# Towards implementing dynamic datum data management in GIS

**Kevin M. KELLY, U.S.A.**

**Key words**: Geodetic, Dynamic datum, Earthquake, GIS

## SUMMARY

The International Terrestrial Reference Frame (ITRF) is rapidly becoming the coordinate system of choice for both global and national geodetic datums and ITRF control coordinates are being disseminated for use in all types of surveying, mapping and GIS applications. Transformations between ITRF datum realizations are becoming increasingly necessary and relevant in these applications. The reality of crustal motion combined with the adoption of ITRF and the use of GNSS for surveying measurements implies that positional coordinates of points anywhere in the world will change as a function of time. By incorporating velocity or deformation and epoch information, it is possible to very accurately keep track of locations. To be useful though, these models and tools must be accessible to the entire geospatial community. Because of its central role in storing and manipulating geographic data and its widespread use, GIS software is a convenient way to make these models accessible to the community. We describe the models and tools necessary to manage coordinate changes with time and briefly touch on software approaches currently under consideration at Esri to enable the management and application of these models to geospatial data stored in the GIS.

# Implementing dynamic datum data management in GIS

**Kevin M. KELLY, U.S.A.**

## 1. INTRODUCTION

The prevasiveness of ITRF as the basis for national national geodetic datums is beoming more and more evident. As Table 1 shows, many countries have already updated their national geodetic datums to an ITRF realization and others are in the process of doing similarly.

WGS84, the operational datum for the global positioning system (GPS) is now closely coincident with the ITRF realization known as ITRF 2000 [21]. In future, if not already, individual nations of sizeable extent will be able to establish their own permanent GPS tracking network and as a by-product their own national geodetic datum based upon ITRF [41]. Several countries have deployed permanent GPS tracking networks to provide accurate geo-referencing for differential GPS positioning and in order to maintain geodetic control at sub-centimeter accuracies. Subsequently, local networks have been densified and rigorous control for surveying, mapping and GIS activities extended. GPS observation campaigns have proliferated in recent years and new superior continental geodetic datums have evolved around the world [40].

**Table 1. Some national geodetic datums based on ITRF.**

| Nation | Datum Name | Reference Frame | Epoch | Ellipsoid |
|---|---|---|---|---|
| Australia | Geocentric Datum of Australia (GDA94) | ITRF92 (1992) | 1994.0 | GRS80 |
| Canada | North American Datum 1983NAD83(CSRS) | ITRF96 (1996) | 1997.0 | GRS80 |
| Europe | European Terrestrial Reference System 89 (ETRS89) | ITRFyy | 1989.0 | GRS80 |
| Israel | Israeli Geodetic Datum 2005 (IGLD05) | ITRF2000 (2000) | 2004.75 | GRS80 |
| Mexico | Red Geodésica Nacional Activa (RGNA) | ITRF92 (1992) | 1998.0 | GRS80 |
| South America | **Si**stema de **R**eferencia **G**eocéntrico para **A**mérica del **S**ur (SIRGAS95) | ITRF94 (1994) | 1995.4 | GRS80 |
| South America | **Si**stema de **R**eferencia **G**eocéntrico para **A**mérica del **S**ur (SIRGAS2000) | ITRF00 (2000) | 2004.0 | GRS80 |
| New Zealand | New Zealand Geodetic Datum 2000 (NZGD2000) | ITRF96 (1996) | 2000.0 | GRS80 |
| Taiwan | Taiwan geodetic datum 1997 (TWD97) | ITRF94 (1994) | 1997.0 | GRS80 |
| WGS 84(G730) | World Geodetic System 1984 | ITRF91 (1991) | 1994.0 | WGS84 |
| WGS 84(G873) | World Geodetic System 1984 | ITRF94 (1994) | 1997.0 | WGS84 |
| WGS 84(G1150) | World Geodetic System 1984 | ITRF00 (2000) | 2001.0 | WGS84 |
| United States of America | North American Datum 1983NAD83(NSRS2007) | ITRF00 (2000) | 1997.0 | GRS80 |

The reality of crustal motion combined with the adoption of ITRF and the use of GNSS for surveying measurements implies that positional coordinates of points anywhere in the world will change as a function of time. By incorporating velocity, episodic deformation and epoch information, it is possible to very accurately keep track of locations. In this paper, we describe software tools currently under development at Esri to enable the management and application of these models to geospatial data stored in a GIS.

## 2. THE NEED FOR TRANSFORMATIONS AND COORDINATE UPDATES

Using GNSS technology positional coordinates at centmeter and even millimeter level accuracy are easily determined. This capability brings with it exposure to coordinates that change over time due to tectonic motion. Fortunately, mathematical models and software tools exist to allow the geospatial community to cope with time-dependent coordinates.

The earth does not behave as a fully rigid body so a geodetic datum which best fits the earth must register earth's geodynamic processes. These are continuously monitored by ITRF realizations along with many regional tracking networks such as the U.S. Plate Boundary Observatory (PBO). Reference frame realizations for the dynamic earth are published every few years by the International Earth Rotation and Reference Systems Service (IERS). Intrinsically then the terrestrial reference frame (TRF) is dynamic because it accounts for the motion of earth's tectonic plates and other deformations of the earth's crust. This means that the coordinates of a point in a TRF at a particular epoch will differ from the coordinates of the same point at another epoch or in another TRF. Any coordinate transformation therefore, between different TRF's, must consider the epochs of the input and output coordinates.

The modern trend is to use global coordinate systems even for local applications. Therefore, it is important to realize that in a global coordinate system the ground on which we survey and map moves constantly. This leads to subtleties in coordinate system definition and use.

The introduction of regional spatial data infrastructures, which can integrate national GIS databases, depends on the existence of a homogeneous coordinate system or the ability for data on disparate datums to be linked by well defined transformation parameters. Only then can regional geographic information be assembled in a common reference system without overlap or duplication [19]. Since ITRF is a global system, modeling the transformations between ITRF realizations permits spatial data to be integrated locally, nationally, regionally and even internationally. Such international unification of geographic information using ITRF coordinate transformations has transpired in Europe under the auspices of EUREF and Comité Européen des Responsables de la Cartographie Officielle (CERCO) [7].

