The North America Reference Frame (NAREF) Project to Densify the ITRF in North America

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BIOGRAPHY

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ABSTRACT

Since the beginning of 2001, the Geodetic Survey Division of Natural Resources Canada (NRCan) has been playing a leading role in the North American Reference Frame (NAREF) Working Group of IAG Sub-commission 1.3c (Regional Reference Frames for North America) in support of the International Earth Rotation and Reference Frames Service (IERS) and International GNSS Service (IGS) initiatives to densify the International Terrestrial Reference Frame (ITRF) in North America. The goal is to provide a consistent reference frame, including velocity models, procedures and transformations, tied to ITRF in which scientific and geomatics results (e.g., positions in tectonically active areas) can be produced and compared. The NAREF densification network has evolved from a hundred continuously operating GPS reference stations to nearly 1000. Several groups in Canada and the U.S. provide weekly coordinate solutions which are combined together in an official NAREF solution that is aligned with the ITRF reference frame of date. These combination solutions are available to the public via the IGS archives with a latency of about 4 weeks. In addition, we have also begun to estimate annual velocity solutions based on the weekly coordinate solutions. The first of these was contributed to the ITRF2005 densification effort currently underway. The resulting velocity field has been used to evaluate crustal deformations in various parts of the continent and to more accurately determine the motion of stable North America. The previous version has been used to define a plate-fixed Stable North American Reference Frame (SNARF) for the Plate Boundary Observatory component of the EarthScope project. This new, high accuracy reference frame may eventually supersede NAD83. Based on six years of experience, we discuss several factors that affect the quality of our solutions, including monumentation, equipment changes and various kinds of biases and noise. We also describe changes in our processing and combination strategies in response to new procedures adopted by the IGS. Finally, future plans for reprocessing all solutions will be presented.

INTRODUCTION

The International Association of Geodesy (IAG) is undergoing growth and evolution, particularly in providing and coordinating geodetic services. The most important service to the GPS community is the International GGNS Service (IGS), formerly the International GPS Service, which promotes international standards for the GGNS data acquisition and analysis, deploys and operates a global GGNS tracking network, and distributes GGNS data and data products, such as precise orbits, clock estimates and coordinate solutions in the International Terrestrial Reference Frame (ITRF). In an effort to densify the International Terrestrial Reference Frame (ITRF), the IGS initiated in 1996 a program of distributed regional processing to better manage the computational load. In 1999 the North American Sub-commission of IAG Commission X (Global and Regional Geodetic Networks) formed a North American Reference

Frame (NAREF) Working Group to promote and coordinate such regional processing in North America. This organizational structure was redefined in 2003 with the NAREF Working Group falling under the Regional Sub-commission 1.3c for North America in Sub-commission 1.3 (Regional Reference Frames). This current structure is depicted in Figure 1.

The objectives of NAREF Working Group are to:

- Densify the ITRF reference frame in North America, in both a temporal as well as spatial sense in order to provide a kinematic description of the Earth's shape as it changes.
- Produce coordinate solutions in IGS SINEX format [IGS, 1996]. Specifically, weekly combinations of submitted regional solutions as well as cumulative solutions with velocity estimates.
- Make data and results available to public through Internet-based archives.
- Study the effects of crustal motion, including tectonic deformations along, e.g., the west coast of North America and in the Caribbean, and post-glacial rebound.

The IGS densification of its global network is based on so-called distributed regional processing, whereby different regional networks are processed separately and later combined with the global network (Blewitt et al., 1998). This is necessary to better manage the computational load required to handle hundreds of stations.

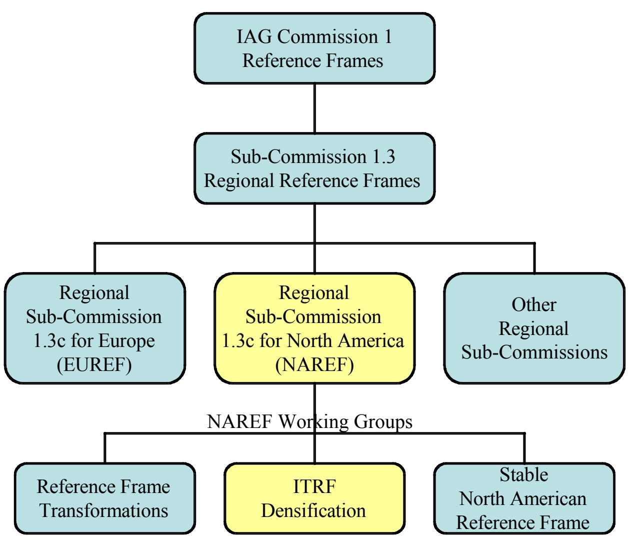

Figure 1: Organizational structure of the IAG Sub-Commission 1.3 and Regional Sub-Commission 1.3c for North America.

