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FROM MAPPING TO VIRTUAL GEOGRAPHY

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Abstract: History of mapping goes back hundreds of years. Many books and articles have been written on this topic as well as many different ways to present our world. This paper will not deal with cartography in a normal sense as indicated by the headline, but will face and argue the necessity of dealing with data that take their origin in the real world and keep the relation to this world. Today geographical data are changed in order to create traditional maps, which over centuries have been rendered on a sheet of paper with two-dimensional presentations in mind.

Many approaches have been made to build up our world in virtual spaces and create an illusion of spatiality, thus many different techniques have been developed to handle the modelling, the data acquisition, and the conversion between different software solutions and coordinate systems with their projections and assumptions on different levels. These initiatives are usually based on two-dimensional map projections and their results suiting the purpose of urban models with well-defined boundaries and limited model sizes.

If you want to deal with the whole world in one model which utilizes a uniform data representation the next step is to deal with a global approach to coordinates and view of the world. Here, escaping flatland means escaping projections. In the Grifinor system within the 3D GeoInformation Project

described at Cupum'2003 in Sendai, Japan a global approach with a geographical coordinate system has been used.

Keywords: Geocentric coordinates, model-map, cartographic projections, urban models

FROM MAPPING TO VIRTUAL GEOGRAPHY

1 INTRODUCTION

Mercator's world map of 1569 bore the legend: "New and improved description of the lands of the world, amended and intended for the use of navigators." (Wilford, 2002)

So Mercator had a specific purpose in mind when he created his famous map back in the 16th century. Even the church maps in the medieval ages were made for a specific purpose, even though these were not to present geography as it is seen by man, but to serve God. The genesis of the Universal Transverse Mercator (UTM) system was given by cross-border military activities and cooperation among countries (actually NATO). They simply needed a common map to be able to coordinate their attacks against the enemy.

All map-making has a certain motivation. Map makers today rather work scientifically with correct mapping of the earth in mind. Nevertheless, it can be observed that governmental agencies and their staff, particularly those that administer national, county, and municipality databases prefer coordinates in 'their' particular projection and planar coordinate system with which they are used to work (Sickle, 2004). In many countries such systems are officially sanctioned by legislation, and military reasons for maintenance of locally specific coordinate systems exist as well. Thus scientific map inventory as conducted by contemporary mapping agencies around the world cannot be regarded as socially, culturally, and politically neutral (Raper, 2000). The choice of projection may be taken out of the hand of the surveyor and laid over to a political decision, where the size of neighbouring countries may influence the choice of projection. As long as we choose a level of abstraction and a mathematical representation to render maps on paper or in digital form, the right solution is a compromise controlled by many parameters.

Currently, the potential of three-dimensional media for map-making has been adopted only partially. Despite the fact that the assumption of a flat Earth is fundamentally wrong map-making efforts are still based on a planar description of measured points. The main reason for the use of planar systems and cartographic projections is cultural and political values along with traditions and simple lack of knowledge.

The main reasons why map-making is based on planar coordinate systems are two. The first is historical, because prior to computers being widely

spread, map-making was dependent on and limited by the paper medium with which it was inherently associated. Methods for and knowledge of creating maps, which have evolved from roots in mathematics, physics, geometry and cartography over thousands of years, were enforcing projections of a plane. The other reason is that calculation of areas, angles, and lengths on the surface of quadric surfaces, such as an ellipsoid, can be complicated and that in many cases a planar representation is sufficient.

New technology, however, enables us to produce even more precise data and create better maps. Maps today serve a huge amount of different purposes and are designed by skilled cartographers. The electronic way of presenting maps on monitors in all sizes have taken a lot of attention among cartographers, lately. The high resolution coloured maps, at least one square meter in size, which every adult will remember from his time in public school will be exchanged for electronic web maps. Cartographers tend to transfer their knowledge of how to create useful maps to the electronic media. What is needed is a proper new paradigm of how to create maps for this new medium. And how to interact with maps and use maps in a new way.

While the new medium demands a new way of rendering two-dimensional maps, a whole new set of possibilities within the domain of virtual geography has already seen the light. Going from two to three dimensions, when representing the earth, gives a completely new paradigm of creating maps, in the following called model-maps, since we are not creating a traditional map but a spatial geo-referenced model that is the closest we have been to a precise representation of the earth until now. But what we are doing at the moment is to miss a great opportunity to leave the world of map projections and leave the traditional way of representing the earth. In an electronic media we can represent the earth and the elements upon it in its correct shapes and sizes. So, if the world looks like an ellipsoid we create an ellipsoid. Surveys from space can be used to create a good model-map of the earth. Today, positions are typically given by global positioning systems (GPS), where calculations and coordinates are determined in a global coordinate system with origin in the centre of the earth. These coordinates again are projected onto a flat geometry to be shown on a screen, maybe even in three dimensions. This is unnecessary.