The surveyors work is also being revolutionized: soon it will be possible to measure control points, cadastral boundaries, points for topographic mapping and even complete engineering surveys within a few seconds in real-time using a single GPS receiver [43]. Emerging technologies such as high-accuracy real-time GPS positioning and Esri's Parcel Editor will significantly improve the positional accuracy of certain GIS databases. These databases will need to keep apace with TRF improvements, reference frame changes and global and local crustal motion. Incoming data may require conversion to the appropriate ITRF realization and epoch or data my need to be output in another ITRF or epoch.

GNSS positions generated from differential correction or network-RTK are in terms of the datum used for the permanent tracking reference stations. If GNSS positions are to be imported into a GIS referenced in a different frame the positions must be transformed to the GIS reference frame. For example, while WGS84 and ITRF2000 reference frames are coincident at the few-centimeter level worldwide, NAD83 differs from WGS84 (and thus ITRF) by up to one meter. For many applications a difference of this magnitude is unacceptable [44].

Modern TRF transformations have become increasingly complex to better accommodate time-dependent processes such as plate tectonics and other geophysical phenomena. Current TRF transformations extend the classical 7-parameter similarity (Helmert) transform to complex 14-parameter transformations; the additional 7-parameters describe the time evolution of the original 7-parameters. In practice this augmented formulation is used to transform precise coordinates between different reference frames and from one epoch to another. These TRF coordinates are presently and will continue to be disseminated for applications in all types of surveying, mapping and GIS applications [41].

Clearly, TRF transformations are becoming increasingly necessary and relevant. To be useful though, these models and tools must be accessible to the entire geospatial community. Because of its central role in storing and manipulating geographic data and its widespread use, GIS software is a convenient way to make these models accessible to the community.

## 3. METHODOLOGY

Position and motion on the earth are not absolute concepts and can be described only with respect to some reference such as a terrestrial reference frame. But if the solid earth is in motion, then either the location of physical points move away from their “statically determined” coordinated locations or the reference frame drifts causing the coordinates to change. Either way the effect is the same: coordinates in motion. To rigorously account for the measureable effects of coordinates in motion we use an equation of the form

$$\mathbf{X} = \mathbf{T} + \mathbf{V} + \mathbf{D} \tag{1}$$

where **X** is the vector of transformed and updated coordinates, **T** represents a 14-parameter similarity transformation sometimes called a time-dependent reference frame transformation, **V** represents coordinate shifts due to secular crustal motion and **D** represents coordinate displacements due to episodic events such as earthquakes. Managing dynamic datums in GIS amounts to storing and managing all the information required to perform calculations using (1). While (1) is simple enough, the information required to compute it can be surprisingly complex.

### 3.1 Reference frame transformation

The 14-parameter time-dependent reference frame transformation has the same form as a 7-parameter similarity (or Helmert) transformation, except that the additional 7 parameters parameters reflect their change over time. For a more complete treatment of 14-parameter time-dependent transformations see for example [2], [25], [29], [35], [37], [39], [41], [42]. Figure 1 illustrates the geometry of the terrestrial reference frame transformation.

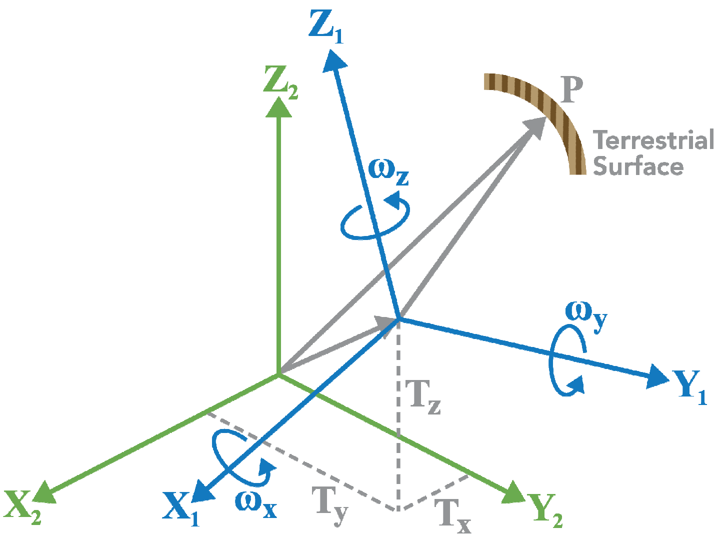

Figure 1. Geometry of the 7-parameter similarity (Helmert) transformation between reference frame 1 and 2. The additional 7-parameters comprise the time-derivatives of those shown here including scale (not shown).

The first term **T** on right hand side of (1) contains the reference frame or datum transformation and is given by [20]

$$\mathbf{P}_{t_0}^{f_2} = \mathbf{T}_t + \left(1+s_t\right)\left(\mathbf{I}+\mathbf{R}_t\right)\cdot\mathbf{P}_t^{f_1} \tag{2}$$

where $\mathbf{P}_{t_0}^{f_2}$ is the vector of geocentric coordinates $\mathbf{P}_{t_0}^{f_2} = \begin{pmatrix} X & Y & Z \end{pmatrix}^T$ in reference frame $f_2$ with reference epoch $t_0$; $\mathbf{P}_t^{f_1} = \begin{pmatrix} X & Y & Z \end{pmatrix}^T$ is the vector of geocentric coordinates in reference frame $f_1$ at observation epoch $t$; **I** is the identity matrix;

$$\mathbf{T}_t = \begin{pmatrix} T_{t,X} & T_{t,Y} & T_{t,Z} \end{pmatrix}^T \text{ and } \mathbf{R}_t = \begin{pmatrix} 0 & \omega_{t,Z} & -\omega_{t,Y} \\ -\omega_{t,Z} & 0 & \omega_{t,X} \\ \omega_{t,Y} & -\omega_{t,X} & 0 \end{pmatrix} \tag{3}$$

