Feasibility of developing a regional deformation model for the South Pacific

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SUMMARY

Due to advances in positioning technology, particularly the widespread availability of commercial PPP services, ordinary GNSS users are increasingly being presented with coordinates in the current ITRF at the epoch of observation and there are no tools to correct these coordinates to the reference epoch of the ITRF or the reference epoch of a national datum. In this paper we consider the South Pacific region as a test case for developing a regional deformation model using published sources. Our study shows that over much of the region the global models from Kreemer et al (2014) provides an adequate basis to estimate secular velocities but, in some extremely tectonically active and complex areas like Vanuatu, Papua New Guinea (PNG) and the Solomon Islands, results from elastic block modeling studies should be incorporated in the velocity model to develop a spatially coherent velocity field. The region is quite seismically active so earthquakes will also make an important contribution to the model. Unfortunately most major earthquakes in the western part of the region (Vanuatu, PNG and the Solomon Islands) do not have published dislocation models so the development of earthquake source models from published sources is more difficult here. For the 2009 Samoa-Tonga Magnitude 8.0 doublet, Beavan et at (2010) present a dislocation model that provides a very good match for the limited displacement measurements and it could be adapted as a source model to estimate datum displacements for Tonga and Samoa.

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1. INTRODUCTION:

Due to advances in positioning technology, particularly the widespread availability of commercial PPP services, ordinary GNSS users are increasingly being presented with coordinates in the current ITRF at the epoch of observation. While most national datums have well defined relationships with the ITRF these are defined at the reference epoch of the ITRF and there is no procedure to shift epoch of observation coordinates in time to the reference epoch. For points that are located in the stable interior of plates it is possible to use the plate Euler poles to estimate site velocities and thus correct positions back to the reference epoch but this procedure will not work for points in tectonically active areas such as plate boundary zones. In order to transform positions in time there must be a deformation model associated with the ITRF that will have the capacity to model and correct for positional shifts associated with tectonic motion in the same way that deformation models associated with some modern datums such as NZGD2000 (Crook et al 2016) or NAD83 (Pearson et al 2014). Deformation models typically consist of two elements: (1) a model of of secular velocities and (2) a series of models of shifts associated with large earthquakes. In addition it may be possible to incorporate postseismic deformation models for select great earthquakes.

In this paper we consider the South Pacific region as a test case for developing a regional deformation model using published sources.

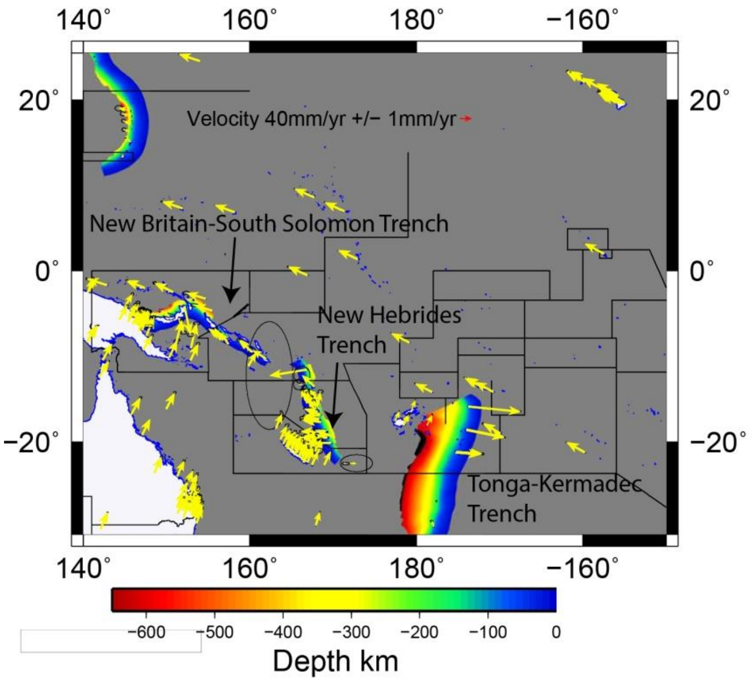

Figure 1 Velocity vectors from the Kreemer et al 2014 solution are shown relative to the ITRF2008 datum. The depth of the descending plate for the New Britain-South Solomon, New Hebrides and Tonga-Kermadec trenches are shown using the depth scale.