It seems as if we continue along the wrong track when we develop our mapping technology into the third dimension. One of the biggest mistakes which can be observed in computer-science is that we often tend to reproduce the way we used to do things, instead of taking full advantage of the technology aiming at the best overall solution. (Mathiassen L. *et. al.*, 2000)

When we go back in time and look at the genesis of coordinate systems and maps, it often was the need for a country to have a geographic system that could serve the purpose of being able to handle properties and legal issues between its owners. So a lot of different systems were “invented”, see Figure 3. A lot of small independent geographic islands were created. Later on, these were refined and some aligned between the countries. New ones were implemented to compensate for the lack of precision and the need for having

common systems due to cross border activities, for instance, on large infrastructure constructions.

At the moment, we can observe a massive production of virtual town models popping up like small independent islands. More and more municipalities around the world have discovered the great advantage of using three-dimensional models of their town for planning and decision making primarily, but also for the purpose of tourist information and other presentational opportunities. If the number of town models increases continuously in the same manner as until now we will soon reach a point where we will face the challenge of combining them in one system covering a whole country. Since the map projection has an implicit error (see Section 2.1) these errors must be handled in the models as well.

This article shows that we can avoid facing these problems, because a digital model simply does not need a projection. A computer can handle space as it is: namely three-dimensional space. Being able to short-cut the way of map making down to a few simple steps where major errors can be avoided should appeal to everyone who is dealing with these issues.

2 CONSTRAINTS OF CARTOGRAPHIC PROJECTIONS

In the following sections we will argue the major impediments of cartographic projections common to all 2D but also 2.5D systems, which exploit three-dimensional graphics on top of flat-world approximation. We address issues about geometric distortion, numerical imprecision, limited spatial extent, theoretical heterogeneity, interoperability issues and computational overhead when using cartographic projections. Based on these arguments we show that avoiding the flat-world metaphor is a feasible challenge with vistas for a better representation of geographic features.

2.1 Geometric Distortion

The purpose of cartographic projections (further only projection) is to map actual earth surface, or its portion, on a plane. Geometrically, this can be done by projecting a portion of a spheroid, which represents the earth, on an intermediate surface that can be developed in a plane, e.g. a cylinder. Even in a digital age this cannot be done without distortion. The problem can be illustrated by trying to flatten a continuous piece of an orange peel. If the piece is small enough, it can be flattened with a small deformation. When attempting to do the same with bigger and bigger pieces, more problems appear. The peel needs to get stretched more and will eventually start to tear and even between the cracks deformations cannot be avoided.

We can observe the same problems when mapping geometry of features from the surface of the earth onto the map plane. If the peel represents the earth surface, then projections can be seen as the performers of the flattening. The difference is that projections apply deformations in a specific, meaningful way, not in an ad-hoc manner as when flattening the peel. Projections aim at minimizing the effect of deformation in a particular area and in a particular quantity. Different projections can eliminate deformations either in lengths, in areas, or in angles, but never in more than one of these quantities. This

results in a classification into equidistant, equal-area and, conformal projections, respectively.

In order to illustrate the magnitude of distortion we use the UTM projection. UTM is a conformal projection, thus length distortion is present. Table 1 shows distortion of a length element in different locations, when a single UTM zone is used (we describe zones in the next section). In such a single coordinate system a model-map of a construction 80.0 metres long, this would in London introduce an 8 centimetres error compared to the measure obtained in the reality. These eight centimetres is a penalty for using the projection, and it cannot be avoided. However, the same measure made in the location of Helsinki would be affected by 4.8 metres error, when transformed to the selected coordinate system.

Table 1: Deformations in the coordinate system UTM zone 30.

	Longitude $\Delta\lambda$ [DDEG]	Latitude φ [DDEG]	Deformation [mm/m]
London	3	51.5	1
Praha	17	50	28
Helsinki	28	60	60
New York	78	40	605

The deformation grows exponentially with the size of the area that is covered by the system. If we expect having a relatively high precision engineering data as a part of large three-dimensional model-maps, for example spanning a whole country or even beyond, then projections may lead to serious problems regarding data quality.

