Realisation of a Geodetic Datum Using a Gridded Absolute Deformation Model (ADM)

R. Stanaway, C. Roberts, and G. Blick

Abstract

This paper describes a schema for a gridded absolute deformation model (ADM) and non-linear deformation patch model that can be used to transform point positions captured in the International Terrestrial Reference Frame (ITRF), or other closely aligned reference frame, to a reference epoch consistently over time for practical applications. The schema described utilises existing models of rigid plate motion, plate boundary deformation and non-linear deformation (e.g. coseismic and postseismic effects or subsidence). Application of an ADM and patch model can enable consistent Precise Point Positioning (PPP) over time and seamless integration of Continuously Operating Reference Station (CORS) networks within deforming zones. The strategy described can also ensure consistency of time-tagged spatial datasets (e.g. laser scanned point clouds and digital cadastral databases) and GIS within a kinematic environment. An ADM can also be used as the basis for static epoch projections of a national or regional kinematic datum. A case study from New Zealand is described.

Keywords

Semi-kinematic datum • Dynamic datum • PPP • Reference frame • Deformation Model

1 Introduction

Geodetic datums can be broadly classified into three categories; static, kinematic (dynamic), and semi-kinematic (semi-dynamic). The purpose of an absolute deformation model (ADM) is to enable coordinates to be propagated between kinematic and static realisations of a datum. Where a deformation model forms an integral part of a geodetic datum, the datum is referred to as semi-kinematic.

Classically, a "static" geodetic datum is defined by the coordinates of geodetic monuments invariant with respect to time, which define its origin, orientation, scale and shape. In reality, the nature of deformation of the Earth's surface is very complex at different spatial and temporal scales. For example, interseismic tectonic motion (plate motion) can be up to 100 mm/year, and coseismic deformation associated with earthquakes can be several metres in magnitude. A kinematic datum (also referred to as a dynamic datum in literature and practice) such as the latest realisation of the International Terrestrial Reference Frame (ITRF), ITRF2008 (Altamimi et al. 2011), is one where the coordinates of geodetic monuments on the Earth's surface vary continuously as a function of time, relative to a geodynamically inert reference frame coupled with the Earth's rotation. Global Navigation Satellite Systems (GNSS) inherently use an ITRF aligned reference frame for estimation of orbit ephemerides and derived positions of GNSS sensor locations. An absolute deformation model (ADM) enables kinematic coordinates in an absolute

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geodetic reference frame such as ITRF to be propagated to a static reference epoch, a process described in this paper as “epoch projection”, in order to distinguish it from classical kinematic conformal transformation methods such as the 14 parameter (7 parameters and their rates of change) Bursa–Wolf transformation.

Continuously changing coordinates pose significant challenges and risks for the majority of users of spatial data, particularly where large data sets (e.g. terrestrial laser scans, Lidar scans, service utility plans and coordinated cadastres) acquired at different epochs need to be integrated harmoniously. Kinematic coordinates increase the risk of litigation where legal definition of “fixed” coordinates are contested. They also increase the likelihood of errors in engineering surveys and damage to sub-surface infrastructure arising from misinterpretation or absence of epoch metadata. In addition, errors in precision navigation applications such as controlled traffic steering (CTS) in precision agriculture, automated mining and other driverless vehicle applications may arise. Designs, layouts and map bases defined in terms of a static datum become misaligned with GNSS positioning systems using Single Point Positioning (SPP) and Precise Point Positioning (PPP) methods used to locate them, due to unmodelled deformation between the reference and measurement epochs.

A semi-kinematic datum is one where complex deformation is modelled as an implicit component of the datum, thus enabling kinematic coordinates acquired by space geodetic techniques to be transformed consistently and accurately to a fixed reference epoch (static datum) over time. This significantly minimises costs and risk for managers and end users of a geodetic datum. Many countries and regions which straddle major plate boundaries and or zones of post-glacial rebound have adopted a semi-kinematic geodetic datum e.g. New Zealand (Blick et al. 2006), Western USA (Pearson et al. 2010), Canada (Henton et al. 2006), Japan (Tanaka et al. 2007) and Papua New Guinea (Stanaway 2004).

