

# Multivariate-Space-Time Cube to Visualize Multivariate Data

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## Abstract

*The data visualization refers to the representation of the data tables with the techniques of computer graphics to enable users to draw the information implicit in data. The multivariable spatio-temporal data consist of the variables of time, location, and attributes that are represented on tables as data fields. The article approaches 3-dimensional Cartesian coordinates to representing adequately the data of a table. The main idea is that each record of the data table is converted to a data plane of two dimensions, i.e. each data tuple of a record is shown as the graphics in a 2-dimensional domain. Then these data planes are arranged along and perpendicularly to the time axis of a 3-dimensional Cartesian coordinate system. This method includes the data of attributes in a space-time cube (STC) to represent adequately the data fields of a table. This approach is called multivariate-space-time cube (MSTC). The multivariate-space-time cube proposed in this paper not only represents visually and adequately the data of a table, but also offers users straight views on non-inclined maps of geographic area. The proposed multivariate-space-time cube is illustrated with the data table of Napoleon's 1812 Russian campaign. All data of the table is represented on a cube showing visually the great loss on soldiers as well as tragic defeat of the campaign.*

## 1. Introduction

The approaches of data visualization have been developed along with the techniques of computer graphics to enable the human to cognize and understand the significance implicit in raw data. Especially, geo-visualization refers to the methods of representing and understanding spatio-temporal data. The techniques of visualizing geographic data provide with the tools of drawing geographic information from geographic data or discovering knowledge implicit in spatio-temporal data. The techniques of data visualization have employed various mathematical approaches to represent data such as Cartesian coordinates, parallel coordinates, star plot, and their combinations. Traditionally, 2-dimensional Cartesian coordinate systems serve as maps to indicate the locations of geographic objects, not indicate their time and attributes. Parallel coordinates and star plots show the relations among the various variables of objects, including the variables of time and location. The data visualization refers to represent visually the data of a table of many fields such as time, location, and attributes with the techniques of computer graphics. The objective of the article is to search an approach to representing multivariate data including the data of time, location, and attributes that are arranged on

a data table. The main idea is to represent each data record of the table on a data plane, i.e. each data plane shows the graphics representing the data of the variables in the data tuple of a record. Then these data planes are arranged along the time axis. The subsequent content presents concisely the researches related in this article and the conceptual framework used in this paper. The third item that is also the main content of the article depicts the approach of multivariate-space-time cube that is developed from the concept of space-time cube proposed by Hagerstrand in 1970. In the fourth item, the data table of Napoleon's Russian campaign in 1812 is used to illustrate the model of multivariate-space-time cube.

## 2. Related Works and Conceptual Framework

In 1970, Hagerstrand included the dimension of time in a traditional 2-dimensional map to form a space-time cube (STC) based on a 3-dimensional Cartesian coordinate system to represent spatio-temporal objects (Hagerstrand, 1970). A space-time cube employs a 3-dimensional Cartesian coordinate system to indicate the positions in space and the positions in time of the entities, phenomena, and events that are jointly called the objects

(Hagerstrand, 1970, Kraak, 2003b, Gatalsky et al., 2004, Yu and Shaw, 2007 and Tran and Nguyen, 2011a) (Figure 1). A space-time cube (STC) represents not only spatio-temporal objects, but also moving objects. A spatio-temporal object is an object having its spatial positions associated with time moments. Meanwhile, a moving object is an object having its spatial positions changing continuously through space (Andrienko et al., 2011a). Space-time cubes do not indicate the data of object attributes. Hence it is necessary to include the attributes of objects in space-time cubes to represent adequately the variables of objects. In a space-time cube, a 3-dimensional Cartesian coordinate system is applied for representing visually spatio-temporal data. The  $x$  and  $y$  spatial components of data are assigned to the  $x$  and  $y$  axes of the Cartesian coordinate system on the  $(xy)$  plane to represent position data. The  $t$  time component of data is assigned to the vertical  $z$  axis of the Cartesian coordinate system to indicate the time. At each time moment  $t_i$ , the position of an object is indicated as a point determined by the coordinates  $(x_i, y_i, t_i)$ . For a spatio-temporal object, each space-time position of the object is indicated in a space-time cube as a point. Meanwhile, a moving object is indicated by its space-time path that is a curve time-ordered connecting the space-time positions recorded during the observation time by the method of time-based, location-based, event-based, or

