Towards a Modernized Geodetic Datum for Nepal: Options for Developing an Accurate Terrestrial Reference Frame Following the April 25, 2015 Mw7.8 Gorkha Earthquake

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Key words:
National deformation models, geodetic reference systems, Nepal

SUMMARY

Along with the damage to buildings and infrastructure, the April 25, 2015 Mw7.8 Gorkha earthquake caused significant deformation over a large area of eastern Nepal with displacements of over 2 m recorded in the vicinity of Kathmandu. In this paper we consider options for a modernized geodetic datum for Nepal that will have the capacity to correct for the earthquake displacements and ongoing tectonic deformation associated with Nepal's location on the India/Eurasian plate boundary.

The current Nepal datum is a classical datum developed in 1984 by the Military Survey branch of the Royal (UK) Engineers in collaboration with the Nepal Survey Department. It has served Nepal well; however, the recent earthquakes have provided an impetus for developing a semi-dynamic datum that will be based on the most current available ITRF and have the capacity to correct for tectonic deformation.

In the scenario we present here, the datum would be based on ITRF2014 with a reference epoch set some time after the end of the current sequence of earthquakes. The deformation model contains a grid of the secular velocity field combined with models of the Gorkha Earthquake and the May 12 Mw7.3 aftershock. We have developed a preliminary velocity field by collating GPS derived crustal velocities from four previous studies for Nepal and adjacent parts of China and India and aligning them to the ITRF. We are currently working on developing patches for the co-seismic part of the deformation using published dislocation models. While these models do a reasonably good job of modelling the deformation, there are some significant discrepancies between their predictions and the limited GPS measurements available. We hope to improve these models by developing revised grids that will incorporate increased GPS and INSAR measurements of the deformation field.

High order control would be a CORS network based around the existing Nepal GPS Array. Coordinates for existing lower order control would be determined by readjusting existing survey measurements and these would be combined with a series of new control stations spread throughout Nepal.

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1. INTRODUCTION

The Survey Department of Nepal is responsible for the geodetic control network in Nepal, which forms the basis of surveying and mapping tasks. A precise control network ensures quality surveying, engineering and mapping activities. Besides the developmental activities, a precise control network ensures accurate cadastral survey, which promotes good governance.

Nepal is located at the conjoint of two converging plates: the Indian plate to the south and the overriding Eurasian plate to the north. Due to the regular convergence of these plates along with the 25th April 2015 Mw7.8 Gorkha earthquake events; the integrity of the existing passive geodetic control network cannot be assured.

Along with the damage to buildings and infrastructure, the Gorkha earthquakes caused metre level co-seismic displacements over a large area in eastern Nepal with displacements of over 2 m recorded in the vicinity of Kathmandu. These displacements potentially cause significant discrepancies between the true post-earthquake position of points in this region and their official coordinates, which are based on pre earthquake values. Because Nepal currently has a static datum (known as the Nepal Everest datum, Manandhar (2011), Spence (1987)), the only way to correct for the co-seismic displacement is to re-survey the control in the affected areas. As a result of the distortions introduced by the earthquake, Nepal is considering introducing a new geodetic datum. In this paper we consider options for a modernized geodetic datum for Nepal that will have the capacity to correct for the earthquake displacements and ongoing tectonic deformation associated with Nepal's location on the India/Asia plate boundary.

2. POSSIBLE OUTLINE FOR A SEMI-DYNAMIC DATUM FOR NEPAL

In this paper we consider the possibility of Nepal adopting a semi-dynamic datum, similar to the NZGD2000 datum that New Zealand has use for the last 15 years (Crook *et al.*, 2015). Normally, a semi-dynamic datum aligned to the version of the ITRF that is current at the time that the datum is released. In this case the obvious candidate would be ITRF2014. While this has not yet been published we expect it will be before Nepal finalizes its national datum. In order to produce stable coordinates, all coordinates are projected to a common reference epoch. It is best to avoid the epoch of the ITRF since this is typically several years in the past when the ITRF was introduced. For a national datum the epoch date should be as current as possible. This is particularly important for Nepal because we want a reference epoch that is after the recent sequence of earthquakes.

