MOVE Cost
Call COST-STSM-IC0903-040213-027633

23 de abril
2013

*Temporal dynamic model for Geographic Information: The cube of Time*

Call for Short Term Scientific Missions -STSM

# Willington Siabato

Final Activities Report

1. Cover letter
2. Host Report
3. COST STSM 2012 Report
4. Article submitted

# Final report

## Objective

***To propose a model for analysing temporal relations and patterns derived from dynamic geographic phenomena***. This model, entitled The Cube of Time (C*t*), was conceived as a framework to identify possible relations and affections of geographic phenomena exclusively considering their temporal associate information. Its main purpose is to identify the way in which phenomena are correlated and evolve over time, and to analyse how different phenomena affect each other. The framework can be and will be experimented in the context of maritime data.

## Institutions involved

Host Institution: Naval Academy Research Institute (L'Institut de Recherche de l'École Navale – IRENav);

Home Institution: Technical University of Madrid (Universidad Politécnica de Madrid).

## Activities performed

During the six weeks period of the STSM, from 25th February to 8th April 2013, the following activities were performed:

1. During the first week, different personal talks with Professors, PhD students, and other researchers at the IRENav were developed. Such talks were useful because I identified common points with several researchers of the IRENav's staff pursuing new potential cooperation activities. The work plan for the coming weeks was also defined.
2. During the second week, in addition to made a presentation for the IRENav's staff regarding my ongoing research activities, we clarified the tasks to be developed during the STSM. We agreed two main tasks as follows. (i) Regarding the online bibliography about spatio-temporal modelling and cross-related topics, write a short paper and submit it to the SIGMOD Record Journal. (ii) Define the initial and fundamental elements for the temporal model.
3. During the weeks 3 and 4, (i) I fulfilled some improvements to *Time*Bliography, the dynamic and online bibliography on Temporal GIS, spaceandtime.wsiabato.info/tGIS.html. (ii) We completed a short paper regarding the functionality and benefits of *Time*Bliography, and submitted it to the *ACM SIGMOD Record Journal*.
4. During the two final weeks, the core elements for the temporal analytical framework were defined. We established the properties and the logic of the cube. Elements such as *Temporal axes, Temporal points, Parallel planes, Bi-temporal planes, and linear functions* were theoretically defined. A draft document describing such elements was outlined. Figure 1 shows a representation of some of these elements. An in-progress draft report describes the core elements deeply. We also specified a case study for testing the model and develop a few experiments in the context of maritime data considering several datasets that the IRENav has collected during the last years.
5. Finally, I assisted to several speeches and talks that were made by other visitor researchers and IRENav's stuff researchers. Multiple academic links resulted from this activity.

## Outcomes and results

As a result of the previous tasks, the following results were obtained:

1. We have submitted a paper to the ACM SIGMOD Record Journal, currently under review.

   Siabato, W., Claramunt, C. & Manso-Callejo, M. Á. 2013, 'Timebliography: A Dynamic and Online Bibliography on Temporal GIS', *ACM SIGMOD Record*, vol. 42, no. 0, p. 0-0.

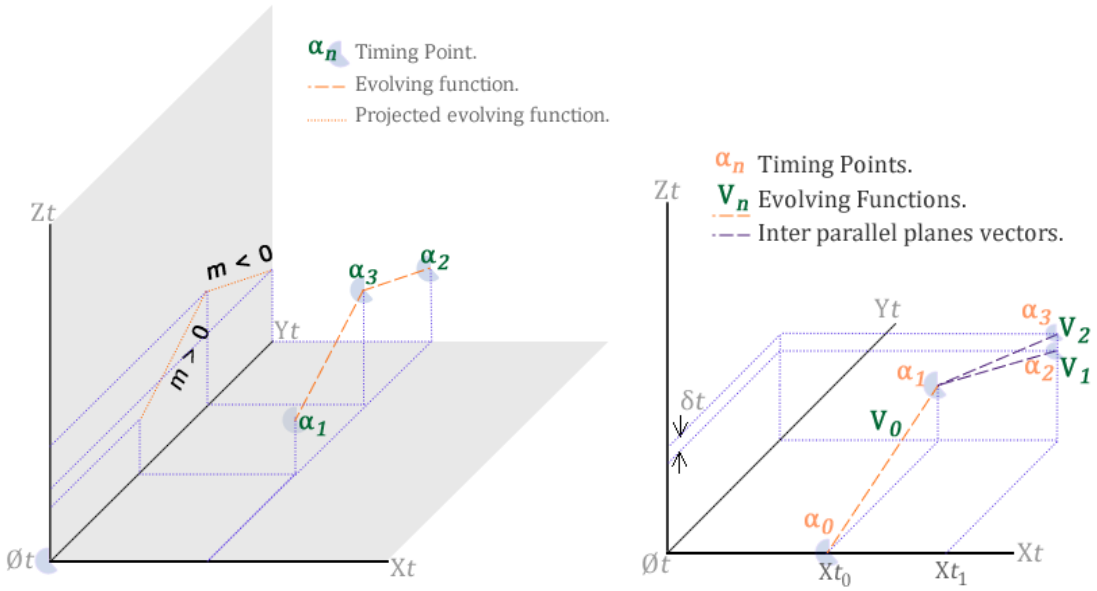


Figure 1. Representation of several constructs of the cube of time.

2. We have significantly improved the online bibliography *Time*Bliography. We expect that this online tool to be useful for researchers relating to spatio-temporal issues, especially in spatio-temporal modelling and Temporal GIS research activities.
3. We have outlined a draft report on the basic definitions of the dynamic temporal framework: The Cube of Time. This report is still in progress.
4. I have established rich academic relationships with IRENav's researchers and other research visitors, especially from Japan and Greece.

