for the non-specialist to understand changes in urban land use. It makes it possible to visualise the intensity, the spread and the forms that urban or urbanising landscapes take. It constitutes a tool for geo-visualisation, communication of model results and decision-making that gives a clear and simple account of urban growth processes. Combined with a DTM, dynamic cartography can be used to analysis the profound changes taking place along the Delhi-Mumbai corridor and in cities like Jaipur, between the 1970s and 2008. It shows the preponderant role of the structure of geographic space over nature, and the forms taken by land use changes, with urbanisation and metropolisation as major geographic factors.

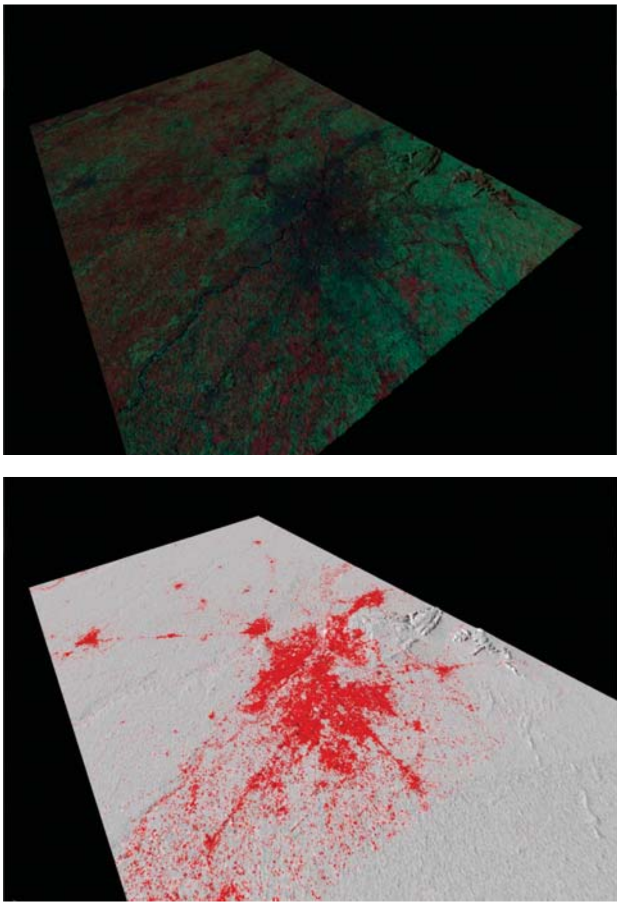

Figure 6. Delhi urban sprawl in 2008 merged with a DTM. DTM merged with a colour composite/DTM merged with a 2008 map of urban sprawl produced by processing an image from a Spot 5 satellite.

4. THE BUILDING OF THE URBAN SPATIO-TEMPORAL GIS

4.1. GEOGRAPHIC AND IMAGE DATABASE IMPLEMENTATION: THE DIGITAL TERRAIN MODEL

Building the spatio-temporal GIS to model the urbanisation of the Delhi-Mumbai corridors involves a number of geographic and image databases[9]. Geo-referenced databases in vector format, such as roads, railways, administrative boundaries and the location of urban centres with their population have all been integrated into the GIS database[10].

4.2. DETECTION, RECOGNITION, IDENTIFICATION AND EXTRACTION OF URBANISED AREAS

Detection of urbanised areas along the Delhi-Mumbai corridor using remote sensing depends on the spectral sensitivity of the sensor and its spatial resolution.[11] The spatial resolutions of satellite images will determine the level at which geographic urban objects can be detected and hence the scale: Kompsat-2 high-resolution metric images will be used to extract buildings (Carton, Gadal, 2007), Landsat and Spot images for zones already urbanised or on the way to becoming so, DMSP images for vast expanses of urban and metropolitan areas home to thousands or millions of inhabitants over several hundred kilometres. The extraction of urbanised areas, whatever the level of geographical analysis and the date, relies on texture recognition and automatic classification methods[12] with multi-spectral images in the visible and infrared bands from the Landsat 1, 5, 7, Spot 3, 4, 5 and Kompsat-2 series. The detection of metropolised and urbanised areas using OPL

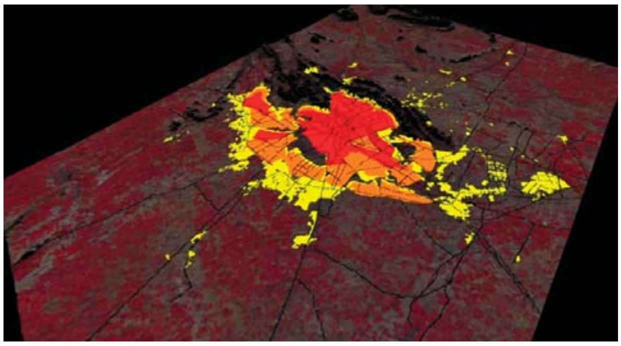

Figure 7. Merged DTM, colour composite, Jaipur urban sprawl between 1975 and 2008.

