Input for Intra-Frame Velocity Models for the U.S. N.S.R.S. in 2022

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ABSTRACT

The United States will be updating the National Spatial Reference System in 2022. There will be four separate terrestrial reference frames all tied to the International Terrestrial Reference Frame. All will be identical to the ITRF at epoch 2022.0, but they will rotate according to Euler Pole Parameters determined for each of the four plates: North America, the Caribbean, the Pacific and the Mariana. While these EPP will describe most motion in these plates, significant horizontal and all vertical motions must be captured by deformation models or Intra-Frame Velocity Models (IFVM). These IFVM will likely derive from a single model based on a densified ITRF. However, these must each account for the EPP for each plate, leaving the relative motions to describe expected deformation throughout the four regional TRF's. How to develop these IFVM's is the focus of much research at the NGS. The simplest solution is simply to grid velocities at the nearly 2000 CORS. The recently completed reprocessing of CORS data has determined velocities for over 20 years. This velocity information works well in densely packed regions of CORS but performs below desired tolerance in sparsely covered regions. A denser grid may be obtained by using supplemental sites from private networks not included in CORS. This works better but uncertainty in the quality of some sites may affect the velocities. More complicated still would be incorporating geophysical models to better interpolate between control CORS. Finally, the use of satellite based InSAR would provide a basis for persistent updates. While InSAR may help in very remote regions such as the Mariana Islands, this can be problematic in North-South trending valleys between mountains, such as are found in the Rocky Mountains. Hence, it is likely that the optimal solution will be a combination of the above.

I. INTRODUCTION

In 2022, The United States will update its existing National Spatial Reference System (NSRS) or Spatial Data Infrastructure (SDI). The planned rollout includes four new Terrestrial Reference Frames (TRFs) tied to an International Terrestrial Reference Frame to describe geometric positions. A geopotential model will also be adopted to define orthometric heights. The plans for these models are detailed in Blue Prints Part I (NGS 2017a) and Part 2 (NGS 2017b), respectively, and further clarified in the recent NGS Strategic Plan (NGS 2019). The focus of this paper is on the underlying deformation models required for each of the TRF's.

In fact, there will be five frames. A densified ITRF model will serve as the basis for the four regional TRF's. This densified ITRF model will adopt an existing reference frame, such as ITRF2008 (Zuheir et al. 2011a) or ITRF2014 (Zuheir et al. 2017a). ITRF models are determined from a limited set of control sites. The desire here is to use additional stations to densify the control and better determine coordinates and motion. In the Americas, SIRGAS (Hoyer et al. 1998) serves as the basis for such a densified ITRF model. The U.S. has joined SIRGAS and will be collaborating on development of an improved SIRGAS model for North America and the Caribbean. SIRGAS, as a group, is only interested in a densified model in the absolute reference frame though. The U.S. has an interest in defining plate-fixed models in support of customer requests. As such, Euler Pole Parameters (EPP) will be determined for each of four plates: North America, the Caribbean and Central America, the Pacific, and the Marianna plates (Figure 1).

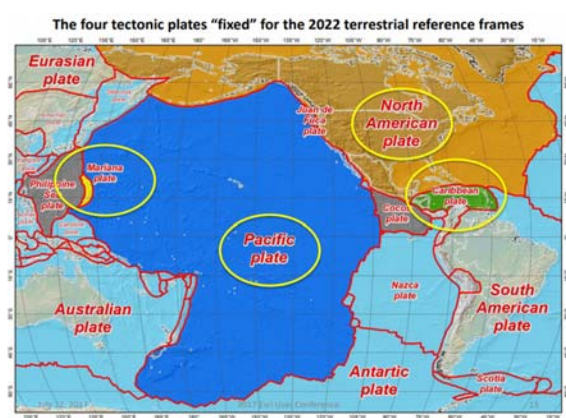

Figure 1The four plates where TRF's will be defined as a part of the U.S. NSRS in 2022.

The expectation for the U.S. NSRS in 2022 is to provide plate-specific frames and any horizontal and vertical motions in those frames over any given period of time. For a surveyor, the intent is that a GNSS survey collected at an observation epoch can be moved to a common epoch by accounting for deformation at the observation site during the intervening time between the observation and the standard epoch.