In (2) $s_t$, $\mathbf{T}_t$ and $\mathbf{R}_t$ represent the time-corrected transformation parameters consisting respectively of scale factor, frame translation vector and frame rotation matrix between $f_1$ and $f_2$ at observation epoch $t$. These time-corrected parameters are computed from the 14 transformation parameters $\mathsf{T} = \left\{T_X, T_Y, T_Z, \omega_X, \omega_Y, \omega_Z, s, \dot{T}_X, \dot{T}_Y, \dot{T}_Z, \dot{\omega}_X, \dot{\omega}_Y, \dot{\omega}_Z \dot{s}\right\}$ using

$$\begin{aligned} &T_{t,X} = T_X + \dot{T}_X\Delta t,\ \ T_{t,Y} = T_Y + \dot{T}_Y\Delta t,\ \ T_{t,Z} = T_Z + \dot{T}_Z\Delta t \\ &\omega_{t,X} = \omega_X + \dot{\omega}_X\Delta t,\ \ \omega_{t,Y} = \omega_Y + \dot{\omega}_Y\Delta t,\ \ \omega_{t,Z} = \omega_Z + \dot{\omega}_Z\Delta t \\ &s_t = s + \dot{s}\Delta t \end{aligned} \tag{4}$$

In (5), $\Delta t = t - t_0$ is the time difference between observation epoch $t$ and the reference epoch $t_0$ of the frame into which positions are being transformed and time-dependent parameters are denoted with an overdot.

The IERS and many national geodetic agencies publish sets of transformation parameters $\mathsf{T}$. These parameters can be stored and managed in a spatial database and then accessed by GIS software applications to perform time-dependent datum transformations on other data residing the GIS database.

### 3.2 Crustal motion

Station coordinates vary both continuously and episodically due to gradual plate tectonic motion, earthquakes, volcanos, landslides and other geodynamic processes. These motions are quantified by global plate tectonic models and local/regional crustal deformation or velocity models. To maintain centimeter or better accuracy station positions must be updated for the effects of crustal motion.

It may be that subsequent to a reference frame transformation, the final coordinates are required at another epoch, or perhaps no frame transformation is required at all, but only a shift in coordinates to account for displacement due to plate tectonic motion or crustal deformation. Presently, there are two types of models available for obtaining point velocities or displacements: plate motion models and deformation or velocity models. When calculating coordinate shifts due to global tectonic plate motion, displacements **D** from (1) are not considered. However, in deforming zones which typically occur at plate margins both secular crustal motion unique to the deforming zone and displacements due to episodic events must be taken into account.

The Earth’s surface is partitioned into a number of tectonic plates that are in constant motion relative to each other at rates typically about several centimeters per year. These plates generally move as rigid blocks; however, at their edges there is a zone often called a plate boundary where they rub against each other and deform, causing earthquakes and other geophysical phenomena [24]. Figure 2 shows the worlds major tectonic plates and from Figure 3 we see that most earthquakes occur along the boundaries of these tectonic plates.

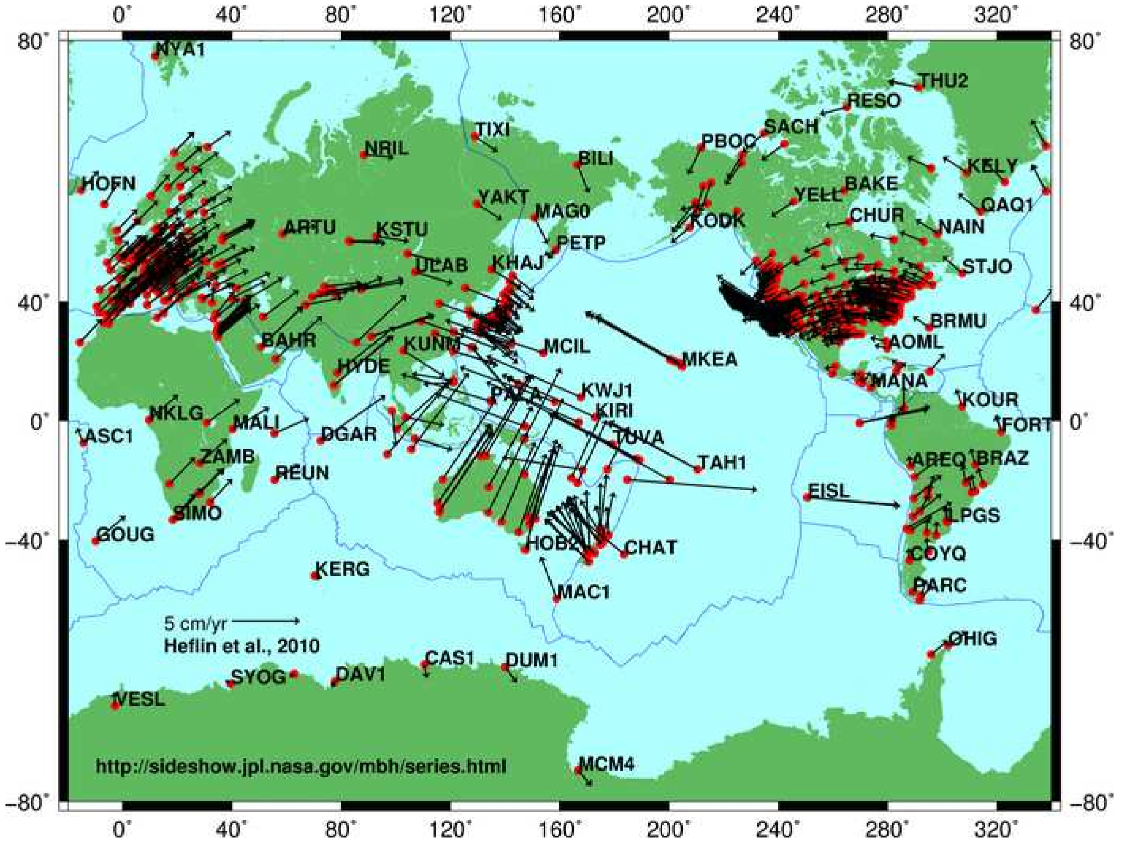

Figure 2. The major tectonic plates and the magnitude and direction of their motion based on Global Positioning System (GPS) satellite data from NASA JPL. Source: http://sideshow.jpl.nasa.gov/mbh/all/images/global.jpg.