In the scenario we present here, the datum would be based on be ITRF2014 with a reference epoch set some time after the end of the current sequence of earthquakes. We propose to use the beginning of the year that the datum is introduced. Consideration could also be given to an epoch slightly in the future to give the datum greater longevity, however, because Nepal is currently experiencing an aftershock sequence and on-going post-seismic deformation, deformation in the interval between the introduction of the datum and a future epoch date is currently too unpredictable to allow coordinates to be accurately projected to a future epoch date.

3. DEFORMATION MODEL

Typically, a deformation model contains two distinctly different elements. The first is a model of the variation of the long term (or secular) crustal velocity across the country and the second is a model or models of the co-seismic deformation associated with any large earthquakes that have occurred since the datum was introduced. Both the velocity model and the co-seismic deformation models are typically grid files so that the estimates of the velocity or co-seismic shifts can be determined using a process of bi-linear interpolation (Stanaway *et al.* 2012).

Our model of the velocity field for Nepal was developed by combining published velocities for Nepal and adjacent parts of China and India from four geodetic studies in the Nepal region. These include 96 measurements from Betenilli *et al.,* (2006), 70 from Jade *et al.,* (2014), 38 from Ader *et al.,* (2012), and 228 from Banerjee *et al.,* (2008). Before these solutions can be combined they must be aligned to a common reference frame. We used the preliminary velocity field from the Repro2 combination which incorporated all GNS data through day 140 of 2014 (Jean and Dach, (2015), Altamimi *et al.,* (2014)) for this purpose. To accomplish this we held the velocities for IGS stations from this set fixed, and aligned all of the other velocity solutions to them. The alignment process required solving for translation and rotation and scale rates to align the vectors that are common between two or more solutions using a least square procedure described by Snay *et al.,* (2015). Figure 1 shows the location of points that are common between two or more velocity solutions and thus were used in alignment process.