## Forthcoming activities

1. To complete the report mentioned above in point 3 and write a position paper in order to submit it to a workshop.
2. To make some experiments of the analytical framework considering the maritime datasets.
3. To make stronger the academic links created.
4. To identify open calls in order to prepare a join proposal between the UPM and the IRENav.

# Timebliography: A Dynamic and Online Bibliography on Temporal GIS

**Willington Siabato**
Technical University of Madrid
w.siabato@upm.es

**Christophe Claramunt**
Naval Academy Research Institute
christophe.claramunt@ecole-navale.fr

**Miguel Ángel Manso-Callejo**
Technical University of Madrid
m.manso@upm.es

## Abstract

This paper introduces an online bibliography on temporal GIS, a research area in which different fields and researchers have provided substantial results and literature over the past few years. We first define the scientific domain of temporal GIS, its origin and recent evolution, and the context of this bibliography. Then, the components and functionalities of the web application that support the online bibliography are described. The bibliography is accessible on the Web at http://spaceandtime.wsiabato.info.

## 1. Introduction

Temporal geographic information systems (T-GIS) can be defined as the integration of the temporal dimension into geographic information systems (GIS) in order to model, manage, and analyse the intrinsic dynamic nature of geographic phenomena. Such integration is still a difficult issue due to the complexity of the modelling, analysis, and visualization of spatio-temporal data within a GIS. The fact that GIS is oriented to the representation of real-world phenomena implies contributions from a large set of scientific disciplines. Without being totally exhaustive, as many other sciences and fields can contribute to it (e.g., Mathematics, Psychology), the foundations of T-GIS are mainly rooted in four sciences: Geography, Computer Science, Information Science, and Geographic Information Science. Each of them contributes at different levels:

(i) Geography is per principle an essential dimension of T-GIS since it provides methods and spatial data analysis foundations for the analysis and understanding of geographic phenomena.
(ii) Computer Science covers the need for conceptual and formal models, spatio-temporal data structures, data query languages, data analysis and visualization methods, algorithms, and user interfaces.
(iii) Information Science is closely related to the organization, storage, retrieval, interpretation, transmission, mining, transformation, and utilization of all sorts of information related to geographic data.
(iv) Geographic Information Science (GIScience), as derived from these three fundamental sciences, integrates them in a sort of unified meta-discipline[1] from which the modelling and analysis of geographic phenomena at large can be studied and solved.

Timebliography (/ɪaɪmˈblɪɒgrəfi/) is an online r e-source created in order to provide students and researchers with a dynamic bibliography whose focus is oriented towards temporal aspects of GIS and other cross-related topics. Several research communities have contributed to the development of T-GIS over the last two decades. However, there still exists the lack of an up-to-date bibliography related at large to T-GIS. This online bibliography intends to cover this lack and complement previous surveys and bibliographic compilations. As T-GIS is clearly a multidisciplinary research subject, the online bibliography involves significant contributions from the above-described sciences. As of December 2012 over 1.100 references have been categorized in 36 topics according to the different research subjects that have made multiple contributions.

In the remainder of the article, section 2 presents a brief description of the origins of T-GIS, while section 3 introduces some previous surveys and bibliographies relevant to T-GIS, describes the components and functionality of the web application, and briefly presents the harvested bibliographic sources and repositories. Section 4 concludes by presenting some future works and recommendations.

## 2. Milestones in spatio-temporal modelling

Before the GIS research community even started thinking about the temporal dimension, other Computer Science domains had already made significant advances in the management and modelling of time.

[1] This was suggested by Helen Couclelis at a GIScience 2012 invited talk.

In particular, research into conventional databases can be tracked back over 50 years [14, 21]. The development of spatial databases began with groundwork for the manipulation of geographic [8] and pictorial data [11] in information systems. Several spatial extensions were implemented into conventional database management systems (DBMS) during the 1980s (e.g., layered and dual architectures [4, 43]). These approaches laid the foundations for what later became the *Integrated Architecture*. This new architecture represented a turning point in the design of spatial databases and favoured the development of spatial DBMS such as POSTGRES [53].

On the other hand, the modelling of time as a specific research subject has been studied much before in several fields, such as natural language [10], information systems [23], logic [28, 37], and artificial intelligence [2]. The integration of time into databases can be traced over the past 30 years [5, 13, 50], whereas the development of spatio-temporal databases began in the late 1980s [6].

It was in the early 1990s that the National Center for Geographic Information and Analysis (NCGIA) first envisioned the need for the integration of time into GIS [38]:

> *We assume that at least some temporal aspects of a GIS with temporal data will be similar to the problems of temporal data in other applications and the results of work done in other areas applicable to GIS.* (p. 2)

Since then, the integration of temporal capabilities into GIS has been a matter of active research. One work considered as a starting point is that introduced by Langran and Chrisman [24] who first established several modelling concepts for the development of T-GIS. In another earlier work, Donna Peuquet [35] had suggested a taxonomy and a comprehensive review of spatial-data models and briefly mentioned the importance of time in spatial data systems and models. As she concluded regarding the integration of the fourth dimension (time) in the spatial data models:

> *This is the one area currently identified in spatial data models and computer spatial data handling where we have barely scratched the surface.* (p. 110)

During the last few years, several spatio-temporal models have been proposed to evolve in this direction. Spatio-temporal modelling trends can be classified considering the theoretical approach on which each model is based, i.e., feature-based (e.g., [26, 27, 54] ), event-based (e.g., [12, 34, 60, 62]), identity-based (e.g., [19]), process-based (e.g., [65]), semantic-based (e.g., [64, 67]), object-oriented (e.g., [7, 32, 40, 55, 57-59, 61]), the space-time composite model (e.g., [24, 25]), simple time stamping (e.g., [20, 39]), or the snapshot model (e.g., [6, 46]). Nowadays, an emerging domain in the modelling of dynamic geographic phenomena is oriented to the analysis and representations of moving objects (points) and trajectories (e.g., [16, 17, 31]).

