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A GPS Based Estimate of the Rotation of the Mariana Plate in both ITRF2008 and ITRF2014

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Versions

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Publication Notes

Part 1 of this report was originally submitted to the Journal of Geodesy in 2018. I would like to personally thank the three reviewers who provided extensive and useful feedback (Donald Argus, Corné Kreemer and a third anonymous reviewer.)

The original paper provided a rotation of the Mariana plate in ITRF2008, and is presented in Part 1 of this report.

During the intervening years the geodetic world moved on from ITRF2008 to ITRF2014. Further, new surveys in Guam and CNMI added information not in the original paper. As such, a complete re-processing of the data allowed the original ITRF2008 rotation to be updated to ITRF2014, as well as to provide the opportunity to compare against, and possibly incorporate the new surveys. This information is presented in Part 2 of this report.

The motivation behind these studies has been for NGS to have the ability to compute an accurate rotation of the Mariana plate within the ITRF, for use in defining the forthcoming MATRF2022 reference frame (NGS, 2017a). That relationship will likely be in the ITRF2020 frame, and since the lessons learned from both the ITRF2008 and ITRF2014 studies may inform the determination of the Mariana plate within ITRF2020, both are presented herein.

PART 1: Rotation of the Mariana Plate in ITRF2008

1 Introduction

This paper represents the results of using GPS data collected by the National Oceanic and Atmospheric Administration's (NOAA's) National Geodetic Survey (NGS), to determine the rotational behavior of the Mariana Plate within an absolute frame (ITRF2008). The data come from two sources. The first were campaign surveys conducted by NGS, and the second were data from four continuously operating GNSS reference stations (CORSs) within the NOAA CORS Network (NCN). The goal was to find Euler pole parameters (EPPs) for the Mariana plate: the location of the Euler pole, and the rotational speed of the plate about that pole. The data used span 20 years and cover 9 islands, representing the largest GPS-data driven resolution of the tectonic rotation of this plate.

Once the EPPs were determined, they were compared with previous relative and absolute estimates, as well as against independent geophysical data as a method of verifying the newly determined rotational behavior.

2 Prior estimates and challenges

Due to its smallness, remoteness and mostly unoccupied islands, very few estimates of the rotation of the Mariana plate exist. Most have been estimates relative to other plates, including Sella et al (2002) who estimated a linear velocity (but only for Guam), with respect to the Philippine and Pacific plates. Their velocity estimates were stated to be "in broad agreement" with published geologic rates (ibid). Similarly (Kato 2003) and (Bird 2003) each estimate EPPs relative to the Philippine plate.

The author is aware of two attempts to estimate the absolute rotation of the Mariana plate: Snay (2003) and Kreemer et al (2014). The Snay (2003) estimate will not be further discussed, as its flawed methodology (presuming a single known CORS velocity on Guam would be identical on Saipan), led to unrealistic EPP values relative to all other known estimates. The EPPs from Kreemer et al (2014), agree well with those found in this paper. However, the amount of data available in this study is much larger and better distributed than that used in Kreemer, allowing for greater redundancy, particularly on the southern four islands of Guam, Rota, Tinian and Saipan.

Aside from Kreemer et al (ibid), all other studies were performed in the early 2000s when the global reference frame determination, global tracking networks, GPS orbit determination and GPS processing software in general were all less optimal than today. Further, the time span was frequently only a few (7 or less) years.

Unfortunately even the most recent plate motion models for the last ITRF (ITRF2008) (Altamimi, et al. 2012) contains no estimate for the Mariana plate.

3 Historic Data Availability

In order to solve for a set of EPPs, independently determined linear velocities needed to be available. These were expected to come from two data sources: continuous GPS stations and from campaign GPS surveys at common points but separated by years.

On most plates, the primary data source would be from Continuously Operating GNSS Reference Stations (CORSs). However, unlike other tectonic plate studies which rely heavily upon dozens if not hundreds or thousands of CORSs, the Mariana plate has only ever had four CORSs in the NOAA CORS Network (NCN). A fifth station, run by the Japan Aerospace Exploration Agency (JAXA), with data processed by the University of Nevada, Reno (UNR; Blewitt et al., 2016), was installed on Guam in 2014, but that data is not in the NCN and with only three years of data to determine its velocity was not included in this study. Only 3 of the 4 NCN CORSs have substantial data (14-25 years). All CORSs are restricted to just two islands, Guam and Saipan, both in the southern 1/4 of the Mariana plate, which also happens to be the portion of the plate rotating most slowly.

In order to better determine the Mariana plate's rotation, repeat campaign data on the more northern islands could augment the sparse CORS data. This was the approach taken by Kato (2003) and Kreemer et al (2014). However, NGS hoped to improve on those studies by adding substantially to the number of campaign GPS-based velocities. Thus in 2017 NGS performed a GPS survey over four weeks, ranging from Guam to Maug, with observations collected at 33 geodetic control points on 10 different islands (Hippenstiel et al 2019). Of that set, 29 points on 9 islands had historic campaign GPS data collected by NGS sometime between 1997 and 2014 (ibid.)

4 Data collection and processing

4.1 CORSs

The NGS CORS team manages data from almost 2000 operational stations, including the determination of coordinate functions representing piecewise continuous linear functions between discontinuities. This processing is independent of any campaign GPS data. Daily solutions are computed, merged into weekly solutions and these weekly solutions serve as the raw data to which the piecewise linear functions are fit within the International Terrestrial Reference Frame (ITRF). At the time of this study, the most recently supported ITRF used in NGS software was ITRF2008. This study did not generate the velocities at the CORSs in Guam and Saipan, it simply adopted the most recent linear velocities from the official NGS site info files. (ftp://www.ngs.noaa.gov/cors/coord/coord_08/) for site GUAM. Similar syntax for GUUG, CNMI and CNMR).

4.2 Campaign GPS

Campaign GPS may yield linear velocities at specific geodetic control points under certain conditions. The first is that the same point must be surveyed at least two different times separated by a span of years, the longer the better. Second, a common global reference frame must be available for any CORSs which serve as control during those separate surveys. The last is that high accuracy orbits are available in that same frame. These conditions were fulfilled by adopting the ITRF2008 frame, and restricting GPS surveys to no earlier than 1994. As mentioned in the previous section, NGS had CORS coordinate functions in ITRF2008 back to 1994 and orbits in the IGS08 frame (effectively identical to ITRF2008 for the purposes of this study). Whether the surveyed geodetic control points actually moved linearly over the span of years is an assumption which will be examined later.

All data from both the historical surveys and the 2017 survey were processed in the ITRF2008 frame using OPUS-Projects (National Geodetic Survey 2017b) employing the hub and spoke method (Gillins and Eddy 2017). Table 1 summarizes the individual surveys and point counts.

Table 1: Historic and recent GPS surveys in Guam and CNMI used to compute velocities in this paper

Year	Survey Name	Total Points Processed	Span	Islands
1997	GPS1194	2	2 days	Guam
2003	GPS1837/Saipan	11	3 days	Saipan
2003	GPS1837/Rota	10	3 days	Rota
2003	GPS1837/Tinian	8	3 days	Tinian
2003	GPS2394	11	20 days	Most northern islands
2004	GPS1987	16	7 days	Guam
2013	GPS3070	3	2 days	Guam

4.3 Determining Velocities

Once the ITRF2008 Cartesian coordinates were known for each occupation, simple linear velocities were computed by differencing new and historic coordinates and dividing by their epoch. Obviously any non-rotational movement of a point between the old and new survey cannot be detected from such a simple approach. Rather than attempt to estimate such potential offsets, this study relied mostly on identifying such points as outliers and removing them from consideration.

The ITRF2008 velocities were then rotated into a local (spherical) ENU system. Because Euler pole rotation has no "up" component, the velocities in the up direction were ignored, and only East and North velocities used as observables, following the basic scheme found in the literature (Ali Goudarzi, et al., 2014; Argus et al., 2010; DeMets et al., 2010).

In addition to the velocities determined through comparison of two surveys on a control mark, the four CORSs on the plate also have their own velocities as determined through linear fits to continuous data, as mentioned earlier.

All of the velocities used, and their error ellipses, are listed in Table 2 and displayed in Figure 1.

Table 2: All velocities computed or available for analysis in this paper. Velocities removed as outliers are in red text.

Island	PID	VN (mm/y)	VE (mm/y)	Survey	Year
Guam	AA4393	2.6 ± 1.7	-7.8 ± 2.1	GPS1194	1997
Guam	TW0537	2.4 ± 2.0	-6.4 ± 2.3	GPS1194	1997
Guam	DH3102	5.6 ± 2.0	-9.7 ± 2.4	GPS1987	2004
Guam	TW0372	3.2 ± 2.1	-8.2 ± 2.6	GPS1987	2004
Guam	DH3017	4.5 ± 2.1	-9.3 ± 2.4	GPS1987	2004
Guam	TW0017	5.7 ± 2.1	-9.6 ± 2.5	GPS1987	2004
Guam	TW0398	3.7 ± 2.1	-10.1 ± 2.5	GPS1987	2004
Guam	DQ3228	4.9 ± 8.1	-11.0 ± 11.3	GPS3070	2013
Guam	DH3029	4.4 ± 7.7	-1.6 ± 10.6	GPS3070	2013
Guam	DF7984	4.4 ± 1.0	-8.8 ± 1.1	CORS (GUUG)	
Guam	AF9627	5.2 ± 1.0	-9.6 ± 1.0	CORS (GUAM)	
Rota	DG4024	8.3 ± 2.1	-11.6 ± 2.4	GPS1837	2003
Rota	DG4009	7.8 ± 2.1	-11.8 ± 2.1	GPS1837	2003
Rota	AA4404	8.5 ± 2.1	-12.8 ± 2.4	GPS1837	2003
Rota	DG4014	7.3 ± 2.2	-12.2 ± 2.2	GPS1837	2003
Tinian	DG4117	12.4 ± 2.3	-18.4 ± 2.5	GPS1837	2003
Tinian	DG4122	12.8 ± 2.2	-18.5 ± 2.4	GPS1837	2003
Tinian	DG4108	12.4 ± 2.2	-18.9 ± 2.4	GPS1837	2003
Tinian	AA4411	12.0 ± 2.2	-19.1 ± 2.5	GPS1837	2003
Saipan	DG3974	13.5 ± 1.8	-18.9 ± 2.1	GPS1837	2003
Saipan	DG3961	11.6 ± 1.8	-18.8 ± 2.1	GPS1837	2003
Saipan	DG3982	14.7 ± 1.8	-18.5 ± 2.1	GPS1837	2003
Saipan	DG3940	13.8 ± 1.9	-19.4 ± 2.1	GPS1837	2003
Saipan	DE7041	13.4 ± 1.8	-19.4 ± 2.0	GPS1837	2003
Saipan	AA4415	12.9 ± 2.4	-18.6 ± 2.7	GPS1837	2003
Saipan	DG3969	13.5 ± 1.9	-19.3 ± 2.2	GPS1837	2003
Saipan	DF9780	12.5 ± 1.5	-18.5 ± 1.5	CORS (CNMR)	
Saipan	AJ6944	4.0 ± 27.1	-10.9 ± 31.0	CORS (CNMI)	
Sarigan	DK2824	1.7 ± 3.0	-26.4 ± 3.4	GPS2394	2003
Alamagan	DK2819	14.7 ± 2.4	-30.4 ± 3.0	GPS2394	2003
Pagan	AA5095	15.8 ± 1.8	-28.2 ± 2.2	GPS2394	2003

Agrihan					

Note the general agreement of three of the CORS-based velocities with their campaign-based velocities on the same islands. CORS site CNMI is a clear outlier, but its data only spans two years. Note also the large standard deviations on the CORS-based velocities, relative to those from campaign GPS surveys. This disagreement comes from different ways of treating the uncertainties, but was accounted for when computing the EPPs from the velocities.

