Computers & Geosciences 89 (2016) 44–56

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

Developing a reversible rapid coordinate transformation model for the cylindrical projection

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ARTICLE INFO

Article history:
Received 19 December 2014
Received in revised form
21 September 2015
Accepted 15 January 2016
Available online 19 January 2016

Keywords:
Inverse transformation
Forward transformation
Numerical models
Map projection
Geographic information systems

ABSTRACT

Numerical models are widely used for coordinate transformations. However, in most numerical models, polynomials are generated to approximate "true" geographic coordinates or plane coordinates, and one polynomial is hard to make simultaneously appropriate for both forward and inverse transformations. As there is a transformation rule between geographic coordinates and plane coordinates, how accurate and efficient is the calculation of the coordinate transformation if we construct polynomials to approximate the transformation rule instead of "true" coordinates? In addition, is it preferable to compare models using such polynomials with traditional numerical models with even higher exponents? Focusing on cylindrical projection, this paper reports on a grid-based rapid numerical transformation model – a linear rule approximation model (LRA-model) that constructs linear polynomials to approximate the transformation rule and uses a graticule to alleviate error propagation. Our experiments on cylindrical projection transformation between the WGS 84 Geographic Coordinate System (EPSG 4326) and the WGS 84 UTM ZONE 50N Plane Coordinate System (EPSG 32650) with simulated data demonstrate that the LRA-model exhibits high efficiency, high accuracy, and high stability; is simple and easy to use for both forward and inverse transformations; and can be applied to the transformation of a large amount of data with a requirement of high calculation efficiency. Furthermore, the LRA-model exhibits advantages in terms of calculation efficiency, accuracy and stability for coordinate transformations, compared to the widely used hyperbolic transformation model.

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1. Introduction

Generally, the geographic coordinate system and the plane coordinate system are two basic coordinate systems in spatial data storage and expression. Geoscience data obtained by global positioning systems (GPS), which is the most popular surveying technique used in the determination of geodetic networks, are expressed with reference to geographic coordinates. In contrast, spatial data applied in various industries (e.g., transportation, land resource management) across many countries are referenced to plane coordinate systems. Therefore, in many data integration applications, the original spatial data that users obtain are not unified in the same coordinate system and a projection transformation between geographic coordinates and plane coordinates is necessary (Zhongming et al., 2013).

On the premise of not involving a coordinate reference datum transformation, a projection transformation can be performed by two styles of models: analytical models and numerical models. Analytical models implement a forward transformation and an inverse transformation according to a complex nonlinear functional relation between the specific geographic coordinate system and the plane coordinate system (Zhizhuo, 1990) and have advantages in terms of accuracy compared to numerical models. However, the analytical model is not applicable in all circumstances, e.g., when reference ellipsoid parameters are unknown or the analytic projection equations do not exist (Ipbuker, 2002). Although many approaches to improving execution efficiency have been proposed, such as using a trigonometric series and Clenshaw summation (Engsager, 2007), skipping the calculation of the convergence and scale (Karney, 2011), and applying differential operator theory (Liucheng, 2013) or complex-variable functions (Bowring, 1990), analytical models remain inapplicable in certain