These approaches have defined different methods and rules for describing temporal characteristics and the dynamic nature of geographic phenomena considering three main focuses of interaction: processes, objects or events. Abraham and Roddick [1] and Pelekis [33] provide a comprehensive overview of spatio-temporal databases and models.

## 3. Online bibliography

Several bibliographic reviews and annotated bibliographies on temporal [9, 22, 29, 47-49, 51, 52, 56, 63] and spatial [18, 35, 42] databases have been published over the past 30 years, while more specific reviews oriented to spatio-temporal issues have also been published [1, 3, 33, 36, 41, 44, 66]. This online bibliography also references 60 previous surveys, bibliographies and studies relating to temporal and spatio-temporal aspects.

The main differences between Timebliography and previous bibliographies are (i) an online, dynamic interface, (ii) a thematic classification used for filtering references, and (iii) the fact that this bibliography is available on the Web with several interactive functionalities. Moreover, a large online documentation including the abstract and a link to the publisher's website through *doi name* is also available. When the *doi name* is not available, a link to other academic databases is provided, e.g., ACM Digital Library, CiteSeerX, DBLP, or Google Books.

Timebliography is organized in four disciplines and 36 areas. These areas reflect the scientific domains mentioned in the introduction.[2] Table 1 shows the main areas in which the defined categories are involved.

### 3.1 Timebliography components

As shown in Figure 1, Timebliography's GUI (graphic user interface) is composed of nine elements: (1) sections and categories, (2) category filters, (3) publication filters, (4) textual filter, (5) pop-up descriptor, (6) timeline, (7) categorized reference list, (8) menu, and (9) multi-categorization.

[2] Categories were defined by considering research agendas (e.g., [30]) and academic programmes (e.g., [15]) that have influenced the GIScience development.

Table 1. Main research areas related to T-GIS

| *Discipline* | *Areas* |
|---|---|
| Geography | Time Geography |
| | Spatial Analysis |
| Computer Science | Databases |
| | Artificial Intelligence –AI– |
| | Temporal Modelling |
| | Data Structures |
| | Visualization |
| Information Science | Information Retrieval –IR– |
| | Geographic Information Retrieval |
| | Temporal Information Retrieval |
| GIScience | GIS |
| | Temporal GIS (Spatio-temporal Data Modelling) |
| | Spatial Data Modelling and Handling |
| | Spatial Data Infrastructures –SDI– |

## Sections and categories

Timebliography is classified into four sections: *Core*, *Secondary*, *Others*, and *Standards*. Each of the sections organizes the 36 categories according to their relevance and impact on T-GIS. In order to identify the section to which a reference belongs easily, they are represented according to three different colours. Similarly, the *Standards* section is categorized using different symbols that represent the standardization institutions (i.e., W3C, ISO and OGC). The 36 categories are classified as follows:

(i) The *Core* section includes the most relevant categories that have impacted the development of T-GIS.

(ii) The *Secondary* section includes the categories that, although not being a direct part of T-GIS, play a relevant role in its development. Key concepts such as the conceptual modelling of time (e.g. AI and Logic) or spatial data modelling and reasoning are considered particularly for the integration of the temporal variable in GIS.

(iii) The *Others* section includes those research areas that, being considered as individual subjects, are not relevant enough to be directly related to the development of T-GIS.

(iv) The *Standards* section includes articles, institutions, norms, and standards that rule temporal and spatio-temporal aspects in GIS and cross-related areas. Mainly, standards from OGC, ISO, and W3C are referenced.

Over 1.100 references are classified according to these categories. A reference can be categorized in one or more areas. Categories are listed in Table 2, while their relative importance is presented in Figure 5 in the Annex. Figure 2 shows the *Core* section.

## Tools and functionalities

The categorized references can be searched and filtered by four criteria: sections and categories, type of publication, article title, and first author's last name.

*Filters*. Users can filter the referenced articles by considering either a specific section, or a category, or a type of publication using the checkbox controls available in the GUI (see Figure 2 and Figure 3).

In the same way that colours are used to recognize sections, the *type of publication* can easily be recognized by nine different font colours (Figure 3). Similarly, the *categories* are represented by a set of geometrical identifiers carefully selected to avoid confusion between them. Overall, any reference is classified into a section, category, and type of publication.

References can also be filtered by taking into account author and title. The *textual filter* supports a search for references according to any criterion specified by the user. While a user is typing a search criterion, the references which match such criteria appear in the timeline. Searches by title can contain any fragment of it but must follow a strict word order, e.g., … *relationships in temporal spaces*. The *textual filter* just considers the first author's last name. This function does not act as a search by multiple keywords.

