Transforming to NAD83

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ABSTRACT

The project for the redefinition of the North American Datum, designated NAD83, will result in a new and improved system of reference for latitude and longitude. Redefined coordinates for 350,000 survey markers across the continent will become the foundation for all new federal topographic maps and for hydrographic and aeronautical charts. Most provincial resource mapping in digital form and most new property mapping will also be referred to NAD83.

Because almost all of the existing maps and charts are based on NAD27, most current geographic information systems, which depend on base maps to ensure universal compatibility of GIS contents, are also referred to the NAD27 system. Users and providers of such place-related information will have to consider the advantages, such as the ability to share data and to display their information at various scales, to be gained by converting their holdings to the updated reference system. Only by having all geographic and land-related information systems share one reference system will GIS users and providers be able to obtain the maximum benefits now and in the future.

This paper describes various common methods that may be used to transform coordinates between reference systems, and outlines software developed at the Geodetic Survey Division to apply some of these methods. A brief description is given of a representative national transformation, computed by the Geodetic Survey Division using this software. Recommendations for selecting methods suitable for individual users, and sources of assistance are also given.

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1. INTRODUCTION

1.1 Concept of a Geodetic Reference System

A geodetic reference system (GRS) provides the accurate foundation for the organization of all information pertaining to land. When all spatial information is based on a standard GRS, it may be readily combined in any way, and by anyone, due to the universal compatibility imparted by the GRS.

There, is however, a duality in the interpretation of the term Geodetic Reference System. A research study done for the Federal Geodetic Control Committee (U.S.) states that "A geodetic reference system can be characterized as a set of land positions whose spatial relationships are known." (Epstein & Duchesneau, 1984). This conflicts with the definition of the Geodetic Reference System 1980 (GRS80) adopted by the International Union of Geodesy and Geophysics (Moritz, 1980), which defines a comprehensive coordinate system for all geodetic applications. These common uses of the terminology need to be resolved in order to understand the processes involved in moving from one system to another.

1.2 Description of NAD83

The NAD83 reference system is a conventional terrestrial system (geocentric) realized by modifying the US Navy Navigation Satellite System (Doppler) reference frame (NSWC 9Z-2) in origin and scale, and rotating it to bring its reference meridian into coincidence with the internationally accepted zero meridian of the Bureau International de l' Heure (BIH). Classical terrestrial network observations and space system data for North America were adjusted together in July 1986, to create a set of 260,000 station positions in the NAD83 system.

1.3 Legal Status

At the present time, NAD27 coordinates are used in Canada for the definition of mineral, oil, and gas exploration rights. This will change following the declaration of an order-in-council requiring the use of NAD83 by all federal departments and agencies.

1.4 Impacts of Redefinition

Following the adoption of NAD83 as the new geodetic reference system for Canada, federal and most provincial mapping agencies will be using it as the foundation for all new maps and charts. Changes to the geodetic coordinates of features due to redefinition will vary from 120 metres westerly in the Yukon to 70 metres easterly in Newfoundland (McLellan, 1978). Up to 30 metres of this difference results from the removal of distortion by readjustment, the remainder results from the change in geodetic reference datum. The plane coordinates used for federal mapping will change by more than 200 metres, primarily in a northerly direction, also due to the change in reference datum.

Relative accuracy and reliability of the new coordinates will be greatly improved over those of NAD27 - not only by relieving distortion, but also by including large numbers of electronically measured distances and position differences obtained from space systems.

1.5 Benefits of NAD83

To properly assess the benefits of the NAD83 project, it is necessary to look beyond the primary users of control survey data to the secondary and tertiary users - those who depend on the geodetic reference system for GIS applications. Their data, originally produced for single-purpose functions, becomes much more valuable if it is universally compatible, and NAD83 will make this compatibility possible. Costs which would have otherwise been incurred to create compatible data sets are thus avoided by the availability of NAD83.

New types of positioning systems now under development will use the NAD83 datum, thus making data gathering and data management easier and more compatible. Prototype Global Positioning System (GPS) satellites are now broadcasting their positions in the NAD83 reference frame. NAD83 coordinates will be used to rectify data from remote sensing satellites such as SPOT before it is provided to users.