2.2 Limited Spatial Range

One of the major impediments of projections is a spatial range in which a projection-based coordinate system can be applied. The range limit is tightly coupled with the deformations discussed in the previous section. The spatial range limitation extends the projections' flat-world feature with the end-of-the-world property. In general, the distortion grows with a distance from a central, undistorted iso-curve on the ellipsoid, e.g. a meridian, which is typical for the projection.

This problem is usually solved by the realization of a set of separate reference systems, referred to as zones, using the same projection method for many different central iso-curves. UTM, for example, was defined to mapping the world, using 60 pre-defined standard zones along 60 pre-defined central meridians, which leads to 60 independent and incompatible coordinate systems. In Figure 1 the numbers refer to zones, each six degrees wide.

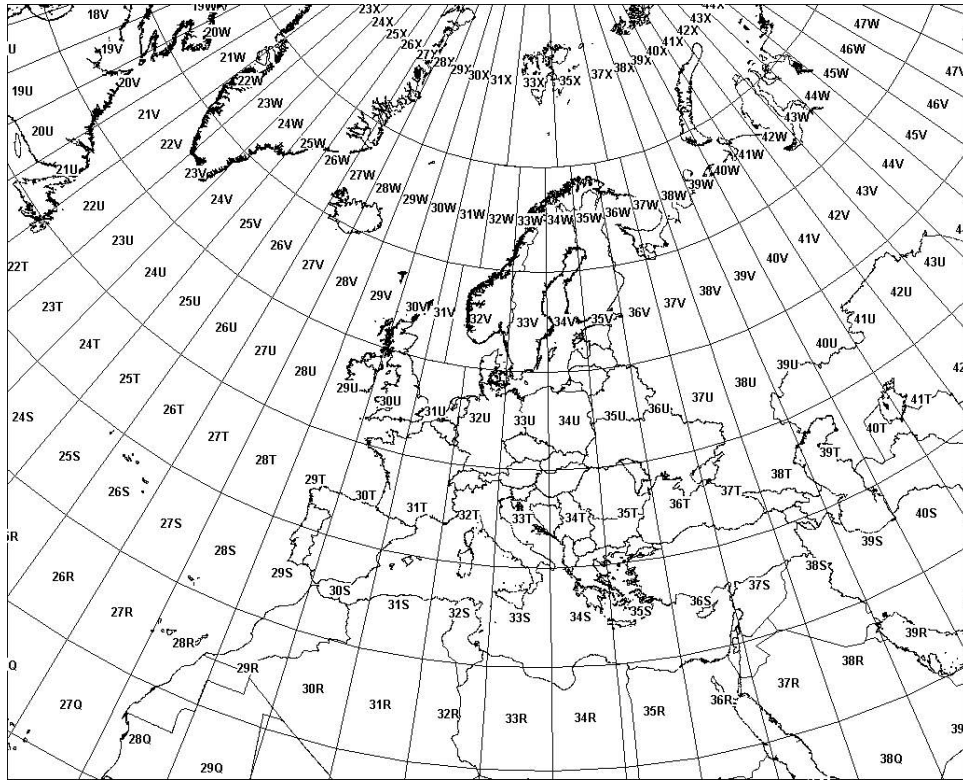


Figure 1: Coverage of UTM map sheets over Europe.

If we accept this 'zonal' solution for the whole globe, we would face a partitioning problem, which is very problematic to deal with. For example, if we choose the UTM based computerized system solution for management of urban and landscape models, our first case will be probably London and the second maybe Stockholm, both exactly on the border between two UTM zones. As a result the ends-of-the-world would appear in the middle of the cities. If we choose different attributes, or a completely different projection, borders would cut other geographic features of interest. The fact is that when we remove the end-of-the-world from one place it will pop up some place else.

Another approach for mapping larger areas is to control the size of the zones in cost of exponentially increasing deformations. In the extreme situation the size of a single partition spans the whole world, which is the case of earth maps, such as the one in Figure 3. No matter what solution we try using projections ends-of-the-world cannot be avoided. And in case of earth maps, apart from the end-of-the-world, distortion approaches infinity and singularity appears at poles. This is inconvenient for model-maps exploiting three-dimensional media.