*Pop-up descriptor*. This descriptor provides users with a detailed description of each reference including the abstract, author's/s' full name(s), publisher, date of publication, and a link to the publisher's website, where extra information and related references can be viewed when available. In some cases, when papers are published under open licence, the link redirects to the article itself. As mentioned above, Timebliography mainly uses *doi name* to link articles' websites; nonetheless, when the *doi name* is not available, other academic databases are linked (see Table 3, Annex 1). If the *doi name* or *CiteSeerX ID* is available, the pop-up shows a green code (*doi:10*.*.*.****) below the abstract. In any other case, the URL website is linked to the article's title. When no website is linked, the title looks red in colour. Figure 4 shows an example of a *pop-up descriptor*. This link extends Timebliography's functionality to the linked repositories, allowing users to acquire more information relating to the reference.


Figure 1. General overview of Timebliography's interface (http://spaceandtime.wsiabato.info)

Table 2. Timebliography's categories by section

| Section I: Core | Section II: Secondary | Section III: Others | Section IV: Standardization |
|---|---|---|---|
| Temporal GIS | Moving Objects and LBS | Interoperability | Standardization |
| Spatio-temporal Modelling | Data Mining and Analysis | SDI and Geoservices | Institutions |
| Temporal Modelling | Spatial Databases | GIS and GIScience | ISO |
| Spatio-temporal Analysis | Spatial Data Modelling | GI and Data | W3C |
| Query Languages | Spatial Data Structures | Software | OGC |
| Case Studies | Spatial Reasoning | Calendars | |
| Time Geography | Databases | 3D/4D | |
| Temporal Databases | AI and Logic | | |
| Surveys and Reviews | Semantics and NLP | | |
| Reports and Studies | IR, GIR and TIR | | |
| | Annotating Time | | |
| | Ontologies | | |
| | Visualization | | |
| | Topology | | |

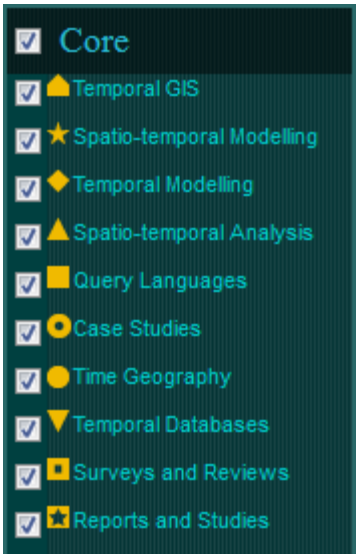


Figure 2. Preview of the *Core* section

*Timeline*. The timeline organizes references chronologically. References are organized left-right according to publication date and top-down according to type of publication. Panning functions allow users to move across the timeline intuitively. Browsing can be annually or monthly. The timeline functionality is based on the API SIMILE [45].

*Reference list*. Timebliography also provides a static, conventional reference list. This list is organized and classified according to the defined categories. It also contains the links available in the *pop-up descriptor*.

*Menu*. The Timebliography menu allows users to browse through its web pages: *timeline*, *reference list* webpage, project description, and home. Last but not least, additional references can be suggested, as well as reporting errors, by using the function *Recommend a New Reference*.

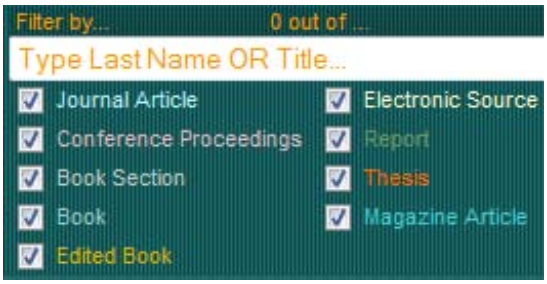


Figure 3. Publication types

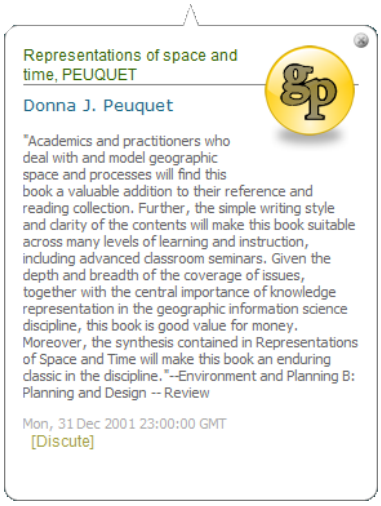


Figure 4. Example of a *pop-up descriptor*

*Multi-categorization*. A reference can be related to one or more areas and, therefore, be part of one or more category. When a user chooses this option, not only will the individual references of the active category be shown, but also those references registered in other categories. The reference will always take the geometrical identifier of the main category.

## 3.2 Online bibliography implementation

As a dynamic bibliography, Timebliography is evolving, both in number of references and in functionality. The first version was made available online in December 2011 and since then, the number of references has been increased by 30% and functionalities for filtering and searching extended. Web metrics based on Google Analytics show that from July 2012 to January 2013 a total number of 905 visits[3] (573 unique visitors) were registered. A bounce rate of 68% and an average visit duration of 04:40 shows that the prototype is being consulted by multiple users multiple times. A returning visitor rate of 43% could be interpreted as satisfactory. Most users are located in Europe, and North and South America.

A thoughtful bibliographic review was done taking into consideration relevant bibliographic sources and databases. The main sources of Timebliography are described in Table 3 (see Annex 1). Further description, statistics, bibliometrics, as well as an up-to-date bibliographic compilation are also available at http://spaceandtime.wsiabato.info.