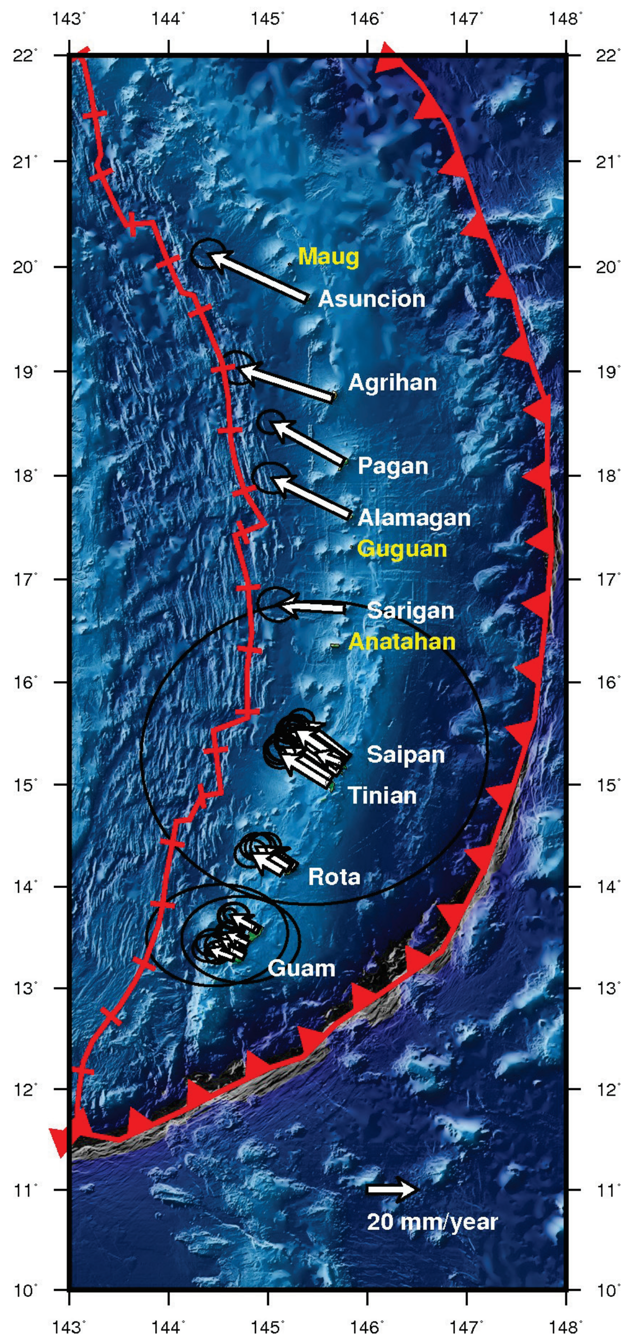

Figure 1: All vectors available from this study, including error ellipses. Plate boundaries are shown in red. Islands discussed in the paper but without an NGS-determined velocity are labeled in yellow.

In Table 2 the velocities on most islands seem to have a general clustering, except Guam, which has a wider deviation of velocities than the other islands. An examination of the velocities by historic survey, however, show better clustering within each group derived from one historic survey. The reliance upon a single historic survey for any given island, except for Guam, is not desirable, as any bias in one historic survey could easily change the outcome of the EPP determination. However, the overall trend in the velocities indicates that there is a clear rotational signal present; if one examines them from south to north, a growing velocity in both north and west is seen such as what would be expected for a plate rotating about a point somewhere to the south and west of Guam.

4.4 Outlier detection and seismic interference

The entire Mariana plate is subject to frequent seismic activity (Mueller et al., 2012). That fact certainly calls into question the idea of using just two campaign GPS occupations to provide a useful velocity that is reflective of plate rotation only. However, not all seismic activity is significant enough to corrupt a presumed linear velocity between two epochs. Furthermore, as mentioned at the beginning of the paper, data is sparse (and therefore valuable) on this plate, so the removal of a point as an "outlier" and/or as being possibly influenced by a seismic event was done with an abundance of caution.

Having said all that, there are definitely some problems with the velocities which were identified and removed before the EPPs were computed.

Analysis of outliers began by considering the official list of "discontinuities" issued by the IGS for IGS 14 for the four CORSs on the Mariana plate (e.g. https://webigs.ign.fr/tfcc/en/station/CNMR/coordinates). Such discontinuities represent an "offset" from a linear velocity trend of each CORS, but such offsets are sometimes attributed to equipment changes (of no special interest to this study) while others are due to known seismic events. Others have no known source. Of the official IGS discontinuities in this region, only two are relevant, being identified with known seismic events:

1. 7.0 Earthquake on 2002(day 116) which moved CORS GUAM 15 mm north
2. 6.7 Earthquake in 2014(day 260) which moved CORS GUUG 20 mm north

The 2002 earthquake would only have affected GUAM as no other CORSs had been installed yet. It also could explain why the two linear velocities tied to the 1997 GPS campaign (points AA4393 and TW0537; the only data available before the 2002 earthquake) disagree with the rest of the island, particularly in the north direction. The existence of that earthquake and their being obvious statistical outliers, the two points AA4393 and TW0537 on Guam have been removed from consideration in this study.

Somewhat puzzling is the 2014 offset for GUUG. It is specifically identified with the M6.7 earthquake 43 km northwest of Guam that day. But GUUG is on the southeast side of Guam, and GUAM, more centrally located on the island shows no discontinuity. What is even more fascinating is that point DH3029 (a clear outlier in its East velocity) lies close to GUUG (closer by far than any other control point). If some event did move GUUG in 2014, it may explain why nearby point DH3029 (with its historic occupation back in 2013) is out of agreement with the rest of the island. However GUUG's velocity since the 2014 discontinuity is identical to its velocity before the discontinuity. Thus GUUG, with a good agreement to the rest of the island will be retained while point DH3029 on Guam was flagged as an outlier.

Two other outliers were identified. The first is CORS CNMI. With only two years of data, its velocity is noticeably out of agreement with the rest of Saipan. In the north velocity alone, it is over 10 standard deviations off of the average for this island. As the cause is generally presumed to be a shortage of data this velocity was flagged as an outlier.

The final outlier to be flagged was unfortunately the only point on the remote island of Sarigan. While there are no other points on Sarigan with which to compare, its obvious failure to abide by the pattern of increasing velocities as one moves north through the islands is clear, particularly in its north velocity (which should, in theory, fall between the Saipan average of 13.2 mm/y and the Alamagan value of 14.7 mm/y). A discussion with the 2017 field crew indicated a possible reason: the mark itself is a concrete pillar some 2-3 feet high and was in a severe state of deterioration when it was found, with cracks running through the entire pillar, such that the entire top (containing the mark) could be removed if one tried. Further it was embedded in soil on a hillside, which might have been susceptible to erosion. Whether or not these issues were the actual cause of this poor fit in north velocity, the point was flagged as an outlier and removed.

In total, this study collected 33 sets of velocities (29 on campaign geodetic control marks, 4 on CORSs). Five outliers (3 marks on Guam, 1 mark on Sarigan, 1 CORS on Saipan) were removed from consideration, leaving a total of 28 velocities (25 on marks, 3 on CORSs) for the determination of the EPPs.

5 Computing the Euler pole parameters

Using the basic method of Ali Goudarzi et al. (2014) the 28 retained horizontal velocities were used to estimate the absolute (within ITRF2008) EPPs of the Mariana plate. The results are found at the top of Table 3, along with the results of previous studies. Each of those will be discussed below except Snay (2003) which is simply listed in Table 3 for the sake of completeness.

For the older, relative EPP studies (Kato et al. 2003 and Bird 2003), those results are first listed in their relative forms, followed by other EPPs which, when combined with the earlier relative EPPs, can be used to infer the absolute (ITRF2008) EPPs of the Mariana plate from those earlier relative studies. Note: Kato et al.'s (2003) reported rotations have been changed in sign, as they reported "clockwise motion is taken as positive", whereas this paper, and all other studies mentioned herein, continue the geodetic tradition of counterclockwise motion being positive (Leick, 1975)

Table 3: Estimates of Euler pole parameters related to the Mariana plate in ITRF2008

EPP	Source	Lat	Lon	$\dot{\omega}_0$ Deg/My	$\dot{\omega}_0$ mas/y	$\dot{\omega}_x$ mas/y	$\dot{\omega}_y$ mas/y	$\dot{\omega}_z$ mas/y
Mariana (absolute)	**This paper**	**11.760 ± 0.161**	**143.501 ± 0.110**	**2.757 ± 0.133**	**9.926 ± 0.480**	**-7.811 ± 0.383**	**5.780 ± 0.265**	**2.023 ± 0.123**
Mariana (absolute)	Snay (2003)	-72.879	100.784	0.363	1.307	-0.020	0.105	-0.347
Mariana (absolute)	Kreemer et al. (2014)	10.78	142.75	2.177	7.839	-6.130 ± 1.506	4.661 ± 0.698	1.466 ± 0.169
Mariana wrt Philippine	Kato et al. (2003)	21.5 ± 0.6	144.6 ± 0.2	3.1 ± 0.3	11.16 ± 1.08	-8.46 ± 1.08	6.02 ± 0.004	4.40 ± 0.01
Philippine wrt Eurasia	Kato et al. (2003)	61.4 ± 0.5	163.7 ± 0.9	-1.00 ± 0.01	-3.60 ± 0.04	1.65 ± 0.04	-0.48 ± 0.0006	-6.60 ± 0.0003
Eurasia (absolute)	Altamimi et al. (2012)	54.23	261.17	0.257	0.924	-0.083 ± 0.008	-0.534 ± 0.007	0.750 ± 0.008
Mariana (absolute)	Kato et al. (2003) & Altamimi et al. (2012) inferred	-9.66 ± 0.64	144.01 ± 0.42	2.36 ± 0.30	8.64 ± 1.081	-6.89 ± 1.081	5.006 ± 0.008	-1.45 ± 0.012
Mariana wrt Pacific	Bird (2003)	43.777	149.205	1.278	4.601	-2.854	1.701	3.183

Pacific (absolute)								

5.1 Comparison to previous EPP estimates

It will be instructive to compare this new set of absolute EPPs to those determined in earlier studies. However, the only realistic absolute EPP report comes from Kreemer et al (2014, Table S2). As mentioned earlier, there have been some relative EPP estimates which, when combined with absolute estimates of the EPPs of the related plate, can yield an inferred set of absolute EPPs for the Mariana plate. Two such studies will be considered: Kato et al. (2003) and Bird (2003). For comparison purposes, all four absolute Euler poles are plotted in Figure 2.