2.3 Numerical Imprecision

Apart from distortions that can be expressed explicitly for particular projections, there is always a certain numerical imprecision introduced when performing transformation of coordinates. Some functions used with projections are not exact and expansion into series must be used. Other

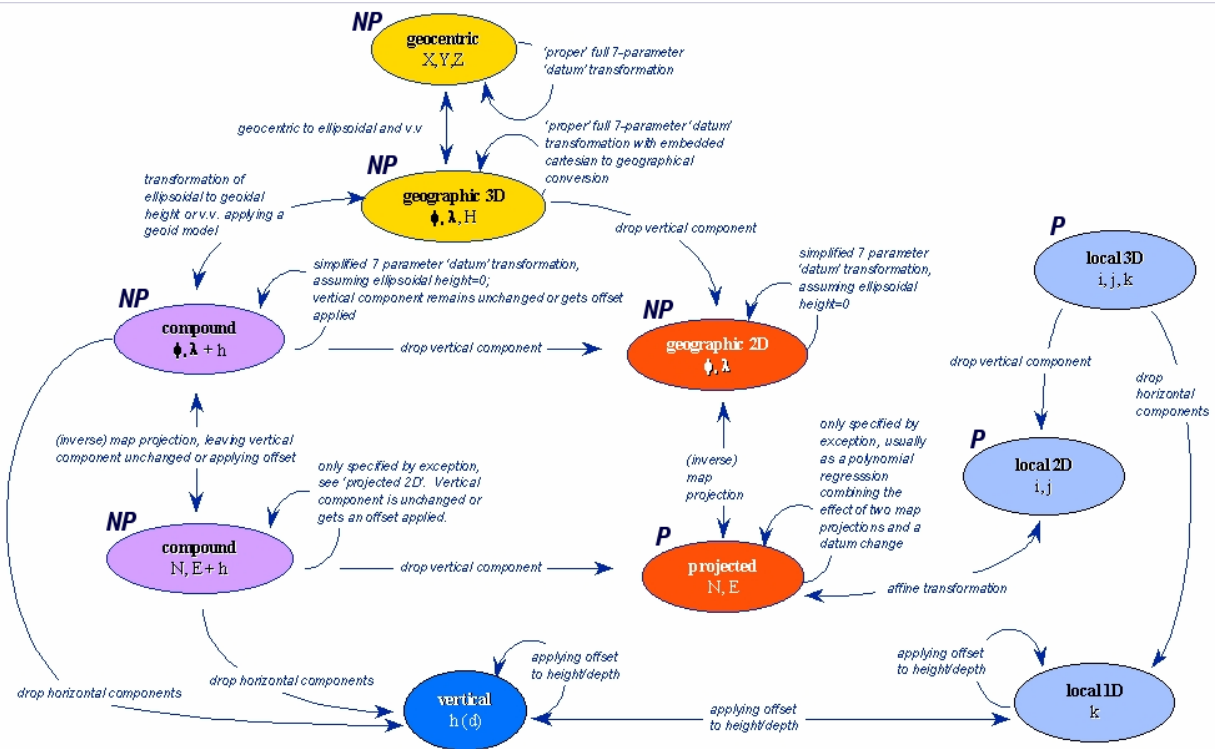


Figure 2: Transformations with geographic data

quantities must be computed iteratively. Most projections actually combine these numerical inconveniencies. In practice, depending on the implementation, the inverse transformation between projections can introduce a numerical error in order of millimetres.

It should be stressed that we talk about precision of the function implemented for a projection transformation, not about numerical precision of the computer, which is in double precision about 10^{-15} . For example transformations between systems without projection, which are denoted in Figure 2 with label *NP*, depend only on the numerical precision of the computer. However, in order to obtain any UTM coordinate, for example, from geodetic coordinates on the ellipsoid, we need to use expansion into an infinite series. Only first significant elements of the series are considered, which introduces the extra imprecision we want to stress. From our experience a UTM transformation error can be 10^4 times bigger than the double numerical precision mentioned already. Hence, performing just one transformation to UTM can introduce an error comparable to ten thousand consecutive transformations between coordinate systems without projection in the double precision.

The numerical error from projection transformation is usually assumed to be at most one millimetre, which is negligible for data presented at scales used by classical maps. Nevertheless, when dealing with three-dimensional models of constructions, technical plans, geodetic data, or when we want an analytical application, only few transformations can seriously damage the data.