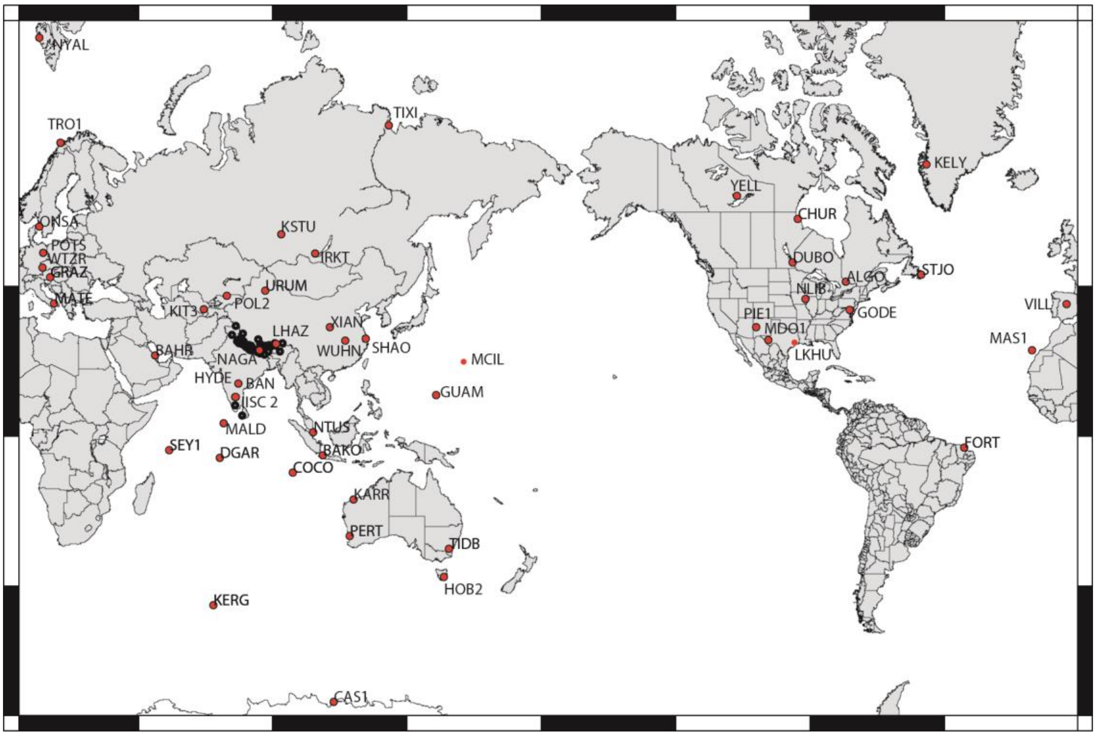

Figure 1: Dots show the location of points that are common between two or more velocity solutions. Red dots and four character IDs show the locations of stations included in the Repro2 combination while black dots show alignment points that do not include any Repro2 combination stations.

The velocity combination contained 1043 unique velocity vectors. While many of these vectors are outside of our zone of interest there are 256 vectors located within the region 76°E and 93°E and 22°N and 35°N, which we can use to determine a velocity grid for Nepal. The resulting velocity vectors are shown in Figure 2.

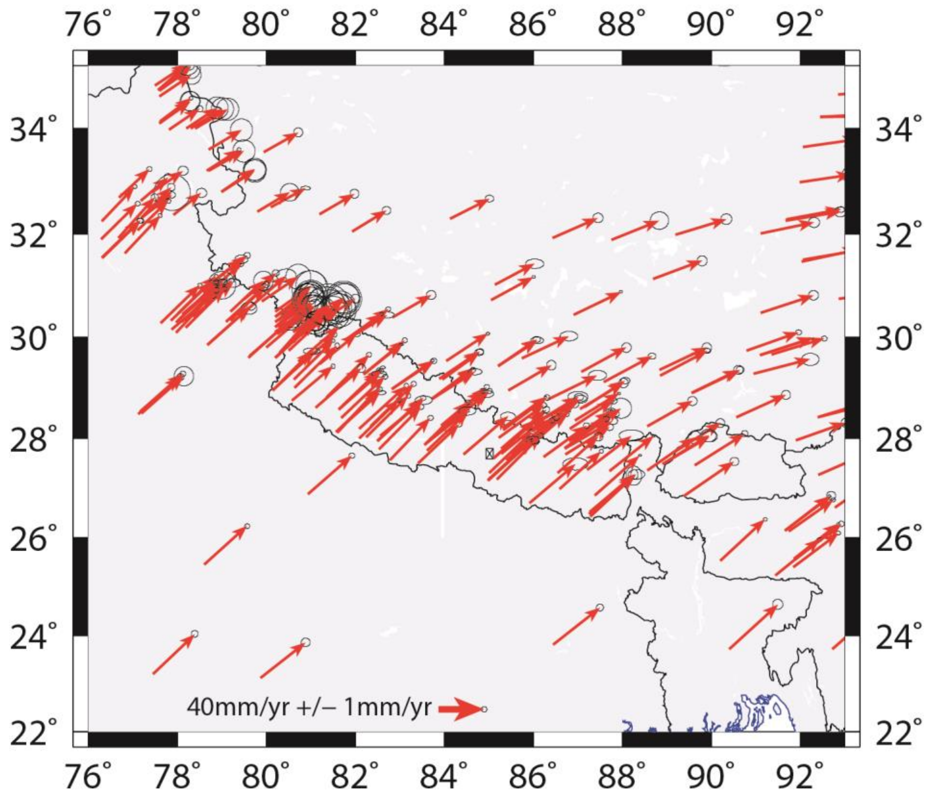

Figure 2: Velocity vectors aligned to IGb08

While we are only interested in a limited region surrounding Nepal, in order to avoid edge effects and incorporate as many stable India velocity constraints as possible, we gridded a much larger region extending from 77°E to 91°E and 22°N to 33°N. The grid was then clipped to cover the region from 80°E to 89°E and 26°N to 31°N (Figure 3). While Figure 3 shows velocity vectors on a half degree spacing the actual gridded velocities have a spacing of 20 points/degree (0.05°). The predicted vectors from the grid have an RMS misfit of ±1.1 mm/yr in the east component, ±1.3 mm/yr in the north.

