A Process-Based Temporal Data Model for Digital Earth

Matthew Y. C. Pang[1] Wenzhong Shi[2] Yongqi Chen[3]

[1] *Department of Land Surveying and Geo-informatics*
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
Fax: (852) 2330 2994
e-mail: lspangyc@polyu.edu.hk
[2] *Department of Land Surveying and Geo-informatics*
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
Fax: (852) 2330 2994
e-mail: lswzshi@polyu.edu.hk
[3] *Department of Land Surveying and Geo-informatics*
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
Fax: (852) 2330 2994
e-mail: lsyqchen@polyu.edu.hk

ABSTRACT This paper develops a Process-based spatio-temporal data model which is an appropriate data model for Digital Earth project. The Digital Earth is a multi-resolutions, three dimensional representation of our planet. An essential requirement of Digital Earth is to integrating various cultural and natural spatial processes and to investigate their complex interactions. With spatial systems theory, representation of spatial processes and their interactions are comparable to these used in different fields of sciences. Thus, Process-based spatio-temporal data model is a general representation of spatial processes of different fields of interest and at different resolutions. Moreover, the developed model provides tools for studying interactions among spatial processes.

1. Digitial Earth

"Digital Earth" is firstly used in Al Gore (1998) which describes a multi-resolutions (i.e. from global to local scales), three dimensional representation of the planet and huge amount of geo-referenced information collected from different sources are integrated. Digital Earth is important for us to understand our planet in the 21st Century due to the following reasons:

First of all, we are in the era of "spatial information flooding". New developments in satellite imagery allow us to collect spatial information over the entire planet with high spatial and temporal resolutions. However, in the last twenty years, a large amount of the spatial information is never employed in solving real world problems and decision-making activities. Digital Earth is a sensible utilisation of the huge amounts of spatial information so that anyone (from school kids to scientists) at every location of the Earth can obtain a complete understanding of our planet spatially and temporally.

Secondary, global warming, deforestation, sustainable long-term developments are the most significant topics in science, resource management and policy making all over the world. They are classified as complex problems. These problems depend on understandings to not only individual phenomena but also the interactions among different constituents in natural and cultural systems. Digital Earth that represents spatial, temporal and textual information over the entire planet is naturally a perfect tool for monitoring and analysing the spatial and temporal interactions among spatial processes in the global complex system.

Current technologies in geographical information systems (GIS) allow us to integrate spatial information from different sources. This is an excellent foundation to develop the Digital Earth. Further extension to existing spatio-temporal models in GIS should include the integration of geographic phenomena over the Earth surface. Consequently, scientists are able to investigate the complex interactions among different manmade and natural phenomena. The paper develops a Process-based spatio-temporal data model for Digital Earth; which a representation scheme for multiple disciplinary spatial processes as well as their interactions in complex real world systems.

2. Modelling Spatial Process in Digitial Earth

Nowadays, we are in the initial phases in developing Digital Earth which integrate existing spatial and temporal information over the entire planet. Tasks in this phase include development of global spatio-temporal database and analytical tools for spatio-temporal topology. These are critical for future development in spatio-temporal simulation. Consequently, an integrated data model for space and time is one of the most important elements in the current development of the Digital Earth.

Current spatio-temporal models of GIS are successful to represent the succeeding changes over a geographic area. However, higher level knowledge about the behaviour of underlie mechanism of the changes (for example, urbanisation, deforestation, economical expansion) are neglected. This is the consequence of handling time in current models. Some models consider time is an additional attribute to space only, others treat space is an attribute to time. As a result, the models can either represent temporal properties of space (e.g. space at different periods of time or model spatial properties of time (e.g. spatial extend of change). None of the current models can represent geographic phenomena spatio-temporally. This is insufficient for users to explore the mechanisms behind the changes.

One essential requirement for Digital Earth is to understand the macro aspect of the entire planet though the complex interactions between humanity and environment. However, interactions are meaningless if we do not consider spatial processes those are initiators of interactions. Current spatio-temporal data model obstructs the utilisation of temporal GIS in Digital Earth for visualising and spatio-temporal data managing purpose only. Thus, a suitable spatio-temporal data model for Digital Earth should maintain not only the raw data of the changes but also provides tool to integrate and to analyse spatial processes (and interactions among the spatial processes) behind the changes.