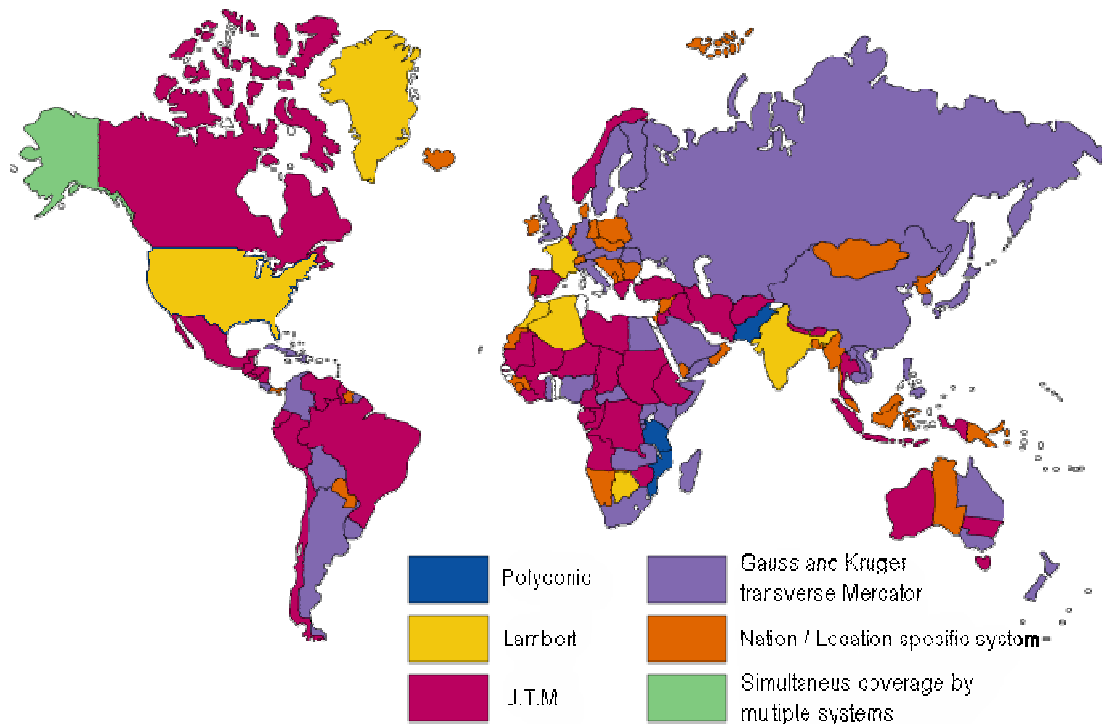


Figure 3: Main projection systems used around the world

2.4 Diversity of Projection-based Reference Systems

Use of projections in practice is extremely heterogeneous, much more than dealing with a set of independent zones within the UTM framework. A general classification of projections still remains to be a challenge. Apart from the classification addressed in Section 2.1, one can be based on characteristics of the intermediate projection surface, which develops an image projected from an ellipsoid into the plane of the map. This way projection can be classified (Buchar and Hojovec, 1996) as simple-conical, simple-cylindrical or simple-azimuthal when the intermediate surface is a cone, a cylinder or a plane respectively; pseudo-conic, pseudo-cylindrical or pseudo-azimuthal when some mathematical conditions correspond to the simple projections but some don't; polyconical when the result image is composed by a projection on an infinite number of cone surfaces; and polyedrical when the reference surface is tessellated and a known projection is repeatedly applied to each tessellation unit. Note however, that there are other projections that cannot be classified in this way. Such projections are usually named after their inventors, e.g. Littrow, Eisenhlohr, Pierce, Adams, Guyou or Tissot projections.

The diversity of projections used in practice is demonstrated in Figure 3, where color depicts the same class of projection but its attributes are different in each country. Note however, that in many countries use of more than one projection is common.

For example, Denmark uses near to a transverse cylindrical conformal projection for the cadastre and the military but UTM (transverse cylindrical conformal) projection is used for topographic works, the Czech Republic exploits the double conic conformal projection with the cone in a generic

position for cadastre but the Gauss-Krüger (transverse cylindrical conformal) projection is used for military purposes, 60% of the states in the USA use the Lambert conic conformal projection, whereas the rest use the Transverse Mercator (transverse cylindrical conformal) based systems in addition to UTM.

Projection used is one aspect of heterogeneities but the number of separate coordinate systems (zones) is another. For example, France including the island of Corse is covered by four zones based on their Lambert projection, California uses six zones, and S-34 in Denmark has two zones. The purpose of the zones is described in Section 2.2.