For many regions in the eastern continental U.S., this is fairly straight forward. The EPP will define most the horizontal motion and the remaining motion is vertical and due to Glacial Isostatic Adjustment (GIA). The last is fairly long wavelength and can be modelled. The Canadian Geodetic Survey already offers such a correction in their positioning products (Craymer and Roman 2018) to best account for horizontal and vertical motion over time. This process becomes much more problematic in regions experiencing dynamic motions such as southern California.

This paper will focus briefly on the definitions and concerns about the EPP and then discuss the various data sets available for densifying the velocity model information for IFVM's. It will conclude with an outlook and future work.

II. Euler Pole Parameters

The determination of the EPP for these plates is not the focus of this paper but is integral to the discussion. The motion for any site on a plate would be determined in an absolute frame (e.g., SIRGAS). If the motion implied by the EPP is removed, the remaining signal then is the motion within that frame.

Since deformation occurs on each side of a plate boundary, this deformation would extend over the boundary in a continuous manner (i.e., no discontinuous signals at the plate edges). Since these deformation models can extend past the plate boundaries, the term Intra-Frame Velocity Model (IFVM) was adopted to describe the motion inside that frame but also beyond its edges.

EPP determination or selection is critical. Any errors in its determination of the EPP will be considered as deformation or motion within the frame. This would unnecessarily complicate the generation of IFVM's and potentially degrade their quality.

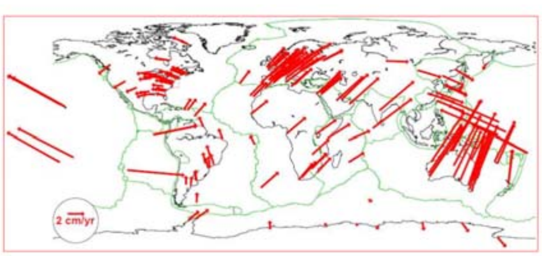

Figure 2Horizontal velocities of the 203 selected sites for ITRF2008 PMM estimation from Zuheir et al.2011b.

Preliminary estimates are already available for the ITRF2008 model (Zuheir et al. 2011b, 2012) as well as the ITRF2014 model (ITRF2017b). Figure 2 shows the velocities in the absolute ITRF2008 frame at the IGS stations. EPP are available for North America, Caribbean and Pacific plates.

Even so, the 2008 EPP estimates will not serve as the final values as they were only developed from a limited set of IGS stations. A great deal more information is required to develop a reliable estimate. Especially for plates subject to deformation along the margins, such as the Caribbean and Marianna plates. In Figure 3, EPP pole is shown as determined from a subset of CORS in the "stable" portion of North America. The ITRF2008 (IGS08) pole position is also shown for comparison. Simply adopting the 2008 EPP parameters determined in Zuheir et al. (2012) is not viable.

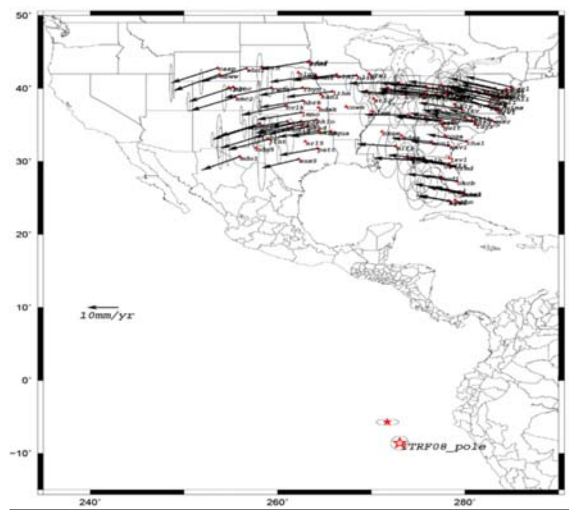

Figure 3EPP determined for a subset of CORS sites as a part of the ITRF2008 reprocessing. The published value for ITRF2008 (IGS08) EPP is also shown.

An important additional difficulty here is that there are no EPP determined for the Caribbean plate for the ITRF2014 solution, even though an estimate was made for the Caribbean in ITRF2008. This was likely due to the uncertainty in the limited set of fiducial points available to make such an estimate. Since SIRGAS has adopted ITRF2014, this means that another path must be pursued to determine EPP for at least the Caribbean if not all four plates.

For the U.S., supplemental sites will be selected to ensure the best estimates for the EPP. These are available from the SIRGAS-CON, UNAVCO (e.g., PBO and COCONet sites), and APREF. These supplemental sites will improve the overall understanding of motion in the absolute frame, and thereby create better EPP estimates and IFVMs.