Future integration of surveys performed using GPS satellites will be greatly facilitated by the geocentric nature of NAD83. Control surveys in both urban and rural areas are now being done using signals from the prototype satellites. Accuracies of two or three parts per million are being routinely achieved, and the integration of such new survey projects with the continental network will serve to further enhance the quality of NAD83 coordinates. Beginning in 1988, Geodetic Survey will be using GPS to tie primary bench marks to the horizontal network at 30-km spacing along levelling routes in southern Canada, thus making NAD83 more accessible to users. Other GPS activities are reported in various papers in this seminar series. By 1992, GPS will offer 24 hours per day of worldwide availability for all surveying and navigation purposes.

There is no doubt that for those who are willing to make the changeover to NAD83, the benefits will be real.

1.6 Moving to NAD83

To take advantage of the NAD83 system, users are faced with the task of converting their data from its existing system. The discussion that follows will present the terminology associated with coordinate systems and transformations, describe various types of transformations and their applications, and finally indicate how the Geodetic Survey Division will provide support to users.

2. COORDINATE SYSTEMS and DATUMS

2.1 Geodetic Datum

In geodesy, it is traditional to represent the approximate shape of Earth by an ellipsoid of revolution. By selecting an appropriate ellipsoid and its position as the coordinate surface for a large area, such as a country or a continent, a standard coordinate system, or **datum**, is created. The coordinate surface is specified ("given" as translated from the Latin "datum") by the location of the origin of the Cartesian coordinate system concentric with the ellipsoid, the directions of its axes, and the size and shape of the ellipsoid.

The realization of the datum is made by computing coordinates of points on the ground from a network of survey observations (NGS,1986). These coordinates **refer** to the datum, but do not define it. A datum is a coordinate system, not a series of estimated coordinates for survey points, and new estimates may be computed without changing the datum.

2.2 Types of Coordinates

Ellipsoidal coordinates are only one way of expressing the position of a point. The concentric Cartesian system coincident with the principal axes of the ellipsoid is another obvious one. A third way that makes reference to the ellipsoidal surface is the great variety of map projections in common use. For a specific datum, the coordinates of a point may be expressed in any of these ways. Thus we may have

Geodetic Ellipsoidal	ϕ,λ_{NAD83}
Geodetic Cartesian	X,Y,Z_{NAD83}
Universal Transverse Mercator	$N,E(UTM)_{NAD83}$

as equivalent expressions, since the indication of the datum automatically implies the relationships amongst the types of coordinates. These relationships are geometrical, and are well specified in the literature, such as Heiskanen & Moritz (1967, pg. 204) or Vanicek & Krakiwsky (1982, pp. 331-332) for ellipsoidal to Cartesian, and Thomas (1952) or Dept. of the Army (1958) for ellipsoidal to UTM.

2.3 Control Survey Adjustment Systems

The process of estimating the coordinates of physical points with respect to a specified coordinate system or datum is accomplished by computing a network of survey observations that relate the survey points to the datum and to each other. The result is a set of coordinate values for the points that constitute an adjustment system. Like the datum, it serves as a standard over a large area, such as a country or a continent. Various adjustments of the control survey network observations may be carried out on the same datum with different constraints, or the same data may be adjusted with respect to various datums.

Often, the adjustment system is given the same name as the datum to which it refers, thus leading to confusion between the two aspects. However, if only one set of adjustment values is published with respect to a particular datum, it is common and useful to imply both the datum and the adjustment by a single reference. Both NAD27 and NAD83 have this connotation. More accurately, the description of the source of coordinates for a control survey point should refer to the adjustment system, and published details of the adjustment should indicate the datum to which it refers.

3. TRANSFORMATIONS

There are three types of coordinate transformation that correspond to the three aspects of coordinate specification as outlined above, namely datum, coordinate type, and adjustment system. Transformations between types of coordinates are straightforward, as are transformations between datums if the differences are known. Transformations between adjustment systems require assessment and modelling of distortion, a much less exact process.

The redefinition of North American geodetic networks involved two aspects - the selection of a new reference datum, and the simultaneous readjustment of survey control network observations to achieve more consistent coordinates (Boal & Henderson, 1988). The transformation of other existing NAD27 coordinates to NAD83 is a prediction of what those coordinates would have been had they been determined with respect to the NAD83 system. Thus, any coordinate transformation method selected must take into account both aspects of this change.