change-based recording (Andrienko and Andrienko, 2011c and Andrienko et al., 2008). The representation of data of moving objects in space-time cubes enables the visual analysis of the movement data (Andrienko and Andrienko, 2010, Andrienko and Andrienko, 2011b, Andrienko and Andrienko, 2011c and Nguyen et al., 2012), or is used to set up the systems of tracking moving objects in real-time (Tran and Nguyen, 2011b). Multivariable spatio-temporal data or multivariate data are the data of the tuples including several elements or the data of the tables having many fields. These data are the values of the dependent or independent variables. In a data table of several fields, the time is an independent variable as its special properties, the fields of spatial position and attributes are the variables dependent on time. With three dimensions, each space-time cube represents the data tuples of three elements, two dimensions for spatial positions  $(x, y)$ , the other for time points  $t$ . The following approaches are proposed by several authors to represent multivariate data. The first uses two cubes, a cube for spatial positions  $(x, y)$  associated with time points  $t$  and a cube for attributes associated with locations (Kraak, 2003a). The second also uses two cubes, a cube for attributes associated with time and a cube for spatial positions  $(x, y)$  associated with time points  $t$  (Li and Kraak, 2005).

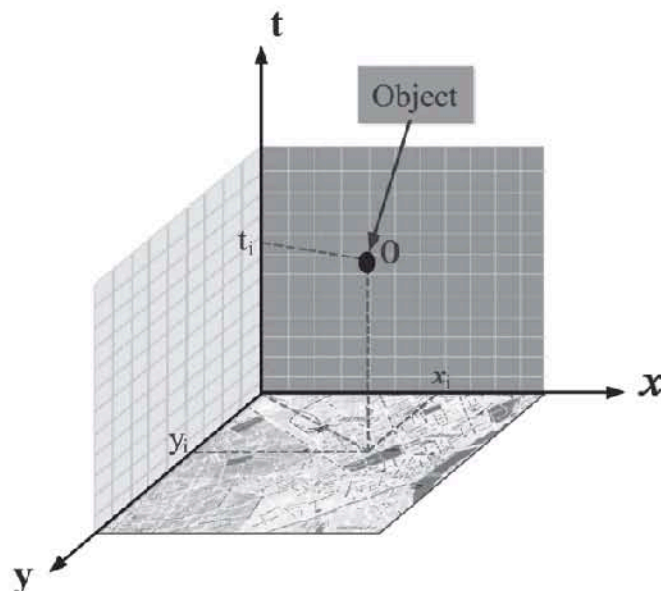


Figure 1: STC formed with 3-D Cartesian coordinates



The third is to share an axis for time and attributes, i.e. in a cube, the time axis is shared between time and attributes, the two others indicate spatial positions, and colors are used as the dimensions representing various attributes (Tominski et al., 2005, Tran and Nguyen, 2011a and Tran and Nguyen, 2011b). Sometimes, in a system representing multivariate data of moving objects in real-time, the spatial positions are indicated as points in a domain that is switched between a 2-dimensional plane and a 1-dimensional axis (Tran and Nguyen, 2011b).

### 3. Multivariate-Space-Time Cube (MSTC)

A multivariate-space-time cube (MSTC) is an expansion of the approach of space-time cube (STC) to represent all fields of a data table in a cube. A multivariate-space-time cube employs a 3-dimensional Cartesian coordinate system to indicate data variables. In a multivariate-space-time cube, two axes indicate the spatial positions and the other the temporal positions of objects, attributes are assigned jointly to one of two axes of locations. In other words, the variable  $t$  of time data is assigned to one of two horizontal axes, the variables  $x$  and  $y$  of the location data are assigned to two other axes of a 3-dimensional Cartesian coordinate system, one is vertical and one is horizontal, and the variables of attributes are assigned jointly to the vertical axis of location data. The color is used to indicate the difference of attributes, each color is considered as a dimension representing an attribute

(Figure 2). The process of visualizing a data table on a multivariate-space-time cube comprises the conversion of the data records of the table to the graphics on data planes and the arrangement of the data planes along the time axis. Each data plane represents a data tuple <time, location, attributes> of a data record corresponding with the time moment in the tuple. A data plane shows graphics representing the data of studied geographic area, the data of object location, and the data of object attributes. The data of the geographic area define the geographic coordinates assigned to the two axes of the plane. The data of attributes are represented as bars lying on the data plane and parallel to the vertical axis of the plane. Colors are used as the dimensions indicating different attributes. Then the data planes are arranged along the time axis, each plane is perpendicular to the time axis at the time moment of the data tuple that it represents (Figure 3). The geographic area displayed on data planes is perpendicular to users' view ray. The variables of attribute data are represented at external edge of each data plane as attribute bars, each bar corresponds with the value of one attribute at the same time moment of the plane. The bars representing the same attribute are indicated by a color and expand along the  $t$  axis as the histogram of the attribute. The variation of each attribute with time is inferred from the histogram bars and the properties of the attribute. The correlation among different attributes at a time moment is considered on the data plane of the moment (Figure 2).