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http://dx.doi.org/10.1016/j.cageo.2016.01.007
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cases that require high calculation efficiency, e.g., spatial data integration, where a substantial amount of geographic coordinate system-based spatial data must be quickly projected to the plane coordinate system for calculation or display purposes. Numerical transformation models, which use control points to construct a polynomial approximation of theoretical coordinates, exhibit various advantages, such as high efficiency and wide versatility, without specifically referencing ellipsoid parameters, and they have been widely used in the aforementioned situations (Yang and Snyder, 2000). Several universal polynomials are applied in numerical models: binary quadratic equations, binary cubic equations, biquadratic interpolation equations, etc. As shown experimentally, the form and degree of the polynomial, together with the distribution and quantity of control points and the transformation area, influence the accuracy and stability of the projection transformation (Yang and Snyder, 2000). On this basis, constructing an appropriate numerical algorithm according to the characteristics of the calculation area or the actual requirements of accuracy and efficiency and thereby realizing an excellent engineering application become an important problem to be solved. SUN Weixin et al. demonstrate that a quadratic orthomorphic polynomial is more appropriate than a binary cubic polynomial and a biquadratic interpolation polynomial for the inverse transformation of a Gauss projection by comparing their calculation precision and stability (Weixin et al., 2013). The experiment also shows that the least square method is more accurate than the direct solution method in terms of solving for these aforementioned polynomials. Hardy proposes a global multi-quadratic transformation model and provides a detailed overview of its applications in geodesy, geophysics, surveying, mapping, photogrammetry, remote sensing, signal processing, geography, digital terrain models and hydrology (Hardy, 1990). Nevertheless, the accuracy of these numerical models is sensitive to the distribution and quantity of control points. Cromley proposes a hyperbolic transformation consisting of two shortened, second-order polynomials and reduces the error uncertainty induced by control points through the use of a graticule to split the transformation area (Cromley, 1991). In this approach, each quadrangle of the graticule is handled as an independent unit, and its four vertexes are used as control points to solve for the polynomial coefficients. On this basis, Ozaki et al. improve the solution efficiency of the hyperbolic function for inverse coordinate transformations using each variable separately in the approximation process (Ozaki et al., 2005). Qi et al. apply Cromley's model on a raster map projection transformation and prove that this model not only satisfies the precision demand but also greatly improves transformation speed (Qi et al., 2002). Bildirici compares Cromley's model with Hardy's model for inverse transformations and concludes that the former model delivers more accurate results (Bildirici, 2003). Xie proposes a MULTI-RANK model in which the parametric solution of a first-order hyperbolic polynomial is amended by cubic and quadratic polynomials (Xie, 2011). Junhua et al. provide a bi-directional iteration algorithm for inverse transformations based on an analysis of the transformation rule between geographic coordinates and plane coordinates (Junhua et al., 2004). On that basis, a variety of strategies using computing clusters or GPU have been developed to accelerate the projection of large geospatial data sets (Behzad, 2012; Finn, 2012). Jenny gives a recent glimpse at some of these studies and demonstrates high-performance projection of raster data in web browsers based on WebGL (Web Graphics Library) (Jenny, 2015). However, in most numerical models, polynomials are used to fit the approximate numerical relationship between geographic coordinates and their corresponding plane coordinates in a local region, without considering the "transformation rule" (or geometric characteristic) of coordinate transformation. As there is a transformation rule between geographic coordinates and plane coordinates, how accurate and efficient is the calculation if we construct polynomials to approximate the transformation rule instead of "true" coordinates?

This paper reports on a grid-based rapid numerical transformation model – a linear rule approximation model (LRA-model) for cylindrical projection transformation, which forms linear polynomials to approximate the transformation rule and uses a graticule to alleviate error propagation. Our experiments on a cylindrical projection transformation between the WGS 84 Geographic Coordinate System (EPSG 4326) and the WGS 84 UTM ZONE 50N Plane Coordinate System (EPSG 32650) with simulated data demonstrate that the LRA-model is comparatively simple and stable for any point in space, although it does not exclude systematic errors due to imperfections in defining the reference ellipsoid. Furthermore, the LRA-model is appropriate for both forward and inverse transformations simultaneously because the inverse equations can be easily derived, and the computational costs and errors can be reduced compared to the hyperbolic model.

The remainder of the article is organized as follows: Section 2 provides the details of the LRA-model, including its principles, polynomials and application process. Section 3 reports on related experiments using the LRA-model on both forward and inverse transformations between the WGS 84 Geographic Coordinate System (EPSG 4326) and the WGS 84 UTM ZONE 50N Plane Coordinate System (EPSG 32650) with simulated data in three zones with different latitudes. In addition, this section provides a detailed comparison between the LRA-model and the hyperbolic model in terms of accuracy, efficiency and stability. Finally, Section 4 discusses and concludes this study. The accuracy and stability of the LRA-model on azimuthal or conic projections will be tested in future research.

2. Linear rule approximation model

2.1. Methodology and model development

The earth can be approximated as a rotational ellipsoid, and on this basis, we can treat "circles" of longitude as a set of ellipses that share the same semi-major axis, semi-minor axis and symmetry axis while treating "circles" of latitude as concentric "circles" with different radii. Lines of latitude and longitude on the ellipsoid surface are continuous and inerratic curves, and their corresponding projection coordinates are continuous, finite and single valued in the cartographic region; otherwise the map projection is meaningless. "Circles" of longitude and "circles" of latitude are very large, even at high latitudes, and they can be approximated as straight lines in a small local region. In addition, this trend remains if we project these two types of "circles" onto a plane map. Moreover, the international map subdivision of basic scale topographic maps generally uses partial lines of latitude and longitude as borders. On one side of the meridian in the Northern Hemisphere, any two arbitrary latitude lines can split longitude lines into "innumerable" line segments, with the slope of the line segments relative to the meridian increasing as the distance from the meridian increases. Similarly, latitude lines can be split bay any two arbitrary longitude lines, with the slope of the line segment relative to the equator increasing as the distance from the equator increases. The slopes of latitude line segments (relative to the equator) and of longitude line segments (relative to meridian) vary in the same manner. Therefore, there is an approximate linear relation between geographic coordinates and plane coordinates using the premise that the transformation region is sufficiently small.

Fig. 1 presents the principle of the projection transformation

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