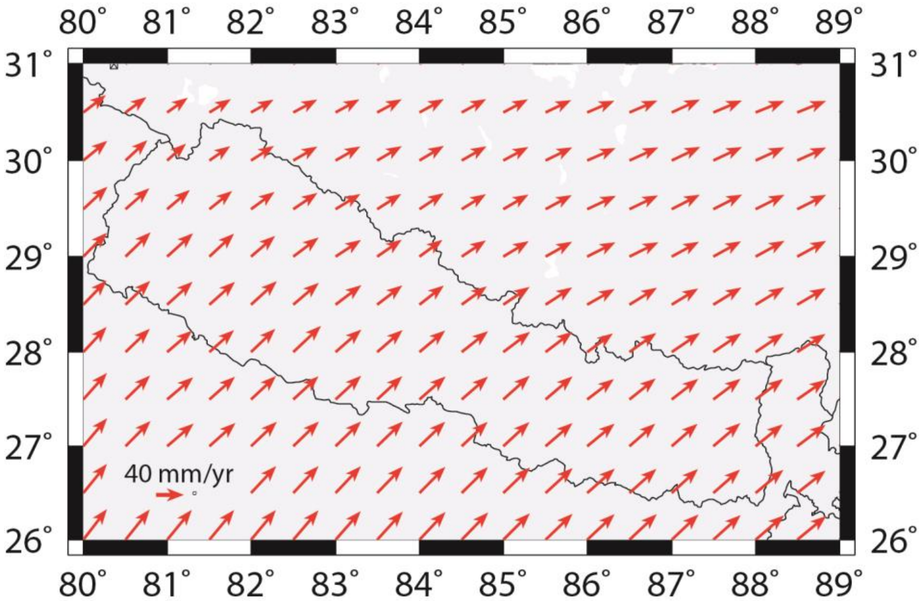

Figure 3: Velocity grid for Nepal and surrounding parts of India and China

As long as the epoch date is later than the last major earthquake in the sequence, the deformation model need only contain a model of the secular velocity field. However, we propose to include models of the 25th April 2015 Gorkha Earthquake and the 12th May Mw7.3 aftershock in order to facilitate the readjustment of survey measurements that predate the earthquakes. We are currently working on developing patches for the co-seismic part of the deformation using published dislocation models (Galetzka *et al.,* 2015, Diego pers. com, 2015). While these models do a reasonably good job of modelling the deformation, there are discrepancies between their prediction of the co-seismic deformation and the limited available GNSS measurements. Because these measurements are based on the offsets from daily cGNSS solutions, they are effectively instantaneous estimates of the earthquake displacements and will not be affected by any post-seismic deformation. In the future we hope to improve these models by developing revised grids that will incorporate the increased availability of GNSS and INSAR measurements of the deformation field that will become available. Figure 4 shows the predicted displacement associated with the 2015 Gorkha Earthquake.

Along with the co-seismic deformation, post-seismic crustal movements are also likely to be occurring after an earthquake the size of the Gorkha Earthquake. In the case of the M7.9 2002 Denali earthquake, the National Geodetic Survey added a model of post-seismic deformation to the HTDP software (Pearson *et al.,* 2013). In the future, we would consider adding a similar model for the Gorkha Earthquake, however, at present there is too short a time series to develop the quantitative models to accurately estimate the deformation.