To further reduce the effort required to combine many small regional networks into a single global one, IGS Regional Network Associate Analysis Centers (RNAACs) such as NAREF are tasked with combining these smaller networks into larger continental-scale networks. Each RNAAC is also responsible for integrating their combination networks into the IGS global network.

NAREF REGIONAL SOLUTIONS

At the present time, six regional solutions are being contributed to the NAREF network. The stations included in each solution for GPS week 1399 are shown in Figure 2.

The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) provides two different weekly solutions. The larger solution covers the entire northern half of North America. It is comprised of 113 stations from a variety of regional, provincial and national networks, including all IGS stations in the northern half of the continent. This solution is obtained using the Bernese GPS Software and is denoted here as GSB.

The second GSD solution covers only Canada and includes a total of 43 stations. This solution is produced using the GIPSY-OASIS II software and is denoted here as GSG.

The Geological Survey of Canada Pacific Division (GSC-Pacific) of NRCan provides weekly solutions covering the Pacific Northwest. It includes 52 stations belonging to the Western Canada Deformation Array (WCDA), the Pacific Northwest Geodetic Array (PANGA), and the British Columbia Active Control System (BCACS). These data are processed using the Bernese GPS Software and denoted as PGC.

The U.S. National Geodetic Survey (NGS) contributes weekly solutions of most Continuously Operating Reference Stations (CORS) in the continental US, Caribbean, Central America, Hawaii, as well as a few Canadian stations. There are more than 760 stations as of GPS week 1399 (November 2006) but only 550 are included in NAREF due to current limitations of the combination software. This subset solution is denoted here as NGS.

The Scripps Orbit and Permanent Array Center (SOPAC) provides daily solutions that cover the western part of the continental U.S. and southwest Canada. The daily solutions consist of approximately 700 stations of which only 150 are combined into a weekly solution for contribution to NAREF. This subset solution is denoted as PBO.