The ADM schema described in this paper shows how existing geophysical deformation models can be adapted into global, regional and local grids for use in positioning system software, GIS and for the realisation of a semi-kinematic datum by means of epoch projection. Unlike relative deformation models, which are already in widespread localised use, an ADM allows for kinematic ITRF aligned coordinates to be transformed directly to a fixed reference epoch. This approach ensures consistency of coordinates derived from space geodetic techniques within a localised reference frame over time. The ADM strategy has specific benefits for SPP, PPP, CORS operation and GIS.

2 The Requirement for an ADM

A major limitation of a static geodetic datum arises from the ongoing divergence between ITRF and the fixed coordinates of a static geodetic network due to rigid plate motion. While the network may not necessarily be deforming internally to any significant degree, the lithospheric plate on which the network sits is moving as a rigid body over the Earth’s asthenospheric mantle. The impact of this deformation is noticeable where precision GNSS techniques are used to compute ITRF coordinates. For example, services such as OmniStar-HP (Omnistar 2012) and NRCan PPP (NRCan 2012) deliver centimetre to decimetre precise ITRF coordinates. The NRCan service also provides coordinates in terms of NAD83(CSRS) but these are only valid within the stable part of the North American tectonic plate. In terms of ITRF, repeat surveys as little as a few months apart are adversely affected by coordinate changes due to tectonic motion, unless the position is transformed to a local system (e.g., Stanaway and Roberts 2010). Satellite-Based Augmentation Systems (SBAS) and improvements to SPP such as the implementation of the new higher resolution L5/E5 interoperable signals (e.g., Roberts 2011) will possibly enable decimetre level real-time positioning for the mass market by 2020. The implications of these improvements are significant as the international geodetic community, as well as vendors of GNSS hardware and associated software, do not currently have a uniform approach to handle this deformation. Another limitation of a static datum arises from the processing of long GNSS baselines. If the static coordinates of a reference station are held fixed, rigid plate rotation of a long baseline will degrade the precision of the point computation as a function of time (e.g., Dawson and Woods 2010).

In order for surveys undertaken at different epochs to be combined or integrated within a kinematic datum, a deformation model has to be applied rigorously, or be embedded within the data. For the model to be applied correctly, all data has to be correctly time-tagged with the epoch of acquisition.

There are two competing drivers for adoption of a kinematic datum. This conflict is between the current user requirements for a static datum (which inevitably leads to inconsistent coordinates of ground-fixed features) and the complexities of geodynamics. On the one hand, there is the need for a kinematic and high precision global reference frame to compute precise GNSS orbits and to monitor real-time changes in the Earth (e.g. Global Geodetic Observing System—GGOS) (Plag and Pearlman 2009). On the other hand, there is the need for coordinate consistency within a localised reference frame to support cadastral surveys, land management, spatial data management, mapping and precision navigation where coordinate stability (and by definition positioning repeatability) are essential (Stanaway and Roberts 2009).

At present, the latest realisation of ITRF fulfils the role of a high precision global scientific datum, but, the kinematic nature of ITRF precludes practical adoption by the majority of users and real-world applications. Rather, a semi-kinematic approach can be adopted to overcome the limitations of both kinematic and static datums, while still retaining the benefits of both.

The current strategy to transform coordinates between kinematic and static datums is to use transformation parameters such as the 14 parameter model adopted in Australia (Dawson and Woods 2010). While this approach works well on rigid tectonic plates such as the Australian plate, it does not adequately capture localised and plate boundary deformation. A higher resolution ADM can overcome these limitations.