The desired goal is that the EPP for North America and the Pacific be reliable at the cm-level for approximately 30 years. Given the inherent instability for the Caribbean and Marianna plates, it is only likely that the

EPP estimates will be cm-level accurate for about a decade.

The intent of an IFVM then is to describe motion inside the given frame at any location between any two epochs. That is no small task. It requires data on almost every spot between controls sites where GNSS signals are monitored continuously. This would need to come from supplemental control stations, space-based observations and/or geophysical models. The most likely solution will likely entail a combination of all of the above.

III. IFVM Determination

As noted in the Introduction, several datasets are available for generation of an IFVM. The easiest simplest is to densify using only the control stations monitored by the U.S. The Continuously Operating Reference Station (CORS) Network consists of nearly 2000 stations that are monitored daily by the NGS. There are many other private networks of continuous GNSS (cGNSS) stations. These can augment the CORS to provide a denser network of control sites. There are geophysical models that can be developed or adopted that would serve to estimate motion in between CORS or other cGNSS sites. Finally, there are remotely sensed imagery that can also estimate motion for vast regions on a near continuous basis. This section will address the pros and cons of such approaches.

A. *CORS*

The existing U.S. Continuously Operating Reference Station (CORS) Network (Figure 4) provides fairly dense coverage across the United States.

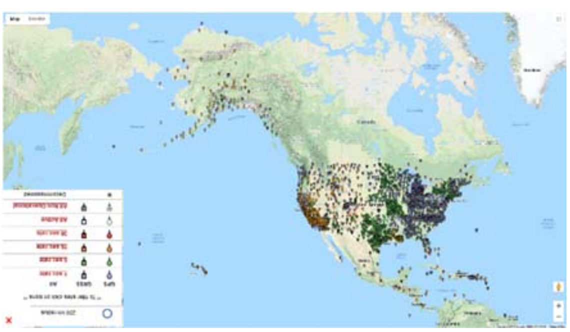

Figure 4CORS Network as of 29 March 2019.

Several of these sites are also IGS sites. These data were recently adjusted together as a part of a Reprocessing effort to align them with ITRF2014. The stacked solutions provide a first estimate of the IFVM by describing the motion at the CORS sites over more than 20 years. Horizontal (Figure 5) and Vertical (Figure 6) motions were captured. A more detailed analysis is underway to model the velocities up to each successive discontinuity. These might arise from antenna changes, earthquakes, etc. The aim is to stack these and describe the expected motion between any two epochs.

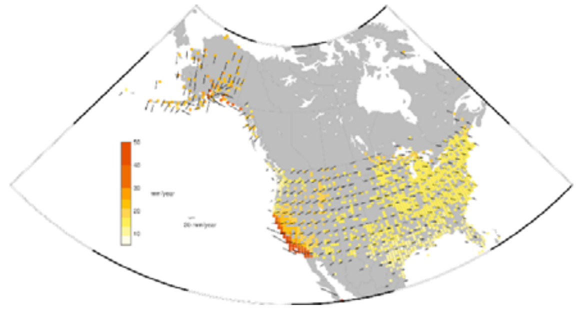

Figure 5CORS Horizonal Velocity field in ITRF2014 derived from reprocessing and stacking. Grid is 50x50 km.

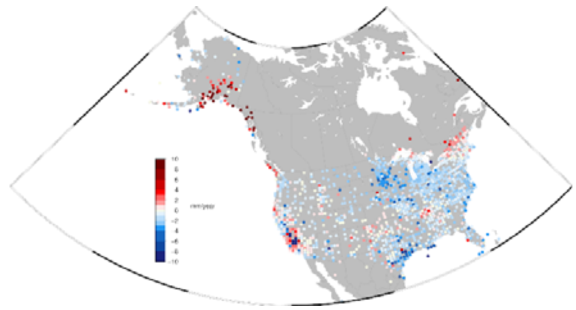

Figure 6CORS Vertical Velocity field in ITRF2014 derived from reprocessing and stacking. Grid is 50x50 km

However, the gaps between the CORS can be significant – especially in very dynamic regions, such as southern California. Hence, reliance solely upon CORS is not the most desirable approach.

B. *cGNSS – Other Networks*

Several networks of cGNSS are available that are not a part of the existing U.S. CORS Network – or at least not completely a part of it. By far, the sites installed by UNAVCO through the NSF grant predominate. The Plate Boundary Observatory (PBO) sites are focused in the western U.S. (Figure 7).