To commit Digital Earth project with temporal GIS, an essential and fundamental research problem is to improve the layer-based representation in temporal GIS. Process-based spatio-temporal data model is the enhanced model with which spatial and temporal interactions among spatial processes and their consequent behaviour in the overall system are analysed and visualised.

Current GIS have limitations in modelling spatio-temporal processes in the dynamic Digital Earth. Current GISs manage spatial data based on cartographic data model. Real world phenomenon is decomposed into separate layers in GIS. Usually, each layer corresponds to a particular theme such as land use, soil type, population distribution. According to different sources of spatial data (e.g. land surveying, remote sensing images, digitising), layer can be represented using vector or raster spatial model. Cartographic data model is useful in handling, integrating and performing analysis over huge amount of spatial data collected from different data sources.

However, cartographic data model has a number of obstacles in modelling spatial process. Firstly, spatial processes produce changes. Vector and raster spatial model cannot dynamically maintain topological relations among real world objects while they are changing. For vector model, adjacent relationships between two spatial objects are examined by testing of point interactions for each object in the coverage. Once a single spatial object is moved, topological relationships among all spatial objects are rebuilt. Vector model cannot effectively maintain topological relationships among rapidly changing spatial objects raised by spatial processes. For raster model; on the other hand, entire space is uniformly decomposed into square pixels. Locations (i.e. row, column) of the pixels imply their adjacent relationships. However, adjacent relationships among pixels do not provide meaningful insight to the topological relationships among line and polygon objects. Raster model is still insufficient for modelling changes to spatial objects.

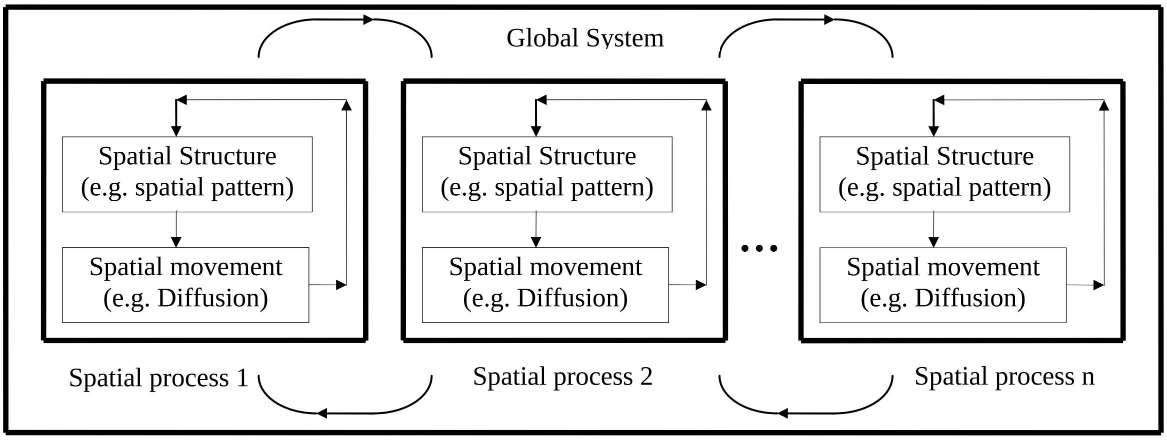

Fig 1. Spatial process and global system

The second limitation is that each layer in cartographic model represents the entire area at a given time. The model is static in nature. The model does not represent changes to spatial objects over time. Changes can be obtained indirectly though comparison of percentage difference between two layers corresponding to the study area of different periods of time. The model can hardly represent spatial process that is dynamic in nature and is usually understood as a logical series of changes to spatial objects.