References are stored in a database repository managed by MySQL 5.0. UTF-8 Unicode encoding has been used to avoid typos in authors' names and article titles. The web application is based on JavaScript (jQuery Library), CSS, Ajax, and HTML standard

[3] From 24/06/2012 to 31/01/2013

4.01. Although most browsers render the application properly, some problems with Internet Explorer 9 have been identified. This browser is not able to organize reference titles as expected. The use of Mozilla Firefox (13+), Chrome, or Safari is recommended for browsing Timebliography. All resources and sources are available upon request.

While Timebliography is loading bibliographic data from the database, a brief how-to tutorial is displayed. This tutorial is intended to show users how to interact with the application.

## 4. Conclusion

To the best of our knowledge, Timebliography is the first attempt to provide an interactive T-GIS bibliography on the Web. This application should provide researchers and postgraduate students interested in the development of T-GIS with an interactive, up-to-date and comprehensive resource to survey previous work in the field. Timebliography considers the state of the art, latest developments, and current trends in T-GIS, as well as in temporal and spatio-temporal modelling and analysis methods and techniques.

We plan to guarantee the evolution of the prototype and maintain the updating of the bibliography by adding new references and including users' feedback. Future functionalities will include search by keywords, semantics extension of the pop-up descriptor, integration of visual aids for multi-categorization, and additional interactions of the timeline with the reference list. The possibility for users to include, and not only suggest, new references in the database could eventually be considered as long as a review procedure is also included. In the near future, when the number of references and users increases, performance issues will be observed and addressed if and when necessary.

As usual in this kind of compilation, we may have overlooked some relevant papers and we would be glad if they were brought to our attention. For this purpose, Timebliography provides a method for suggesting the inclusion of overlooked references.

The bibliography is fully accessible online at http://spaceandtime.wsiabato.info

## Acknowledgements

This article was supported by the Doctoral Programme of the Technical University of Madrid (Grant ref. CH/056/2008) and partially supported by the UPM Training and Mobility of Research Programme (Resolution 28/06/2012). Willington Siabato is on leave from UPM and he is currently a research visitor at the Naval Academy Research Institute.

## References

1. Abraham, T., Roddick, J.F.: Survey of spatio-temporal databases. *GeoInformatica*, 3(1), 61-99. (1999)
2. Allen, J.F.: Maintaining knowledge about temporal intervals. *Communications of the ACM*, 26(11), 832-843. (1983)
3. Al-Taha, K.K., Snodgrass, R.T., Soo, M.D.: Bibliography on spatiotemporal databases. *ACM SIGMOD Record*, 22(1), 59-67. (1993)
4. Aref, W.G., Samet, H.: Extending a DBMS with Spatial Operations. In:.Günther, O., Schek, H.-J. (eds.) *Advances in Spatial Databases - 2nd Symposium*. Lecture Notes in Computer Science -LNCS-, vol. 525, pp.299-318. Springer Verlag, Berlin - Germany (1991).
5. Ariav, G.: A temporally oriented data model. *ACM Transactions on Database Systems (TODS)*, 11(4), 499-527. (1986)
6. Armstrong, M.P.: Temporality in spatial databases. In: *GIS/LIS'88: Accessing the World*, pp.880-889. American Society for Photogrammetry and Remote Sensing, Falls Church-VA-USA (1988).
7. Becker, L., Voigtmann, A., Hinrichs, K.H.: Temporal support for geo-data in object-oriented databases. In: Wagner, R.R., Thoma, H. (eds.) *Database and Expert Systems Applications*. Lecture Notes in Computer Science -LNCS-, vol. 1134, pp.79-93. Springer Verlag, Berlin - Germany (1996).
8. Berman, R.R., Stonebraker, M.: GEO-OUEL: a system for the manipulation and display of geographic data. *ACM SIGGRAPH Computer Graphics*, 11(2), 186-191. (1977)
9. Bolour, A., Anderson, T.L., Dekeyser, L.J., Wong, H.K.: The role of time in information processing: a survey. *ACM SIGMOD Record*, 12(3), 27-50. (1982)
10. Bull, W.E.: Time, Tense, and the Verb: A Study in Theoretical and Applied Linguistics, with Particular Attention to Spanish, vol.19. University of California Press, Berkeley-CA-USA (1960).
11. Chang, S.-K. , Fu, K.-s. (eds.): Pictorial lnformation Systems Springer Verlag, Berlin - Germany (1980).
12. Claramunt, C., Thériault, M.: Managing Time in GIS: An Event-Oriented Approach. In: *Recent Advances in Temporal Databases: Proceedings of the International Workshop on Temporal Databases*, pp.23-42. Springer Verlag, London-UK (1995).
13. Clifford, J., Warren, D.S.: Formal semantics for time in databases. *ACM Transactions on Database Systems (TODS)*, 8(2), 214-254. (1983)
14. Codd, E.F.: A Relational Model of Data for Large Shared Data Banks. *Communications of the ACM*, 13(6), 377-387. (1970)