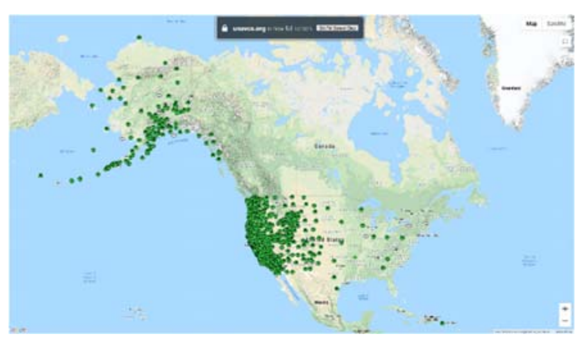

Figure 7PBO sites installed by UNAVCO under NSF funding. Roughy, 400 are already a part of the CORS Network.

Additionally, UNAVCO maintains COCONet (Figure 8) in the Caribbean region. Again, many of these sites are a part of the CORS Network, but others are available.

Figure 8COCONet stations in the Caribeban installed by UNAVCO under an NSF contract.

Some of the data shown in Figure 7 and 8 are also a part of the SIRGAS-CON (Figure 9), but again there many new sites that could be added to provide density to the fiducial control.

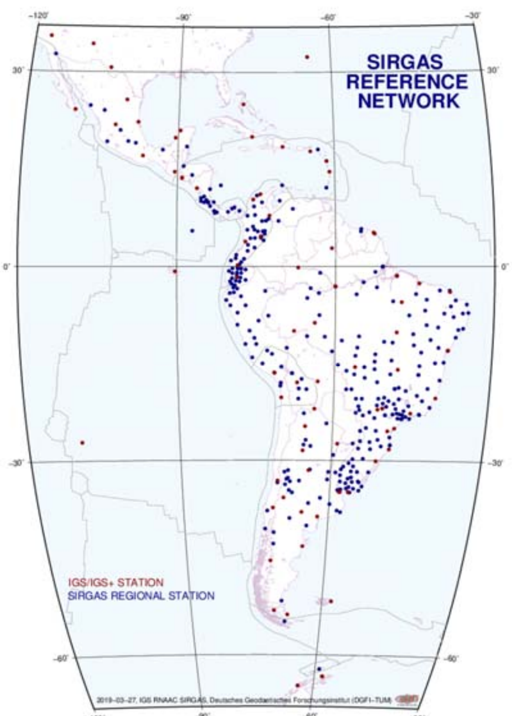

Figure 9SIRGAS Continuously Operating Network (SIRGAS-CON). Stations provide definitive control in defining a densified ITRF.

Finally, Asia-Pacific Reference Frame (APREF) is a regional reference frame group to which the U.S. is also member. This group archives data at many sites (Figure 10) that would aid in developing the Pacific plate EPP and IFVM. Many of their sites are already a part of the CORS Network, but others could be added to augment the existing fiducial control.

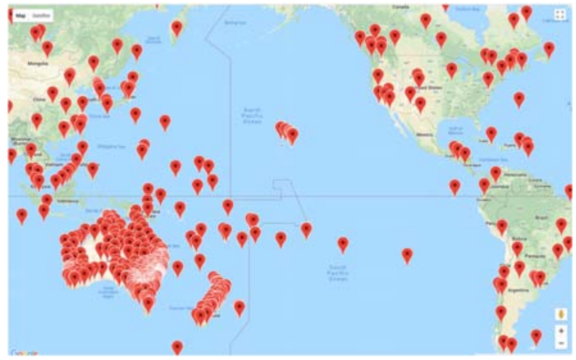

Figure 10APREF Stations in the Paciifc region.

C. *Geophysical Modelling*

Much of the analysis that has gone into the previous discussions is focused on the geokinematic modelling. That describes the motion of the stations (CORS or CORS + cGNSS) in the ITRF and applies simple models (gridding, collocation, etc.) to interpolate in between these sites. Geophysical modelling seeks to describe the source of the motion and provide a physical reason for the movement.

To some extent, NGS already uses this. The Horizontal Time-Dependent Positioning (HTDP) software (Pearson and Snay 2013) is inherent in a lot of our existing processing streams and work flows. HTDP incorporates many aspects of geophysical modelling attempting to patch areas where significant earthquakes occur. The limitation of this model is that it only accounts for horizontal motion.

