Practical considerations for determining Euler Pole Parameters for the terrestrial reference frames in the United States

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Key words: GNSS/GPS, Positioning, Reference Frames

SUMMARY

As part of its mission to maintain the National Spatial Reference System (NSRS), the U.S. National Geodetic Survey (NGS) plans to modernize the NSRS in 2022. As part of this modernization, NGS will define four new terrestrial reference frames for the North American, Pacific, Caribbean and Mariana tectonic plates based upon ITRF14 and the Euler Pole Parameters of the stable parts of those plates.

However, the determination of the rotation of the so-called "stable" part of any tectonic plate requires that several issues be resolved as part of the overall solution. These include defining the part of the plate considered "stable", the treatment of non-rotational horizontal secular and episodic motions, the availability of and quality of geodetic data for each tectonic plate, the use of non-GNSS methods in Euler pole determination and the stability of the Euler pole itself. The Pacific and North American plates each have many Continuously Operating Reference Stations (CORSs) that can be used in the determination of plate motion. The Mariana and Caribbean plates, however, are much more sparse in their CORS data availability and therefore present unique challenges when it comes to determining the Euler pole parameters. This paper provides the current state-of-the-art for each of these issues for each of the four plates; with each plate being chosen since it contains a significant part of the United States and its Territories.

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1. INTRODUCTION

The National Geodetic Survey (NGS) of the United States has a mission to define, maintain and provide access to the National Spatial Reference System (NSRS) to meet the nation's economic, social and environmental needs. As part of this mission, NGS will define and maintain four terrestrial reference frames (TRFs) in 2022 to cover the United States territory with significant civilian populations (National Geodetic Survey, 2017). These frames are: the North American Terrestrial Reference Frame of 2022 (NATRF2022), the Caribbean Terrestrial Reference Frame of 2022 (CATRF2022), the Pacific Terrestrial Reference Frame of 2022 (PATRF2022) and the Mariana Terrestrial Reference Frame of 2022 (MATRF2022), with intended use on the North American, Caribbean, Pacific and Mariana tectonic plates, respectively. Coordinates anywhere can be computed in any of the TRFs, but they will vary and have more error when computed in a frame that is not "rotating with" the plate for which the frame is named.