Heterogeneity of projections continues with datums. In order to constitute a coordinate reference system projection is associated with a set of parameters and a realization of the relationship between an ellipsoid, which is used by a projection, and the planet earth. Such sets are referred to as datums. The relationships are realized through man-made marks fixed in the nature with geodetic coordinates on the ellipsoid known for each mark. It is difficult to address the exact number of datums and ellipsoids used, but for example *GeoTIFF* raster format has around 120 datums based on 35 ellipsoids. In practice this results in about one thousand different projection-based coordinate systems, where each has to be defined using a particular ellipsoid, datum and cartographic projection.

This partially demonstrates that theoretical background and classification of projection-based systems is highly heterogeneous. It involves so many aspects to consider, that staff, including experienced professionals without a degree in cartography, easily get confused. Producers of commercial GIS tend to claim that the problem of transforming geographic data between projections is solved. It depends on what exactly is meant by 'solved'. If 'solved' means that there are implementations of formulas that can transform a coordinate from one well described reference system into another well described reference system, then it might be true on the condition that the transformation is theoretically possible. However, if by 'solved' is meant conceptual clarity, a simple straightforward application, or preserving and reporting data precision, then the solution is not at all satisfactory. And chances are slim that it will ever be satisfactory.

2.5 Interoperability Issues

Substantial standardization efforts are carried on in the name of geographic data interoperability, such as efforts by OpenGIS Consortium or SEDRIS. Their goal is to facilitate the ability to freely exchange spatial information about phenomena related to the earth surface, and to cooperatively run computer systems capable of manipulating such information (Buehler and McKee, 1996). Acceptance and deployment of such a standard is definitely an improvement for geographic data exchange, however it should not induce a misleading belief that upon adoption of such a standard, the technology for operating geographical data will have a simple straightforward solution. This is not likely to be the truth. One of the major interoperability impediments can be attributed to heterogeneities of projections described in the previous section, which leads to a semantic diversity of data structures used for geographic data (Vckovski, 1998).

Addressing all possible coordinate systems used by geographic data is very important, because the majority of data is referenced through the projection-based systems today. However, due to the diversities discussed in the previous section a standardized identifier with the ability to address any of the systems is semantically complex and has many optional elements. When the identifier is created and approved by qualified personnel, the result can clarify the spatial reference of datasets in a uniform manner, which facilitates interoperability. But it does not help to understand the referencing issue for many people who could use the data. This harms interoperability of geographic data on a different and we believe on a more important level than the one covered by standardized syntax.

Projections indirectly, but significantly, hamper development of geo-information systems to run cooperatively. These systems are coded by programmers, who are also human beings, and who must have a substantial understanding of the concepts, which they want to implement. Dealing with the issue of projections whenever a coordinate is about to be processed is a big burden. We know from our experience that a project can get exhausted or struggle with this. After all, a solution that can automatically deal with all the nuances and exceptions of the projection-based coordinates would grow into an extremely complex system. An automated decision is actually nearly undesirable, when dealing with projected coordinates. Thus, the decision about transformations of coordinates is often left on users of contemporary GIS. This does not help interoperability on level of computerized systems either.

An accepted standard for geographic spatial data is a great achievement for an exchange of datasets, however due to heterogeneities of projections the interoperability remains limited. Use of standards in itself does not solve the problems of projection-based systems, which are inherently complicated and thus hamper interoperability.

2.6 Computational Complexity of Cartographic Projections

Processing of coordinates is paramount to most operations when dealing with digital maps or model-maps in the same way as in other domains of computer graphics. Let's illustrate complexity of transformations induced by projections on a function $f(X, Y) \rightarrow \varphi$, which formalizes how to obtain a geodetic latitude φ of a point from its X, Y coordinates in a transverse cylindrical projection, such as UTM.

$$\varphi = \varphi_1 - \frac{\nu \tan \varphi_1}{\rho} \left(\frac{D^2}{2} - \frac{D^4}{24} (5 + 3 \tan^2 \varphi_1 + 10C - 4C^2 - 9e) + \frac{D^6}{720} (61 + 90 \tan^2 \varphi_1 + 298C + 45 \tan^4 \varphi_1 - 252e^2 - 3C^2) \right) \quad (1)$$

The theory expressed by the formula is unimportant here, an important point is to address its complexity. Note that the result of latitude φ depends on φ_1 , which is an approximate estimation of φ . This estimation must be found iteratively before evaluating the formula above. In addition, φ_1 does not have

an exact solution; it is based on expansion into an infinite series. This function $f_1(M,N) \rightarrow \varphi_1$ further depends on the radial curvature M and traversal curvature N at the given point on the ellipsoid for each iteration, where both M,N in turn depend on the parameters of the ellipsoid. The other functionals in the Equation 1, namely ρ , ν , D , e , and C , depend on the parameters of the ellipsoid and on φ_1 .