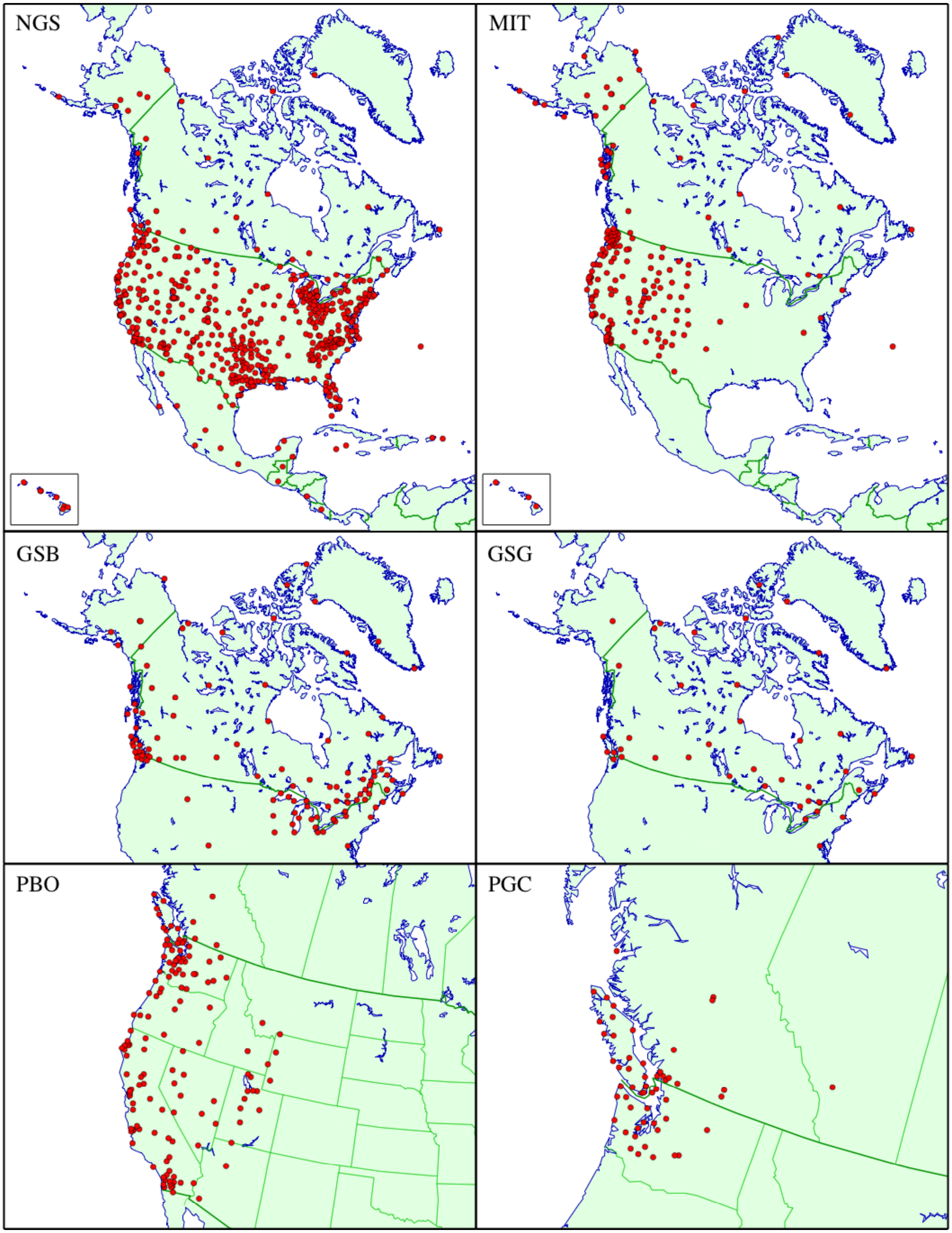

Figure 2: Contributions to the NAREF densification network for GPS week 1399: NGS) U.S. National Geodetic Survey CORS network of subset of 550 stations; MIT) MIT PBO network of subset of subset of 185 stations; GSB) GSD Bernese GPS Software network of 113 stations; GSG) GSD GIPSY network of 43 stations; PBO) SOPAC preliminary PBO network of subset of 150 stations; PGC) GSC-Pacific network of 52 stations.

Finally, the Massachusetts Institute of Technology (MIT) publishes official daily solutions for the Plate Boundary Observatory containing about 670 stations. A subset of 185 of these stations is combined into weekly solutions for use in the NAREF network. This subset solution is denoted here as MIT.

NAREF WEEKLY COMBINATION PROCEDURE

The six regional solutions described above are combined on a weekly basis into a single NAREF combination. Some overlap among these networks provides redundancy for checking for outliers and enables the determination of correct relative weighting of the different solutions with respect to each other and to the global IGS weekly solution.

The weekly NAREF combinations are produced using GSD's SINEX Software by Rémi Ferland, the IGS Reference Frame Coordinator. It is the same software suite used to produce the weekly IGS combinations and cumulative solutions. The weekly combination strategy is also modeled after the procedure used by the IGS Reference Frame Coordinator to produce the official weekly IGS global combination. It is divided into two main parts. The first part produces the unconstrained NAREF combination and consists of the following steps:

1) Constraints used in each regional solution are removed.
2) Each regional solution is aligned to a subset of stations from the IGS weekly solution of same week using a 7 parameter transformation.
3) Each regional solution covariance matrix is scaled by the weighted root mean square (WRMS) of the residuals from the transformation in step 2. Typical scale factors are given in Table 1 for GPS week 1399.
4) Residuals are tested for outliers which are removed from the regional solution and steps 2-4 are repeated again until no outliers remain in any solutions.
5) All regional solutions are combined together by summation of normal equations to give a single combination solution.
6) The combined solution is re-aligned to the IGS weekly solution of the same week using a 7 parameter transformation.
7) The covariance matrix of the combined solution is scaled by the WRMS of residuals from the transformation in step 6.
8) Residuals are tested for outliers which are removed from the regional solutions and steps 2-8 are repeated until no outliers remain in the combined solution.

The second part of the combination imposes the reference frame constraint that provides a solution integrated into the IGS weekly solution. A minimum constraint integration can be obtained by constraining a priori a single station to its coordinates and weights from the IGS weekly solution. A more fully integrated solution is obtained using a subset of common IGS stations from the IGS weekly solution.