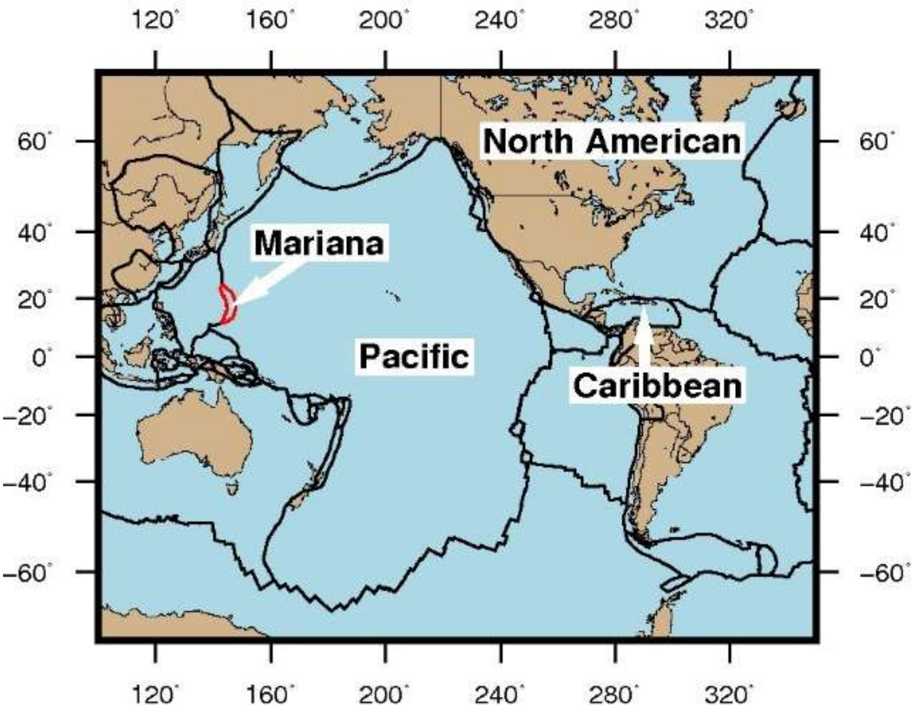

Figure 1 Tectonic plates for the modernized NSRS

The theory of plate tectonics says that the earth is made up of layers and that the uppermost layer, the crust, is broken up into thin rigid plates that move on the surface. These motions are characterized by Euler poles, as all motions on the surface of a sphere can be characterized as a rotation about a fixed point on the surface (e.g., Cox & Hart, 1986). Various plate motion models (DeMets et al., 1990; Bird, 2003; Altamimi et al., 2017) have been made that present Euler pole parameters for tectonic plates relative to another plate using geological methods. These are relative Euler poles since they characterize the motion of one plate with respect to another as opposed to a global reference frame like the International Terrestrial Reference Frame (ITRF).

The new NGS plate-fixed frames are ITRF-based frames with the plate rotations removed. Each of the new TRFs will have micro-rotational rates (in milliarc-seconds per year) about each of the ITRF2014 X-, Y- and Z- axes as the three Euler pole parameters (EPPs). From these three EPPs, latitude, longitude and rotation rate about a location on the surface of the earth can be derived. Residual motion in the plate-fixed frames will be accounted for in an Intra-Frame Velocity Model (IFVM). All motion at a point can be accounted for as a combination of plate rotation and IFVM as described in equation [1].

$$\dot{\boldsymbol{X}}_{TOTAL} = \dot{\boldsymbol{X}}_{EPP} + \dot{\boldsymbol{X}}_{IFVM} \qquad [1]$$

2. DATA AVAILABILITY

2.1 Continuous GNSS data

NGS manages a network of Continuously Operating Reference Stations (CORSs) that provide Global Navigation Satellite System (GNSS) data at all network stations. In total there are over 2500 active and previously active stations in the network with spatial coverage across the United States and its territories. A select subset of these CORSs will be the primary tool used to determine EPPs for the frames.

The CORS network, shown in Figure 2, has over 2400 stations on the North American plate, 110 on the Pacific plate, 45 on the Caribbean plate and 3 on the Mariana plate. The velocity solutions from the CORS network provide daily positioning information at the geometric reference point (GRP) of each of the stations, which may or may not reflect the overall motion of the plate itself. Local effects such as subsidence, slumping or other localized processes may bias the velocity as observed at the GRP. Water withdrawal can cause ground to sink locally which can cause nearby GNSS stations to move horizontally toward the center of the sinking. Stations near plate boundaries, such as in the western part of the Conterminous United States (CONUS) show plate deformation in that part of the plate and their motions do not reflect the overall plate rotation of the rigid plate. These areas are characterized by frequent earthquakes.

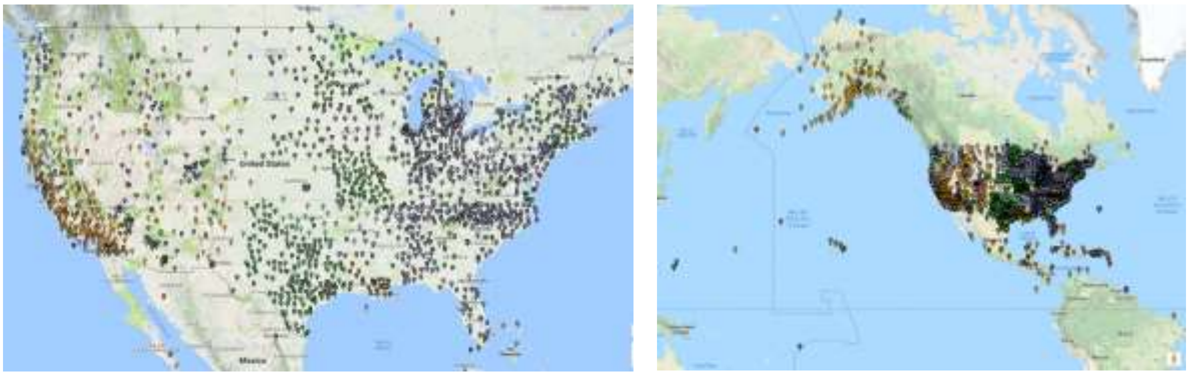

Figure 2 CORS locations in the Conterminous United States (left) and across all four plates with significant U.S. civilian populations (right).