Regardless of the heterogeneities of projections discussed in Section 2.4, the computational complexity is higher compared to transformations between non-projected systems (see Figure 2). Nevertheless, well implemented transformations are only a few times slower, or even comparable with transformations between geocentric and geodetic coordinates in three dimensions, which do not involve any cartographic projection. However, due to the theoretical complexity early implementations can easily be made inefficient. On the other hand, exaggerated strives for a performance gain usually leads to problems described in Section 2.3.

Such a scenario is a challenging ground for implementations of new libraries that perform transformations between projections more efficiently. However, when dealing with model-maps in three-dimensional space, we know that the most efficient way to deal with projections is to avoid them completely. This is also the main message of this article. We want to address the full potential of three-dimensional media in map-making, not in terms of visualization and interaction, but with respect to the concepts of geographic referencing.

3 GEOCENTRIC APPROACH TO MODEL-MAPS

Three-dimensional media allows map-making solutions that completely eliminate the need for projections. It is so because three-dimensional media allows visualization and exploration of three-dimensional geometry directly in virtual three-dimensional space. Therefore there is no constraint in the form of the flat paper medium any more and, as a consequence all the impediments about geometric distortion, numerical imprecision, limited spatial extent, theoretical heterogeneity, interoperability issues and computational overhead, presented in the previous sections, can be neglected. Also the representation would be conceptually correct in comparison to the flat-world approximation.

We propose to use three-dimensional coordinates related to the centre of the earth for model-maps in order to avoid the difficulties with projections. This new concept for map-making has also new inconveniences, namely data storage size and numerical precision of three-dimensional media hardware. Need for more storage space is caused by the fact that three dimensional space deals with more coordinates and that geocentric coordinates require double-precision numbers, thus in general more and/or bigger numbers need to be stored. The second challenge is to deal with the big numbers of geocentric coordinates in graphics hardware. Today the hardware works with single-precision which allows direct rendering of geometries from the earth