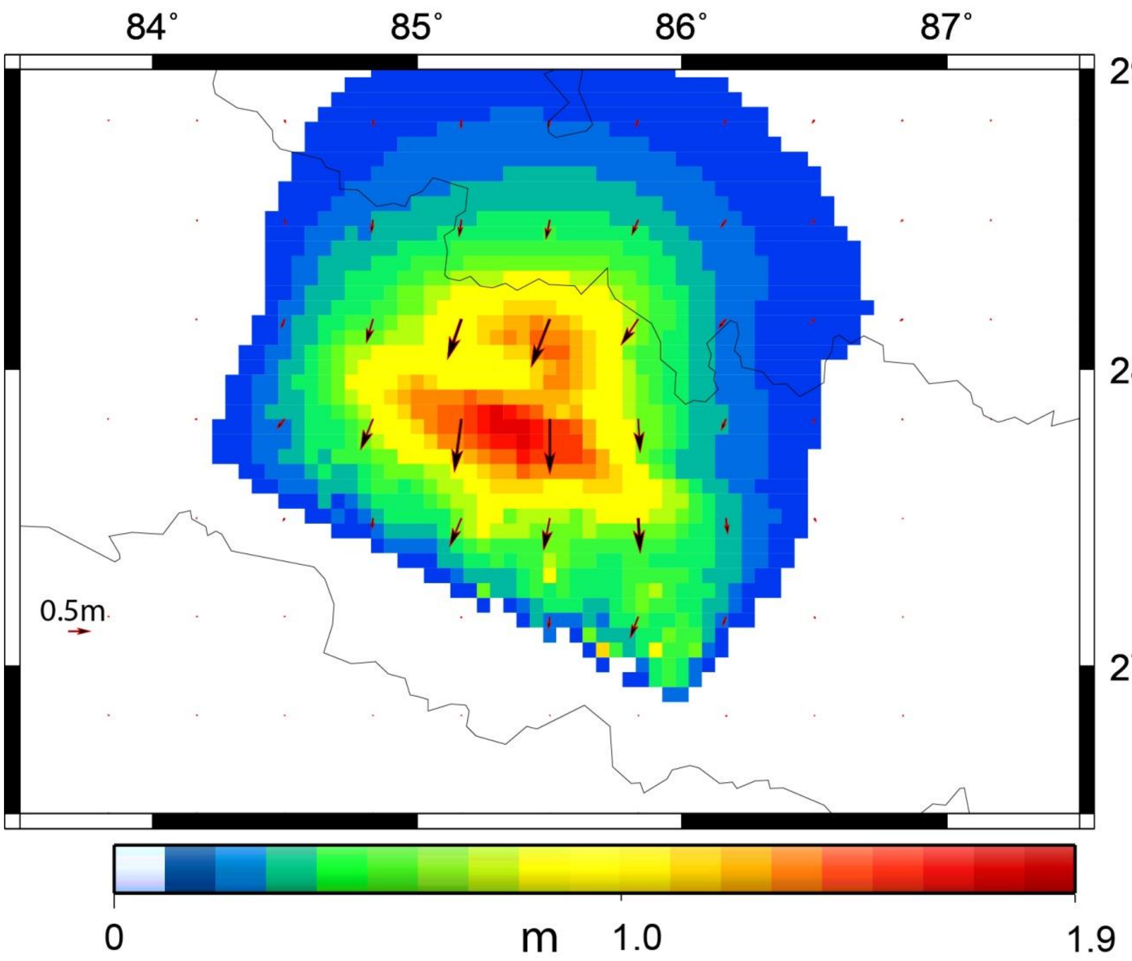

Figure 4: Predicted displacement associated with the 25th April 2015 Mw7.8 Gorkha Earthquake inferred from the dislocation model from Galetzka *et al.* (2015).