2.2 Other Data Sources

While velocity vectors from CORSs are the primary data to use in Euler pole determination, the motions of these sites can be reflective of local effects instead of rigid plate motion. Long timeseries make for better velocity estimates at these stations, as seasonal and secular signals, as well as offsets due to episodic activities such as earthquakes and equipment changes, can be better modeled or averaged out. Earthquakes and equipment changes tend to cause jumps in the time series that are accounted for with step functions. Sites near plate boundaries are inherently unstable and do not necessarily reflect the overall motion of the rigid plate, therefore boundary sites ideally are not included in the determination of the EPP. An ideal CORS for EPP determination is located in a stable region has a long data time span of at least several years with few data gaps, as well as demonstrated site and monument stability. It is not always the case that a plate has sufficient CORSs for Euler pole determination, therefore other methods must be explored.

Non-CORS data sources can come from geodetic or geological methodologies. Geodetic methods include survey GNSS data taken from repeat observations on passive geodetic marks over many years. This technique will be explained in greater detail in Section 6. Another geodetic method is to track changes via repeat satellite observations from IfSAR. Geological sources include paleomagnetic data that can be used to determine seafloor spreading rates over geologic timespans, tracking the pattern of magnetic pole reversal on either side of a seafloor spreading zone over millions of years. Transform fault geometry can be used in a similar way to determine a pole of relative rotation between two plates. Earthquake focal mechanisms and slip vectors have been used to determine relative plate motion as well (Deng & Sykes, 1995).

3. NORTH AMERICAN PLATE

The North American plate (Figure 3) stretches from the mid-ocean ridge in the middle of the Atlantic to the eastern shore of the Pacific Ocean and from the southern edge of the Gulf of Mexico to the middle of the Arctic Ocean. It contains large areas of land mass over the United

States, Canada, Mexico and Greenland as well as a large swath of ocean into the Atlantic. Determination of the EPPs for North America will be done in conjunction with IAG Subcommission 1.3c: North American Reference Frame (NAREF). Much of the land mass and population of the United States is located on the North American plate, including the entirety of 48 of the 50 states and part of a 49th state. With so much land mass, there are over 2400 CORSs on the plate, providing plenty of options for determining EPPs. Many studies have been done into its rigid plate motion (e.g., Sella et al., 2002).

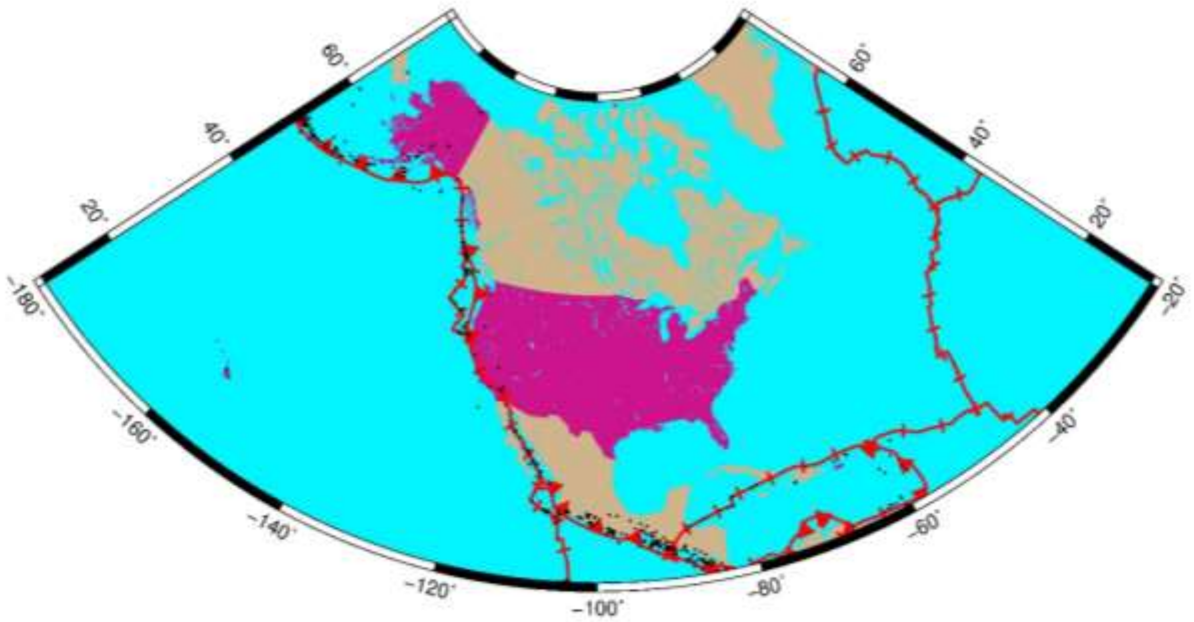

Figure 3 The North American plate. The thick red lines show plate boundaries and the black dots show earthquakes of Mw > 6.0 that have occurred 1990 – 2018.