Published velocities for the South Pacific region are shown in Figure 1. In the South Pacific context an Euler pole correction would apply to most of eastern Polynesia and Micronesia (Pacific plate) and New Caledonia (Australian Plate) but this procedure will not work for regions adjacent to active plate boundaries. In the South Pacific region this includes tectonically active areas such Tonga, Fiji, Vanuatu, the Solomon Islands and PNG, which contain most of the land area and population centers in the region. Maintaining a datum capable of sustainably producing accurate coordinates will require a deformation model that has the capacity to model and correct for positional shifts associated with tectonic deformation.

2. DEFORMATION MODELS

In areas that are located on the boundaries of tectonic plates, the motion is more complicated because the points are deforming or moving relative to each other in complex ways. In this case a mathematical model, usually called a Deformation Model, is used to calculate the trajectory of points. This usually includes a way of estimating the constant or secular velocity of each point and a way of calculating the effect of any earthquakes that may have occurred between the time that the coordinates were measured (epoch of observation) and the reference epoch. The effect of earthquakes is an instantaneous offset while the effect of the velocity increases linearly with time. The total motion is just the sum of the earthquake and constant velocity terms. In practice both the velocity and earthquake shifts are stored as a series of grid files which are used to estimate the appropriate values for an arbitrary point by linear interpolation. The basic idea of a Deformation Model is illustrated in Figure 2, which shows the trajectory of a point affected by a constant velocity and two earthquake shifts.