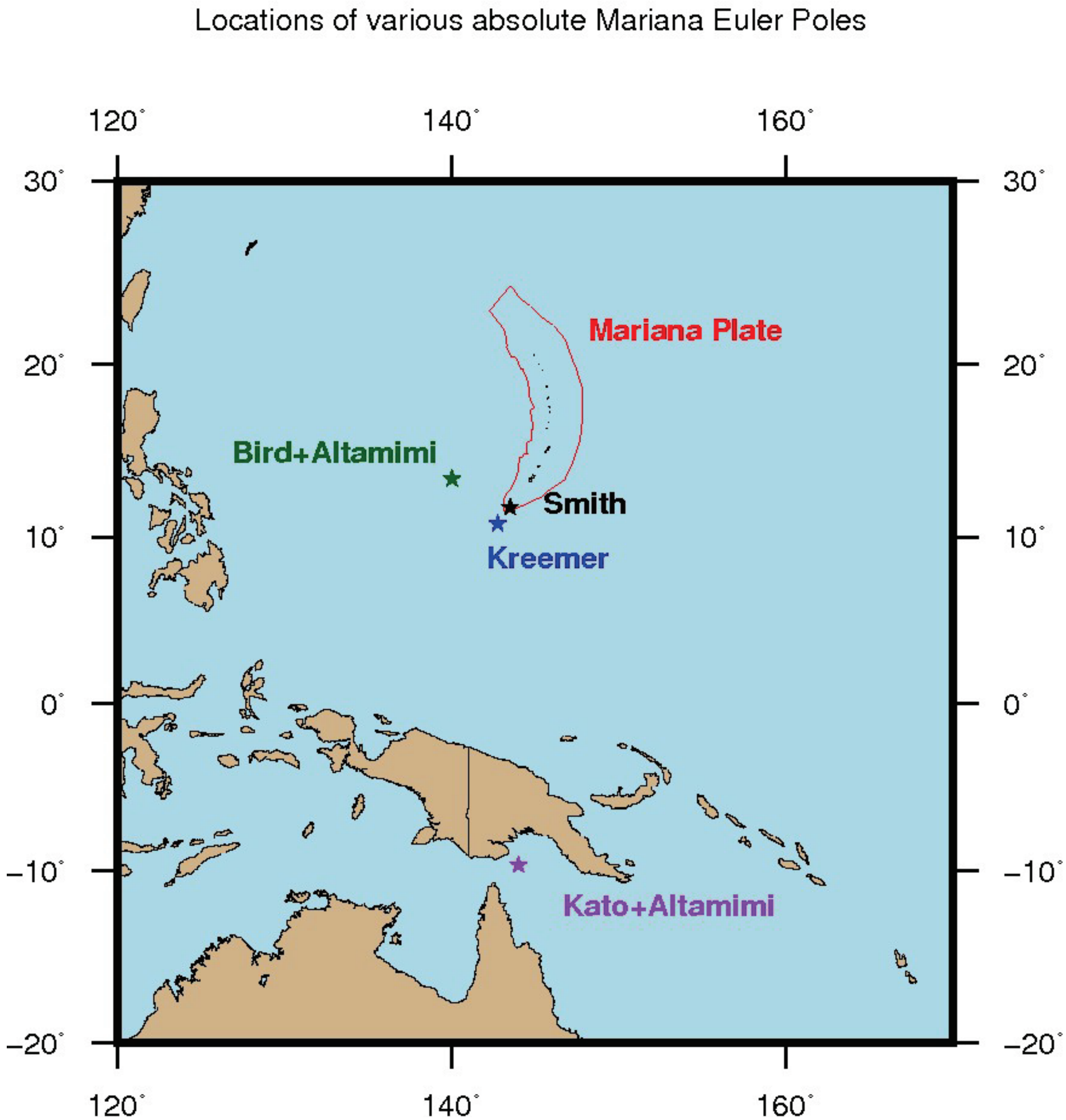

Figure 2: Locations of four absolute Mariana Plate Euler poles in the ITRF2008 frame (Snay pole is off the map, deep in the Antarctic)

5.1.1 Kreemer et al (2014)

The most recent attempt to determine the absolute rotation of the Mariana plate was performed by Kreemer et al (2014). In that study, they used one continuous GPS station (called "CNM0", being a concatenation of CNMI and CNMR data) and three campaign marks from Kato et al. (2003) on islands Pagan, Guguan and Anatahan (Kreemer et al. 2014; Supporting information Table S1: ftp://gneiss.nbmg.unr.edu/kreemer/GSRM_G3/supp_table1_corrected.doc). Although NGS archives do not include surveys of geodetic marks on Guguan and Anatahan, their archives do include points on Pagan. In fact, a comparison of latitude and longitude seems to imply that Kato's point "PAGA" corresponds exactly to NGS point "PAGAN 1" with PID AA5095. However, the ITRF2008 velocity of PAGA as reported by Kato et al. (2003) and used by Kreemer et al (2014) disagrees with those from NGS slightly in the east (-30.1 mm/year versus -28.2 mm/year from NGS) and significantly in the north (9.9 mm/year versus 15.8 mm/year from NGS).
When used to compute EPPs for the plate, these velocities have residuals which are much smaller for the Kreemer et al (2014) than this study (+0.8 mm/year North and -2.6 mm/year East versus +5.7 mm/year North and +4.0 mm/y East for NGS). A variety of reasons for this are speculated. First, the time-span of the Kato et al. (2003) data was seven years

(1992-1999), during which time no evidence of significant seismic activity near Pagan could be found. For that same point, the NGS time-span was 14 years (2003-2017), during which time the volcano on Pagan erupted (2006). As such, there is reason to cast suspicion on the velocity from NGS surveys. Second, with only four points used in the Kreemer et al. (2014) study with which to compute the EPPs, residuals are naturally expected to be smaller than in this study, where 28 velocities were used.

On the other hand, the Kato et al. (2003) velocities appear to be too small in the north direction, in general, as evidenced by the following: Assuming the plate is rotating rigidly, then a pattern of increasingly large velocities (in both east and north) should be discerned as one examines the islands by increasing distance from the Euler pole. Assuming for now that the pole is somewhere south and west of Guam (as per both Kreemer et al (2014), and this study, later), then velocities should increase as the islands are examined from south to north. Note the locations of Anatahan, Guguan and Pagan in the chain (see Figure 1), and compare the NGS velocities (Table 2) with those from Kato et al. (2003) as reported in Kreemer et al (2014). Further, note that the velocities on Saipan agree at both campaign marks and CORSs (averaging at about 13 mm/y in the north and -19 mm/y in the East), lending support to the idea that the NGS-based velocities as determined from campaign data are reliable.

Starting at Saipan and moving northward, the velocities in the east direction reported by both NGS and by Kato et al. (2003) (via Kreemer et al., 2014) behave quite consistently with one another, increasing from about -19 mm/year on Saipan to -38.5 mm/y on Asuncion (with Pagan and Alamagan having very slight deviations from the monotonically increasing pattern).

In the north direction, however, the velocities as determined by NGS begin at about 12-14 mm/y on Saipan and increase northward to about 17.7 mm/y at Asuncion. While not perfectly monotonic (especially considering the already mentioned outlier on Sarigan), all of the other velocities from Saipan through Asuncion are in the 12-17 mm/y level, whereas Kato et al. (2003) puts the Anatahan, Guguan and Pagan north velocities all below 10 mm/y. For this reason alone it seems obvious that any EPPs determined from NGS velocities must disagree with those based upon Kato et al. (2003). This is likely the primary source of disagreement between the Kreemer et al. (2014) EPPs and those from this study.

Despite these differences in input data, the Kreemer et al (2014) EPPs agree reasonably well in both location of the pole and magnitude of the rotation, at least as compared to later studies (see below). However, relative to the formal accuracy estimates out of both this study and Kreemer et al. (2014), the two estimates of the EPPs only agree to between one and six standard deviations of one another, depending on which EPP is considered.

5.1.2 Kato et al. (2003)

Kreemer et al. (2014) used some of the data from Kato et al. (2003), so it may be worthwhile to briefly consider that earlier study. Kato et al. (2003) estimated EPPs for the Mariana plate relative the Philippine Sea plate, as well as EPPs between the Philippine Sea plate and the “Stable Eurasian Reference Frame”. Combining these two EPPs with those of the ITRF2008 Eurasian plate (Altamimi et al., 2012), yields an inferred absolute EPP set for the Mariana plate.

Kato et al. (2003) matches well to both the longitude of the absolute Mariana plate Euler pole and plate rotation rate seen earlier (144.01° vs 143.48° and 8.64 mas/y vs 10.013 mas/y). However the Kato/Altamimi-inferred latitude of the Euler pole (-9.66°) is significantly south of where this study puts it (+11.817°). That means the 10.013 mas/year rotational velocity estimated in this study only induces a velocity of some 3.4 and -4.1 mm/year, north and east on Guam, while Kato’s 8.64 mas/year rotational velocity induces 1.8 and -52.2 mm/year north and east. One can see this in Kato’s (2003) figure 2 (orange vectors), although those vectors are relative to the Eurasian plate (about 8 of the 52 mm/year motion is due to the Eurasian plate’s motion relative to the ITRF).

What this means is that Kato et al. (2003) has overestimated the magnitude of the relative velocities on Guam relative to Eurasia and, by extension, the absolute velocities on Guam itself. Kato was not the only one to do so. In Sella et al. (2002) the motion of Guam relative to the Pacific plate is listed at 63.4 mm/year at an azimuth of 104.9 degrees.

However, if one combines the EPPs of the Mariana plate determined in this study with the latest EPPs for the Pacific plate (Altamimi, et al., 2012), then the velocity of Guam relative to the Pacific plate becomes 32.3 mm/year, at an azimuth of 100.5 degrees. That's good agreement in azimuth, but it implies Guam moving at about half the velocity observed by Sella et al. (2002).

In summary, the Kato et al. (2003) seems to suffer from some unexplained data processing issue which causes its inferred absolute EPPs to lie far outside the realm of realism for this plate.

5.1.3 Bird (2003)

One final estimate of the EPPs which will be considered comes from (Bird 2003) but in that paper, the Mariana plate EPPs were reported relative to the Pacific plate. Using the same approach as above, Bird's relative EPPs will be combined with the absolute EPPs of (Altamimi et al., 2012), only this time for the Pacific plate. As before, the two EPPs are combined to determine the inferred absolute EPPs for the Mariana plate.

While the Bird/Altamimi-inferred absolute Euler pole has much better latitude and rotation rate agreement with this study, the Euler pole itself falls about 5 degrees due west of Guam. If this were true, then the velocities on Guam should point almost perfectly north in the ITR2008 frame, rather than at the ~27 degrees north of west which this study has shown.

5.1.4 Discussion

Consider the vintage of the GPS processing software used by Kato et al (2003), Bird (2003) and Sella et al. (2002) and the general lack of available geodetic data for the Mariana plate. Consider also all of the improvements in reference frame and orbit determination since 2003, and it is not entirely surprising that the values determined in this study differ substantially from estimates of 15 years ago.

One additional, likely significant source of this discrepancy appears to be the determination of velocities on Guam in Kato et al. (2003.) If the Guam velocities are ignored in Kato et al. (2003), one can discern a fairly rapid reduction in velocity magnitude running from Agrihan to Saipan, very much in alignment with that seen in this study. Considering Guam's location, "pinched" between the Mariana trench and the Mariana trough, it may be possible that Guam is not exhibiting rigid body rotation. Considering the number of faults near Guam (Mueller, 2012) or hypothesized to be on Guam itself (ibid), as well as the preponderance of Mw > 6 earthquakes near Guam (ibid), it seems reasonable to assume that Guam, of all the islands on this plate, appears to be the one least likely to be undergoing simple rigid body rotation. It is also possible that Guam is not exhibiting rigid body rotation because it is the closest to the subduction zone which may be (partly) locked and thereby causing elastic strain accumulation in the Mariana plate. However, if that were the case, the residual vectors on Guam should be toward the northwest, rather than the southwest, which was found herein (see next section, and Figure 3). One could infer from this that there is no, or minimal, locking happening at the subduction megathrust. This conclusion is further supported by the residual vectors of Kreemer et al. (2014) pointing toward the southeast (see next section, and Figure 3).

Further evidence of this is presented in a later section on residual motion. If this is the case, it also helps explain why Guam has such a diversity of velocities as compared to the other islands. Guam's north and east velocity shows a standard deviation of over 1.0 mm/year each, whereas velocities on Rota, Tinian and Saipan exhibit smaller standard deviations of about 0.2 to 0.7 mm/year.