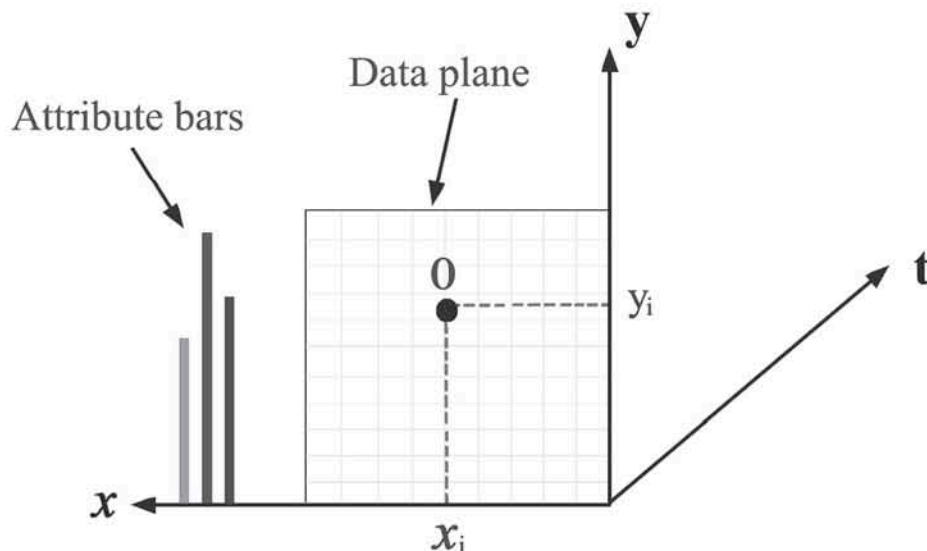


Figure 2: MSTC formed with the data planes and 3-D Cartesian coordinates

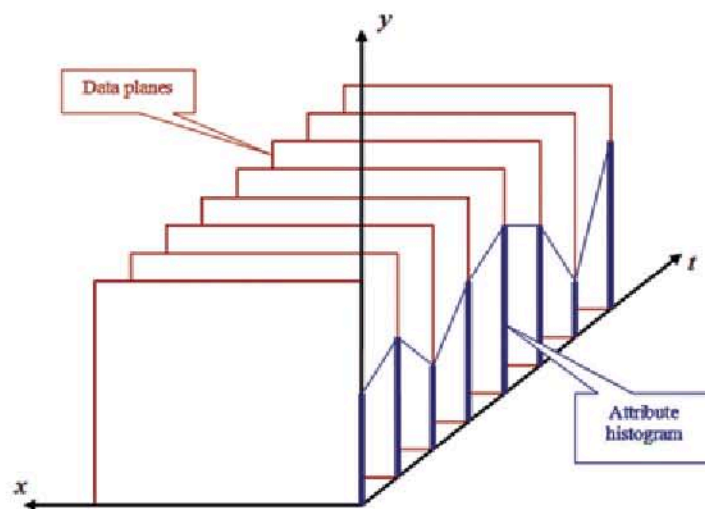


Figure 3: Data planes along the time axis in MSTC

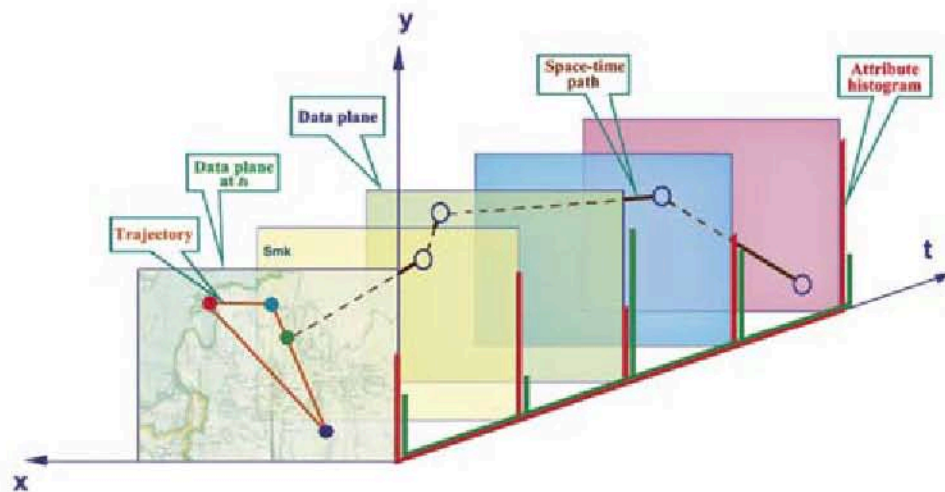


Figure 4: MSTC to represent movement data

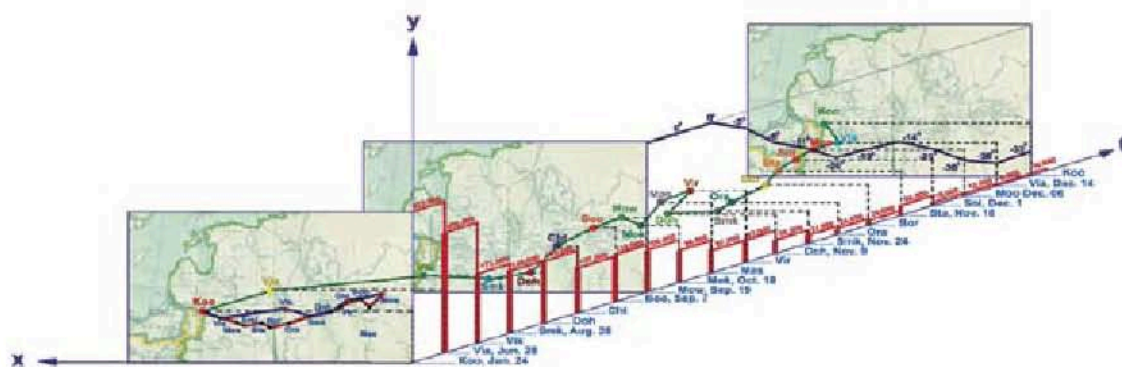


Figure 5: MSTC to represent the data table of Napoleon's 1812 Russian campaign



For movement data, the curve time-ordered connecting the spatial positions of an object on the data planes constitutes the space-time path (temporal trajectory) of the object (Figure 4). The temporal trajectory indicates the spatial positions associated continuously with temporal positions of the object. The spatial position of an object at a time moment is indicated as a point on the data plane of that time moment or inferred from the temporal trajectory. The dynamic mode of a multivariate-space-time cube provides with the controlled display of data planes. A time cursor is designed on a time axis to control automatically or manually the display of data planes one after another. For the dynamic mode, the time cursor slides on the time axis from the left to the right, when the cursor reaches a time moment, the data plane corresponding to the moment and the data before this moment turn up. The multivariate-space-time cube not only represents adequately the components of multivariate data, but also offers users straight views on non-inclined maps of geographic area and vertical histogram of attributes along time axis.