Thirdly, spatial processes of different disciplines are interconnected in a whole system. Change of one variable of a particular process effects a change in the other process and eventually effects behaviour of the whole system. Mathematically, a spatial system that comprises of interconnecting spatial processes is represented as:

$$dx_1 (t) / dt = F_1 (X_1(t), X_2(t), X_3(t), X_4(t), \ldots, X_n(t); \Phi; t)$$
$$dx_2 (t) / dt = F_2(X_1(t), X_2(t), X_3(t), X_4(t), \ldots, X_n(t); \Phi; t)$$
$$dx_n (t) / dt = F_n (X_1(t), X_2(t), X_3(t), X_4(t), \ldots, X_n(t); \Phi; t) \quad \text{Eq. 1}$$

Where $X_1(t)$, $X_2(t)$, …. $X_n(t)$ are components of the n-th dimensional vector space V^n which are fully describing the behaviour of the system; Φ is the vector of the parameter that characterises the system's structure and context; T is the independent time variable. In each function of equation 1, rate of change of spatial process is the function of all other spatial processes in the systems. As a result, spatial process is much more than any sequence of changes. Spatial process is the result of interaction among different components in a complex spatial system. Spatial process also implies a logical sequence of changes that is carried on in some definite manner, which leads to some recognisable result (Getis and Boots, 1978). The both models aim to represent when, what, where are the changes to objects instead of processes cause the change and how processes interact.

3. Spatial System Theory

An important issue in Digital Earth is to study the macro behaviour of the planet though a unified representation for different geographic phenomena as well as their interactions. Process-based spatio-temporal data model is different from contemporary models of temporal GIS with its background theory. Spatial system theory (SST) is the backbone theory of Process-based saptio-temporal data model instead of cartographic principles in current temporal GIS.

Spatial system theory is an extension to general system theory, which provides a universal framework for representing, and understanding complex system which possesses spatial and temporal properties. Fundamental unit of studying is spatial process. Behaviour of global system is the results of interactions among spatial processes in the system. Moreover, spatial process can be considered as a system in which contains two components: spatial structure and spatial movement (Figure 1). Spatial structure is the spatial configurations of objects being studied and spatial movement is the change to spatial structure. Like all systems, interactions among spatial structure and spatial movement characterise behaviour of spatial process. Moreover, the interaction among spatial structure and spatial movement is able to describe the complex interactions among spatial processes in a complex spatial system (Figure 1). For instead, spatial structure of population can be the initial force of spatial movement in land use changing process. At the same time, spatial movement of land use changing process can affect spatial structure of both land use and population settlement.

SST possesses numinous advantages in developing Digital Earth. SST is application independent, the unique representation of spatial processes can apply to represent and to study complex systems of different disciplines. Mostly important, SST is a unique approach with which

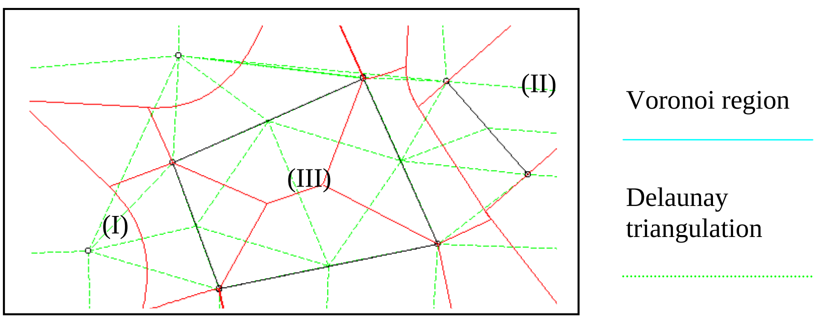

Fig. 2. Voronoi regions and Delaunay triangulation for point (I), line (II) and area (III) objects.

behaviour of complex system is studied through spatial and temporal properties of interacting geographic phenomena.

4. Voronoi Spatial Model

Apart from the spatial systems theory, Process-based spatio-temporal data model adopts Voronoi spatial model to represent spatial, temporal properties of spatial processes instead of field-based and object-based models, which are commonly used in current GIS.

$$V(p_i) = \{p \mid d(p, p_i) \le d(p, p_j), j \ne i, j = 1......n\} \qquad \text{Eq. 2}$$

Gold (1997) has stated a number of requirements for managing global spatio-temporal information. Voronoi spatial model is an appropriate model for managing global spatio-temporal information. Since large sets of objects are stored in the Digital Earth, it is impossible to rebuild the topological structure of the whole data set for evolution of one object. Hence, one important requirement is that topological relations among object must be maintained in incremental (or local) instead of contemporary batch fashion. Moreover, this incremental approach for maintaining topological structure is capable to develop spatio-temporal data model in which space and time possess equal importance. This is also important for modelling behaviour of spatial process as previously mentioned.