In order to test the impact of the more variable Guam-based velocities, a set of Euler pole parameters were computed using the same data as before, but eliminating all data on Guam. The output EPPs and error estimates are not significantly different from the with-Guam solution: $\phi_0 = 11.284° \pm 0.282°$, $\lambda_0 = 142.925° \pm 0.185°$, and $\dot{\omega}_0 = 8.770 \pm 0.555$ mas/yr. Comparing these with the previous values shows that, aside from about a half-degree displacement of the pole in both latitude and longitude and a 12% drop in the rotation rate, the EPPs match well with those determined earlier. Nonetheless, the standard deviations of the EPPs have risen a bit, particularly in latitude of the Euler pole which almost doubled in standard deviation.

Thus it is concluded that the variability of the Guam velocities are not significantly interfering with the determination of the Euler pole parameters themselves, while removing them adds uncertainty rather than tightening up the adjustment. Therefore it doesn't seem worthwhile to remove Guam for "possibly not behaving like a rigid body".

5.2 Residuals

This paper has presumed that the Mariana plate is undergoing rigid plate rotation, in order to solve for the EPPs. Therefore, any residual horizontal velocities should represent deviation from that hypothesis. Table 4 shows the magnitude of the residual velocities, relative to the total observed velocities.

Table 4: Absolute and (non-Eulerian) residual horizontal velocity magnitudes by island(s)

Island(s)	**Average observed velocity**	**Average residual velocity**
Guam	10.6 mm/y ± 1.0 mm/y	2.3 mm/y (21.7 %)
Rota	14.5 mm/y +/- 0.6 mm/y	1.3 mm/y (8.9 %)
Tinian	22.5 mm/y +/- 0.2 mm/y	1.9 mm/y (8.4 %)
Saipan	23.1 mm/y +/- 0.7 mm/y	1.7 mm/y (7.4 %)
Northern Islands	36.9 mm/y +/- 4.7 mm/y	4.8 mm/y (13.0 %)

These residuals are also plotted in Figure 3. Note in Figure 3 the quasi-, but not quite random, nature of the residuals. Specifically, note the apparent spreading separation occurring between Guam/Rota and Tinian/Saipan. Such patterned movements may be indicative of some systematic non-rigid plate rotational motion, such as a separation occurring between Rota and Tinian. It does not seem likely to be a systematic problem in the data, as the Rota, Tinian and Saipan data all are tied to the same historic survey, while Guam is tied to three other historic surveys. No evidence of a fault between Rota and Tinian was found by the fairly comprehensive study done by Mueller el al. (2012), and none appear obvious on the bathymetry, so the cause of this seeming separation between these islands remains unknown. However, Kato et al. (2003) indicated that the Mariana plate is undergoing arc-parallel extension at a rate of 1.5×10^{-8} / yr. That conclusion agrees well with the general nature of the residuals in this paper which imply an extension rate of 1.4×10^{-8} / yr.

The data in Table 4 and Figure 3 indicate that 90% of the observed linear velocities in the islands of Rota through Saipan can be explained as rigid body rotation about an Euler pole. This assumption breaks down slightly for the northern islands, and breaks down substantially for Guam. The lack of data on the northern islands as well as knowledge of recent earthquakes seems a possible indicator for why the northern island data does not seem to behave as well as the Rota-Saipan data, though arc parallel extension goes a long way toward explaining the residual behavior too.

In order to better understand the outliers, a review of all major seismic events including earthquakes with Mw > 6.5 and at a depth no greater than 200 km as well as volcanic eruptions was conducted. Earthquake data was acquired from the USGS earthquake archive (https://earthquake.usgs.gov/earthquakes/), while volcanic eruption data was found on the "Volcano Live" website (http://www.volcanolive.com/)

Of those events, a few may help identify the cause of certain outliers. A 2016 earthquake near Agrihan may be a cause of the Pagan and Asuncion outliers. But if this is so, it does not explain Agrihan's small residual. If the spreading seen between the Rota/Guam group and the Tinian/Saipan group is caused by a major seismic event, it does not appear to be one that occurred between those island groups. Rather, it seems to be the central point for extension of the plate as a whole.

Finally, the clustering of events around the island of Guam itself further supports the hypothesis that Guam is especially prone to non-linear velocities and therefore linear velocities from campaign data on Guam are not well suited for determining the EPPs of the Mariana plate, at least not over large spans of time, such as the outlier points (AA4393 and TW0537) which spanned 20 years (1997-2017).

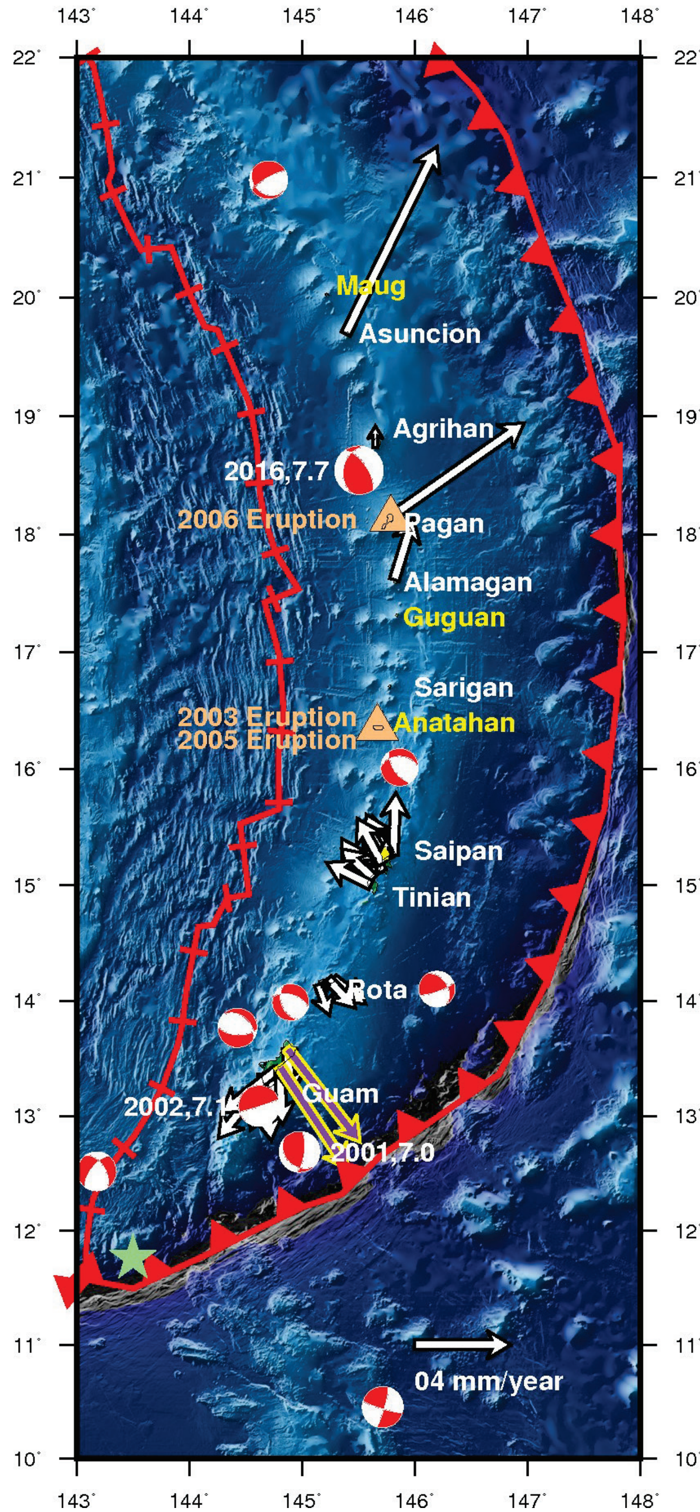

Figure 3: Residual horizontal velocities after removal of Euler pole rotation (no outliers shown), with major seismic events of the last 20 years. Earthquakes greater than Mw 7.0 are labeled. The green star is the Euler pole computed in this paper. The two purple vectors on Guam are residual vectors from Kreemer et al. (2014)

6 Summary and Conclusions

A new GPS survey of select geodetic control points on the Mariana tectonic plate was performed in 2017. This new survey was used to compute ITRF2008 coordinates on those points, and these coordinates were then compared to older ITRF2008 coordinates on the same points based on historic GPS surveys ranging from 1997 through 2014 in order to derive velocities. In all, a total of 25 sets of North/East velocities were determined and these were combined with velocities from three CORSs for a grand total of 28 velocities used to solve the inverse Euler pole problem to determine the absolute Euler pole parameters of the Mariana plate under the assumption that it is undergoing rigid plate deformation.

The location of the Euler pole was determined to be just southwest of Guam (ϕ_0 = 11.760° ± 0.161°, λ_0 = 143.501° ± 0.110°) and rotating at a rate of $\dot{\omega}_0$ = 9.26 ± 0.480 mas/year (2.757 ± 0.133°/My). This rotation is nearly four times faster than the fastest rotation rate of any other tectonic plate developed in the ITRF2008 plate motion model (Altamimi et al., 2012). However, this estimate also has standard deviations that are 10 to 100 times larger than those in the ITRF2008 plate motion model, which might be expected considering the small size of the plate and the limited data available.

This estimate of the rotation rate is in poor agreement with those implied by earlier studies (Kato, et al. 2003), (Bird 2003) but those studies used older data, less data and could only imply an absolute set of EPPs when combined with external information. In contrast, a relatively recent absolute set of EPPs was determined by Kreemer et al. (2014), and had remarkably good agreement with the values found herein. However, Kreemer et al. (2014) used only four velocities and of those three were from Kato et al. (2003). Those three were shown to be likely too small in north velocity, which helps explain the slight disagreement between this study and Kreemer et al. (2014).

Further, this paper has hypothesized that the determination of velocities on Guam may be complicated by the possibility that geologic factors are preventing the Guam portion of the Mariana plate from rotating like a rigid body. Nonetheless, it was also shown that the wide variability of velocities on Guam does not significantly affect the determined EPPs. More important seems to be accurate determination of velocities at locations far removed from the Euler pole, specifically the remote northern islands of the Mariana chain.

Finally, a study of the residual motions, after removal of the estimated rigid body rotation, shows a few interesting things. First, the Mariana plate seems to be, at about the 90% level, undergoing rigid body rotation with two exceptions. Additionally, Guam seems to have a diverse set of intra-island motions not captured by Euler pole rotation. Finally an apparent spreading signal was detected between the islands of Rota and Tinian, likely being part of a larger north-south extension of the plate as a whole.

7 Future Work

An expansion of the approach laid out in this paper, using the historic data from NGS and Lamont Doherty (and others, if found) could be attempted in the future. NGS performed high accuracy GPS surveys in Guam in 1992 and on the northern islands in 1993 as part of the Pacific Rim Project (Snay, 2003; Frakes, 1994), while Lamont Doherty repeatedly surveyed the northern islands between 1992 and 1998 (Kato et al., 2003). In addition, some of the marks on the northern islands were installed by either the U.S. Army Corps of Engineers (e.g. ASUNCION AZIMUTH MARK) or the U.S. Geological Survey (e.g. PAGAN 1), indicating that geodetic data on these points may also reside in the archives of those organizations. However any use of data before about 1994, would require some assumptions in order to approximate ITRF2008 coordinates prior to 1994 (see also Kato et al. (2003), paragraph 5).

Additionally, the effect of non-white noise sources in CORS time series could be considered when determining CORS-based velocities.

Lastly, the data at continuous GPS site OGU2 could be processed by NGS and a velocity determined, consistent with the four CORSs in the region. If this were done, then OGU2 would provide a fifth continuous GPS-based velocity for a future study.