9 This geo-referenced and spatialised data was produced by processing SRTM WR-2 DTMs and images from the Landsat 5 and 7, Spot 3, 4 and 5 and Kompsat-2 satellites taken between 1975 and 2008.

10 The DTM for the Delhi-Mumbai corridor was produced in three stages: generation of the relief surface using interpolation calculation, DTMs which were then assembled to cover (mosaic) the spatial continuum between the two metropolises. The DTM generated was then split into two at Ahmedabad for reasons of computing power and screen display. The results of the classifications, extractions of urbanised spaces and spatio-maps of urbanisation produced from satellite images taken between 1975 and 2008 were then merged (by draping) with the two DTMs generated.

11 The detection and recognition of urban areas is less successful using images captured by Landsat 1 MSS type sensors dating from 1975 than with Landsat 7 ETM+ data from 2001.

12 These mathematical methods are based on identifying the radiometry (spectral responses) of urban objects such as buildings. Each spectral response corresponds to the nature of the roofing material used on the urban objects.

sensor images taken at night in the visible near infrared (VNIR) spectrum involves statistically improving the recognition of urban areas by convolution. Spatial representations of urban areas produced at different dates were converted into vector format, resulting in spatial cartography representing the urban area in two different data formats, raster mode and vector mode (figure 2).

4.3. DATA MERGING

3D dynamic maps are generated by successively merging geographic information derived from satellite remote sensing, i.e. the area covered by urban objects between 1975 and 2007. The DTM covering the target is merged with the vector format spatio-maps or raster mosaics, i.e. these are merged to cover the entire 1,500 kilometres of the Delhi-Mumbai corridors. Two types of DTM/spatio-map mergers were generated using Landsat 1, 5, 7, Spot 3, 5 and Kompsat-2 images: one combining vector format spatio-maps of urban sprawl, and those merged with the distribution of built objects. They highlight the insertion of urban land use structures into the physical space on regional and local scales.

Merging the DTM with spatio-maps of building density produced from DMSP F-15 satellite images shows the entire urbanisation process along the length of the Delhi-Mumbai urban development corridor. DTM/spatio-map mergers of urbanisation are performed every time the satellite images are captured. Dynamic animation is generated by sequencing the images at different dates on the DTM.

5. 3D DYNAMIC CARTOGRAPHY OF THE DELHI-MUMBAI URBANISATION CORRIDOR

5.1. INTEREST FOR THE REPRESENTATION OF URBAN GROWTH

Integrating 3D and dynamic representation is useful in that it places urbanisation processes back in their geomorphological and geographic context. The former is provided by the DTMs, the latter by the spatio-maps produced from satellite images. Dynamic geo-visualisation immediately reveals whether or not there has been any transformation of the geographic area, such as the process of urban sprawl and densification of Mumbai between 2002 and 2006.

The use of 3D dynamic cartography considerably increases DTM value and potential because it offers the opportunity to analyse the changes in processes associated with urbanisation and to see what impact topography has on the growth of urban centres. The urban growth of the city of Jaipur is blocked to the east by the Aravalli mountain chain. The city has thus developed in a semi-concentric form towards the south and west.