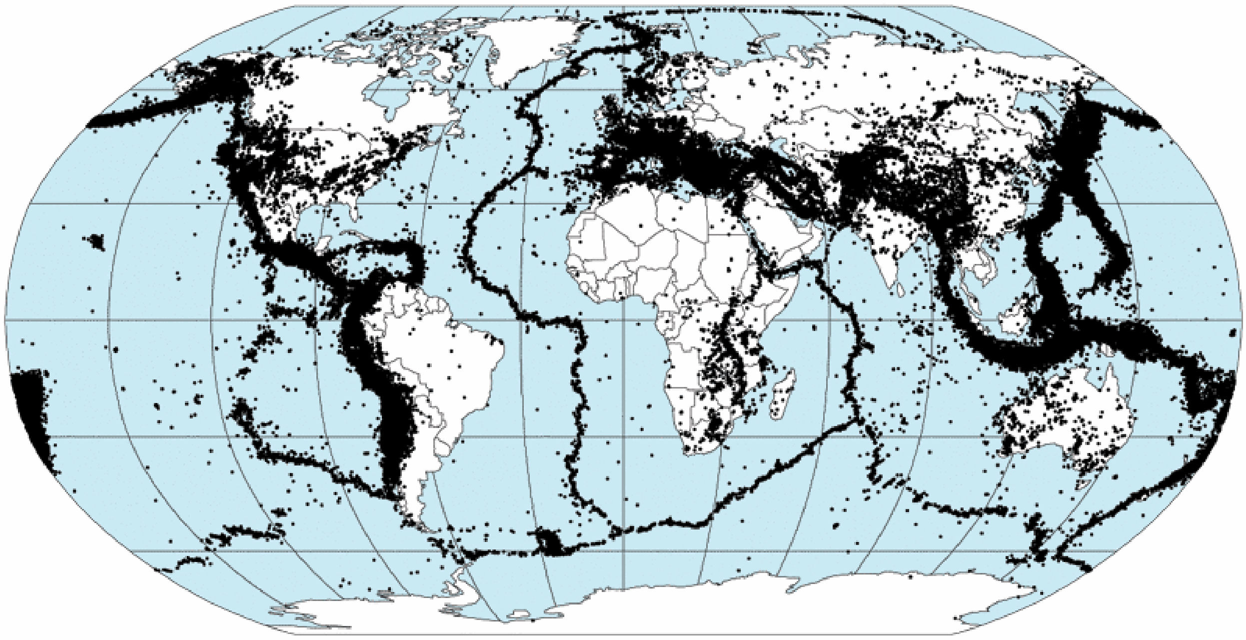

Figure 3. The 15 major tectonic plates showing earthquake epicenters between 1963-1998.
Source: http://denali.gsfc.nasa.gov/dtam/seismic/.

A plate motion model comprises a list of so-called Euler pole positions for each plate and the scalar relative angular rotation rate (velocity) for that plate. The concept of an Euler-pole is shown in Figure 4.

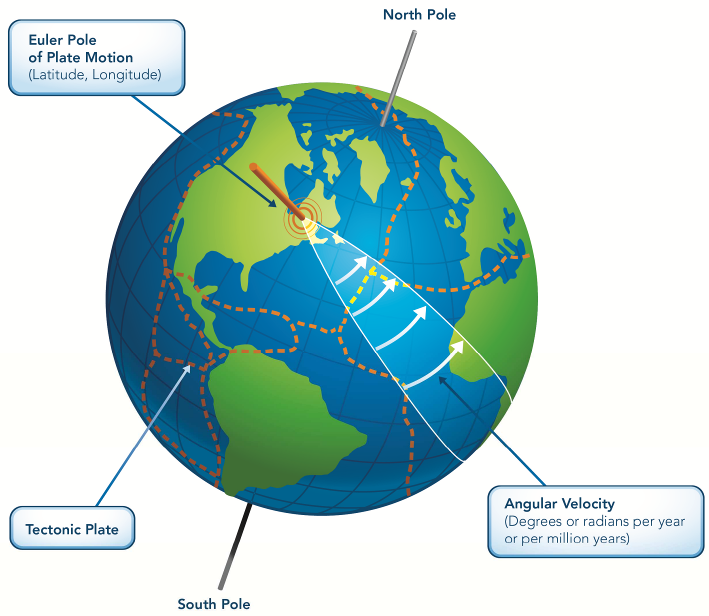

Figure 4. Concept of an Euler rotation pole. In this example, the African plate rotates anticlockwise realtive to the North American plate about an Euler pole axis located in North America.

Global relative plate motion models have been derived using geological and geophysical data, and more recently, precise inter- and intra-plate geodetic measurements.

The ITRF is crust based which means it is realized by a set of positions of points fixed on the solid Earth crust [25]. But if the frame is to remain fixed in a global sense to the crust and the crust moves, then the frame must move with the crust. Global plate motion models which estimate the motion of the tectonic plates over time are used to maintain the alignment of the ITRF axes. Therefore, if coordinates in a particular frame are required at a time other than the reference time at which the frame was realized, then plate motion must be applied. Plate motion models yeild the required coordinate displacements to account for shifts in location due to crustal motion. The most recent ITRF realization, ITRF 2008, has its frame orientation kept closely aligned with the global plate motion model NNR-NUVEL-1A [1]. The parameters of NNR-NUVEL-1A are shown in Table 2 [6].