Voronoi spatial model describes point, line and area objects as well as their topological relations in terms of Voronoi regions. The mathematical expression of the Voronoi region is defined as (Okabe et al. 1994):

In equation 2, the Voronoi region of spatial object p_i ;$V(p_i)$, is the region defined by the set of locations (p) in space where the distance from p to the spatial object p_i ;$d(p, p_i)$, is less than or equal to the distance from p to the other spatial object p_j ;d(p, p_j ;j = 1…..n). In the other words, spatial objects those share common lines as their Voronoi regions are closely separated and they share neighbouring relations.

Voronoi spatial model combines the advantages of object model and field model in representing spatial process. As a tessellation of space; like field model, Voronoi spatial model has well definitions of neighbouring relationships among spatial objects. When a spatial movement reforms an object, topological relations among the reformed objects and its neighbours are updated only. Thus, the overall spatial structure is updated immediately and this is known as local update of topological relations (Gold, 1990, 1991). On the other hand, like object model, spatial object in Voronoi data model is represented as point, line or area object. Real world objects do not decompose into spatial units. Moreover, Voronoi region is an excellent representation of optimal spatial structure generated by many spatial processes.

5. Process-Based Spatio-Temporal Data Model

5.1. Conceptual Model

Process-based spatio-temporal data model is an extended representation scheme of temporal GIS and is capable to analyse interactions among spatial processes in complex systems. Accordingly to spatial system theory, spatial process consists of two principle components: spatial structure and spatial movement (Coffey, 1981). Spatial structure and spatial movement are mutually depended. Spatial movement changes spatial structure; meanwhile, it is initiated by spatial structure as well. Like all system, interactions of spatial structures and spatial movements are the most important in understanding behaviour of a spatial process. Process-based spatio-temporal model describes interactions among spatial structure and spatial movement though the following equations:

$$e_1(t) = sF_1\,(X_1(e_1(t)), X_2(e_2(t)), \ldots, X_n(e_n(t)), \; t)$$
$$e_2(t) = sF_2\,(X_1(e_1(t)), X_2(e_2(t)), \ldots, X_n(e_n(t)), \; t)$$
$$e_n(t) = sF_n\,(X_1(e_1(t)), X_2(e_2(t)), \ldots, X_n(e_n(t)), \; t) \qquad \text{Eq. 3}$$

$$X_1(e_1(t)) = tF_1\,(e_1(t_0\ldots t), e_2(t_0\ldots t), \ldots, e_n(t_0\ldots t), X_1(t_0), \; t)$$
$$X_2(e_2(t)) = tF_2\,(e_1(t_0\ldots t), e_2(t_0\ldots t), \ldots, e_n(t_0\ldots t), X_2(t_0), \; t)$$
$$X_n(e_n(t)) = tF_n\,(e_1(t_0\ldots t), e_2(t_0\ldots t), \ldots, e_n(t_0\ldots t), X_n(t_0), \; t) \quad \text{Eq. 4}$$

Equation 3 describes the effect of spatial structure to spatial movement. e_i is the list of spatial movement of spatial process i, spatial movement are sequentially ordered according to the parameter time, t. Spatial process, $X_i(e_i(t))$ from initial time, t_0 to t is described as the change of spatial structure from t_0 to t. In the other words, status of spatial process 1 at t_1 is defined as the spatial structure, $X_1(e_1(t_1))$ after the spatial movement occurred at t_1 is applied. sF_i is function of spatial operators provided by the model that describe the spatial relations among different spatial structures in the system.