To avoid possible problems with undetected outliers in the solutions, each weekly NAREF combination solution is compared with that from the previous week. Any large discrepancies are removed from the current regional solutions and the combination repeated from the beginning.

Redundancy is an important consideration in the combination for detection of outliers and to ensure reliable alignments and covariance matrix scaling. Unfortunately, in the NAREF weekly combinations only a small percentage of the stations have redundant solutions; i.e., solutions in more than one regional network. Table 2 gives the number of common stations between the different networks for a typical NAREF combination week (1399). Table 3 summarizes the number of stations with redundant solutions. Almost 70% of the stations have no redundant solutions.

Table 1: Covariance matrix scale factors for individual regional solutions.

Solution	Scale Factor
GSB	10.25168
GSG	2.40821
MIT	2.55631
NGS	23.95379
PBO	1.83934
PGC	2.20854

Table 2: Number of common stations between different regional networks.

Number of Common Stations						
Solution	**GSB**	**GSG**	**MIT**	**NGS**	**PBO**	**PGC**
GSB	112	43	28	45	16	20
GSG	43	43	17	38	8	9
MIT	28	17	183	121	99	25
NGS	45	38	121	569	99	19
PBO	16	8	99	99	140	37
PGC	20	9	25	19	37	55

Table 3: Number stations with redundant solutions.

	Number of stations	Percentage
Total	708	100%
In 1 solution	488	69%
In 2 solutions	94	13%
In 3 solutions	95	13%
In 4 solutions	21	3%
In 5 solutions	7	1%
In 6 solutions	3	0.4%

NAREF WEEKLY COMBINATION RESULTS

A total of 305 weekly NAREF combinations solutions have been computed for GPS weeks 1095 (Jan 2001) to 1399 (Oct 2006) using the above procedure.

The internal fit of each of the weekly solutions can be described in terms of the RMS of the differences between each aligned regional solution and the final minimally constrained NAREF combination. The time series of these residual RMS values for each of the regional solutions is given in Figure 2, as well as the RMS of the differences between the NAREF and IGS weekly combinations.

Over all of these weeks the RMS of the residuals for each regional solution are less than 3 mm for north and east component and 5 mm vertically. It is worth noting that the RMS for PGC and MIT solutions looks better then the others (less then 1 mm for north and east component and around 2mm for vertical component). The reason for this is that the PGC solution covers only a very small region and the baseline lengths are much shorter than in other solutions. The MIT solution is a combination of solutions from the two PBO processing centers and is also aligned to the IGS, resulting in a more homogeneous solution than the other contributions.

The time series of the RMS fits of the final NAREF weekly combinations with respect to the IGS weekly combinations are given in Figure 3 for both the minimally constrained and over-constrained solutions. The north and east component RMS of these differences vary from about 1-3 mm for the minimally constrained solutions and 1-2 mm for the overly-constrained solutions. The vertical RMS is around 7 mm for minimally constrained and around 4 mm for over-constrained solutions. Realizing that the noise level of the IGS weekly solutions is of the order of a few mm, the NAREF weekly combinations can be considered statistically compatible with the IGS combinations.

NAREF CUMULATIVE SOLUTION AND VELOCITY ESTIMATION STRATEGY

The NAREF weekly combination solutions can themselves be combined together into a single so-called “cumulative” solution with velocity parameters used to model the linear rates of change of the coordinates for each station. In some cases the time series of coordinates for a site contains offsets or discontinuities due to, e.g., changes in equipment that introduce biases in the coordinates. At such stations more than one set of coordinate and velocity components are estimated; one before and one after each discontinuity. The multiple coordinate and velocity solutions at these stations can later be constrained to be equivalent to each other unless there is good reason to expect them to be different; e.g., after earthquake-induced discontinuities.

The cumulative solution and velocity estimation strategy is modeled after the procedure used by the IGS Reference Frame Coordinator to produce the official IGS cumulative solution. It consist the following steps:

1) Constraints used in the NAREF weekly solutions are removed
2) Weekly solutions are aligned to a subset of 11 sites in the IGS realization of ITRF2005 (IGS05).
   - 7 parameter alignment of coordinates (3 translations, 3 rotations & scale change)
   - Alignment at each weekly epoch; i.e. coordinates of reference sites propagated to epoch of weekly NAREF solution.
4) All aligned weekly solutions are combined together in a cumulative solutions (summation of normals) and velocities are estimated
5) NAREF cumulative solution (coordinates and velocities) is re-aligned to subset of IGS05 coordinates and velocities.
   - 14 parameter alignment (3 translations, 3 rotations & scale change together with their respective rates of change).
6) Aligned NAREF cumulative solution is constrained to a subset of IGS05 coordinates and velocities.
7) Estimated velocities between discontinuities at each station are optionally constrained to be equivalent to each other.