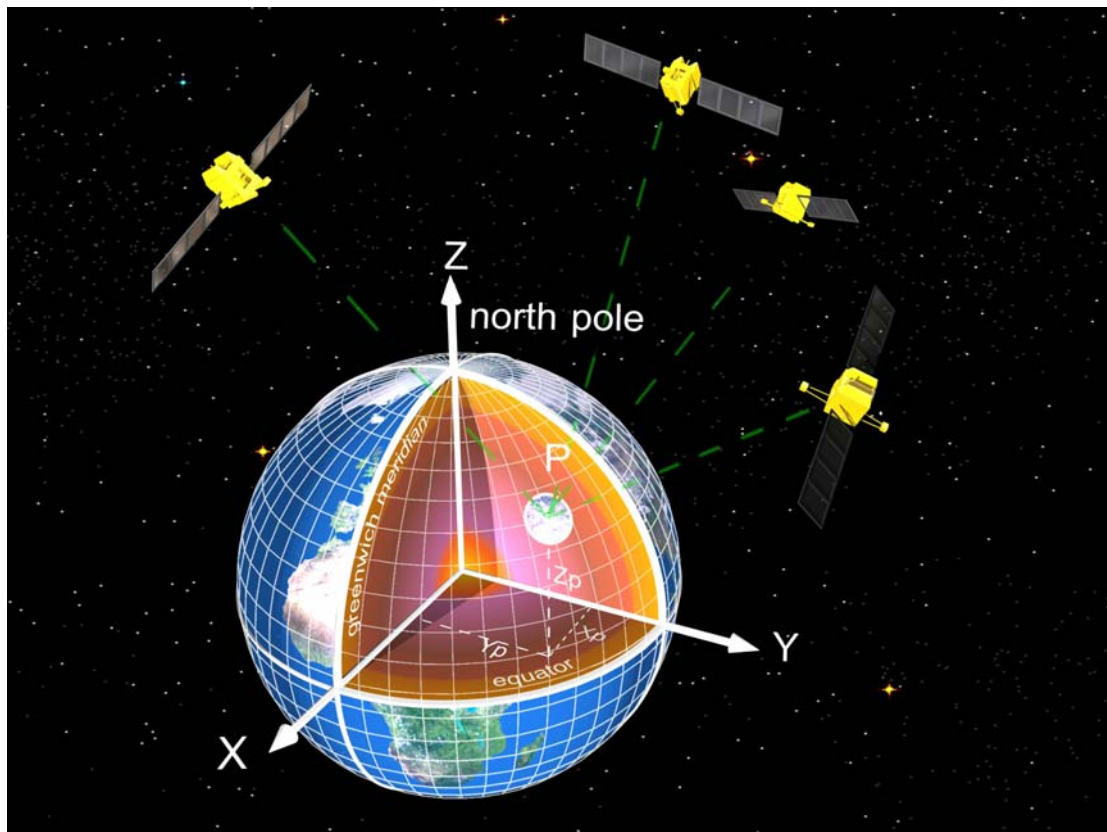


Figure 4: The global coordinate system also used with GPS

surface using geocentric coordinates with one metre precision. However, these difficulties are not of such a magnitude that they would prevent the three-dimensional geocentric concept from being viable for the future. In order to reference features on the surface of the earth GPS are used today. These systems, namely NAVSTAR-GPS, GLONASS and DORIS (supplemented by GALILEO in the future) provide global positioning in a single geocentric Cartesian coordinate system implemented by World Geodetic System 1984 datum (WGS84)(see Figure 4). These satellite systems based on microwave signals play a very important role in space geodesy already, but the impact of their observation techniques on various fields of geodesy, navigation, transportation, civil engineering or meteorology is rapidly growing. The simplicity, cost and speed of use, which is unparalleled by any classical surveying method, allows individuals to geo-reference features from our environment.

Literally anyone can read a position of a GPS receiver antenna in this geocentric coordinate system instantly with the accuracy of a few dozen meters. With two receivers and a differential method one can improve the precision to centimetres or even millimetres (Strang and Borre, 2000). With such positioning technology designers, architects, planners and landscape architects can geo-reference their models by themselves without any hassle about cartographic projections.

The only piece currently missing is a computerized system that would provide a management of such geo-referenced models into one model-map that can

be contributed and explored by users around the globe. There is no urge for such a solution today, because the new opportunities of such global visual system have not been recognized broadly yet. Another reason can be that a lot of work has been invested in systems that implement the flat-world concepts of classical cartography and it is much easier to exploit three-dimensional media as an extension on top of these solutions, of course in cost of the limitations mentioned already.

In the Grifinor project (Bodum L. *et. al.* 2005) we see the use of a global model-map as a viable effort, which leads to new opportunities to represent any geometry as we observe it in nature regardless its size. The model-map provides visual means to geographic representations and visual navigation through geo-referenced information, which allows us to use the same representation for both visualization and analytical purposes. This simplifies and clarifies the geographic referencing to other domains that can benefit from existing or contribute to new geographic applications much easier than with traditional two dimensional maps.

4 CONCLUSIONS

This paper presents rational arguments for use of unprojected coordinates while creating three-dimensional urban and landscape models. Although reasoning is obvious, the implementation unfortunately is not. The three-dimensional urban models created at the moment are very trivial in terms of creation and usability and should be considered as an early approach into this domain. The arguments presented in this paper make it clear that it would be a fatal decision to continue the efforts within the domain on the basis of traditional map-making. Larger and more complex models like the Grifinor system can handle also show the necessity of a global approach to map-making. At the moment everything will be object oriented and stored and referenced in databases the complexity and management of these systems would increase unnecessarily much due to the use of map-projections. One can argue that this mainly is in the case of very large models, but since we already today have maps covering whole countries or even the whole world it is not very difficult to imagine that these systems will become generic spatial in the future. Like in the previous centuries where maps were made in small pieces and slowly put together over time the models created these days present the same approach. The demand for models that fit together over the whole country or more is not far away.

When we look to the domain of three-dimensional visualization, where games and rapid prototyping systems are storming the markets it is obvious to take the most advantage one can get out of these developments and use them in the best way possible to serve the domain of map-making. The best value map-making can get from three-dimensional media is when both visual experience and three-dimensional spatial referencing are fully exploited. Currently only the first one is utilized. The moment the map fits into the three-dimensional models and we get a model-map it will be possible to gain the full potential out of this combination.

A lot of obstacles are lying in the way. Systems are not really ready though the algorithms are; the user is definitely not ready since the change to a global coordinate system demands a whole new set of tools and not least understanding and competence. Hopefully, the transition to a global approach will happen at least with the same speed as we increase the numbers of models and the use of them. It could be nice to get rid of cartographic projections in the creation process of model-maps as fast as possible.

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