3 The Absolute Deformation Model Concept

An "absolute" deformation model implies that the deformation is modelled with respect to an Earth-Centred Earth-Fixed (ECEF) reference frame consistent with the latest IERS Conventions, such as ITRF. An ADM can be used to predict ITRF (absolute) site velocities at any location. The ITRF site velocity is then used to compute the displacement of the location between the epoch of measurement or acquisition and a reference epoch. An ADM can also be used for processing of long GNSS baselines by forward propagation of the ITRF coordinates of a CORS reference station from a reference epoch. This approach enables processing and network analysis to be accomplished wholly within ITRF thereby eliminating the effects of unmodelled plate rotation and deformation between the measurement and reference epochs. The ADM can then be used in reverse propagation mode to compute the rover station coordinates at the reference epoch. An ADM can become an integral component of any semi-kinematic datum definition, with reference epoch (static) coordinates of the datum realised by epoch projection.

4 Gridded Representations for an ADM

A global grid of different resolutions (e.g. 1° or 0.1°) of ITRF site velocities can be estimated from existing geophysical deformation models and rigid plate motion models (e.g. Kreemer et al. 2003; Bird 2003; Drewes 2009; DeMets et al. 2010; Argus et al. 2011; Altamimi et al. 2012) and known site velocities. Approximately 94 % of the Earth's surface lies on rigid tectonic plates where localised deformation rarely exceeds more than a few mm/year (e.g., Stanaway and Roberts 2009) and the site velocity for grid nodes on the stable portions of those plates can be estimated directly using the Euler pole definition for each rigid plate (e.g. Stanaway and Roberts 2009). Improved precision using rigid plate models can be achieved by higher precision definition of microplates and crustal blocks. The larger the number of plates defined, the lower the uncertainty of the site velocity at any given location.

For the 6 % of the Earth's surface located within active deforming zones, the rigid plate assumption is limited by the effects of locked faults within any plate boundary zone. The source rigid plate model can be augmented with models of locked faults within plate boundary zones, so that the resulting effects of interseismic strain accumulation can be modelled more correctly and applied to the computed rigid plate site velocity. In many areas within plate boundary zones, locations on the opposite plate can mimic the motion of the adjoining plate while an active fault is locked. Application of this type of model has already been implemented in the Western USA (Snay 1999; Pearson et al. 2010). This strategy can be applied globally where models of locked faults are well-defined.

A regular ADM grid can be interpolated in much the same way as a geoid model (e.g. by bilinear interpolation) in order to estimate a site velocity. The grid size would dictate the accuracy of the interpolated velocity. A coarse model will generate velocities with large uncertainties in rapidly deforming boundary zones, hence the resolution of the model is an important consideration. For example, two nodes of the grid may lie on different tectonic plates. A standardised interpolation method in this instance is not ideal. For ellipsoidal surface grid sizes with dimensions less than 1°, the planar assumption of the grid does not significantly degrade the precision of the interpolation.

The deformation grid size can be decreased (e.g. to 0.01° or 0.001°) in tectonically active areas, rapidly rotating microplates or crustal blocks; however, the precision of higher resolution grids is a function of the precision of the source geophysical model, and by extension, the density of geophysical and geodetic observations used to build the model. A gridded ADM can have a nested structure to account for more complex deformation in locations of higher geodetic strain rates. To minimise deformation model file sizes, it should be possible to clip a portion of the model to cover the local region, in a similar way to the use of geoid models in GNSS receiver controllers, for example.