NAREF CUMULATIVE SOLUTION AND VELOCITY ESTIMATION RESULTS

The cumulative solution and velocity estimation includes all weekly NAREF solutions up to and including GPS week 1399. Beginning with week 1400 the IGS changed its processing procedures to use absolute antenna phase center calibrations which created an significant offset in coordinates from previous solutions based on relative calibrations. It will be necessary to recompute all previous regional solutions and NAREF combinations using these new procedures once precise orbits based on absolute calibrations are available for this older data.

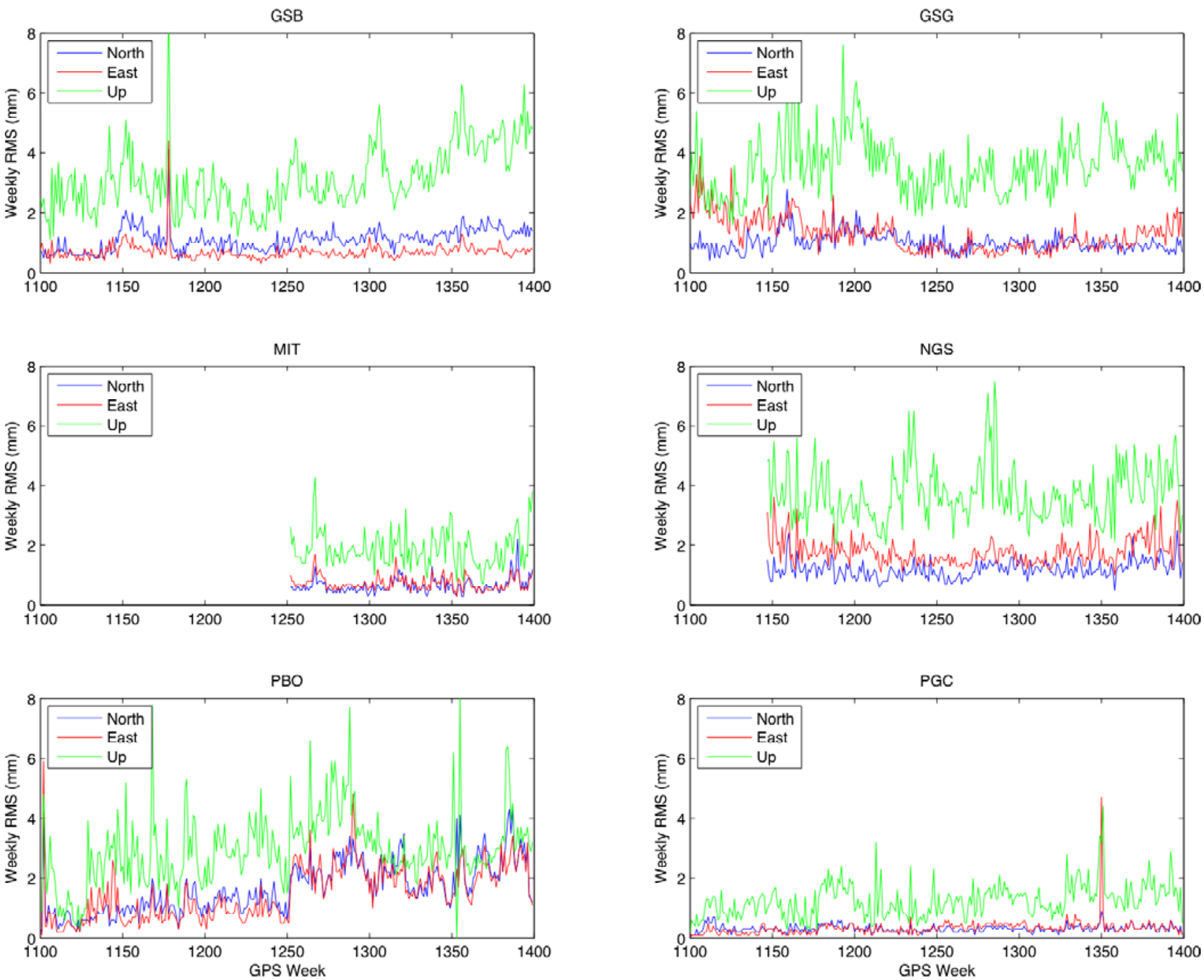

Figure 2: RMS of weekly regional solutions with respect to NAREF weekly minimally constrained solutions.