5.2. LIMITS OF 2D/3D DYNAMIC SPATIAL REPRESENTATION

5.2.1 SIZE, SCALE AND RESOLUTION

The limits of 2D/3D dynamic cartography are neither conceptual nor methodological. Quality and level of precision depend for the most part on the geographic information used or generated from DTMs and

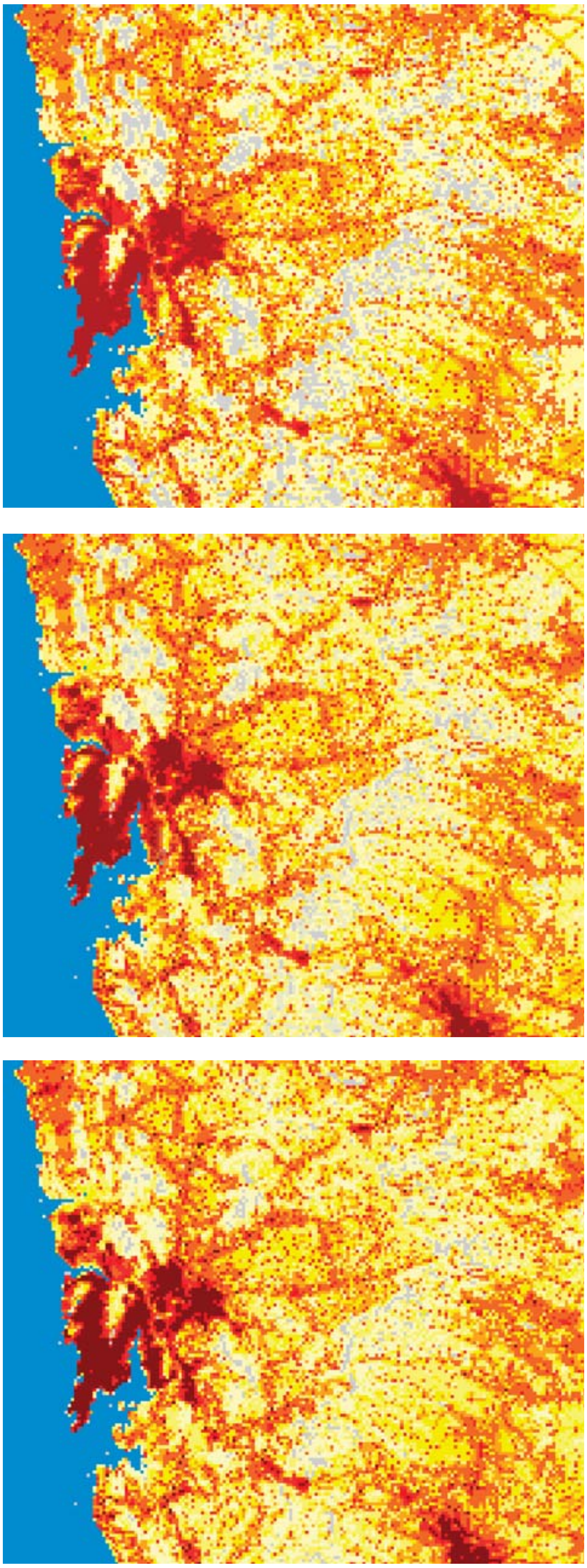

Figure 8. 2D dynamic cartography of urban growth in Mumbai between 2006 and 2007.

Expansion of Mumbai between 2002 and 2007 using DMSP Landscan data.