3.1 Common Survey Control Points

Transformation of coordinates between adjustment systems can take place when values for control points are known in both systems (i.e. "common" points). Great care must be taken to ensure that the data points to be transformed are indeed compatible with the values for the chosen common points. For example, the compatibility of data digitized from map sheets is not ensured solely by the map sheet series having the same control survey adjustment system, such as NAD27. The control point coordinates may have changed considerably over the years due to strengthening, densification and recomputation of the survey networks.

3.2 Transformation Methods

The following techniques provide several alternatives for accounting for differences in datum and adjustment systems. Some address only one of these tasks, while others attempt to handle both. In all cases, it is assumed that the coordinates of the common points in both adjustment systems, and the points to be transformed, are of the same type.

Transformation methods increase in complexity from simple shifts, through scaling and rotation of axes, to distortion modelling and local refinements for overdetermined systems. Some differences may be known *a priori*, such as when the relationship between two datums is specified. Other differences may need to be computed.

3.3 Changes in Datum

The most common and elementary transformation involves the simple addition of constant values to effect a **translation** of the origin of the coordinate system. Such a shift is usually determined by taking the mean shift of selected common points, and assuring that the range of these shifts does not vary significantly. This type of transformation is generally applicable to local or mapping plane coordinates, to ellipsoidal coordinates, and to geodetic Cartesian coordinates.

When known *a priori*, or found to be significant, average changes in the **scale** along each of the reference axes, and **rotations** about them, may be applied. This type of transformation is applicable to two- or three-dimensional Cartesian coordinates, but is not usually applied to ellipsoidal coordinates.

For plane coordinates, the combination of two shifts, one scale, and one rotation parameter is known as a **Similarity** (or **Helmert**) **Transformation**, and preserves orthogonality in the transformed coordinates. In the geodetic Cartesian system, a similarity transformation consisting of seven parameters (three shifts, three rotations, and one scale), combined with a specification of reference ellipsoids for each system, gives the **Datum Transformation** between the two systems.

3.4 Distortion Modelling

To account for variation in relative positions due to distortion between two control survey adjustment systems, additional modelling parameters must be introduced. This is to smoothly distribute distortion among common control points, so that it is not localized where one local datum shift model meets another.

Assigning separate scale and rotation parameters to each axis in a plane system results in the six-parameter **Affine Transformation.** Unlike the similarity transformation, the affine transformation enables some local modelling of linear distortion in addition to applying the shift in datum.

Fitting a **polynomial model** with respect to each axis over a large area of variable distortion provides a continuous representation of the differences between the two sets of coordinates. It is preferable to first remove the differences in datum to allow the polynomial to model only distortion, which is often a second-order effect compared to the datum difference.

Since the computation of distortion parameters usually involves more common control points than the minimum required, an estimation process such as least squares is often employed. Differences between the observed and modelled displacements at these points are the residuals of the computation.

However, the actual values of the common points are definitive and are retained.

To ensure that distortion is not localized in the neighbourhood of a common point, the technique of **residual interpolation** may be used to refine the predicted displacement. The weighted mean of the residuals at the surrounding common points is applied, with the weights varying inversely as a function of the distance. This technique is applicable to all types of transformation methods outlined above.

4. TRANSFORMATION SOFTWARE

Specialized software has been developed at the Geodetic Survey Division of the Canada Centre for Surveying, and is available to users. Geodetic Survey will supply the FORTRAN77 source code in a form compatible with a variety of computers, and will provide advice on its use. Other transformation software is available from several government, educational, and commercial sources.

4.1 Program **DATUM** can be used to estimate a datum transformation consisting of up to seven parameters. It requires two sets of input geodetic ellipsoidal coordinates, with or without geoid data, plus a specification of the corresponding reference ellipsoids.

4.2 Program **SCTRANS** (**S**ystematic **C**oordinate **TRANS**formation) applies the seven-parameter datum transformation, and either ellipsoidal or geodetic Cartesian coordinates may be selected on both input and output. Using the Vening Meinesz relationships (Heiskanen and Moritz, 1967, pg. 200), geoid values for deflections and separation (ξ,η,N) may also be transformed to another reference datum. Several default datum relationships are built into the software, and more are easily added. Most have been determined from *a priori* knowledge of the specification of the datums.

4.3 Program **ESTPM** (**E**stimation of **S**econdary **T**errestrial **P**ositions for **M**apping) (Blais, 1979) has a dual capability - computing a polynomial distortion model from two sets of input ellipsoidal coordinates, and applying the model to a third set of input values. Residual modelling is incorporated, using an inverse exponential function of the square of the distance to determine the weights. The user can specify the degree of the polynomial, and the extent of the effect of the residual interpolation.