8 Appendix A: Variances and scaling in ITRF2008

The standard deviations of the velocities in Table 2 are not a-priori values, but rather are a-posteriori. Thus, if used as-is in a standard Least Squares Solution (LESS) within the 2nd order Gauss-Markov Model (GMM; Schaffrin and Snow, 2017a) for the solution of Euler pole parameters (EPPs) they will yield a variance of unit weight exactly equal to 1.0.

There are multiple reasons for reporting them as such:

1) The a-priori error estimates of velocities based on campaign data are a function of the a-priori error estimates of the positions of the campaign data, and those positional error estimates are almost certainly too optimistic.

2) The CORS-based and campaign-based velocities are determined in different ways, so it would be best to report them in a way that attempts to normalize them to one another

Addressing each of these reasons in turn:

Optimistic Position Errors: The positions for the campaign data were determined using NGS software "OPUS Projects" (Gillins and Eddy, 2017). In recent years, a number of internal studies (Mark Schenewerk, NGS, Personal Communication) performed at NGS have shown that the standard deviations from the most recent version of OPUS Projects are at least 8 times too small (variances are 64 times too small). If these overly optimistic position errors are not corrected, they will directly cause over-optimism in the velocity error estimates.

CORS velocity errors vs. Campaign velocity errors: Although both velocity types come from GPS data, both the quality and quantity of data, as well as the software used to compute the velocities are different. Further, any a-priori error estimate can be assumed to be scaled incorrectly, so it is often assumed that similar datasets have similar scaling problems (that is, one variance of unit weight suffices for a common set of input data). However when two input datasets are significantly different, it is appropriate to solve for two (or more) variance components, using the Variance Component Model (VCM; Schaffrin and Snow, 2017b). The choice to use the VCM was validated by the results: In the LESS within the VCM the variance of unit weight for the CORS velocities (20.74) was significantly closer to 1.0 than the variance of unit weight for the campaign velocities (1643.95). This means the campaign-based a-priori velocity standard deviations are 40.5 times too small (too optimistic), whereas the CORS velocity standard deviations are only 4.6 times too small (but still too optimistic).

The magnitudes (×4.6 and ×40.5) of the square roots of the variances of unit weight of the velocities imply that the a-priori formal accuracy estimates of the input velocities are seriously unrealistic. For this reason, the reported standard deviations in Table 2 are a-posteriori (scaled by 4.6 and 40.5 as appropriate). This has three advantages:

1) The reported standard deviations are more realistic

2) The reported standard deviations are consistent between the two types of input velocities

3) The reported standard deviations can be used in a simpler Least Squares Adjustment, where only one variance of unit weight need be computed.

A word of caution should close out this appendix: the use of the VCM presumes all noise sources are Gaussian and also that all systematic errors have been removed. Arguments against both assumptions could be made. CORS time series, for example, are presumed to have power-law plus white noise characteristics. Yet this should not have any impact on this study (Kevin Choi, NGS, Personal Communication), and since only three of the input velocities came from CORS, any further examination of this issue is deferred for future investigation. As for systematic errors, it is possible that they remain in the data considering that non-linear velocities may have corrupted the (presumed linear) input velocities. This might be because the plate is not rotating like a rigid body or unmodeled discrete motions like earthquakes (particularly in the discrete position-based velocities) have not been accounted for. However the existence of such biases in the data cannot easily (or in some cases, at all) be verified. Furthermore, the results of this math model have yielded quite reasonable results under the presumption of unbiased linear input velocities.

PART 2: Rotation of the Mariana Plate in ITRF2014

9 Introduction

Part 1 of this report was originally a stand-alone paper which used historic GPS data, compared against data from a 2017 survey, in order to compute the rotation of the Mariana plate in ITRF2008. While the results were complete, the publication process of that paper was suddenly halted in 2018. Shortly thereafter, three important and relevant issues came to pass. They were:

a) The ITRF2008 frame was replaced by ITRF2014
b) The National Geospatial-Intelligence Agency (NGA) volunteered to collect GPS data in Guam to support NGS efforts in the area (as a piggyback to work NGA was already planning in the area)
c) NOAA's Office of Coastal Management (OCM) volunteered to collect GPS data in the Commonwealth of the Northern Mariana Islands (CNMI) to support NGS efforts (as a piggyback to work OCM was already planning in the area)

Since the driving purpose for NGS determining the rotation of the Mariana plate is to define the forthcoming MATRF2022 reference frame, and because that frame is likely to be defined relative to the (forthcoming) ITRF2020 reference frame, it was deemed worthwhile to re-process the data from the original paper (Part 1), but now in ITRF2014, and see how the rotations compared. This would serve as a test bed for the eventual use of that same data in ITRF2020 when it comes time to define MATRF2022.

Additionally, with two new surveys it was seen as interesting to analyze the two new surveys and see how they agree with the rotation in ITRF2014, and to consider enveloping those surveys into an updated rotation in ITRF2014.

The remainder of this report will follow a similar outline to Part 1. When possible, information which was already presented in Part 1 will simply be referenced, rather than repeated.

10 Re-processing in ITRF2014

In 2019, \NGS fully adopted ITRF2014 (Altamimi et al, 2016). This adoption included:

a) Orbit production in the IGS14 frame
b) Re-processing all data in the NOAA CORS Network(NCN) to create new coordinate functions in ITRF2014
c) Updating all OPUS tools to support ITRF2014

Using the same data from Part 1 of this report, an attempt was made to completely replicate the processing done in ITRF2008, but now in ITRF2014. However certain changes prevented a comprehensive replication of the original processing. Specifically, some stations in either the IGS Network or in the NCN which had ITRF2008 coordinate functions had been removed (or partially removed) from the creation of ITRF2014 coordinate functions. Additionally, station-by-station changes, such as adding or removing discontinuities occurred between ITRF2008 and ITRF2014. All of this meant that the very network itself (availability of station data, etc.) was expected to change the rotation as computed in ITRF2014, when compared to the rotation computed in ITRF2008.

The hub and spoke method (Gillins and Eddy, 2017) was adopted for session processing, and CNMR was the CORS chosen as the hub whenever it was available, since Saipan is more centrally located on the plate than Guam. Further, an attempt was made to include the same set of CORSs with each session. This was not possible due to the long history of these surveys and the commissioning, de-commissioning and occasional data outages of stations.

There were a total of 71 sessions spread over 10 projects to process. Table 5 below contains a simple summary. This is an expansion of Table 1.

Table 5: Historic and recent GPS surveys in Guam and CNMI used to compute velocities in this paper

Year	Survey Name	Total non-CORS points processed	Span	Islands	# sessions	Hub	# CORSs total
1997	GPS1194	2	2 days	Guam	2	GUAM	6-7
2003	GPS1837/Saipan	11	3 days	Saipan	3	GUAM	13-14
2003	GPS1837/Tinian	8	3 days	Tinian[1]	3	GUAM	13-14
2003	GPS1837/Rota	10	3 days	Rota	3	GUAM	13-14
2003	GPS2394	11	20 days	Most northern islands	14	CNMR	12-14
2004	GPS1987	16	7 days	Guam	6	CNMR	8-12
2013	GPS3070	3	2 days	Guam	2	CNMR	15
2017	GC2017*	33	26 days	All of the above	23	CNMR	15-17
2019	OCM2019*	10	10 days	Saipan, Rota, Tinian	11	GUUG	15-17
2019	NGA2019*	3	8 days	Guam	4	CNMR	13-17

* These names are unique to this report, as these projects stood apart from the NGS tracking/project numbering system

Once session processing was complete, a least squares adjustment, tightly constrained to the chosen hub completed the processing, yielding ITRF2014 coordinates at 32 geodetic control marks. Unlike Part 1 of this report, some of those marks now had 3 occupations through time, rather than 2. This was an intentional design request by NGS (to both NGA and OCM) to repeat occupations on select points and also to collect data on other points which had only ever had 1 historic occupation, yielding new velocities not available in the ITRF2008 computations.

10.1 Marks with more than 2 occupations

With the collection of new GPS occupation data on 12 marks (9 by OCM and 3 by NGA), NGS now had in its holdings an expanded set of occupation data from which to compute velocities. Specifically, the changes in the campaign GPS data which went into the ITRF2008 study were:

- 7 marks which had 2 occupations, now had 3
- 3 marks which had 1 occupation, now had 2
- 2 marks which had 0 occupations, now had 1

Of particular interest are those seven marks with 3 occupations. With 2 occupations there is no question about how the linear velocity is computed, but with 3 or more occupations certain choices had to be made. The most obvious choices, assuming that this analysis will stick with linear velocities, were:

1) Fit a linear velocity through 3 (or more) occupations
2) Make every combination possible [N*(N-1)/2] linear velocities with N occupations] and evaluate whether to use one, some, or all of them

These ideas were weighed against other issues. For instance, provided the correlations between velocities are properly accounted for in #2, this seemed a good way to get multiple velocities into the mix, while allowing for earthquakes and other outliers to be filtered out. For instance, with 3 occupations there are 3 possible linear velocities (all correlated). Let's call those three occupations "A", "B" and "C", in chronological order. One can make velocities by connecting occupations AB, BC and AC. If, for instance, we knew that an earthquake occurred between occupations "A" and "B", then one might throw out velocities AB and AC (both of which span time AB) leaving only BC. While this sounds viable, in theory it is not, and for a few reasons. First, specific to this paper, the timespan "BC" for those 7 points with 3

[1] Mark DG3988 (163 3227 UH 26) on Saipan was also observed and processed with the Tinian data for these sessions.

occupations is only 2 years, which turns out to be far too short to properly derive a linear velocity in the "few mm/year" range. Secondly, the approach, in essence, invalidates the ITRF2008 study where no significant attempt to throw out linear velocities due to earthquakes (specifically) was made.

For example, all of the occupation data (including new occupations from OCM and NGA) are shown in Figure 4. Take just one mark, mark DG3982 (which turns out to be illustrative of the entire set of 7 marks with 3 occupations). The three linear velocities which can be computed from the three occupations are shown in Table 6 (standard deviations scaled to reflect the final variance of unit weight of the adjustment; see section 10.3)

Table 6: The three possible linear velocities computable from the three occupations on mark DG2982

Island	PID	VN (mm/y)	VE (mm/y)	Survey Pair	Year Pair	Span	A/B/C
Saipan	DG3982	12.8 ± 2.0	-19.6 ± 2.1	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Saipan	DG3982	7.8 ± 25.6	-9.7 ± 25.9	GC2017 / OCM2019	2017 / 2019	2 y	B/C
Saipan	DG3982	11.5 ± 2.7	-16.5 ± 2.7	GPS1837 / OCM2019	2003 / 2019	16 y	A/C

In Table 6, a few things can be noted, which are common to the 6 other points with 3 occupations. First, the standard deviation of the 2-year velocity is significantly larger than for the 14 or 16 year combinations. Second, that standard deviation is so large as to overwhelm the actual size of the velocity itself. Finally, the magnitude of the 2 year velocity is in obvious disagreement with the 14 and 16 year velocities. In fact, to prove that it is an outlier, this analysis was expanded to look at all velocities on the four islands of Guam, Rota, Tinian and Saipan. Using a 2 sigma iterative outlier removal approach[2], every 2 year velocity was flagged as an outlier on its respective island, while the 14 and 16 year velocities tended to agree with one another and with other velocities on those islands.

Based on this observation, it is clear that simply breaking the occupations into multiple (correlated) linear velocities, particularly where one of them is of short duration, is not the right approach. Using non-linear velocities remains a possible long-term approach, but since that approach isn't even being taken on the four CORSs in the area, it seems premature to apply it to campaign GPS data. Therefore, approach #1, of fitting one linear velocity to the 3 occupations was adopted.