15. DiBiase, D., DeMers, M., Johnson, A., Kemp, K.K., Luck, A.T., Plewe, B., Wentz, E.: Geographic Information Science and Technology Body of Knowledge, 1st edn. Association of American Geographers, Washington D.C. - USA (2006).
16. Erwig, M., Güting, R.H., Schneider, M., Vazirgiannis, M.: Spatio-Temporal Data Types: An approach to modeling and querying moving objects in databases. *GeoInformatica*, 3(3), 269-296. (1999)
17. Güting, R.H., Böhlen, M.H., Erwig, M., Jensen, C.S., Lorentzos, N.A., Schneider, M., Vazirgiannis, M.: A foundation for representing and querying moving objects. *ACM Transactions on Database Systems (TODS)*, 25(1), 1-42. (2000)
18. Güting, R.H.: An introduction to spatial database systems. *The VLDB Journal — The International Journal on Very Large Data Bases*, 3(4), 357-399. (1994)
19. Hornsby, K.S., Egenhofer, M.J.: Identity-based change: a foundation for spatio-temporal knowledge representation. *International Journal of Geographical Information Science*, 14(3), 207-224. (2000)
20. Hunter, G.J., Williamson, I.P.: The development of a historical digital cadastral database. *International Journal of Geographical Information Systems*, 4(2), 169-179. (1990)
21. Institute, C.B.: Conference on data systems languages records, 1959-1990, (CBI 11). In: *Conference on Data Systems Languages -CODASYL-*, University of Minnesota Libraries, Minneapolis-MN-USA (1959).
22. Kline, N.: An update of the temporal database bibliography. *ACM SIGMOD Record*, 22(4), 66-80. (1993)
23. Langefors, B.: Theoretical analysis of information systems, 1st edn. Studentlitteratur, Lund - Sweden (1966).
24. Langran, G., Chrisman, N.R.: A framework for temporal geographic information. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 25(3), 1-14. (1988)
25. Langran G.: Time in geographic information systems, 1st edn. Taylor & Francis, London-UK (1992).
26. Maldonado-Ibañez, A., Vázquez-Hoehne, A.: Diseño de primitivas geométricas espacio-temporales para describir fenómenos dinámicos. *GeoFocus*, 10(1), 232-251. (2010)
27. Mark, D.M.: Toward a theoretical framework for geographic entity types. In: Frank, A.U., Campari, I. (eds.) *Spatial Information Theory: A Theoretical Basis for GIS*. Lecture Notes in Computer Science -LNCS-, vol. 716, pp.270-283. Springer Verlag, Berlin-Germany (1993).
28. McArthur, R.P.: Tense logic. D. Reidel Publishing, Dordrecht - The Netherlands (1976).
29. McKenzie, E.: Bibliography: Temporal databases. *ACM SIGMOD Record*, 15(4), 40-52. (1986)
30. McMaster, R.B., Usery, E.L. (eds.): A research agenda for Geographic Information Science CRC Press, Boca Raton-FL-USA (2004).
31. Noyon, V., Claramunt, C., Devogele, T.: A relative representation of trajectories in geogaphical spaces. *GeoInformatica*, 11(4), 479-496. (2007)
32. Parent, C., Spaccapietra, S., Zimányi, E.: Spatio-temporal conceptual models: data structures + space + time. In: *7th ACM International Symposium on Advances in Geographic Information Systems -ACMGIS`99-*, pp.26-33. ACM, New York-NY-USA (1999).
33. Pelekis, N., Theodoulidis, B., Kopanakis, I., Theodoridis, Y.: Literature review of spatio-temporal database models. *The Knowledge Engineering Review*, 19(3), 235-274. (2004)
34. Peuquet, D.J., Duan, N.: An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographical Information Systems*, 9(1), 7-24. (1995)
35. Peuquet, D.J.: A conceptual framework and comparison of spatial data models. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 21(4), 66-113. (1984)
36. Peuquet, D.J.: Making space for time: Issues in space-time data representation. *GeoInformatica*, 5(1), 11-32. (2001)
37. Prior, A.N.: Past, present and future, 1st edn. The Clarendon Press, Oxford-UK (1967).
38. Renato Barrera, Khaled K. Al-Taha: models in temporal knowledge representation and temporal DBMS. *Technical Report* (Report 90-8). National Center for Geographic Information and Analysis, Santa Barbara-CA-USA (1990).
39. Renolen, A.: History graphs: conceptual modeling of Spatio-Temporal Data. In: *GIS Frontiers in Business and Science Conference*, International Cartographic Association -ICA-, Bern - Switzerland (1996).
40. Renolen, A.: Modelling the real world: conceptual modelling in spatiotemporal information system design. *Transactions in GIS*, 4(1), 23-42. (2000)
41. Renolen, A.: Temporal Maps and Temporal Geographical Information Systems. *Dimension: Contemporary German Arts and Letters* 1-12. (1997)
42. Ríos Viqueira, J.R., Lorentzos, N.A., Brisaboa, N.R.: Survey on spatial data modelling approaches. In: Manolopoulos, Y., Papadopoulos, A., Vassilakopoulos, M.G. (eds.) *Spatial Databases: Technologies, Tech-*

*niques and Trends*, pp.1-22. IGI Global, Hershey-PA-USA (2005).