#### 4. Napoleon's 1812 Campaign In Russia on Multivariate-Space-Time Cube

In 1867, Charles Joseph Minard represented Napoleon's march on a traditional 2-dimensional map (Friendly, 2002). He represented the data of places where the army passed by the symbols on the map. The data of the army size were represented by the width of the flow line. The data of date were indicated by text. The direction of advance and retreat were indicated by two different colors. The data of air temperature were represented by a polyline beneath the flow line (<http://biotechnorati.co.uk/2010/08/charles-joseph-minards-figurative-map-of-the-fate-of-napoleons-army-in-russia.html>). Up to 2003, Kraak represented the campaign on two space-time cubes, a cube for the temporal trajectory of the troops and a cube for the size of the army associated with its locations. Kraak's cubes offer users impressive visual graphs on great size as well as tragic defeat of Napoleon's 1812 campaign in Russia. However, Kraak's method used two cubes to represent the campaign data and the space-time cubes provided users with inclined views on geographic map of horizontal plane (<http://www.itc.nl/personal/kraak/1812/minard-itc.htm>). The movement data of Napoleon's

1812 campaign in Russia comprises the following variables:

- the time moments when the troops arrived in a city or battle;
- the location of the city or battle where the troops passed;
- the number of soldiers at the moment when the troops came into a city or battle;
- the air temperature on the retreat.