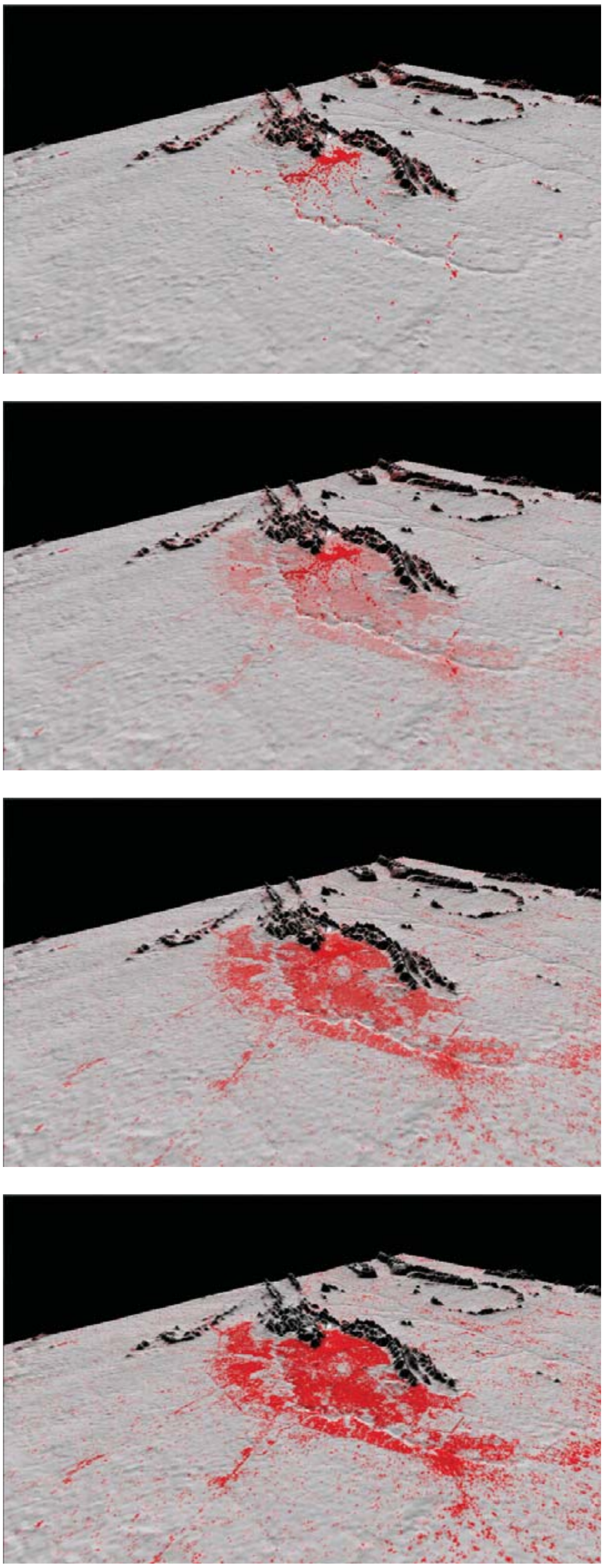

Figure 9. 3D dynamic cartography of urban growth in Jaipur between 1975 and 2008.

Simulation of urban growth between 1975 and 2008. 3D dynamic geo-visualisation shows urban distribution over 33 years. It was obtained by automatic extraction from Spot 3 multi-spectral images taken in 2008 and merged with a DTM.

satellite images. The spatial resolution of DTMs and spatio-maps and their ability to replicate the reality of the terrain and of territorial processes depend on the scale of application[13]. The issues of managing and processing large geographic databases and of production costs and timescales are currently the main factors limiting the application of 3D geo-visualisation to urban planning (Kwan et al, 2005; Zhu et al, 2008; Zhu et al, 2009).

The spatial resolutions of Landsat and Spot images and of SRTM 2 DTMs provide for good modelling of urban dynamics at regional scale. The DMSP images, meanwhile, provide a global representation of changes in the geographic space along the full 1,500 kilometres of the Delhi-Mumbai development corridor and of urban centres with over a million inhabitants. In contrast, only high spatial resolution metric images (such as those from Kompsat-2 or Ikonos 1A) can be used to analyse processes of urbanisation and change in land use at building unit and plot level. These satellite images can be used, for example, to analyse the socio-economic functions of buildings or to identify conflicts over land use triggered by urbanisation (Gadal, 2009). On the other hand, the size of these images adds considerably to the size of the GIS and requires considerable computing power to integrate the DTM into a single file and produce a 3D dynamic visualisation.

For applications at building or urban island scale in urban planning, for example, the DTMs used will be produced from GPS readings and remote sensing images accurate to within centimetres. These approaches are appropriate to small areas, but cannot be used on the scale of conurbations or networks of conurbations, i.e. land areas covering dozens or hundreds of square kilometres.

5.2.2 ERRORS AND MODEL ACCURACY

The existence of errors in DTMs is another limitation. Some areas are characterised by a lack of altimetric measurements on a par with the STRMs used. In the case of these DTMs acquired through radar interferometry, the errors are largely concentrated on boundaries between land and sea or land and water (rivers and lakes). These artefacts may considerably alter the 3D representation (figure 10).

Another limit encountered is linked to the calculation model. The 3D restitution of relief may vary widely from one algorithm to another, from one method of calculation to another. It depends partly on the type of convolution filter used to reduce the level of pixellisation.