**Table 2. Plate rotation vectors for the NNR-NUVEL-1A geophysical plate kinematic model [DeMets]**

|  | Rotation vector |  |  | Cartesian rotation vector |  |  |  |
|---|---|---|---|---|---|---|---|
| Plate Abbrev. | Euler Pole Latitude | Euler Pole Longitude | Omega [deg/Ma] | Omega X | Omega Y [radians/Ma] | Omega Z | Plate Name |
| AFRC | 50.569 | -73.978 | 0.2909 | 0.000891 | -0.003099 | 0.003922 | Africa |
| ANTA | 62.986 | 244.264 | 0.2383 | -0.000821 | -0.001701 | 0.003706 | Antarctica |
| ARAB | 45.233 | 4.464 | 0.5455 | 0.006685 | -0.000521 | 0.006760 | Arabia |
| AUST | 33.852 | 33.175 | 0.6461 | 0.007839 | 0.005124 | 0.006282 | Australia |
| CARB | 25.014 | 266.989 | 0.2143 | -0.000178 | -0.003385 | 0.001581 | Caribbea |
| COCO | 24.487 | 244.242 | 1.5103 | -0.010425 | -0.021605 | 0.010925 | Cocos |
| EURA | 50.631 | 247.725 | 0.2337 | -0.000981 | -0.002395 | 0.003153 | Eurasia |
| INDI | 45.505 | 0.345 | 0.5453 | 0.006670 | 0.000040 | 0.006790 | India |
| NOAM | 2.438 | -85.895 | 0.2069 | 0.000258 | -0.003599 | -0.000153 | America |
| NAZC | 47.804 | 259.870 | 0.7432 | -0.001532 | -0.008577 | 0.009609 | Nazca |
| PCFC | -63.045 | 107.325 | 0.6408 | -0.001510 | 0.004840 | -0.009970 | Pacific |
| SOAM | -25.325 | 235.570 | 0.1164 | -0.001038 | -0.001515 | -0.000870 | America |
| JUFU | -30.054 | 58.870 | 0.6658 | 0.005200 | 0.008610 | -0.005820 | Juan de Fuca |
| PHIL | -38.011 | -35.360 | 0.8997 | 0.010090 | -0.007160 | -0.009670 | Philippine |
| RIVR | 20.428 | 253.128 | 1.9781 | -0.009390 | -0.030960 | 0.012050 | Rivera |
| SCOT | -25.273 | 261.234 | 0.1705 | -0.000410 | -0.002660 | -0.001270 | Scotia |

Coordinate shifts arising from global plate tectonic motion, term **V** in (1), are calculated using

$$\mathbf{V}^{f} = \Omega \cdot \mathbf{P}_{t_0}^{f} \tag{5}$$

where $\mathbf{V}^{f} = \begin{pmatrix} v_X & v_Y & v_Z \end{pmatrix}^{T}$ is the vector of velocity components in reference frame $f$ and $\Omega$ is a rotation matrix composed of published angular velocity components (referred to the fixed ITRF frame axes), given by [35]

$$\mathbf{\Omega} = \begin{pmatrix} 0 & -\Omega_Z & \Omega_Y \\ \Omega_Z & 0 & -\Omega_X \\ -\Omega_Y & \Omega_X & 0 \end{pmatrix} \tag{6}$$

When coordinates observed in a particular frame at epoch $t$ are required at the reference epoch $t_0$ plate tectonic motion must be accounted for by calculating point velocities using (6) and then shifting or updating the coordinates using

$$\mathbf{P}_{t_0}^{f} = \mathbf{P}_{t}^{f} + \mathbf{V}^{f}\delta t \tag{7}$$

Within plate boundary zones, crustal deformation is often much too complex for global plate motion models to accurately predict. Regional deformation or velocity models estimate local crustal motion by analyzing long-term repeated geodetic measurements to produce a velocity field for the region. These models typically comprise regional grids for interpolating the continuous secular motion at any point along with sets of parameters for input into analytical expressions of a so-called dislocation model to predict motion caused by episodic events such as earthquakes. The interpolation grids, dislocation model parameters and analytical expressions enable the motion at any location within the model domain to be predicted [27]. These grids and analytical expressions yeild the coordinate displacements represented by **D** in (1).

## 4. GEODETIC DATA MODEL FOR DYNAMIC DATUM DATA MANAGEMENT

Modeling deformation and representing deformation are two different things. The representation may be multiple grids which are all the GIS needs for updating positions. However, there is no doubt that GIS applications can be developed to also model deformation using various kinds of data stored inside or outside its spatial database.

Presently no standards exist for how displacements are derived nor the data formats of the models used to represent them. Each geodetic agency may derive displacements using different models and may publish results in their own unique data format. While the methods used to model displacements are always subject to improvements in our knowledge of the processes that drive them, their representation for purposes of disssenimation to the geospatial community could be standardized. This would streamline their incorporation into various commercial and open-source GIS, GPS/GNSS and field data collection and processing software.

As a first step in determining where and to what extent standards are needed we inventory the data required to calculate reference frame transformations and displacements. We then organize these data into a geodetic data model which highlights their relationships, dependencies and commonalities. If such a data model is correct, or nearly so, then once the required data are gathered and stored according to the model, we can develop software tools that use them to operate on other geospatial data to perform desired frame transformation and displacement calculations. In this way we can track locations of even very large geospatial datasets through changes in reference frame and as global or local crustal deformation occurs.

Advantages of approaching the problem in this way are that the data model is extensible allowing for other computational applications to be built that operate on the data. For example, there is no reason why the data model cannot include data used by geodesists and geophysicists to derive deformation and displacement models. All that is required is an extension of the data model so that new or existing algorithms or programs can operate on these source data. What’s more exciting are the possibilities this creates for assimilating and integrating datasets that could help in the deformation modelling processes.