The large stable part of North America is in the eastern part of the plate. In the western third of the continent (the Rocky Mountains and west), there is a significant amount of deformation happening that locally impacts motion, making it not indicative of the motion of the rigid plate. In particular this deformation is in the Basin and Range province near the transform plate boundary with the Pacific plate. Southern California, the far western land of CONUS, is located on the Pacific plate and has a completely different motion than the rest of CONUS. This difference is highlighted in Figure 4. Another major zone of deformation is the Alaska orogeny, where the continent is bending where the Pacific plate subducts the North American plate. This is a plate boundary zone that is deforming and therefore is not rigid.

Even in the eastern part of the plate deformation is occurring. Glacial Isostatic Adjustment (GIA) is happening over the Hudson Bay region in response to the melting of the Laurentide Ice Sheet at the end of the Last Glacial Maximum. This phenomenon causes the land in this area to continue to rise where the ice dome had been and in doing so, there are large areas of contraction with horizontal motion towards the center of the uplift (Kreemer et al., 2018; Sella et al., 2007). Subsidence in other areas such as in the southern part of the U.S. around

Louisiana causes a similar effect, causing horizontal motion toward the center of the subsidence area. The residual motion of the CORSs in CONUS is shown in Figure 4.

Figure 4 Residual CORS velocities with the North American plate rotation removed.

4. PACIFIC PLATE

The Pacific plate, as shown in Figure 5, is a very large plate that is mostly made up of ocean basin, but there are areas of exposed land within it as well. Most of this land is either on volcanic islands located at hotspots or it is along a deforming plate boundary zone such as California or American Samoa, which can be a challenge for determining the overall motion of the stable part of the plate. United States territory on the Pacific plate includes southwestern California, the Hawaiian Islands, Wake Island and American Samoa. These places all have CORSs, with 110 stations within the CORS network being located on the Pacific plate. NGS will work to align PATRF2022 with the Asia-Pacific Reference Frame, which is part of IAG Subcommission 1.3e.

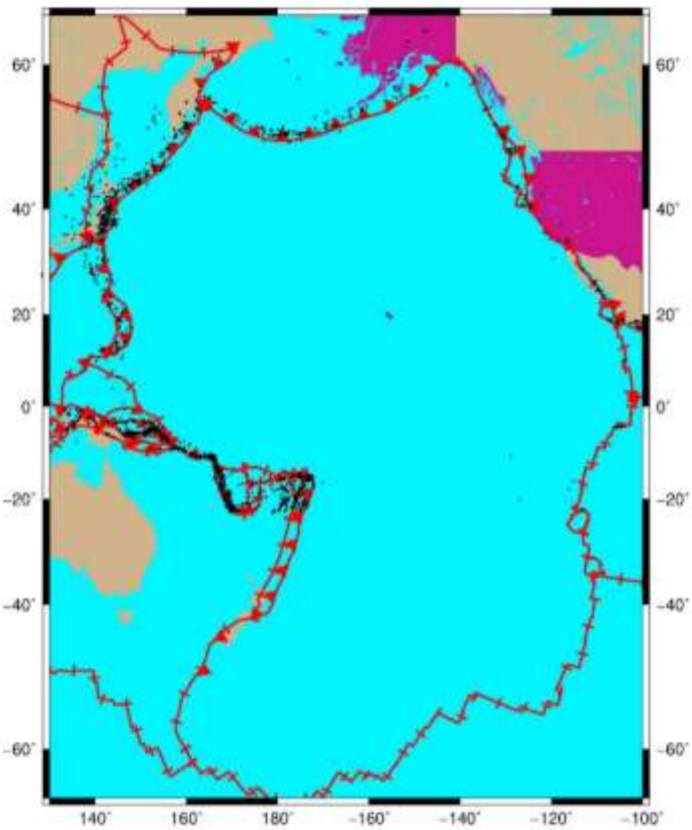

Figure 5 The Pacific plate. The thick red lines show plate boundaries and the black dots show earthquakes of Mw > 6.0 that have occurred 1990 – 2018.