4. CONTROL

High order control for the proposed Nepal datum would be based on a CORS network with coordinates that are rigorously aligned to the ITRF. This network would adopt as many of the existing Nepal GPS Array (www.tectonics.caltech.edu/resources/kmlnepal.html) stations as possible. A preliminary evaluation of the stations in the array indicates that 20 of these sites maybe available to act as a CORS network for Nepal. However, four sites download only sporadically due to problematic data links, which results in long latency periods. The distribution of potential CORS stations is shown in Figure 5.

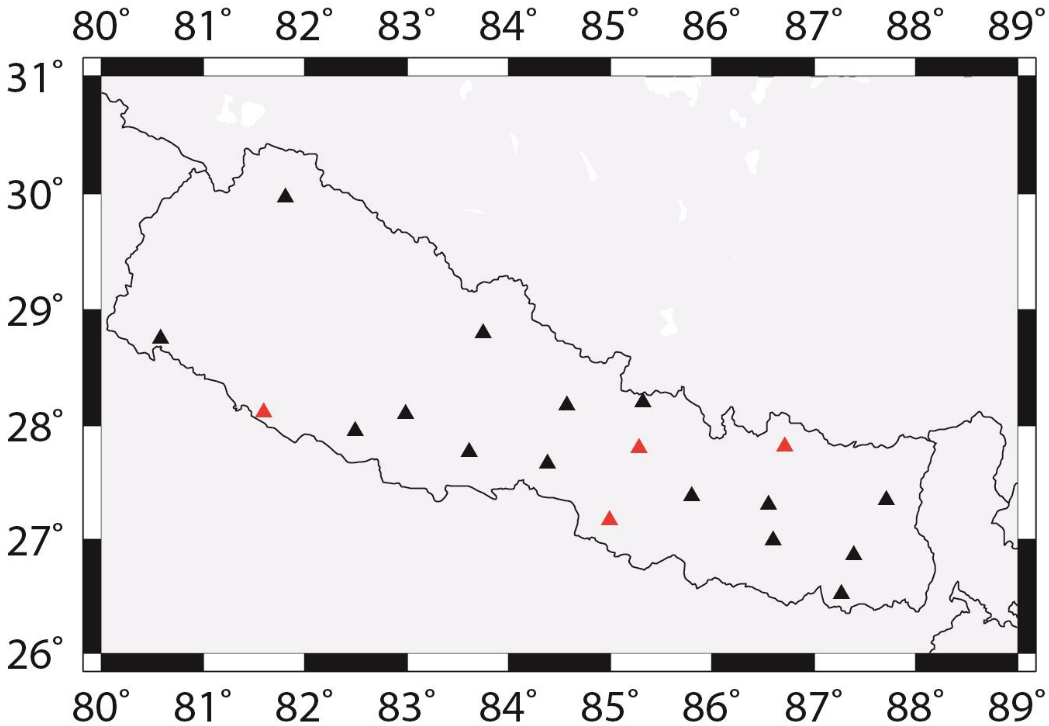

Figure 5: Location of stations from the existing Nepal GPS Array that are potential stations for a Nepal CORS network. Black triangles show the location of triangles with near real time downloading while red triangles show stations with latency of several weeks to several months.

Coordinates for existing lower order coordinates would be determined by readjusting existing measurements using least square adjustment packages that can apply the deformation model combined with new surveying data, particularly in the Kathmandu area. This will require that observation dates are available for all historic measurements and it will require that the data is available in a digital form. Comparing the old and new coordinates from existing control will allow a series of correction grids to be developed and these will provide the basis of an accurate datum transformation between the modernized and original Nepal datums. The correction grid will be used to transform coordinates and spatial references in geodatabases into the new system.