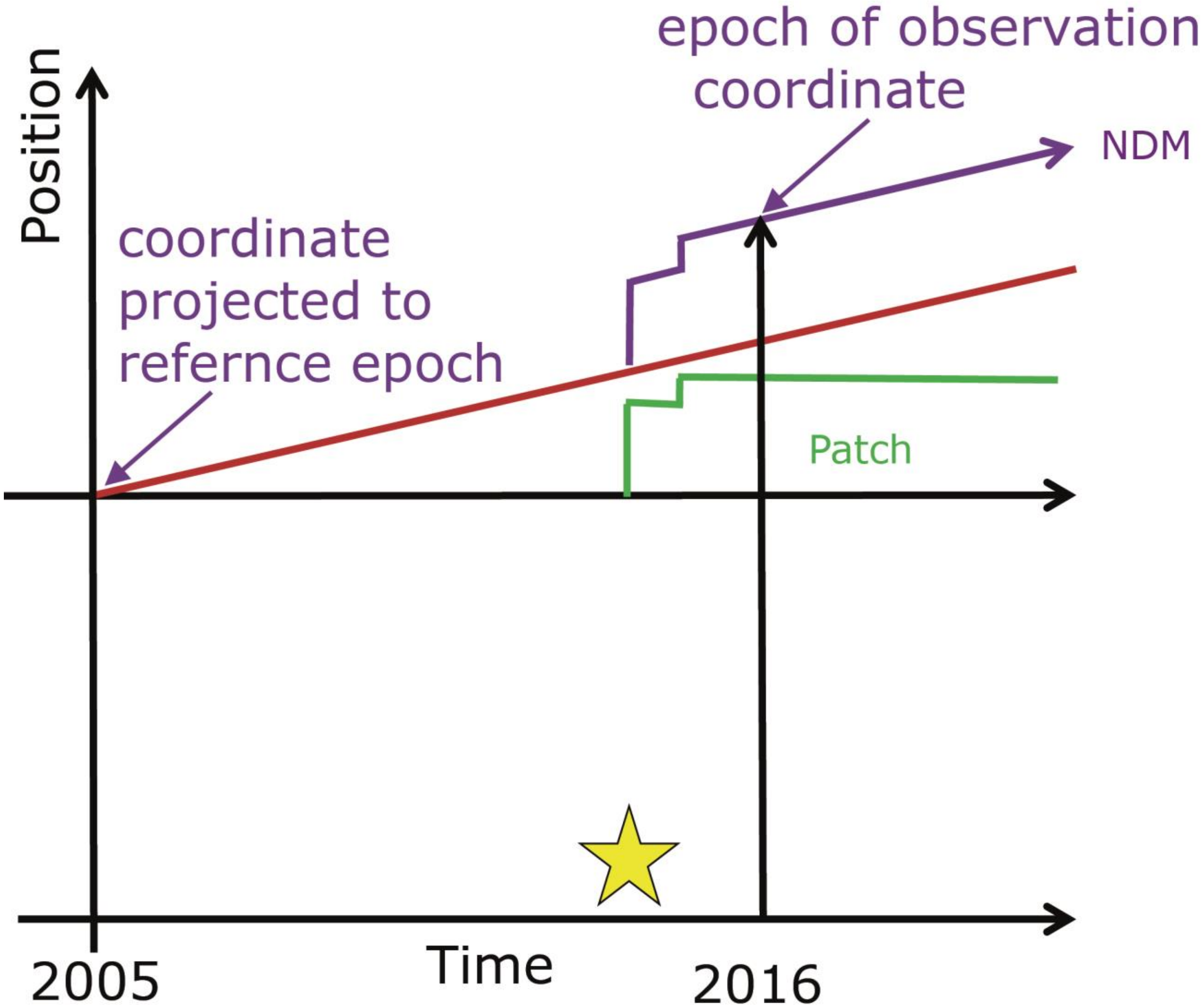

Figure 2 Schematic diagram of a deformation model. Red line shows the secular velocity and green line co-seismic contribution to the deformation model. The purple line shows the deformation model including both contributions. In this example the coordinates are projected to 2005, the reference epoch of ITRF 2008.

As noted above, deformation models typically consist of two elements, a model of secular velocities and a series of models of shifts associated with large earthquakes. . Models of post seismic deformation have been incorporated in some recent deformation models (Pearson et al. 2017, Pearson et al. 2013). Altamimi et al. (2016) has also incorporated models for postseismic deformation into their time series analysis for ITRF2014. We do not intend to incorporate models of post seismic relaxation in the regional deformation model for the South Pacific because we do not currently have any measurements to support such models although this would be considered if another large earthquake occurs in the region.

One of the more challenging aspects of implementing this is developing the interseismic deformation model that can apply to any point in the region. Two approaches are commonly used: (1) development of a regional velocity field by interpolation of GPS velocities using methods such as those described in Beavan and Haines (2001), or (2) Development of a regional elastic block model that accounts for the influence of small scale tectonic blocks and elastic strain due to locking along their boundaries (e.g., McCaffrey, 2002). The first approach has been implemented in the establishment of New Zealand's deformation model (Crook et al 2016), while the second approach has been used in the development of the deformation model for the United States' dynamic datum (Pearson et al., 2014). The first approach (interpolation) works well if the model is underpinned by a dense GNSS velocity field, such as that in New Zealand. However, in regions where there is sparse coverage of GNSS velocities it can be necessary to go to a block modeling approach underpinned by knowledge of the location of the active fault zones and plate boundaries in the region.

3. DATA SOURCES SECULAR VELOCITIES

To make a global deformation model, feasible we plan to make maximum use of existing global models. For the secular velocity component the velocity grid produced by the Kreemer et al 2014 global strain project makes a very good starting point. If we compare the velocities shown in Figure 1 with the calculated values from Kreemer et al's (2014) global velocity grid, the RMS residual is 7 mm/yr. However this value is affected by 30 significant outliers. If these are removed the RMS residual reduces to 3 mm/yr. As shown in Figure 3 these are nearly all associated with tectonically complex areas in Vanuatu, The Solomon Islands and PNG. The misfit in this region appears to be due to the sparsity of the data available in the southwest Pacific Islands compared to the spatial variation in the velocity field here. As a result the approach defined by interpolating GPS velocities (as used in the Kreemer et al., 2014 and Beavan and Haines, 2001) is not appropriate for the development of a coherent velocity model to underpin a dynamic datum. As part of this project we would develop methodologies to incorporate the results of more detailed local studies. In the case of the South Pacific region, results from a series of elastic block modeling studies (Wallace et al., 2004, 2005, 2014, 2015, Power et al., 2016) should be combined to develop a spatially coherent velocity field for Vanuatu, PNG and the Solomon Islands to better model the rapid spatial variation of velocities there. NAD83 similarly underpinned by a velocity field developed from elastic block modeling (Pearson et al 2014). Such data could easily be incorporated into regional model. In addition, new velocity measurements must be incorporated as they become available. For example, Fiji has a few very sparse measurements, although Tabua (2017) indicated that these would be significantly densified as part of the Fiji datum modernization program. In order to combine these studies we plan to use the quasi-least-squares process developed by Snay et al (2016) to rigorously align all for the data to the ITRF2014 frame.