5. CARIBBEAN PLATE

The Caribbean plate (Figure 6) is located within and around the Caribbean Sea. It is much smaller than the Pacific or the North American plates. The Caribbean plate is a small plate where almost all of the exposed land is located along the deforming edge of the plate, making determination of rigid plate motion particularly difficult from land-based CORS data. The northern plate boundary is not completely known, presenting another challenge to EPP determination. United States presence on the Caribbean Plate includes the Commonwealth of Puerto Rico and the U.S. Virgin Islands. Along with the United States territory on the plate, there are many small island nations that are located upon the plate. Most of them have available CORS data and the plate for the most part is dense with CORSs, however the loose organization means that the data come from many sources and many networks and are not as consistent as they are on the North American plate. NGS will work in conjunction with SIRGAS and IAG Subcommission 1.3b to define the rotation of this plate for the NSRS.

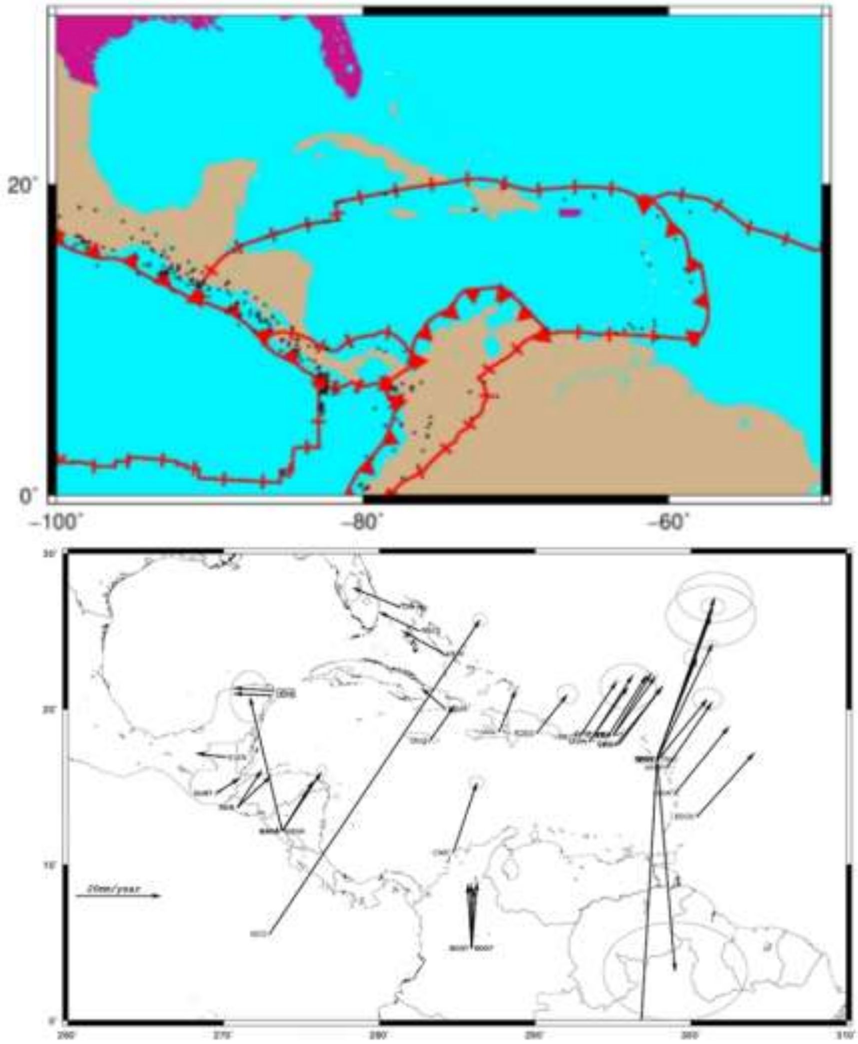

Figure 6 The Caribbean plate. (top) The thick red lines show plate boundaries and the black dots show earthquakes of Mw > 6.0 that have occurred 1990 – 2018. (bottom) IGS08 velocities of the CORSs within or near the plate.