Trans4D (Snay et al. 2018) does a much better job of estimating motion simply by accounting for vertical motion. Again, earthquakes and other signals are modelled and constrained by GNSS fiducial control.

The inherent risk in using geophysical modelling is that the sources being modelled are unobserved (the inverse problem). Hence, erroneous or incomplete observations may result in a poorer model. Often times, it is necessary to have some other constraints to bound the solution space sufficiently to generate a reliable model.

D. *InSAR*

Finally, InSAR is an area that is starting to show promise. Bekaert et al. (2017) demonstrated the utility of InSAR in modeling the subsidence for the Hampton Roads region in Virginia. However, a limitation in the use of InSAR is the need to provide fiducial control. InSAR is great for determining relative velocities, but some control is required to establish an absolute velocity in a frame. This scope of this study was also limited due to the lack of historical satellite based SAR.

With Sentinel-1 (Attema et al. 2010) already launched and collecting data, this will change. Sentinel-1 data are already available and in use for determining velocities in remote regions of the world. A significant overhead is required for downloading and processing the data to produce the interferograms. Even more is required to convert those into velocities to determine motion in an absolute frame such as SIRGAS.

Coverage is for nearly all land areas except Antarctica, though it is degraded at high latitudes. Additionally, InSAR coverage can be degraded if mountainous regions are oriented in a north-south direction as we have in the North America. It becomes unreliable a s a means of estimating motion in the long valleys between the mountain ranges. This would be exceptionally helpful for remote regions such as the Marianas islands. The islands themselves are fairly rigid, but they are embedded in the Marianna plate. This is only a thin crescent of fairly thin crust and is crushed between the Pacific and Philippine plates. Significant deformation is occurring there. InSAR offers a real opportunity to monitor this deformation and update the EPP and IFVM models for that plate.

There is limited ground control (CORS) available. It may be desirable to install ground reflectors akin to those developed by Geosciences Australia. With these tied into the ITRF via an IERS survey, the fiducial control would be established. There are many persistent scatterers available on the islands (i.e., World War II wreckage) to serve as control for the motion.

Finally, the NASA-ISRO SAR Mission (NISAR) mission (NASA 2017) is forthcoming in 2021. This too will provide another L-band, space-based SAR for velocity determination. Discussions have begun with NASA to investigate a potential InSAR service for production of velocity maps.

IV. Summary and Outlook

Certainly, this topic been explored before. Wang et al (2009) proposed models to describe a path towards a dynamic reference frame. Bock and Klein (2018) investigated use of cGNSS combined with geophysical models. This included potentially modelling seasonal effects. Beavis and Brown (2014) also explored mechanisms to account for seasonal and episodic events in order to provide better control data for velocity field modelling.

The California Department of Transportation actually commissioned a report to describe what would be required to develop a Dynamic Reference Frame (Bock and Klein 2018) for their state. They looked at many of these issues and determined that the CORS Network was insufficient by itself. In southern California, the Southern California Integrated GPS Network (SCIGN) provides a regional densification of the U.S. NSRS. Using these sites as a supplement, additional information was available to densify the deformation model.

They also examined use of geophysical models to further interpolate in between the control sites (e.g., CORS + SCIGN). The NGS will follow on this study and also examine the use of Interferometric Synthetic Aperture Radar (InSAR).

The most likely scenario for the use of data for such densification will be that NGS will use all of the above. Certainly, the CORS must be used as a part of this determination. The CORS will provide the access to the NSRS. Therefore, it is essential that they be a part of the definition of the TRF's and the associated IFVMs. Where additional information is available, stations from other networks will be added to the CORS. These include those maintained by UNAVCO, SIRGAS, and APREF. Geophysical modelling will likely have some part of predictive aspects of the motion modelling, particularly in dynamic regions such as southern California. Finally, InSAR will be available for monitoring remote regions that are problematic and expensive to monitor.

All of these will be combined to provide a densified ITRF model describing motion in an absolute frame. It is expected that the NGS will not attempt to model all signals, only those from continental down to a regional scale. It will be left to local and regional groups to observe and model local features.

For example, there are two scales of subsidence occurring in southern Louisiana. Much of the region is subsiding slowly, but there are more erratic events occurring in the surface areas. NGS has a number of CORS sites that have been driven to refusal and provide reliable estimates of the former. Such signals would be incorporated into the IFVM. The surface deformation would not. By providing a reliable regional model, the residual motion at the surface is more easily detected and can be taken into account for practical engineering and scientific concerns.

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