5. TOOLS FOR SURVEYORS TO CONNECT TO THE NEW DATUM

Nepal will need a mechanism to allow surveyors to realize coordinates in the new datum. This can be done by establishing a network of control coordinates. The topographic maps in Nepal, published in sheets covering 7.5 arcminutes of latitude and longitude, map the densely populated Terai and Middle Mountain regions. The less populated, high mountain regions are mapped on 15 arcminute sheets. If high order control points were established at a density of one per topographic base map sheet, this would give a density of about 1 station per 10-15 km in the populated regions of Nepal and one per 25-30 km for the mountainous areas. High level passive control marks, which have been used in previous earth deformation studies, should be resurveyed as a matter of urgency as they can contribute to the velocity model. For points that will contribute to the velocity field, processing must be done using techniques that provide coordinates and velocities that are aligned rigorously to the ITRF. For new static control, which are not intended to be used for measuring velocities, processing using commercial software will be adequate. Once the new stations have been established and surveyed, the data will be adjusted relative to the CORS to determine coordinates in the new datum. This requires the use of adjustment software that supports the use of deformation models, for example SNAP developed Land Information New Zealand (LINZ, 2013) or HTDP (Pearson and Snay, 2013). Sufficient points with existing Nepal Everest coordinates should be included to allow the transformation grid to be developed.

In addition to the network of passive control marks, the Survey Department could consider developing web based products and other infrastructure to allow surveyors to connect their surveys directly to the CORS network. At its simplest this might take the form of hosting RINEX files from the CORS on its own website, or even training Nepali surveyors to use the existing UNAVCO web interface for this purpose (www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html). However, the UNAVCO web interface has some limitations for providing data in the form that surveyors can use easily. For this reason, it would be desirable to have the RINEX data hosted locally in Nepal on a server under the control of the Survey Department.

Eventually, it may be possible to incorporate, at least some of, the CORS network in a NetworkRTK facility. In this regard, some of the stations in the Nepal GPS Array are already producing high rate GPS data so developing a Nepali NetworkRTK should not be particularly difficult. It may also be possible to develop capacity for online data processing along the lines of the existing PositioNZ-PP, AUSPOS or OPUS services.

6. CONCLUSION

Because of the effect of the 25th April, 2015 Gorkha earthquake, significant earth deformation has occurred in a large area of eastern and central Nepal centered on the Kathmandu Valley. As a result, the geodetic control in this region is significantly distorted with published geodetic control coordinates being displaced from their true position on the ground by up to 2 m. Correcting these distortions will require a new geodetic datum.

In this paper we consider the possibility of Nepal adopting a semi-dynamic datum, similar to the NZGD2000 datum that New Zealand has use for the last 15 years (Crook *et al.*, 2015). The new datum would be based on ITRF2014 and include a national deformation model. The reference epoch needs to be set after the completion of the current earthquake sequence. Because of the extensive work carried out by the earth deformation community over the last two decades, many of the models and much of the infrastructure required to support a datum are already available in Nepal. For example, we demonstrate that an adequate velocity model for Nepal can be developed from measurements that have been published in a series of recent papers. In addition, published dislocation models that can form the basis of earthquake patches are available. A national CORS network is often incorporated in dynamic datums because it provides a key role in providing the high order control, monitoring the stability of the datum and enabling users to tie surveys into the datum using the most reliable control available. In the case of Nepal, the CORS run by UNAVCO, which have been established for earth deformation monitoring can also form the basis of a national CORS network.

Of course, a significant amount of work needs to be done before a semi dynamic datum can be established for Nepal. Existing survey control will have to be coordinated in terms of the new datum through a mixture of readjustment and resurveying of existing control points and new control points. Also, the transformation (correction grids) between the existing Nepal Everest datum and the new datum will have to be developed in order to transform coordinates and spatial references in GIS databases into the new system. However, for the most part, this work is not specific to a semi-dynamic datum and would be required regardless of whatever type of geodetic datum Nepal adopts.

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BIOGRAPHICAL NOTES

Since 2011 Chris Pearson has been a lecturer/research fellow at School of Surveying, Otago University where he has been active in measuring earth deformation and has collaborated with LINZ to develop tools such as PositioNZ-PP and made contributions to the NZGD2000 datum. Prior to this he worked for the US National geodetic Survey where he was project lead for maintaining the US National Deformation Model. Chris is currently acting as advisor to the Government of Nepal on modernizing their national datum.

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