5 Patching of Seismic Deformation and Non-linearity

Linear (constant velocity) and non-linear (episodic) deformation should ideally be separated in practice. Linear deformation supports a stable localised reference frame, whereas episodic and localised non-linear deformation does not. The ADM is essentially a gridded velocity model with an assumption that site velocities are generally linear over long periods of time; however, non-linear effects such as site velocity changes, coseismic and postseismic deformation need to be modelled by supplementary patching (Fig. 1). In locations where there has been significant localised deformation (i.e. from an earthquake), engineering and dimensional tolerances may be exceeded and these are determining factors for implementation of a patch model (Winefield et al. 2010). Where fault scarps (at bedrock level) result in abrupt changes in cadastral boundaries, it is expected that the coordinates in the local system will have to be changed to reflect the reality on the ground (e.g. Blick et al. 2009). In both these instances, a new reference epoch needs to be defined for geodetic infrastructure in affected areas to account for localised deformation. A supplementary patch deformation model, separate from the ADM, is required to enable propagation between current ITRF, coordinates at the original reference epoch and the updated epoch post-earthquake. The same gridded format can be applied to the patch model, however the key difference between the two, is that the patch model has fixed displacements, whereas the ADM models site velocities. A patch model can apply to an event at a specific epoch, or can also be a summation of different discrete deformation events between any two epochs. The patch model would be interpolated in much the same way as the ADM. Another advantage of using a patch model is that it can absorb any unmodelled post-seismic deformation and imprecision in the ADM (e.g. where the modelled site velocities disagree with observed velocities on bedrock sites). The patch model would encompass the seismically affected area, to the extent that the magnitude of the deformation decreases below the tolerance threshold for the ADM.

The deformation data for a patch model can be derived from a number of sources. A dense network of geodetic monuments can be reobserved within the affected zone to compute the deformation field, augmented by remote sensing techniques such as analysis of interferometric synthetic aperture radar (INSAR), high resolution imagery (particularly in urban areas) and high-intensity airborne laser scanning (LiDAR) acquired before and after the earthquake. Dislocation models can be also used (as described in HTDP, Pearson et al. 2010) to compute seismic deformation and is often the only method that can be used in the absence of geodetic observations and remote sensing data.

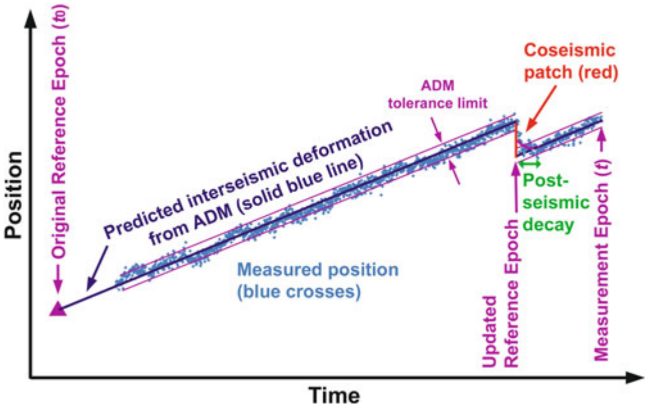

Fig. 1 Schematic representation of a typical positional time-series showing how an ADM and patch model is applied in practice. The ADM models the interseismic site velocity within defined tolerance limits and the patch models non-linear deformation associated with an earthquake

Postseismic deformation is typically represented by an exponential decay function; however, exponential decay can also be represented by step functions in the patch model until the interseismic velocity is recovered. Coseismic effects from aftershocks can also be significant and these can preclude the use of constant exponential decay terms derived from the main-shock. Alternatively the postseismic deformation can be combined with the coseismic deformation within a single earthquake patch, but, this approach precludes the use of the deformation model while the postseismic deformation is occurring.

CORS specific coordinate changes resulting from monument disturbance, receiver firmware and antenna changes should be handled differently. These effects need to be carefully defined and modelled for Network Real-Time Kinematic (NRTK) applications, but are not representative of localised tectonic deformation, and need to be decoupled from tectonic modelling and interpolation.

6 Vertical Deformation Models

In principle an ADM can be three dimensional to include modelling of vertical deformation, for example arising from tectonic deformation, glacial isostatic adjustment (GIA), or subsidence due to groundwater redistribution and compaction. In most regions of the Earth, vertical deformation in excess of solid-earth tide, ocean-tide loading and seasonal loading effects, is insignificant at a level of 1 mm/year. If required, a one dimensional vertical deformation model can be utilised in localised areas where vertical deformation is significant. CORS NRTK networks require precise modelling of vertical deformation in order to prevent degradation of the NRTK solution. A vertical deformation patch model can also be applied in the same way as a seismic patch model for horizontal deformation.

7 An ADM and Patch Model in Practice

Equation (1) shows how an ADM and patch model can be used to propagate coordinates between kinematic and static realisations of a geodetic datum.