10.2 ITRF2014 Velocities

All told, NGS now had 36 velocities on 36 geodetic control marks, broken down as follows:

1) 22 velocities on 22 marks, using identical occupation data as per the ITRF2008 study (Part 1 of this report), but now in ITRF2014
2) 7 velocities on 7 marks that had participated in the ITRF2008 study, but now updated from 2 occupations to 3
3) 3 velocities on 3 marks which had not previously participated in the ITRF2008 study, but now have 2 occupations
4) 4 velocities on 4 CORSs updated to ITRF2014

Figure 4 below shows the breakdown of the above information. An "A" means an occupation before 2017, a "B" means an occupation in the GC2017 survey and a "C" means an occupation after 2017. Solid black arrows show pairs of occupations which were used to create a velocity in the original ITRF2008 study. A dashed black arrow shows a new group of (2 or 3) occupations leading to a new velocity, due to the OCM2019 and NGA2019 surveys. Note that this includes two types of points: those who went from 1 occupation to 2, gaining 1 velocity (labeled as A/C) and those who went from 2 occupations to 3, updating their velocity to one that is a fit through 3 occupations (as discussed earlier).

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[2] The 2 sigma filter was applied separately to VN and VE. If *either* component was found to be an outlier, the paired velocities were discarded as an outlier.

Designation	PID	Island	1997 GPS1194	2003 GPS1837	2003 GPS2394	2004 GPS1987	2013 GPS3070	2017 GC2017	2019 OCM2019	2019 NGA2019
GUM ARP	AA4393	Guam	A					B		
TOGUAN	TW0537	“	A					B		
AAFB	DH3102	“				A		B		C
BEACH	TW0372	“				A		B		
GGN 2205	DH3017	“				A		B		
SALISBURY	TW0017	“				A		B		
SOLEDAD	TW0398	“				A		B		
GGN 1952	DQ3228	“					A	B		
GGN 2456	DH3029	“					A	B		
DUGI	DG4024	Rota		A				B		
JP SN BUDBAS	DG4009	“		A				B		
TATGUA 2	AA4404	“		A				B	C	
TIDAL 3	DG4014	“		A				B		
VIL	DE7086	“		A					C	
ANT	DG4117	Tinian		A				B		
CARMEN	DG4122	“		A				B		
LOOP	DG4108	“		A				B	C	
TIQ C	AA4411	“		A				B	C	
TIDAL 3	DE6136	“		A					C	
AMP 1	DG3974	Saipan		A				B	C	
GRPN 9	DG3961	“		A				B	C	
JE JONES	DG3982	“		A				B	C	
KING	DG3940	“		A				B		
SAIPAN AZ MK	DE7041	“		A				B		
SPN A	AA4415	“		A				B		
TAM 4	DG3969	“		A				B		
Pill BOX	DE7924	“		A					C	
SARIGAN AZIMUTH MARK	DK2824	Sarigan			A			B		
ALAMAGAN RM 3	DK2819	Alamagan			A			B		
PAGAN 1	AA5095	Pagan			A			B		
AGRIHAN LDGO	DK2827	Agrihan			A			B		
ASUNCION AZIMUTH MARK	DK2820	Asuncion			A			B		

Figure 4: All occupations and occupation-pairs leading to velocities for the ITRF2014 rotation computation

In addition to the occupations leading to velocities, listed in Figure 4, a substantial number of additional occupations exist in NGS archives. These data should be considered as potential candidates for re-occupation with GNSS in the future, since they all are marks with only one historic occupation. They are listed in Appendix B.

Once ITRF2014 positions, with their respective a-posteriori dispersion matrices were available, linear velocities and a-priori weight matrices were computed. As was explained earlier, there were slight changes expected to the ITRF2014 positions, relative to ITRF2008 positions, and thus slight changes to velocities. Additionally, the four CORSs of the NCN had new coordinate functions computed in ITRF2014, which differed from ITRF2008. As before, this study will adopt the last computed velocity for a CORS out of all of the solutions in the ITRF2014 SINEX file. The new velocities, as computed in ITRF2014 are:

Table 7: All ITRF2014 velocities computed or available for analysis in this paper. Velocities removed as outliers are in red text. Velocities which incorporate new occupations since the ITRF2008 study are highlighted.

Island	PID	VN (mm/y)	VE (mm/y)	Surveys	Years	Span	A/B/C
Guam	AA4393	3.2 ± 1.9	-8.1 ± 1.9	GPS1194 / GC2017	1997 / 2017	20 y	A/B
Guam	TW0537	2.8 ± 3.0	-4.7 ± 3.3	GPS1194 / GC2017	1997 / 2017	20 y	A/B
Guam	DH3102	4.0 ± 1.8	-5.7 ± 1.9	GPS1987 / GC2017 / NGA 2019	2004 / 2017 / 2019	15 y	A/B/C
Guam	TW0372	0.6 ± 3.4	-7.3 ± 3.4	GPS1987 / GC2017	2004 / 2017	13 y	A/B
Guam	DH3017	2.3 ± 2.9	-5.7 ± 2.9	GPS1987 / GC2017	2004 / 2017	13 y	A/B
Guam	TW0017	3.3 ± 2.9	-5.4 ± 2.8	GPS1987 / GC2017	2004 / 2017	13 y	A/B
Guam	TW0398	1.3 ± 2.9	-6.0 ± 3.1	GPS1987 / GC2017	2004 / 2017	13 y	A/B
Guam	DQ3228	3.4 ± 17.4	-8.6 ± 17.8	GPS3070 / GC2017	2013 / 2017	4 y	A/B
Guam	DH3029	2.5 ± 13.1	-2.7 ± 14.0	GPS3070 / GC2017	2013 / 2017	4 y	A/B
Guam	DF7984	4.1 ± 1.3	-6.7 ± 1.3	CORS (GUUG)			
Guam	AF9627	4.4 ± 1.0	-8.0 ± 1.0	CORS (GUAM)			
Rota	DG4024	7.7 ± 2.2	-10.8 ± 2.5	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Rota	DG4009	7.2 ± 2.4	-10.9 ± 2.6	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Rota	AA4404	7.3 ± 1.8	-10.5 ± 2.0	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Rota	DG4014	6.5 ± 2.3	-12.2 ± 2.7	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Rota	DE7086	6.8 ± 2.5	-11.1 ± 2.8	GPS1837 / OCM2019	2003 / 2019	16 y	A/C
Tinian	DG4117	10.9 ± 2.2	-18.3 ± 2.4	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Tinian	DG4122	11.7 ± 2.3	-17.5 ± 2.4	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Tinian	DG4108	12.0 ± 1.9	-17.8 ± 1.9	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Tinian	AA4411	11.4 ± 1.8	-16.5 ± 1.8	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Tinian	DE6136	8.3 ± 4.4	-13.4 ± 4.3	GPS1837 / OCM2019	2003 / 2019	16 y	A/C
Saipan	DG3974	11.9 ± 1.9	-17.9 ± 1.9	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Saipan	DG3961	12.0 ± 2.0	-18.0 ± 2.1	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Saipan	DG3982	12.7 ± 2.1	-19.2 ± 2.2	GPS1837 / GC2017 / OCM2019	2003 / 2017 / 2019	16 y	A/B/C
Saipan	DG3940	12.8 ± 2.4	-18.2 ± 2.5	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Saipan	DE7041	13.2 ± 2.2	-18.1 ± 2.3	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Saipan	AA4415	13.0 ± 4.0	-18.3 ± 4.2	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Saipan	DG3969	13.7 ± 2.5	-18.4 ± 2.6	GPS1837 / GC2017	2003 / 2017	14 y	A/B
Saipan	DE7924	12.1 ± 2.6	-17.4 ± 2.7	GPS1837 / OCM2019	2003 / 2019	16 y	A/C
Saipan	DF9780	12.9 ± 1.0	-18.1 ± 1.0	CORS (CNMR)			
Saipan	AJ6944	11.1 ± 60.9	-17.9 ± 69.6	CORS (CNMI)			
Sarigan	DK2824	-0.3 ± 3.7	-22.6 ± 4.2	GPS2394 / GC2017	2003 / 2017	14 y	A/B
Alamagan	DK2819	13.6 ± 4.0	-27.4 ± 3.6	GPS2394 / GC2017	2003 / 2017	14 y	A/B
Pagan	AA5095	14.8 ± 1.8	-26.0 ± 1.9	GPS2394 / GC2017	2003 / 2017	14 y	A/B
Agrihan	DK2827	11.2 ± 3.3	-33.7 ± 4.4	GPS2394 / GC2017	2003 / 2017	14 y	A/B
Asuncion	DK2820	15.9 ± 3.0	-36.2 ± 3.8	GPS2394 / GC2017	2003 / 2017	14 y	A/B

The outliers (flagged in red) in the above table were determined through an iterative 2-sigma outlier rejection criteria for the islands of Guam, Rota, Tinian and Saipan. It is curious to note that this new outlier rejection, as applied to

ITRF2014 rather than ITRF2008 positions and velocities led to the rejection of some new outliers while re-integrating some velocities that had previously been flagged as outliers in the ITRF2008 study.

Here are the outlier changes since the ITRF2008 study:

As before:

1) Agrihan's VN is not in agreement with the other northern islands, but its geographic importance was seen as too important to drop.
2) Sarigan's VN is also out of agreement, but to such a degree that it must be dropped as an outlier.
3) Guam's DH3029 remains an outlier

Changes to ITRF2008 velocities

1) Guam's AA4393 and TW0537 are no longer outliers (giving the only 20 year velocities in the study)
2) Saipan's DG3029, after acquiring a 3rd occupation, now has a velocity that is an outlier
3) CORS "CNMI" on Saipan is no longer an outlier
4) All of these gained a 3rd occupation and an updated velocity that remains viable: DH3102 (Guam), AA4404 (Rota), DG4108 (Tinian), AA4411 (Tinian), DG3974 (Saipan), DG3961 (Saipan)

New Velocities:

1) Rota's DE7086 gained a 2nd occupation leading to a viable velocity
2) Tinian's DE6136 gained a 2nd occupation leading to a viable velocity
3) Saipan's DE7924 gained a 2nd occupation leading to an outlier velocity

It is encouraging to see all four CORSs agree with the campaign based velocities, and also for CORS "CNMI" to no longer have an outlier velocity (though its standard deviation, based only on 3 years of data, remains large.

As in the ITRF2008 report, the Variance Component Model (VCM; Schaffrin and Snow, 2017b) was used to solve for the Euler pole parameters while simultaneously solving for the a-posteriori variances of unit weight for the campaign-based velocities and the CORS-based velocities. This led to the standard deviations reported in Table 7. However, the variances of unit weight, as determined in ITRF2008 versus ITRF2014 are substantially different. This will be examined next.

10.3 Formal uncertainties and variance components: ITRF2008 vs ITRF2014

The use of the VCM in both ITRF2008 and ITRF2014 allowed the LSA engine to not only solve for the three Euler pole parameters, but it solved for the variance of unit weight of the input discrete-based velocities separately from that of the CORS-based velocities. A cursory look at the standard deviations associated with the velocities (Part 1, Table 2 and Part 2, Table 7) shows that they are in good general agreement with one another. To be exact, the a-posteriori (scaled by the variance of unit weight) standard deviations of the discrete-based velocities in ITRF2014 are smaller than those in the ITRF2008 study by a factor of 0.78. Further, the CORS-based a-posteriori standard deviations are effectively identical between studies (ignoring CNMI with its short data span), though the ITRF2014 standard deviations are just slightly larger than ITRF2008 values by a factor of 1.03.

This would seem reasonable agreement between the two studies, and it is, but what hasn't been mentioned yet is the vast difference between the variances of unit weight between the ITRF2008 and ITRF2014 study which led to these a-posteriori standard deviations. This information is found in Table 8.