From the historic documents (James and McGhee, 2006; <http://www.historyhome.co.uk/eight/france/moscow.htm>; [http://en.wikipedia.org/wiki/French\\_invasion\\_of\\_Russia](http://en.wikipedia.org/wiki/French_invasion_of_Russia); <http://www.britannica.com/EBchecked/media/70821/Statistical-map-of-Napoleons-Russian-campaign-of-1812-The-size>), the data variables of the campaign are recorded on the table below. The data table consists of 20 records and 7 fields, which are referred as the following:

- The position in time of a data record,  $i$
- The day when the army came into a city or battle
- The city or battle where the army came
- The abbreviated name of cities
- The geographic locations of cities
- The number of soldiers corresponding to the location where the army came
- The air temperature corresponding to the place and time of the army on retreat.

The table of multivariable spatio-temporal data of Napoleon's 1812 campaign in Russia is represented on a multivariate-space-time cube including 20 data planes rectangular to the time axis. Each data plane indicates the data of position and the army's size on a certain day of operation. The position data are indicated by the geographic coordinates on data planes, the number of soldiers is indicated by the bars on external edges of data planes and the air temperature is indicated by a point on the external edge of data planes (Figure 5). These data plane are arranged in time line along time axis from June 23<sup>rd</sup>, 1812 when Napoleon's army went to war from Kovno in order to advance into Moscow on September 19<sup>th</sup>, 1812 and retreat off Moscow in order to come back Kovno after December 14<sup>th</sup>, 1812.

Table 1: Data table of Napoleon's 1812 campaign in Russia

<i>i</i>	<i>Date</i>	<i>Place</i>	<i>Abbreviated place</i>	<i>Geographic coordinate</i>	<i>The number of soldier</i>	<i>Temperature (°C)</i>
0	Jun. 23	Kovno	<i>Koo</i>	$(x_{koo}, y_{koo})$	422,000	
1	Jun. 28	Vilna	<i>Via</i>	$(x_{via}, y_{via})$	400,000	
2		Vitebsk	<i>Vik</i>	$(x_{vik}, y_{vik})$	175,000	
3	Aug. 18	Smolensk	<i>Smk</i>	$(x_{smk}, y_{smk})$	145,000	
4		Dorogobuzh	<i>Doh</i>	$(x_{doh}, y_{doh})$	145,000	
5		Chjat	<i>Cht</i>	$(x_{cht}, y_{cht})$	127,100	
6	Sept. 7	Barodino	<i>Boo</i>	$(x_{boo}, y_{boo})$	135,000	
7	Sept. 19	Moscow	<i>Mow</i>	$(x_{mow}, y_{mow})$	100,000	0
8	Oct. 18	Mojaisk	<i>Mok</i>	$(x_{mok}, y_{mok})$	96,000	0
9		Malojaroslavets	<i>Mas</i>	$(x_{mas}, y_{mas})$	87,000	-5
10		Virna	<i>Vir</i>	$(x_{vir}, y_{vir})$	87,000	-8
11	Nov. 9	Dorogobuzh	<i>Doh</i>	$(x_{doh}, y_{doh})$	55,000	-11
12	Nov. 24	Smolensk	<i>Smk</i>	$(x_{smk}, y_{smk})$	37,000	-26
13		Orsha	<i>Ora</i>	$(x_{ora}, y_{ora})$	24,000	-19
14		Botr	<i>Bor</i>	$(x_{bor}, y_{bor})$	20,000	-14
15	Nov. 28	Studianka	<i>Sta</i>	$(x_{sta}, y_{sta})$	50,000	-25
16	Dec. 1	Somorgoni	<i>Soi</i>	$(x_{soi}, y_{soi})$	18,000	-30
17	Dec. 6	Molodeczno	<i>Moo</i>	$(x_{moo}, y_{moo})$	12,000	-38
18	Dec. 14	Vilna	<i>Via</i>	$(x_{via}, y_{via})$	8,000	-33
19		Kovno	<i>Koo</i>	$(x_{koo}, y_{koo})$	10,000	

The time of each data plane is noted on the external edge of each data plane. The space-time path time-ordered connecting the places Napoleon's troops passed on the data planes represents the relation between space and time of the troops. The bars of the number of soldiers on the edges of data planes represent the army's size corresponding to the place and time. The bar histogram indicates the change of the army's size. The curve connecting the temperature points on the edges of data planes indicates the variation of the weather on the days of retreat off Moscow of the troops. The trajectory of flow line is indicated on the first data plane on the day of June 23<sup>rd</sup> in Kovno. With the approach of data plane, we represented the movement data of Napoleon's campaign on one cube, a multivariate-space-time cube. Especially, in the dynamic mode, a time cursor is designed on a time axis to control automatically or manually the display of data planes one after another.