43. Schilcher, M.: Interactive graphic data processing in cartography. *Computers & Graphics*, 9(1), 57-66. (1985)
44. Sellis, T.: Research issues in spatio-temporal database systems. In: Güting, R.H., Papadias, D., Lochovsky, F.H. (eds.) *Advances in Spatial Databases*. Lecture Notes in Computer Science -LNCS-, vol. 1651, pp.5-11. Springer Verlag, Berlin - Germany (1999).
45. SIMILE-Project, http://code.google.com/p/simile-widgets/. Retrieved 17/12/2012.
46. Sinton, D.F.: The inherent structure of information as a constraint to analysis: Mapped thematic data as a case study. In: *First International Advanced Study Symposium on topological data structures for Geographic Information Systems*, pp.1-17. Harvard University Laboratory for Computer Graphics and Spatial Analysis, Cambridge-MA-USA (1978).
47. Snodgrass, R.T.: Temporal databases status and research directions. *ACM SIGMOD Record*, 19(4), 83-89. (1990)
48. Snodgrass, R.T.: Temporal databases. In: Frank, A.U., Campari, I., Formentini, U. (eds.) *Theories and methods of spatio-temporal reasoning in geographic space*. Lecture Notes in Computer Science -LNCS-, vol. 639, pp.22-64. Springer Verlag, Berlin - Germany (1992).
49. Snodgrass, R.T.: Temporal object-oriented databases: a critical comparison. In: Kim, W. (ed.) *Modern Database Systems*. pp.386-408. Addison-Wesley/ACM Press, New York-NY-USA (1995).
50. Snodgrass, R.T.: The temporal query language TQuel. *ACM Transactions on Database Systems (TODS)*, 12(2), 247-298. (1987)
51. Soo, M.D.: Bibliography on temporal databases. *ACM SIGMOD Record*, 20(1), 14-23. (1991)
52. Stam, R.B., Snodgrass, R.T.: A bibliography on temporal databases. *Data Engineering Bulletin*, 11(4), 53-61. (1988)
53. Stonebraker, M., Rowe, L.A.: The design of POSTGRES. *ACM SIGMOD Record*, 15(2), 340-355. (1986)
54. Thériault, M., Claramunt, C., Villeneuve, P.Y.: A spatio-temporal taxonomy for the representation of spatial set behaviours. In: Böhlen, M.H., Jensen, C.S., Scholl, M.O. (eds.) *Spatio-temporal database management*. Lecture Notes in Computer Science -LNCS-, vol. 1678, pp.1-18. Springer, Berlin - Germany (1999).
55. Tryfona, N., Pfoser, D., Hadzilacos, T.: Modeling behavior of Geographic Objects: An experience with the Object Modeling Technique. In: Olivé, A., Pastor, J.A. (eds.) *Advanced Information Systems Engineering*. Lecture Notes in Computer Science -LNCS-, vol. 1250, pp.347-359. Springer Verlag, Berlin - Germany (1997).
56. Tsotras, V.J., Kumar, A.: Temporal Database Bibliography Update. *ACM SIGMOD Record*, 25(1), 41-51. (1996)
57. Venkateswara-Rao, K., Govardhan, A., Chalapati-Rao, K.V.: An object-oriented modeling and implementation of spatio-temporal knowledge discovery system. *International Journal of Computer Science & Information Technology*, 3(2), 61-76. (2011)
58. Wachowicz M.: Object-oriented design for temporal GIS, vol.15. Taylor & Francis, London-UK (1999).
59. Worboys, M.F., Hearnshaw, H.M., Maguire, D.J.: Object-oriented data modelling for spatial databases. *International Journal of Geographical Information Systems*, 4(4), 369-383. (1990)
60. Worboys, M.F., Hornsby, K.S.: From objects to events: GEM, the geospatial event model. In: Egenhofer, M.J., Freksa, C., Miller, H.J. (eds.) *Geographic Information Science*. Lecture Notes in Computer Science -LNCS-, vol. 3234, pp.327-344. Springer Verlag, Berlin - Germany (2004).
61. Worboys, M.F.: A unified model for spatial and temporal information. *The Computer Journal*, 37(1), 26-34. (1994)
62. Worboys, M.F.: Event-oriented approaches to geographic phenomena. *International Journal of Geographical Information Science*, 19(1), 1-28. (2005)
63. Wu, Y., Jajodia, S., Wang, X.S.: Temporal database bibliography update. In: Etzion, O., Jajodia, S., Sripada, S. (eds.) *Temporal Databases: Research and Practice*. Lecture Notes in Computer Science -LNCS-, vol. 1399, pp.338-366. Springer Verlag, Berlin - Germany (1998).
64. Yuan, M.: Modeling semantical, temporal and spatial information in geographic information systems. In: Craglia, M., Couclelis, H. (eds.) *Geographic information research: Bridging the Atlantic*. vol. 1, 1st, pp.334-347. Taylor & Francis, London-UK (1997).
65. Yuan, M.: Representing complex geographic phenomena in GIS. *Cartography and Geographic Information Science*, 28(2), 83-96. (2001)
66. Yuan, M.: Temporal GIS and spatio-temporal modeling. In: *3rd International Conference on Integrating GIS and Environmental Modeling*, pp.21-26. University of California, Santa Barbara-CA-USA (1996).
67. Yuan, M.: Use of a three-domain representation to enhance GIS support for complex spatiotemporal queries. *Transactions in GIS*, 3(2), 137-159. (1999)