6. MARIANA PLATE

Wedged between the western edge of the Pacific plate and the Philippine plate on the western edge of the Pacific Ocean is the volcanic island arc on the Mariana plate. Guam is the southernmost island territory on the plate and the Commonwealth of the Northern Mariana Islands (CNMI) extends to the north of that. Only the southernmost three islands (Tinian, Saipan and Rota) of the CNMI have significant populations. Additionally, the islands to the north have very little geodetic infrastructure. For example, of the 5 continuous GNSS stations that have ever operated on the plate,one of them has been non-operational for years, one of them is non-NGS and all of them are located in the southernmost one third of the plate. This is a very remote set of islands that has had very few scientific studies done on it. It was not even included in the ITRF 2014 plate motion model (Altamimi et al., 2017).

Between 1997 and 2013, 29 survey marks were measured with GPS on the northern uninhabited islands of the Mariana islands by NGS. In 2017, an NGS survey crew visited these islands to re-observe the stations using GPS in order to specifically develop a rotational model for the plate. From these re-occupations, linear velocity vectors were estimated for the entire plate. This is important since this island arc is experiencing some rotation within itself and the "bending plate" is not necessarily rigid. The Mariana plate has experienced many large earthquakes over recent years and there are several active volcanoes around the island chain, a sign that the entire plate is contaminated by deformation. NGS will work with IAG Subcommission 1.3e (APREF) for the determination of EPPs. The few studies that have been done show clear rotational signal in the plate.

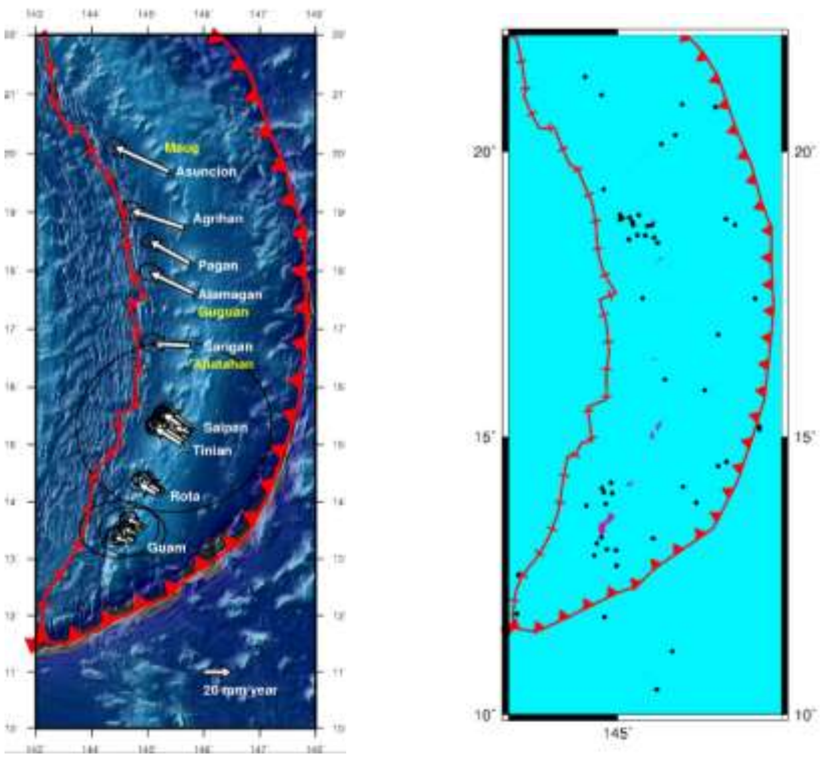

Figure 7 The Mariana plate. (right) GPS velocity vectors and their 95% error ellipses as determined from repeat survey observations of passive marks and three CORSs. (left) The thick red lines show plate boundaries and the black dots show earthquakes of Mw > 6.0 that have occurred 1990 – 2018.

7. SUMMARY

With new plate-fixed reference frames slated for release in 2022, NGS is working to determine Euler pole parameters for the North America, Pacific, Caribbean and Mariana plates in order to provide alignment parameters to the ITRF. Each plate is unique in its availability of data, its tectonic stability and the partnerships to consider for determining these parameters.

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BIOGRAPHICAL NOTES

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