Table 8: A comparison of variances of unit weight between the ITRF2008 and ITRF2014 studies

	Discrete-based VUW	CORS-based VUW
ITRF2008	1643.95	20.74
ITRF2014	6203.33	199.17
ITRF2014/ITRF2008	3.773	9.603
Square Root	1.943	3.099

What Table 8 tells us is that from ITRF2008 to ITRF2014, the formal positioning estimates (standard deviations of the ITRF X, Y and Z coordinates coming from OPUS-Projects) are about 2 times smaller (more optimistic) compared to those computed in the ITRF2008 frame for the previous study, and that the CORS-based velocities are about 3 times smaller (more optimistic) than those in the ITRF2008 study. Considering that in ITRF2008 the variance of unit weight for discrete-based velocities was 1643.95, this meant that already in ITRF2008 things were too optimistic by a factor of about $\sqrt{1643.95} = 40.5$. Doubling that already-too-large optimism, to a factor of $\sqrt{6302.33} = 78.76$, was an unfortunate step backwards in providing realistic uncertainty estimates out of OPUS.

As the cause and need to remove this over-optimism has been discussed before, no further discussion on the topic will ensue. However, as the VCM corrects for this error, in the end, the EPP results coming from this study remain sound, with realistic error estimates.

11 Computing the Euler pole parameters

Within the VCM, the LESS for the Euler pole parameters for the Mariana plate in the ITRF2014 frame have been determined, and are listed in Table 9.

Table 9: Euler pole parameters for the Mariana Plate in ITRF2014

EPP	Source	Lat	Lon	$\dot{\omega}_0$ Deg/My	$\dot{\omega}_0$ mas/y	$\dot{\omega}_x$ mas/y	$\dot{\omega}_y$ mas/y	$\dot{\omega}_z$ mas/y
Mariana (absolute)	**This paper**	**12.141 ± 0.144**	**143.723 ± 0.105**	**2.851 ± 0.145**	**10.263 ± 0.522**	**-8.089 ± 0.416**	**5.937 ± 0.288**	**2.159 ± 0.133**

Unfortunately no other studies seem to currently exist which have attempted to estimate the Mariana rotation in ITRF2014 (Kreemer, personal communication.) As such, there is no direct comparison with which this estimate may be made. Comparing this estimate to those in ITRF2008 is disingenuous considering the already evidenced differences just from changing the frame.

One conclusion is interesting from this study – the Euler pole itself has moved both north and east from its ITRF2008 estimated position, closer to Guam and situated more firmly on the Mariana plate itself. This makes sense relative to the conclusion in Part 1 of this report that Guam is “pinched” between the Mariana trench and the Mariana trough and is possibly not undergoing rigid body rotation. If Guam is more deforming than it is rotating, it serves as a sort of foci about which the rest of the plate rotates. Having the Euler pole nearer to Guam definitely shores up that interpretation.

11.1 Examination of residuals

It may prove useful to investigate the residual velocities in this study versus those in ITRF2008 to see if certain assumptions from the ITRF2008 study held up, such as the detection of back arc spreading and whether the residuals as a whole show a sign of reduction.

Figure 5 shows the residual velocities after removing the Euler rotation in ITRF2014. A comparison with Figure 3 shows a great deal of similarity, but some marked differences. In order to focus on those differences, an examination of the four southern islands will be presented. Figure 6 shows a side by side comparison of residuals for Guam, Rota, Tinian and Saipan in the two studies (ITRF2008 and ITRF2014).

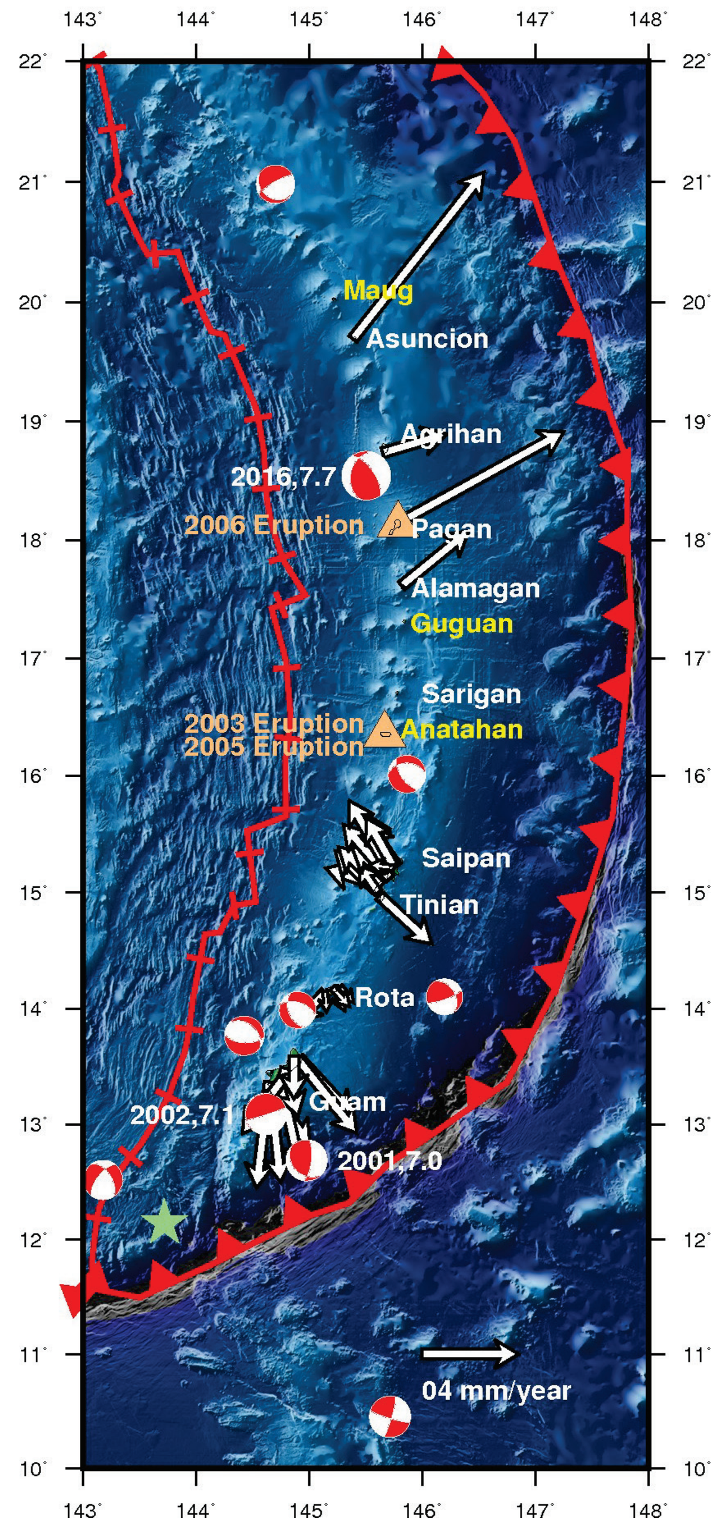
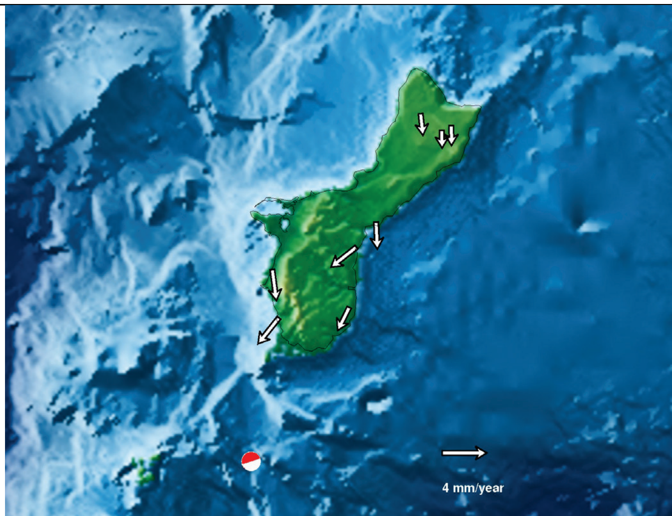
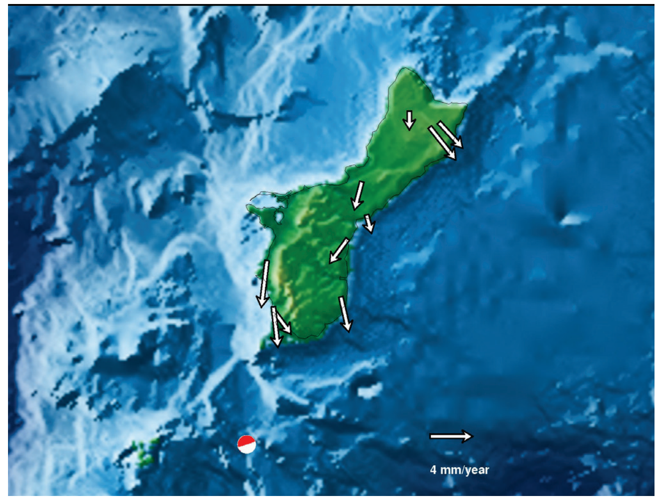
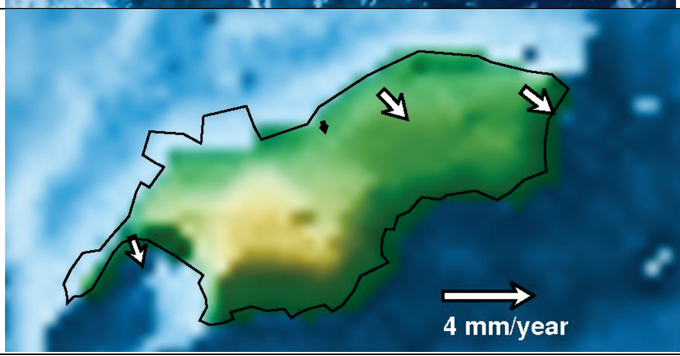
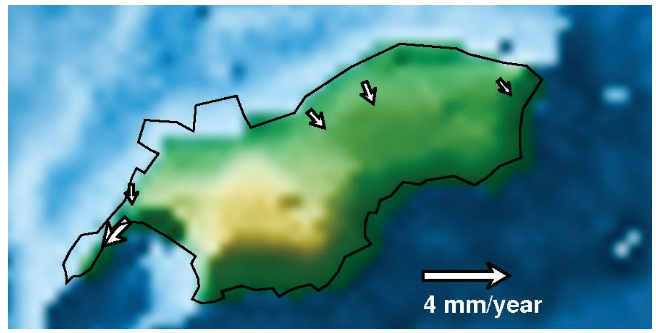
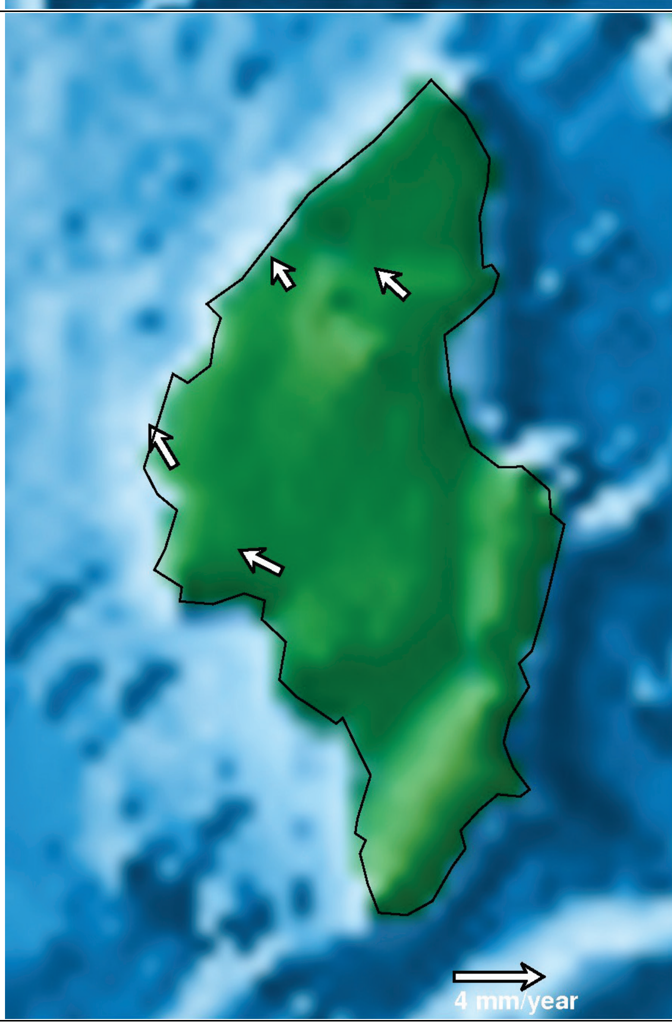


Figure 5: Residual horizontal velocities in ITRF2014 after removal of Euler pole rotation (no outliers shown), with major seismic events of the last 20 years. Earthquakes greater than Mw 7.0 are labeled. The green star is the Euler pole computed in this paper.