### 4.1 What is a data model?

A data model is a method for describing a system using a structured set of data. For example, the set of variables used in a computer program is the data model for the program. Data models provide an orderly way to classify objects and their relationships. A geographic data model is a representation of the real world usable by a GIS to perform interactive queries, produce maps and execute analyses. Data models also furnish ways to model the behavior of systems by describing how things on, inside or above the earth interact with each other [18]. Examples of data models are: [18], [46], [45], [47].

In the geodetic data model (GDM) some entities are nothing more than a list of parameters; for example, reference frame transformation parameters. Other entities have a spatial component such as the boundaries of tectonic plates. More importantly, the objects comprising the data model exhibit specific relationships and behaviors with respect to one another that we can capture and exploit when performing interactive queries or executing analyses.

The advantage of a GIS approach lies in its flexibility and extensibility for both researchers and non-researchers. Structuring and organizing data, in our case geodetic data, allows accurate representations of information that can be tailored to the needs and interests of users by location, spatial extent and type of information desired [46]. For national geodetic and geological agencies, the GDM is invaluable in enabling better management and sharing of data with other researchers, agencies and the public. The GDM can also be a catalyst in earth science research by allowing assimilation and integration of heretofore uncombined datasets, potentially leading to new scientific discoveries.

### 4.2 Dynamic datum data model

A preliminary geodetic data model has been proposed by [13]. Components drawn from this model are applied here to create a data model for managing reference frame and crustal deformation information. Once structured in a coherent way, the data become input to software tools that drive any number of analyses and applications.

We begin with a list of data types required to perform the analyses we desire such as calculate reference frame transformations and apply dislocations to geographic locations. The information required to accomplish this are shown in Figure 5. Figure 6 reflects how these data are stored and inter-related in a spatially-enabled relational database. With this structure implemented in a spatial database, such as an ArcGIS geodatabase, graphical user interfaces (GUI) can be developed for interactive data entry, scripts (e.g using Python or VBA) can be written for batch data loading and more sophisticated applications created that operate on the stored data. These can include computing reference frame transformations, position updates due to tectonic plate motion and point dislocations caused by earthquakes. Vertical motion grids can also be incorporated into the data model for applying vertical offsets.

The real advantage derives from the ability to query the data in simple or complex ways and visualize them in a variety of traditional 2D map styles as well as in three-dimensional displays. If data are time-tagged, time based animations are also possible. Standard GIS database query tools can allow users to perform many types of data queries or build specialized applications that use the data in specialized ways. To illustrate this, notice that a new data type is shown in Figure 6 called Faults. Although not shown explicily in Figure 6, one of the attributes we store in the Earthquakes table is Focal Mechanisms. These additional data illustrate the extensibility of the data model. Here we have extended the data model to allow storage of focal mechanisms and fault geometry and their relationship to earthquake data already stored in the database. We now have access to powerful focal mechanism query and visualization capabilities. For example, we can quickly list and visualize all earthquakes occuring on a particular fault, between certain dates, within a particular region and that had magnitude greater than some specified value.

Another advantage of the GIS approach comes from the ability to easily add new information about the existing data simply by adding new fields in the data tables. Since the data model is extensible, we can add entirely new data types and generate new queries. We can also assimilate and combine data into new analyses and experiment with them to assist in discovering new phenomena and create quantitative models.