Meanwhile, effect of spatial movement to spatial structure is described in equation 4. Similar to equation 3, $X_i(e_i(t))$ is spatial structure of spatial process, i after spatial movement defined by $e_i(t)$ is applied. Spatial structure is a function of temporal operators, tF_i. The function defines the effect of spatial movements of all interacting spatial process from t_0 to t. $X_i(e_i(t))$ is devised by applying all spatial movements to the initial spatial structure, $X_i(t_0)$.

5.2. Elementary Structure

The elementary structure of Process-based spatio-temporal data model is shown in figure 3. Spatial process is spatially represented by spatial structure that is represented as a collection of point, line or area spatial objects (i.e. $X_i(t_0)$). Spatial relations among those spatial objects are implicitly maintained though Voronoi neighbouring relations.

With Voronoi spatial model, history of spatial structure is maintained in an incremental fashion. Thus, temporal properties of spatial process are represented as a series of spatial movement in the log file. The model can be further developed so that it integrates with a specially designed dynamic model that describes the dynamic interactions among spatial structures and spatial movements (Pang and Shi, 1998b).

Historical statues of spatial process are retrieved by sequentially applying spatial movements to initial spatial structure. Though the evolution of the spatial process, users are able to investigate properties of spatial structure (i.e. sF_i , e.g., average separation of Voronoi neighbours) and how the spatial structure initiates succeeding spatial movement. On the other hand, spatial movement contains the actual temporal operators (i.e. tF_i , e.g., add/delete, move, merge/subdivide operators) those modify the stored spatial structure. The effects of spatial movement on spatial structure can be easily discovered. In this sense, behaviour of spatial process can be investigated though the mutually dependency between spatial structure and spatial movement investigate.

Moreover, the similar approach can be applied to study the interactions among spatial processes. With a spatial structure of one particular spatial process at time *t*, users are capable to search all spatial processes if there is a spatial movement which occurs immediately after *t*. Further study can be performed to study if there is mutual dependency between the spatial structure and the retrieved spatial movement.

6.Conculsions

This work presents a Process-based spatio-temporal data model to integrate spatial processes in the Digital Earth. Handling of complex interaction is the most critical requirement in order to achieve long-term success in contemporary planning and scientific problems. Digital Earth project have to develop a uniform representation of spatial processes in different fields of interest and in different resolutions in space and time. Moreover, Digital Earth should also provide tools for studying the complex interactions among spatial processes. This paper focus to enhance current spatio-temporal data models to study spatial processes and their interactions. The current spatio-temporal data models represent sequential changes in space and in time; however, they ignore the mechanisms (i.e. spatial processes) behind these changes.