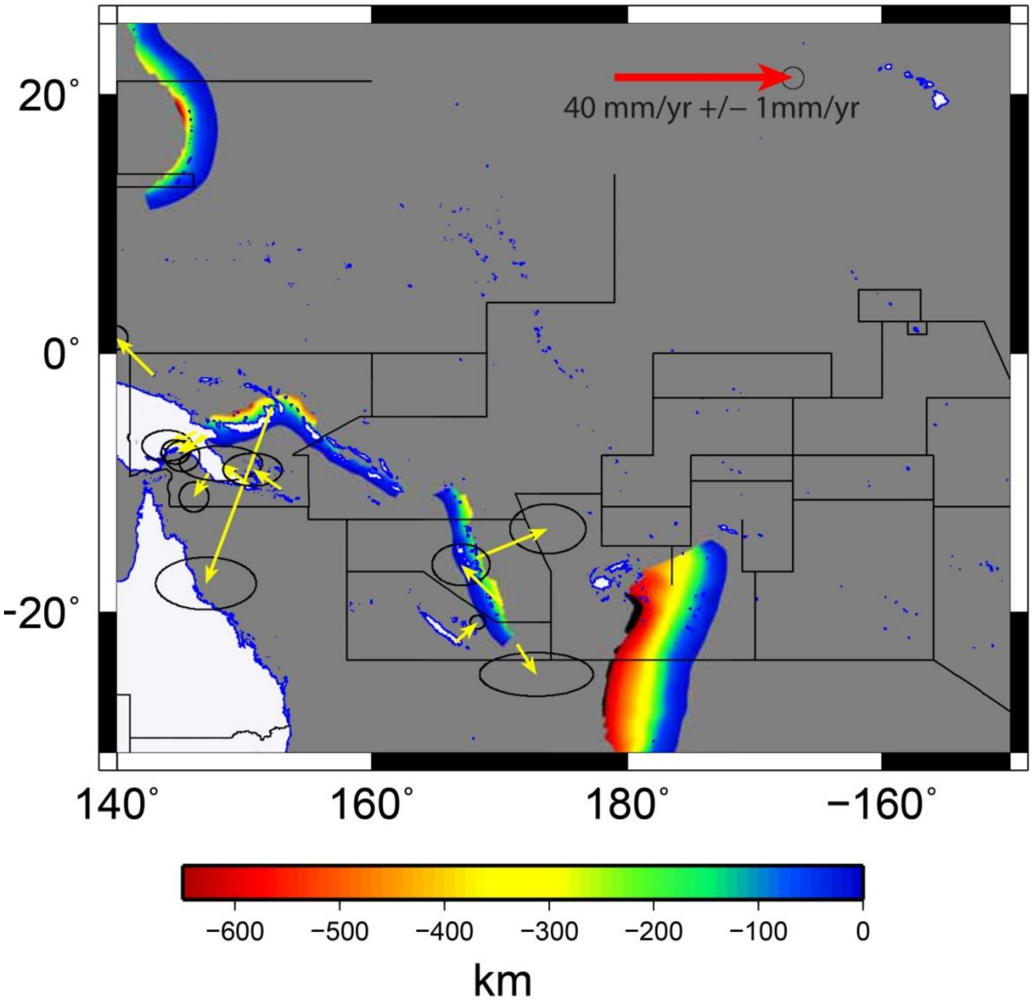

Figure 3 Residual vectors greater than 4.5 mm/yr compared to the Kreemer et al's (2014) global velocity model

4. DATA SOURCES FOR EARTHQUAKE SHIFTS

Figure 4 shows the historic seismicity from the UGSG catalogue from the South Pacific region. Clearly the region has a high rate of earthquakes capable of producing significant coordinate shifts. For the 2009 Samoa-Tonga Great Earthquake, Beavan et at (2010) present a dislocation model for this earthquake that provides a very good match for the limited displacement measurements and it would be a possible source for earthquake patches for Tonga and Samoa. A similar type of source model could be developed for the 2007 Solomon

Islands earthquake (Taylor et al., 2007), and perhaps others. Unfortunately there are few published studies for earthquakes in Vanuatu, The Solomon Islands and PNG so the development of earthquake sources would be challenging in these areas. We hope that the datum modernization process for these countries will eventually produce a significant increase in density of continuous GNSS (cGNSS) stations stations that will allow accurate earthquake patches to be developed in future.