6. CONCLUSION AND OUTLOOK

The construction of geographic information systems using geo-visualisation and 2D or 3D dynamic spatial modelling is becoming increasingly widespread. There have been numerous developments in the integration of time and of geographic change models into the GIS, and in the geo-visualisation and 3D modelling of land areas, landscapes and geographic objects. The dynamic representation of transformations of geographic space has also been much improved. The current limits on geographic information systems are: (i) the sheer size of the geographic databases and the management problems this entails (ii) the quality of the data and the databases,

13 The level of DTM spatial resolution is primordial when the relief is low, making it possible to determine whether or not there are any variations in altitude. For applications on the regional scale, lower precision is offset by the larger areas covered, of the order of a hundred or so kilometres. The SRTM DTMs used in the analysis of urbanisation processes along the Delhi-Mumbai corridor cover an area of 34,255 km² with a spatial resolution of 90x90 metres.

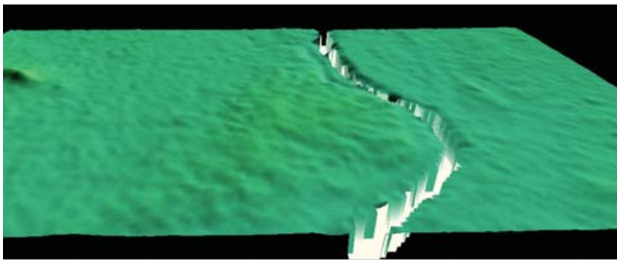

Figure 10. Exemple of an error on a SRTM WR-2 TDM.
The illustration above shows a section of a river that was poorly digitised during the 2000 campaign.

which determines the precision of the representation and the potential for producing geographic knowledge. The limits of 2D/3D dynamic cartography are thus neither conceptual nor methodological.

Methods for monitoring urbanisation over time are fundamental to forward planning and land use management and planning at national, regional or conurbation level. They have already proved useful in highlighting areas of conflict created by the urbanisation of farmland (Gadal, 2009), determining epidemiological impacts on populations (Lekaviciute, 2007) or calibrating the environmental standards to be applied (Zittoun, 2006). Integrating social, environmental and ecological indicators into the 3D dynamic GIS would give rise to a 3D dynamic GIS capable of monitoring and analysing environmental and ecological impacts. The indexation of economic and socio-demographic models would make it possible to project future demand for infrastructure and services and, on a more prosaic level, to plan the future investments in land required.

Geo-visualisation of land use transformation offers a decision aid for development, forward planning, the monitoring of various "territorialised" markets or even geo-marketing, and an opportunity for better management of the environment, populations and land areas. In making the phenomena they represent easy to read and understand, these models constitute excellent monitoring systems for non-geographers.

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APPENDIX 1: GLOSSARY

GIS: It is not easy to give an unequivocal definition of a Geographic Information System (GIS). The various definitions possible relate both to the geographic data and information used, the intended purpose of the system, and the original professional and scientific field of the author. There are very many applications, uses and developments of a Geographic Information System, each of which has its own distinct definition within each disciplinary or cross-disciplinary body. "The semantic plurality of the term Geographic Information System GIS automatically makes any definition difficult. Giving a single definition for the concept and for the management and analysis tool that a Geographic Information System represents would be hard, so "vague" is the term. As a result, there are as many definitions of the term GIS as there are programs, applications or users. The emergence of GIS in the 1980s stems from the considerable increase in micro-computer capacity, from the growing intensity of environmental and land development problems, and from the resulting appeal of multidisciplinary and multi-themes approaches (Gadal, 2008). A Geographic Information System can nevertheless be defined by its basic function of processing geographic information. For many authors writing in English, "A GIS is a computer-based system that provides the following four sets of capabilities to handle geo-referenced data: (1) input, (2) data management (data storage and retrieval); (3) manipulation and analysis; (4) output." (Pazner et al, 1989). "The GIS functions concern the (1) capture, (2) structuring, (3) manipulation of geographic information, the (4) analysis, and (5) presentation of modeling (Raper et al, 1992).

Geo-visualisation (or geovisualisation): geo-visualisation is a shortened form of the term geographic visualisation. Geo-visualisation refers to the integration of different approaches in cartography, GIS, image analysis, dynamic animations, a form of 2D or 3D spatial representation in a static or dynamic (animated form), as is the case here. In other applications, geo-visualisation refers to the exploratory analysis of data. Some consider geo-visualisation to be a branch of data visualisation (Chang, 2008). Geo-visualisation of representations of geographic dynamics generated by remote sensing and GIS is characterised by the ability to locate geographically an object, a portion of the geographic space represented.

Spatio-map: this is a map generally created by interactive digitisation in a vector format (made up of lines linked by points, nodes and vertices) derived from a digital satellite or airborne remote sensing platform (raster format).