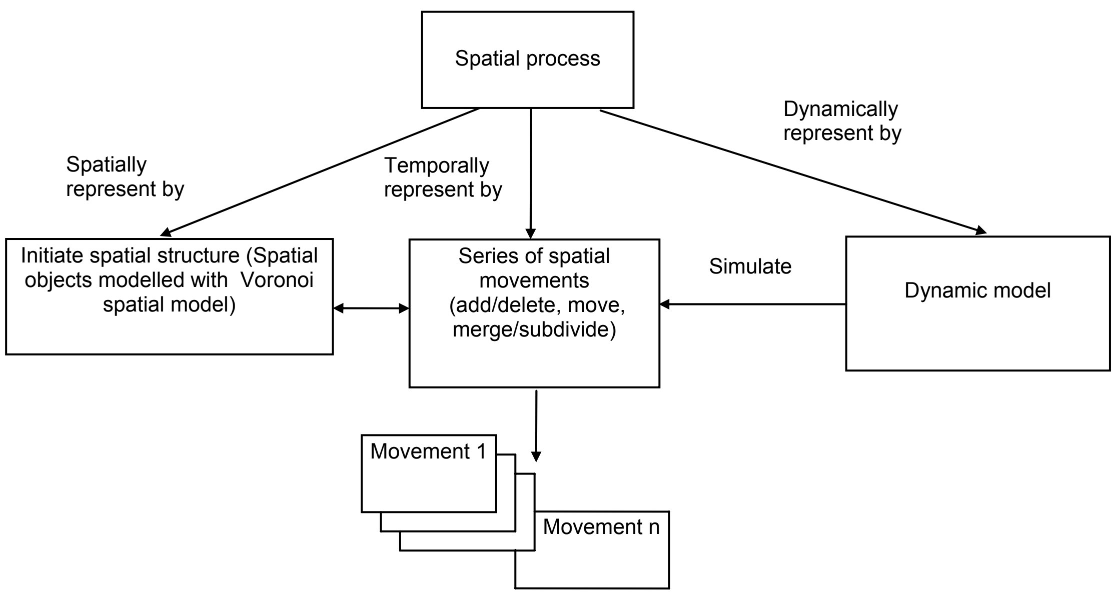

Fig.3 Elementary structure of Process-based spatio-temporal model

The paper argues that neither vector nor raster model is the suitable choice to model spatial process. Voronoi spatial model that models space and time based on incremental approach overcomes the limitations of current spatio-temporal data models. This paper suggests a Process-based spatio-temporal data model that represents spatial processes of multiple disciplines based on Voronoi spatial model. Spatial systems theory is the backbone principle of the developed model. The theory suggests an universal approach for studying spatial and temporal behaviour of spatial process though interactions among spatial structure and spatial movement. Spatial systems theory perfectly agrees with the requirements of Digital Earth. Though the above illustrations, it has been shown that representation of spatial process in the Proess-based spatio-temporal model (Eq. 3, 4) is more natural to the representation used in different fields of sciences (Eq. 1). Process-based spatio-temporal data model is capable to interactions among spatial structure and spatial movement (i.e. behaviour of spatial process) without restriction on fields of interest or resolutions. Thus, Process-based spatio-temporal data model is an more appropriate model than current spatio-temporal data models.

Due to the limits of length of this paper, this paper discusses the Process-based spatio-temporal data model conceptually. Apart from spatio-temporal data model, both the hierarchical and dynamically modelling of spatial process are essential in Digital Earth. Details in extending Process-based spatio-temporal data model to support hierarchically and dynamically modelling are covered in Pang and Shi (1998a) and Pang and Shi (1998b) respectively.

Acknowledgements

The work presented in this paper is supported by the Central Research Grant of the Hong Kong Polytechnic University (Project No. G-S461).

References

Al Gore 1998, The Digital Earth: Understanding our planet in the 21st Century. Given at the California Science Center, Los Angeles, Califoria, on Juanuary 31, 1998, URL: www.digitalearth.net.cn

Getis, A., Boots, B. 1978, Models of Spatial Processes: An Approach to the Study of Point, Line and Area Patterns, Cambridge University Press, 198.

Gold, C. M. ,1990, Spatial Data Structure - The Extension from One to Two Dimensions. In : NATO Advanced Research Workshop, Mapping and Spatial Modelling for Navigation, Eds.: Pau, L. F., 11-39.

Gold, C. M., 1991, Problems with Handling Spatial Data - the Voronoi Approach. In: CISM Journal, 45: 65-80

Gold, C. M.,1997, The Global GIS, In: Proceedings of the International Workshop on Dynamic & Multi-Dimensional GIS, Eds.: Lee, Y. C., Li, Z. L., August 25-26, 1997, 80-91.

Getis, A. & Boots, B., 1978, Models of Spatial Processes: An Approach to the Study of Point, Line and Area Patterns, Cambridge University Press, 198.

Okabe, A., Boots, B & Sugihara, K. ,1992, Spatial Tessellations: Concepts and Applications of Voronoi Diagrams, John Wiley & Son Ltd., 532

Pang, Y. C. & Shi, W. Z., 1998a Modeling Hierarchical Structure of Spatial Processes using Voronoi Spatial Model. In Proceedings of Spatial Data Handling' 98, Eds. : Poiker. T.K. and Chrisman, N., Vancouver, July 1998. 34-44.

Pang, Y. C. & Shi, W. Z., 1998b, Dynamic modelling in GIS using Voronoi-based cellular automata. In: Proceedings of International Conference on Modelling Geographical and Environmental Systems with Geographical Information Systems, Eds. : Lai, P.C., Leung, Y. and Shi, W. Z., Hong Kong, June 22-25, 1998,607-612