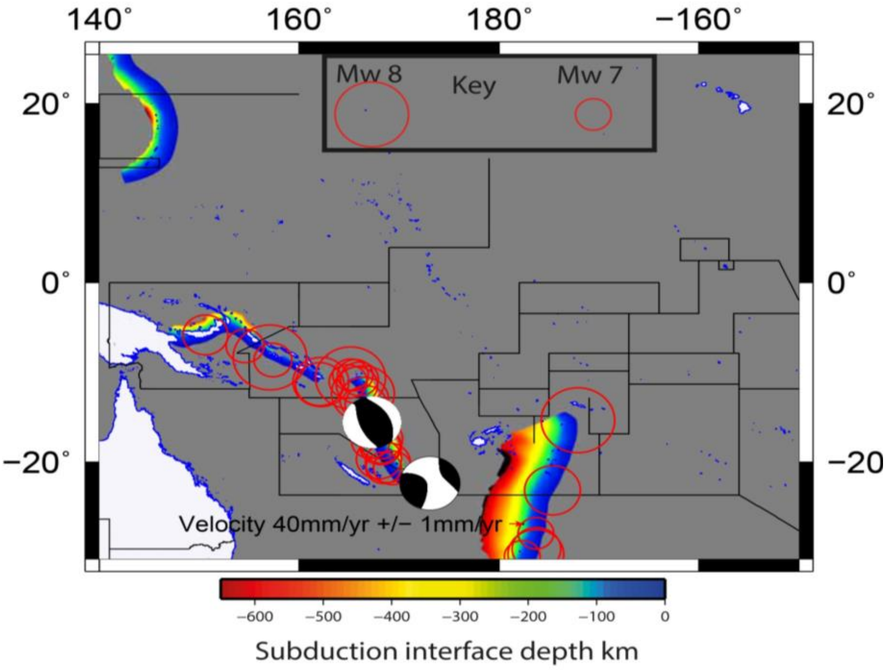

Figure 4 Compilation of earthquakes 2005-2015 for the South Pacific region with magnitudes greater than 7. The depth of the descending plate in subduction zones are shown using the depth scale. Focal mechanisms for the two most recent earthquakes are also shown (Occurring on YMD 2016 04 28 and 2016 08 12).

5. CONCLUSION

Most of the South Pacific Island developing nations are tectonically active and will require a deformation model to allow modern positioning technology such as PPP to be used to its full potential. We have investigated the feasibility of developing a regional velocity model that makes maximum of exiting global data sets. Our results suggest that over much of the region, the Kreemer et al (2014) global velocity solution will provide sufficient information to estimate the secular velocity component of the deformation model. However, this model has large residuals and is based on a low spatial density of geodetic velocities. Thus, a more desirable approach is to incorporate results from regional block modeling studies from Vanuatu, The Solomon Islands, PNG, and elsewhere. Developing earthquake sources is problematic because for many of the earthquakes no published dislocation models exist. However, for the 2009 Samoa-Tonga double earthquake, a published dislocation model does exist (Beavan et al 2009). Preliminary evaluation suggests that it would be sufficient to develop a patch for this earthquake. Incorporating a patch for this earthquake would improve the deformation model, as it generated coordinate changes of up to 0.4m in both Samoa and Tonga and both countries may need to readjust their geodetic networks as a result.

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BIOGRAPHICAL NOTES

Chris Pearson Chris is a research fellow at the Otago University School of Surveying where he is active in developing tools to provide accurate coordinates in deforming regions. Currently he is helping the Survey Department of Nepal to develop a new datum after the Gorka Earthquake. Chris completed a PhD at the University of Otago in 1991 and a PostDoc at Columbia University. Between 1993 1nd 2001 Chris was a research fellow at the School of Surveying where he was involved in measuring earth deformation. Between 2001 and 2011

Chris worked for the US National Geodetic Survey where he was geodetic advisor to the state of Illinois working with IDOT on geodetic/positioning issues and he was also responsible for maintaining the HTDP program. Chris is now a research fellow/lecturer at Otago University School of Surveying. Chris is a member of the New Zealand Institute of Surveyors and an honorary member of the Illinois Professional Land Surveyors Association.

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