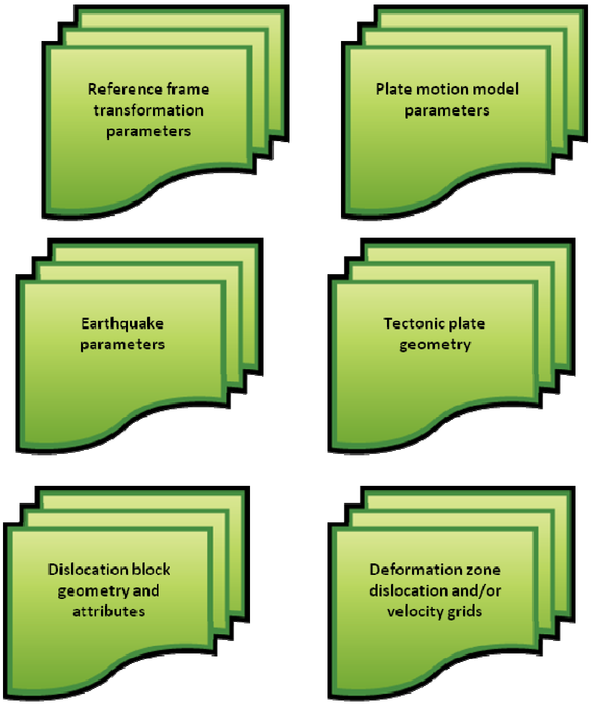

**Figure 5. Data required for calculating reference transformations and dislocations.**

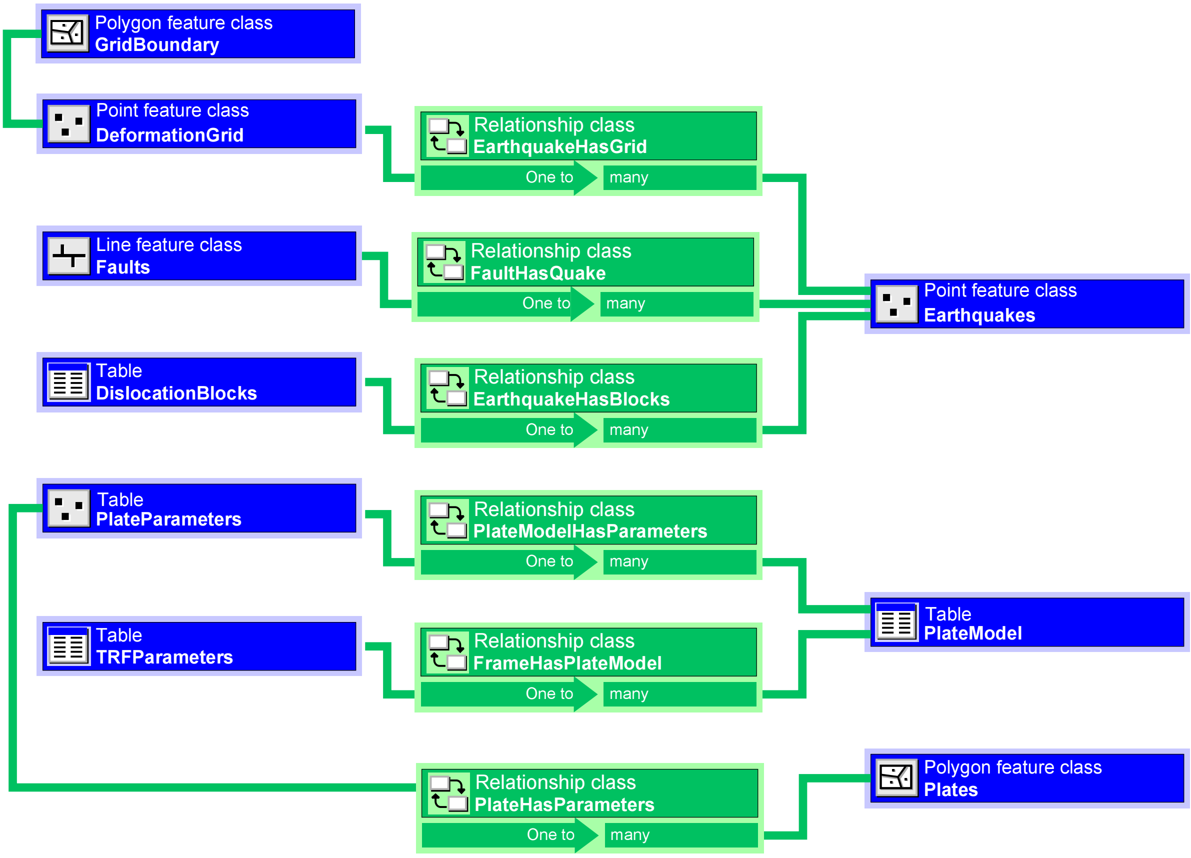

**Figure 6. Dynamic datum data model.**

## 5. CONCLUSION

To be useful the time-dependent reference frame transformations and deformation models and tools described herein must be accessible to the entire geospatial community. Geographic information systems, because of their central role in storing and manipulating geographic data and their widespread use, provide a convenient and strategic way to disseminate these models to the community. GIS is used in most, if not all, applications where these models are required – all brances of land and hydrographic surveying and mapping, terrestrial and airborne laser scanning, navigation and earth science research. Thus, not only can GIS effectively store displacement models and apply them to other geospatial datasets, but also GIS can be instrumental in deriving these deformation models in the first place. Such a workflow where deformation models are developed in a GIS environment makes their publication and dissemination in widely used and familiar GIS formats a simple, stramlined and efficient process.

## REFERENCES

1. Altamimi, Z., X. Collilieux and L. Métivier (2011). ITRF2008: an improved solution of the international terrestrial reference frame. Journal of Geodesy, DOI 10.1007/s00190-011-0444-4.

2. Beavan, J. and J. Haines (2001). Contemporary horizontal velocity and strain rate fields of the Pacific-Australian plate boundary zone through New Zealand. *J. Geophys. Res., 106*, pp. 741-770.

3. Boucher, C. and Z. Altamimi (1996). International terrestrial reference frame. *GPS World, 7(9)*, pp. 71-74.

4. Blick, G., N. Donnelly and A. Jordan (2006). The practical implications and limitations of the introduction of a semi-dynamic datum – a New Zealand case study. Presented at the 2006 Geodetic reference Frames 2006 Symposium, Munich, Germany.

5. Dawson, J. and J. Steed (2004). International terrestrial reference frame (ITRF) to GDA94 coordinate transformations. Geoscience Australia, Minearals and Geohazards Division, Version 01.03.2004, http://www.ga.gov.au/image_cache/GA3795.pdf

6. DeMets, C., R.G. Gordon, D.F. Argus and S. Stein (1994). Effect of recent revisions of the geomagnetic reversal timescale on estimates of current plate motions. *Geophysical Research Letters*, 21(20), pp. 2191-2194.

7. Ihde, J. et al (2000). European Spatial reference Systems – Frames for Geoinformation Systems. www.euref-iag.net/symposia/book2000/P_198_205.ps

8. Ihm, I., B. Chang, H. Kim and J. Braunstein (2006). An algorithm for generation of non-uniform meshes for finite difference time domain simulations. *2006 12th Biennial IEEE Conference on Electromagnetic Field Computation*, Miami, FL, DOI: 10.1109/CEFC-06.2006.1632845.

9. Jordan, A., P. Denys and G. Blick (2005). Implementing localized deformation models into a semi-dynamic datum. IAG Conference proceedings, Cairns, 2005.

10. Jordan, A.M. (2005). Implementing localized deformation models into a semi-dynamic datum. Master's Thesis, University of Otago, Duneidn, New Zealand.

11. Jonavovic, R.D., M. Tuba and D. Simian (2008). An algorithm for multi-resolution grid creation applied to explicit finite difference scheme. *ICCOMP'08 Proceedings of the 12th WSEAS international conference on Computers*, World Scientific and Engineering Academy and Society (WSEAS) Stevens Point, Wisconsin, USA

12. Junkins, D. and S.A. Farley (1995). National transformation version 2 users guide. Geodetic Survey Division, Geomatics Canada.