## Annex 1

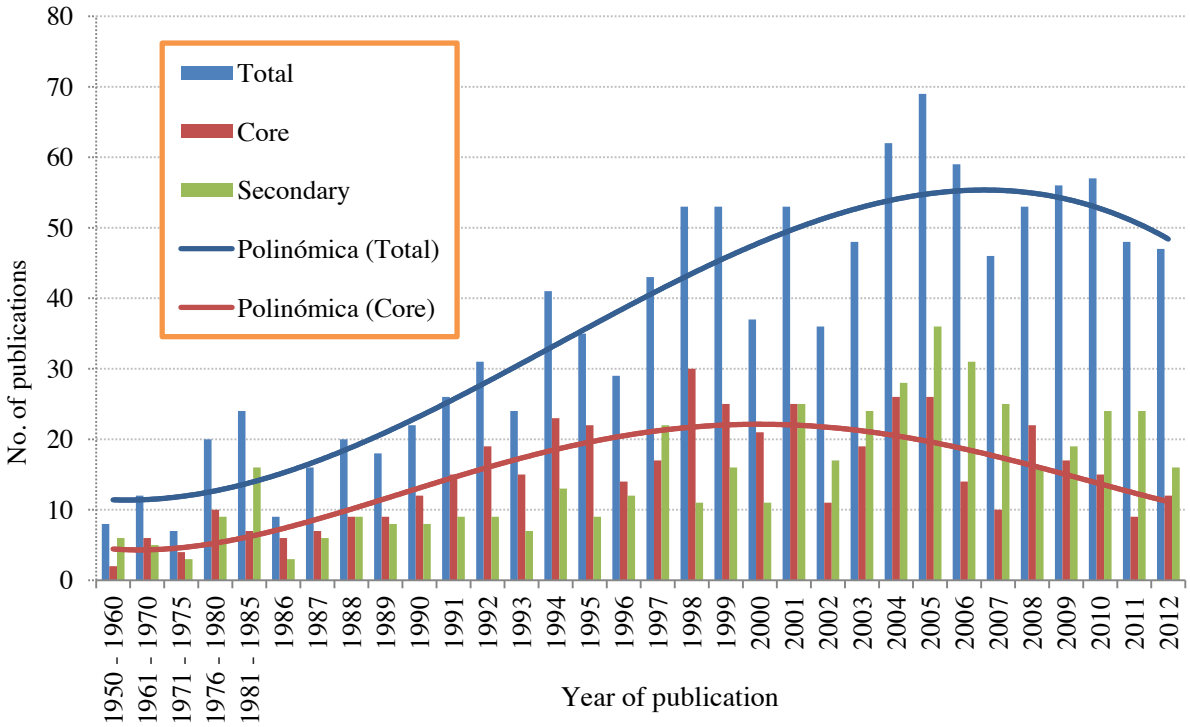


Figure 5. Trends in the publication of spatio-temporal topics compiled in Timebliography

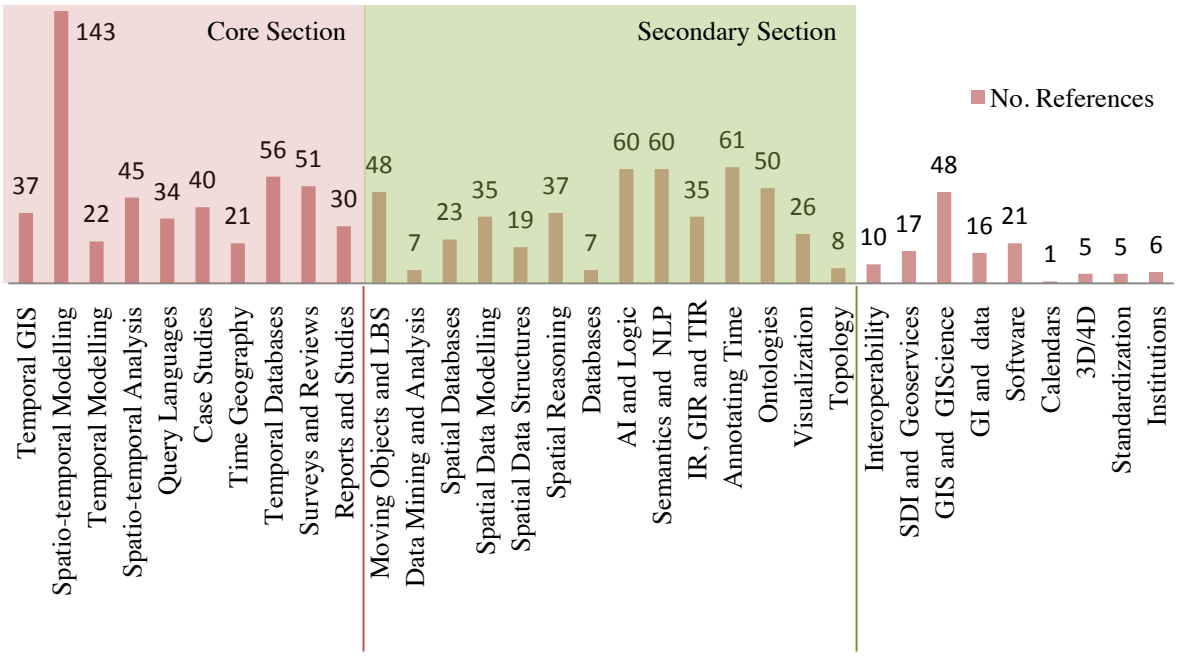


Figure 6. Number of references per category

Table 3. Main scientific databases searched for the definition of Timebliography

| **Source** | **URL** |
|---|---|
| ISI Web of Knowledge | http://isiknowledge.com |
| IEEE Xplore Digital Library | http://ieeexplore.ieee.org |
| ACM Digital Library | http://dl.acm.org |
| SpringerLink | http://www.springerlink.com |
| Scopus | http://www.scopus.com |
| Scirus | http://www.scirus.com |
| ScienceDirect | http://www.sciencedirect.com |
| CiteSeerX | http://citeseer.ist.psu.edu |
| Pion Publications Ltd. | http://www.pion.co.uk |
| The DBLP Computer Science | http://www.informatik.uni-trier.de/~ley/db |
| WorldCat | http://firstsearch.oclc.org |
| Ingenta | http://www.ingentaconnect.com |
| Engineering Village | http://www.engineeringvillage2.org |
| The AutoCarto Archives | http://mapcontext.com/autocarto/proceedings |
| International Archives of the ISPRS | http://www.isprs.org/publications/archives.aspx |
| EBSCO Host | http://search.ebscohost.com |