Island	ITRF2008	ITRF2014
Guam		
Rota		
Tinian		

Saipan

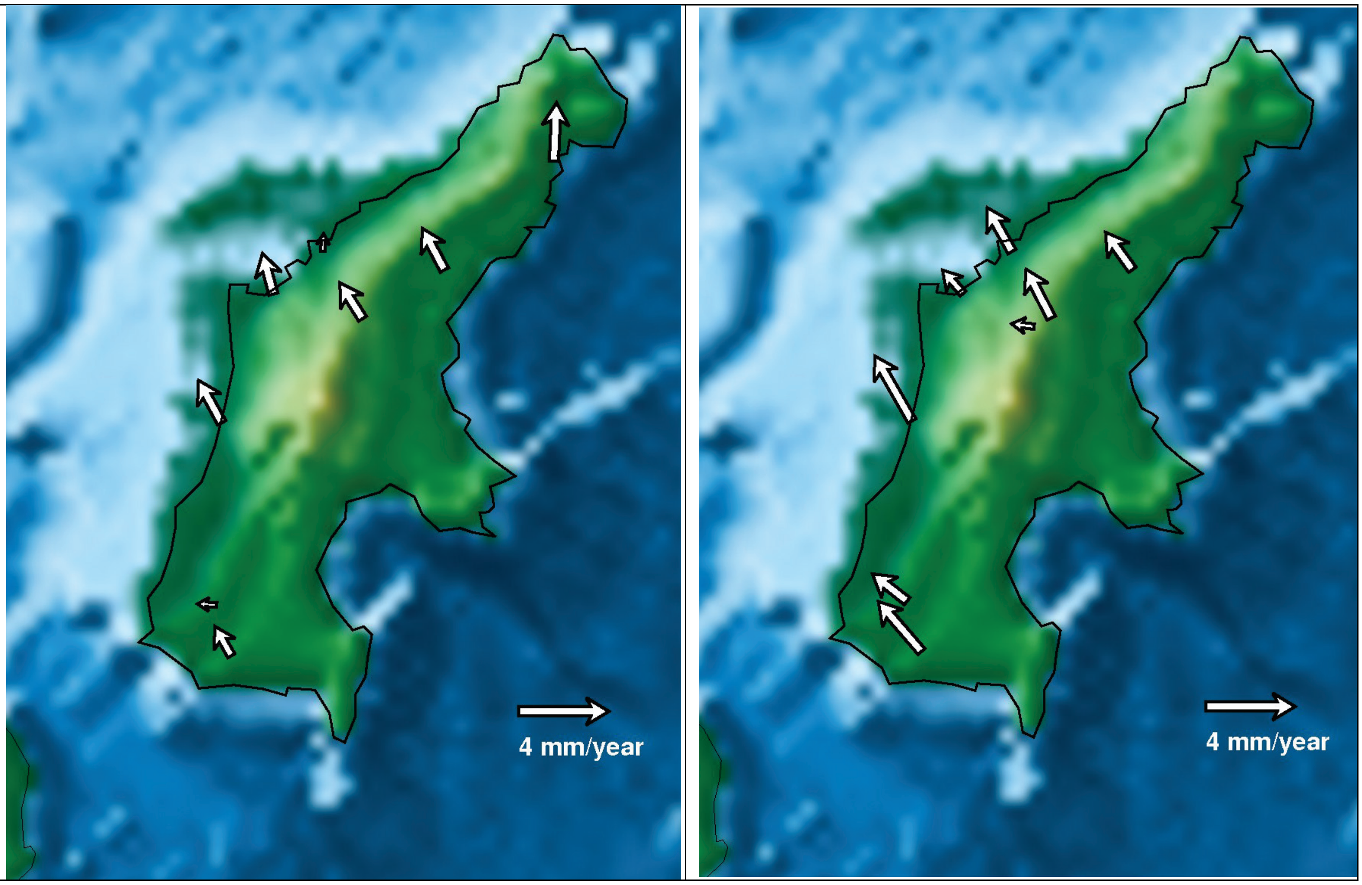


Figure 6: Island-by-island residual comparison, ITRF2008 versus ITRF2014

Certain commonalities and certain differences can be seen between the residuals in Figure 6. The separation signal between the Guam/Rota group (trending south) and the Tinian/Saipan group (tending north) remains the same in both studies, though Tinian now has one outlier residual trending south. As this outlier is a new point that just barely fit within the 2 sigma outlier rejection criteria itself, it does not significantly detract from the argument that there is a spreading signal happening on the plate, with a central location between these two island groups. Looking, as was done in the ITRF2008 study, at the north residual on Asuncion, the south residual on Guam and their distance apart, these data imply an extension rate of 1.43×10^{-8} / yr which agrees well with both Part 1 of this report (1.5×10^{-8} / yr) and the Kato (2003) value (1.43×10^{-8} / yr).

Numerically, the average velocities and their residuals in ITRF2014 are (compare this with Table 4 in Part 1):

Table 10: Absolute and (non-Eulerian) residual horizontal velocity magnitudes by island(s) in ITRF2014

Island(s)	Average observed velocity	Average residual velocity
Guam	7.3 mm/y ± 1.4 mm/y	3.1 mm/y (42.5 %)
Rota	13.2 mm/y +/- 0.3 mm/y	1.1 mm/y (8.3 %)
Tinian	19.9 mm/y +/- 2.4 mm/y	2.3 mm/y (11.6 %)
Saipan	22.1 mm/y +/- 0.6 mm/y	2.2 mm/y (10.0 %)
Northern Islands	33.9 mm/y +/- 4.5 mm/y	5.8 mm/y (11.1 %)

12 Summary and Conclusions

A new set of Euler pole parameters (EPPs) for the Mariana plate have been determined within the ITRF2014. The EPPs were determined in much the same way as earlier for ITRF2008, but with two new surveys and update ITRF2014 coordinate functions at CORSs.

The new Euler Pole agrees well with the ITRF2008 pole, but is now closer to Guam, which has meant that removing the rotational velocities has not significantly reduced the overall observed velocities on that island. The new pole does maintain a generally 90% (88% to 92%) removal of velocities from Rota, Tinian and Saipan and has improved residuals slightly in the northern islands of CNMI.

13 Data

All velocity data used in this paper are found in Table 2 and Table 7. Additional metadata about each point can be found at the National Geodetic Survey (NGS) website (https://www.ngs.noaa.gov/cgi-bin/ds_pid.prl/1) organized by PID. The velocities were derived from GPS observation files which are stored in the archives of NGS, according to project number. While no automated tool exists to extract this raw data, it is available to the public through requests sent to the NGS information center: *ngs.infocenter@noaa.gov*.

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15 Appendix B : Marks with a single GPS Occupation in Guam/CNMI in NGS archives

The primary purpose for NGS computing the rotation of the Mariana plate is to support the forthcoming MATRF2022 reference frame. One way to improve the EPP determination could be through additional surveys on passive control. To facilitate such future surveys, the table below is a list of marks with just a single geodetic quality GPS occupation in the Guam and CNMI region that are in NGS archives, at a date after 1994.

Table 11: Marks with only 1 historic geodetic quality GPS occupation after 1994, and thus no velocity. Marks in red are assumed destroyed.

Designation	PID	Island	Survey	Year
AGRIHAN AZIMUTH MARK	DK2818	Agrihan	GPS2394	2003
1 C 25	DH3084	Guam	GPS1987	2004
163 0000 TIDAL 11	AA4394	Guam	GPS1987	2004
GGN 0012	DH2969	Guam	GPS1987	2004
GGN 1969	DH3070	Guam	GPS1987	2004
GGN 0001	DH3104	Guam	GPS1987	2004
CRUSHER	TW0376	Guam	GPS1987	2004
TAMUNING	TW0402	Guam	GPS1987	2004
BARRIGADA	TW0465	Guam	GPS1987	2004
MACAJNA	TW0504	Guam	GPS1987	2004
AGANA MONUMENT	TW0516	Guam	GPS1987	2004
YIGO GG	TW0420	Guam	GPS1987	2004
VILLAGE GG	TW0437	Guam	GPS1987	2004
SABLAN CASTRO	DH3061	Guam	GPS1987	2004
GGN 2583	DH3035	Guam	GPS1987	2004
GGN 2256	DH3071	Guam	GPS1987	2004
GGN 1962	DH3070	Guam	GPS1987	2004
GGN 1218	DH2991	Guam	GPS1987	2004
GGN 1217	DH2990	Guam	GPS1987	2004
CUB	TW0509	Guam	GPS1987	2004
ARP GUM	DH3067	Guam	GPS1987	2004
GGN 2623	DQ3229	Guam	GPS3070	2013
GGN 1453	DH2997	Guam	GPS2493	2007
GGN 1467	DH3097	Guam	GPS2493	2007
DSC 1	DK7596	Guam	GPS2493	2007
163 0000 TIDAL 4	TW0041	Guam	GPS2492	2008
GGN 1215	DH2989	Guam	GC2017	2017
163 0000 TIDAL 5	TW0042	Guam	GC2017	2017
ED 1	DH3095	Guam	NGA2019	2019
163 0000 V	DQ9504	Guam	NGA2019	2019
MAUG	DK2822[3]	Maug	GPS2394	2003
MAUG[4]	DQ9502	Maug	GC2017	2017
MAUG RM 2	DQ9503	Maug	GC2017	2017
ROP B	AA4401	Rota	GPS1837	2003

[3] During the GC2017 survey, this mark was searched for but not found. Based upon its position and descriptive data, the field crew concluded that it had likely eroded and fallen into the sea.

[4] See the line above, where an identical designation is used. This happens frequently with geodetic control marks. A "designation" is not unique, while a PID is.

GRO C	AE4364	Rota	GPS1837	2003
TAM 1	DG4003	Rota	GPS1837	2003
ICM JR	DG4017	Rota	GPS1837	2003
TAM 5	DG4023	Rota	GPS1837	2003
SATO 6	DG3926	Saipan	GPS1837	2003
KRD 6	DG3949	Saipan	GPS1837	2003
163 3227 UH 26	DG3988	Saipan	GPS1837	2003
TIDAL 1	AA4407	Tinian	GPS1837	2003
DAGU	DG4133	Tinian	GPS1837	2003
TAM 10	DG4136	Tinian	GPS1837	2003