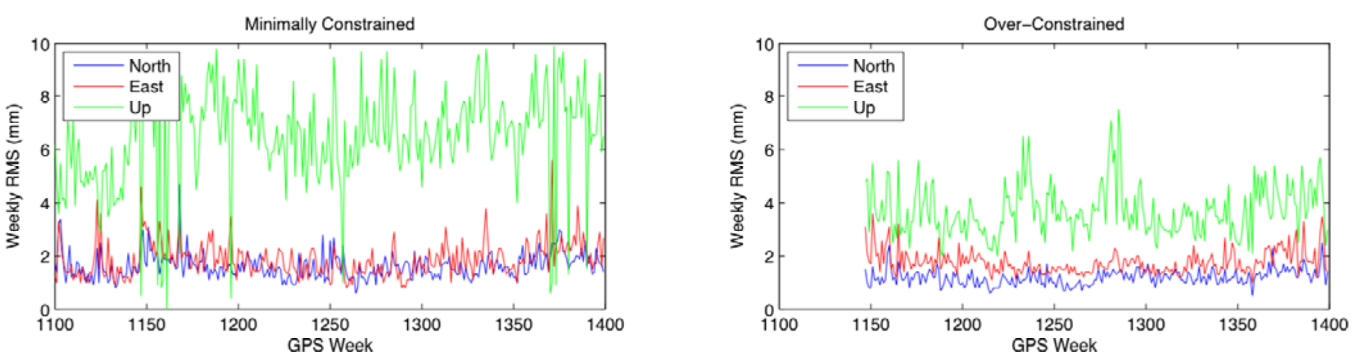

Figure 3: RMS of NAREF weekly solutions with respect to IGS weekly combinations.

Table 4: Descriptive statistics for the cumulative solution.

Number of input solutions	305
Time span (GPS Weeks)	1095-1399
Number of input coordinate obs.	119435 x 3
Total number of stations	906
Number of stations used	578
Number of coordinate parameters	4164
Degrees of freedom	354141

A total of 906 stations were available for the cumulative solution. To avoid unreliable velocity estimation approximately 260 stations with less than two years of data were omitted from the solution. Another 50 stations collocated with others at the same site (mostly redundant backups at U.S. Coast Guard sites) were removed to keep the number of parameters manageable. Finally, 20 other stations were excluded due to poor data quality (e.g., too many discontinuities, frequent data gaps, etc.) leaving a total of 578 stations in the cumulative solution. Table 4. summarizes some basic descriptive statistics of the cumulative solution.

The estimated horizontal velocities from this solution are plotted in Figure 4. The velocity field is dominated by the tectonic plate motion of North America. The residual velocities after removing the ITRF2005 estimate for North American plate motion are given in Figure 5. Nearly all of the horizontal velocities are removed indicating the NAREF velocities are in very good agreement with the ITRF2005 plate motion estimate. Although the patterns of tectonic deformation along the active plate margin of the west coast and Alaska are apparent, little horizontal intraplate motions remains for the more stable portion of the continent.

The estimated vertical velocities are plotted in Figure 6. The pattern of uplift in central Canada and subsidence around the periphery of maximum extent of the glacial ice margin agrees remarkably well with that expected from glacial isostatic adjustment (GIA). Similarly, the pattern of uplift along much of the west coast reflects the tectonic deformation occurring in that region. On the other hand, uplift in northern part of Louisiana remains to be explained.

FUTURE WORK

As mentioned above, the IGS began using absolute antenna phase center calibrations for all GPS stations and satellites beginning with GPS week 1400. This introduced a significant discontinuity at all stations. In addition, the IGS decided to use domes-specific phase center calibrations. Prior to week 1400 the same calibration was used for antennas with and without domes even though it is well-known that domes can cause phase center biases of a few cm. It will thus be necessary to reprocess all regional solutions and NAREF combinations using these new procedures to ensure consistency of the NAREF time series before and after GPS week 1400. The IGS has just begun regenerating older precise orbits and we expect to begin a NAREF reprocessing effort shortly thereafter.