Propagation from a kinematic datum to a static datum (fixed reference epoch) is given by:

$$\begin{bmatrix}\phi\\ \lambda\end{bmatrix}_{t_0} = \begin{bmatrix}\phi\\ \lambda\end{bmatrix}_{t} + \begin{bmatrix}\dot{\phi}\\ \dot{\lambda}\end{bmatrix}_{ADM} \cdot (t_0 - t) - \begin{bmatrix}\Delta\phi\\ \Delta\lambda\end{bmatrix}_{PATCH} \qquad (1)$$

where, t_0 is the reference epoch of the static datum (in decimal years), t is the epoch of the kinematic datum (in decimal years), $(\phi, \lambda)t_0$ are the coordinates computed at the reference epoch (decimal degrees), $(\phi,\ \lambda)t$ are the kinematic datum coordinates at the measurement epoch (decimal degrees), $(\dot{\phi}, \dot{\lambda})_{ADM}$ is the absolute site velocity interpolated from the ADM (decimal degrees/year), and $(\Delta\phi, \Delta\lambda)_{PATCH}$ is the accumulated non-linear deformation between the reference and measurement epochs interpolated from the most up-to-date patch model (in decimal degrees). If the deformation model rates and patches are described in terms of topocentric East and North components, then these terms would be required to be transformed into equivalent latitudes and longitudes in decimal degrees. A vertical deformation model would be applied in a similar way, with latitudes, longitudes and their rates in Eq. (1) substituted by h (ellipsoidal height) and height rate terms.

The patch model can be applied directly to the coordinates at the reference epoch to derive post-event coordinates. Where kinematic datum coordinates (e.g. SPP and PPP) are used in affected regions, coordinates at the measurement epoch are first propagated back to the reference epoch of the local datum using the ADM before the patch model is applied. Patch models should be updated after each major seismic event to include any other episodic deformation that has occurred between the reference and measurement epochs.

To show how the combined ADM and patch approach works in practice, a case study for a complex deformation environment in the Gisborne region, in the North Island of New Zealand, is presented here (Fig. 2). In this case study, deformation in the region is defined by both a 0.1° ADM (to model interseismic deformation) and a 0.1° patch model (to model non-linear deformation). The ADM and patch are derived from geophysical modelling and time-series analysis of a dense network of CORS and campaign GNSS measurements.

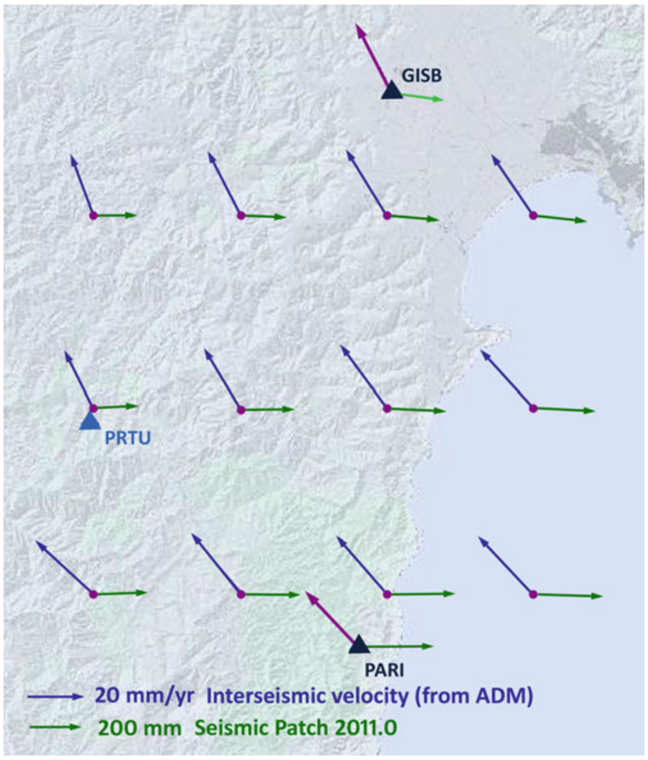

Fig. 2 Example of a gridded ADM and patch model with 0.1° resolution in the Gisborne region of New Zealand, showing ADM (interseismic) site velocities and a deformation patch (non-linear deformation between reference and measurement epochs)