13. Kelly, K.M. (2009). A preliminary geodetic data model for geographic information systems. Paper No. G23C-0699, *AGU 2009 Fall Meeting, San Francisco, 10-14 December 2009*. http://www.agu.org/meetings/fm09/program/index.php

14. Kovalevsky, J., I.I. Mueller and B. Kolaczek (editors). (1989). Reference Frames in Astronomy and Geophysics. Kluwer, Boston.

15. Krysl, P., E. Grinspun and P. Schroder (2002). Natural hierarchical refinement for finite element methods. *International Journal for Numerical Methods in Engineering*, 56(8):1109 – 1124.

16. Lambeck, K. (1988). Geophysical Geodesy. Oxford University Press, Oxford.

17. LINZ (2003). Implementation of a deformation model for NZGD2000. *OGS Technical Report 20, Office of the Surveyor-General, Land Information New Zealand.*

18. Maidment, D. (2002).Arc Hydro: GIS for Water Resources. Esri Press, Redlands, CA.

19. Manning, J. and J. Steed (1999). GDA – The basis for better spatial business in a regional setting. Australian Land Information Group (AUSLIG), Canberra, Australia.

20. Meyer, T. H. (2010). Introduction to Geometrical and Physical Geodesy: Foundations og Geomatics. Esri Press, Redlands, CA.

21. Merrigan, M. J. et al. (2002). A refinement to the World geodetic System 1994 reference frame. *ION GPS 2002*, *24-27* September 2002, Portland, OR.

22. McCarthy. D.D. and G. Petit (Eds.). (2004). IERS Technical Note No. 32: IERS Conventions (2003). BKG, Frankfurt.

23. Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half space. *Bull. Seismol. Soc. Am.*, 75(4):1135–1154.

24. Pearson, C., R. McCaffery, J. Elliott and R. Snay (2010). HTDP 3.0: Software for coping with the coordinate changes associated with crustal motion. *ASCE J. Surv. Engrg.* **136**(80).

25. Petit, G. and B. Luzum (eds.) (2010). IERS Conventions (2010). IERS Technical Note 36, Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2010. 179 pp., paperback, in print.

26. Savage, J. C. (1980). Dislocations in seismology. Dislocations in solids, F. R. N. Nabarro, ed., North-Holland, Amsterdam, 251–339.

27. Snay, R.A. and E. Herbrechtsmeier (1994). The TDP-H91-CA model for historical deformation in California. *Manuscripta Geodaetica*, 19: 180-198.

28. Snay, R. and C. Pearson (2010). Coping with tectonic motion. *The American Surveyor*, **7**(9).

29. Snay, R.A. (1999). Using HTDP software to transform spatial coordinates across time and between reference frames, *Surveying and Land Information Systems,* 59(1), 15-25.

30. Snay, R.A. & T. Soler (1999). Part 1 - Modern Terrestrial Reference Systems. *Professional Surveyor*, 19(10), 32-33.

31. Snay, R.A. & T. Soler (2000). Part 2 - The evolution of NAD83. *Professional Surveyor,* 20(2), 16, 18.

32. Snay, R.A. & T. Soler (2000). Part 3 - WGS 84 and ITRS. *Professional Surveyor*, 20(3), 24, 26, 28.

33. Snay, R.A. & T. Soler (2000). Part 4 - Practical considerations for accurate positioning. *Professional Surveyor*, 20(4), 32-34.

34. Snay, R.A. (2003). Horizontal Time-Dependent Positioning, *Professional Surveyor*, 23(11), 30, 32, 34.

35. Soler, T. (1998). A compendium of transformation formulas useful in GPS work, *Journal of Geodesy*, 72(7-8), 482-490.

36. Soler, T. & L.D. Hothem (1998). Coordinate systems used in geodesy: Basic definitions and concepts, *J. Surv. Engrg., ASCE*, 114(2), 84-97.

37. Soler, T., N.S. Doyle & L.W. Hall (1999). Rigorous transformation of GPS-determined vector components, *Proc. ION GPS-99*, Nashville, TN, September 14-17, 27-3

38. Soler, T. (2001). Densifying 3D GPS networks by accurate transformation of vector components, *GPS Solutions*, 4(3), 27-33.

39. Soler, T. & J. Marshall. (2002). Rigorous transformation of variance-covariance matrices of GPS-derived coordinates and velocities, *GPS Solutions*, 6(1-2), 76-90.

40. Soler, T., N.D. Weston, & H. Han. (2002). Computing NAD 83 coordinates using ITRF-derived vector components, *Proc. XXII FIG International Congress, ACSM/ASPR Annual Conference, April 19-26, Washington D.C.*, 6 pg.

41. Soler, T. & J. Marshall. (2003). A note on frame transformations with applications to geodetic datums, *GPS Solutions*, 7(1), 23-32.

42. Soler, T. & R.A. Snay (2004). Transforming positions and velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983, *J. Surv. Engrg., ASCE*, 130(2), 49-55.

43. Steinberg, G. and G. Even-Tzur (2005). Establishment of national grid based on permanent GPS stations in Israel. *Surveying and Land Information Science, 65(1)*, pp. 47-52.

44. Trimble Navigation Limited (2004). Why postprocess GPS data? Mapping and GIS White Paper. http://trl.trimble.com/docushare/dsweb/Get/Document-210840/MGISPostprocessingWhitePaper_0205_lr.pdf

45. Von Meyer, N. (2004).GIS and Land Records: The ArcGIS Parcel Data Model. Esri Press, Redlands, CA.

46. Wright, D., M. J. Blongewicz, P.N. Halpin and J. Breman (2007). Arc Marine: GIS for a Blue Planet. Esri Press, Redlands, CA.

47. Zeiler, M. (2001). Modeling Our World: The ESRI Guide to Geodatabase Design. Esri Press, Redlands, CA.

## BIOGRAPHICAL NOTES

## CONTACTS

Mr. Kevin M. KELLY
Esri., Inc.
380 New York Street
Redlands, California
U.S.A.
Tel. +909 793 2853
Email: kevin_kelly@esri.com
Web site: www.esri.com