4.4 Program **GSRUG** (**G**eodetic **S**urvey **R**outine between **U**TM and **G**eographic) computes the projection of ellipsoidal coordinates onto the Universal Transverse Mercator mapping plane, and vice versa. The program will handle 3-degree zones (MTM) as well as the standard 6-degree zones, and default zone computation is built in - with the option of specifying a preferred zone.

4.5 Program **NBSTER** computes the projection of geodetic coordinates onto the New Brunswick Stereographic mapping plane, and vice versa.

5. WHO TO CONSULT

5.1 National Transformation

Geodetic Survey Division has computed a representative transformation to convert coordinates of control survey points between the NAD27 and NAD83 systems, for use in situations where adjustment of observed data is not feasible. This transformation is based on published NAD27 values for the primary control network, and on provisional values for NAD83 (pending the integration of secondary control networks in the provinces and territories), as computed in the continental adjustment of July 1986.

This transformation is computed in two parts: first, program SCTRANS is used to apply an average shift between the NAD27 and NAD83 datums (computed using program DATUM), and then program ESTPM is used to model the distortion between the NAD27 and NAD83 adjustment systems.

Geodetic Survey will be distributing parameters for this transformation, plus the corresponding software, and advocating its use for all situations in which consistency with surrounding control survey networks is of greatest importance. Use of this unique transformation will ensure that different users will always produce the same new values for the same points - a great advantage in reducing potential sources of confusion or disagreement.

5.2 Local Transformations

Many developers and users of geographically-referenced information systems may prefer to use local transformation techniques that are built into their systems, or at least, techniques that provide lower computational overhead than that of the national transformation. To assist these users in computing transformation parameters for their applications, tables of shifts at 7.5-minute grid point intervals will be computed from the national transformation.

Users of such local transformations must be aware that coordinates for features will not be identical to those computed from an adjacent or overlapping definition, either of their own or of other users.

5.3 Advice From Government Agencies

Geodetic Survey will provide the national transformation software and parameters to all provincial government surveying and mapping agencies, and will respond to requests for assistance in using and understanding the procedures. Other users are encouraged to contact these agencies - the same ones they normally contact for control survey data - for advice on which transformation methods are recommended and supported in their region of concern.

6. SUMMARY and RECOMMENDATIONS

6.1 Converting Control Surveys

In Canada, not all control survey observations were included in the NAD83 adjustment. While many will be included in the simultaneous secondary integration, many more will not be ready or are not suitable (Boal & Henderson, 1988). In converting these other control survey points to the NAD83 system, it is always preferable to recompute the survey observations to the new values for the control to which it is tied. Transformation of coordinates of control survey points should be considered as an alternative only if the observations are not available.

6.2 Selecting a Transformation Method

Many software packages exist to compute transformations for plane coordinates, most of which use the similarity transformation as a basis. Users of these methods must realize that they are applicable to small areas only, since both the aspects of change in datum and of distortion due to readjustment both produce non-linear differences between the NAD27 and NAD83 systems. The US National Geodetic Survey has found it convenient to use 1-degree quads, but also found it necessary to refine the estimates with residual interpolation to model the non-linearity over that range.

In Canada, there are too many large gaps between framework arcs - or even between the satellite densification surveys - to use such a method, since several common control points are required to compute the transformation parameters in each area. Therefore the model using a continuous polynomial surface was selected for the definitive national transformation. The Geodetic Survey Division strongly recommends the use of this standard transformation as the method of choice.

In areas of dense survey control, users of plane techniques may be able to obtain sufficient common points in small areas. But in areas of sparser control, the tables of shifts at 7.5-minute intervals, computed from the national transformation, should be used. This will provide implicit agreement with the national transformation, and avoid selecting too large an area or too few common points to compute the parameters.

6.3 Estimating the Accuracy

Finally, to gain an indication of the accuracy of any transformation, techniques such as inspecting predictions at common points, and reserving common points from the computation of the parameters, should be used. Then the user will better be able to determine whether the method selected suits the requirements of the application. Since this accuracy is extremely difficult to quantify, and is cumulative with any error in the determination of the original coordinates, it is difficult to make accuracy statements about transformed coordinates. Recomputation of the original observations is the best way to estimate accuracies.

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