A rover GNSS sensor observes ITRF2008 ellipsoidal coordinates at epoch 2011.008 (3rd January 2011) computed by a global PPP solution as follows:

$$\text{ITRF2008 Epoch 2011.008} \quad \phi_t = -38.81419294°, \\ \lambda_t = 177.69787906°$$

The ITRF site velocity for the rover station is computed by bilinear interpolation of the ADM as follows:

$$\phi\,\text{rate} = 21.6\ \text{mm/yr}\ \ (0.0000001948\ \text{deg/yr})$$

$$\lambda\,\text{rate} = -11.0\ \text{mm/yr}\ \ (-0.0000001263\ \text{deg/yr})$$

The patch model at epoch 2011.0 is interpolated in order to estimate non-linear deformation between epochs 2000.0 and 2011.0

$$\Delta\phi = 0.000000079° \quad \Delta\lambda = 0.000002107°$$

Equation (1) is then used to compute ITRF2008 at epoch 2000.0 (approximating the static datum NZGD2000) coordinates of the rover as follows:

$$\begin{aligned}\begin{bmatrix}\phi\\ \lambda\end{bmatrix}_{t_0} &= \begin{bmatrix}-38.81419294\\ 177.69787906\end{bmatrix}\\ &\quad + \begin{bmatrix}0.0000001948\\ -0.0000001263\end{bmatrix}\cdot(2000-2011.008)\\ &\quad - \begin{bmatrix}0.000000079\\ 0.000002107\end{bmatrix}\end{aligned}$$

so, the rover coordinates at epoch 2000 (t_0) are estimated as follows:

$$\phi_{t0} = -38.81419516^\circ, \qquad \lambda_{t0} = 177.69787834^\circ$$

As the rover is in reality a 4th order NZGD2000 geodetic station, the coordinates can be compared with the tabulated values which are as follows:

$$\text{NZGD2000 (tabulated)} \qquad \phi = -38.81419503^\circ,$$
$$\lambda = 177.69787831^\circ$$

The difference between the estimated and tabulated values are 3 mm in East and 5 mm in North components. The estimates using the ADM and patch model are sufficiently close to the reference epoch coordinates within standard positioning tolerance limits.

8 Maintenance and Evolution of an ADM

An ADM can only improve as more CORS come online and the network of passive geodetic monuments (stable ground marks not continuously occupied by a space geodesy sensor) with known site velocities expands, especially in tectonically active regions characterised by complex deformation. Campaign style GNSS measurements over a dense network of stable passive geodetic monuments in a deforming zone allow for high resolution modelling of the deformation field. Together with longer time-series for CORS and passive stations, these observations result in improved definitions of intraplate deformation and fault models, as well as identification of microplates and crustal blocks where networks are sparse. Ongoing refinements of an ADM and associated patch models can mitigate the need for regular updates of a locally used reference epoch. Monitoring of the performance of the model can identify when actual deformation differs from the modelled deformation outside specified tolerance limits. In these instances the ADM can be redefined if the site velocity is incorrect, or alternatively the patch model can be updated to accommodate unmodelled deformation.

9 Conclusion

High precision GNSS positioning and navigation is rapidly highlighting the disparity between ITRF and closely aligned reference frames such as WGS84 to classical static geodetic datums. The disparity is brought about by the increasingly widespread use of PPP and the sensitivity of this technique to deformation of the Earth due to plate tectonic activity. In order for precision GNSS techniques to continue to deliver coordinates stable at an adopted reference epoch all significant deformations should be modelled in a consistent way. The modelling schema described in this paper shows how this can be achieved in practice. The schema also shows how permanent deformations arising from seismic activity, uplift and subsidence can be applied by patching techniques.

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