In the multivariate-space-time cube, the time cursor slides on the time axis from the left to the right in order to indicate the historic days of the campaign. When the cursor reaches some historic day:

- the corresponding data plane turns up;
- the historic place turns up on the first data plane;
- the trajectory and the space-time path are prolonged at the same time;
- the histogram of soldier number adds a bar;

To visualize the data of Napoleon's 1812 campaign in Russia, the multivariate-space-time cube with the approach of data plane provides users with straight views on the geographic map of Europe clearly from the border between Poland and Russia to Moscow as well as cities the troops passed. The dynamic mode of the cube offers users each event of the campaign in time line (Figure 6).



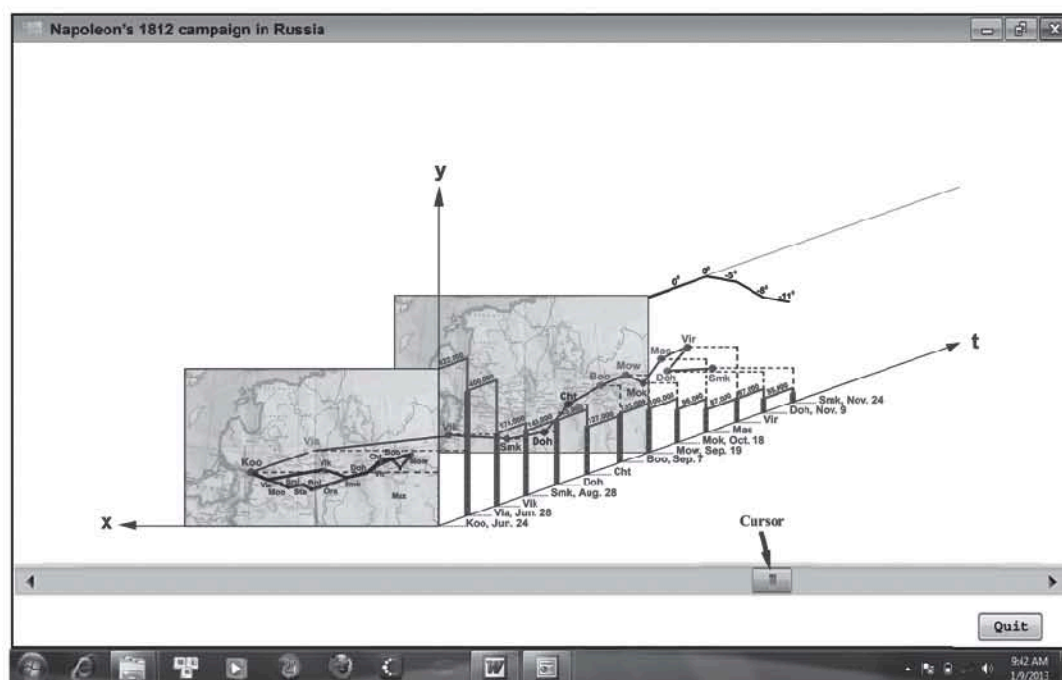


Figure 6: The dynamic mode of MSTC for Napoleon's 1812 Russian campaign

## 5. Conclusion

A multivariate-space-time cube (MSTC) employs a 3-dimensional Cartesian coordinate system to represent multivariate data, including data of time, position, and attributes. The multivariate-space-time cube approaches the concept of data plane to represent the data variables of each data tuple or each data record of a table. The data planes of various time moments are arranged in time line along and perpendicularly to the horizontal time axis. A multivariate-space-time cube not only represents object positions associated with time as a space-time cube, but also represents object attributes on the  $t$  axis as the histograms of attributes. Hence, a multivariate-space-time cube can be used to represent multivariate data. The major characteristics of a multivariate-space-time cube are:

- to represent concurrently the components of data including position and attributes changing with time;
- to show the trajectory and the space-time path of the movement;
- to offer users straight views on the geographic map of the study area with the clear information of the geographic area;

- to provide users with the variation of an attribute over time and the correlation among attributes at a time moment.

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