During this reprocessing effort we also plan to add more redundant solutions for as many stations as possible, especially those in the CORS network. Many CORS stations are only in the NGS regional solution and therefore have no independent quality control checks. SOPAC is planning to expand their PBO network to include as many of these CORS stations as possible to greatly improve the redundancy in the weekly NAREF combinations.

ACKNOWLEDGMENTS

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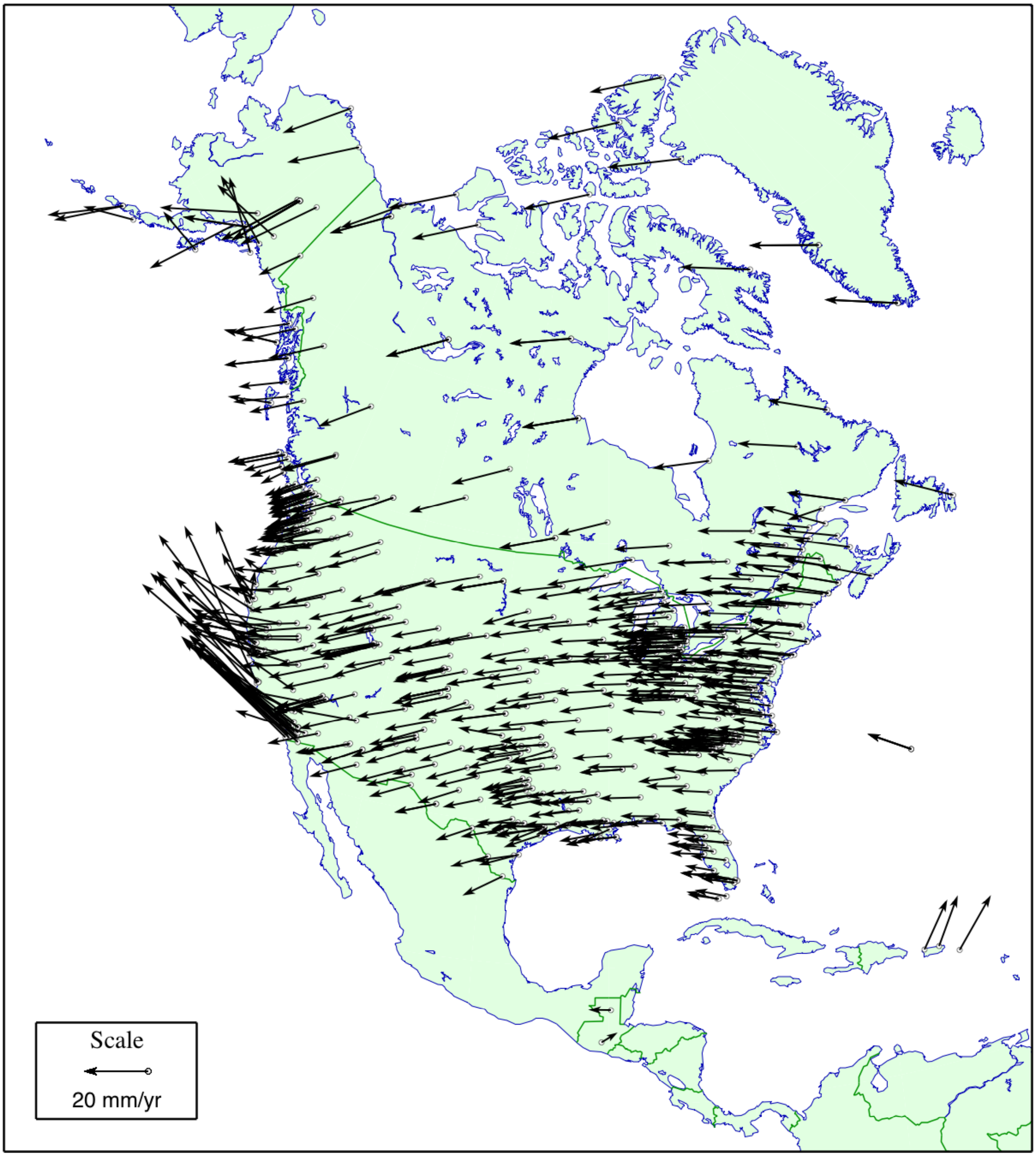

Figure 4: Horizontal velocities from NAREF cumulative solution.

Figure 5: Residual horizontal velocities from NAREF cumulative solution after removal of ITRF2005 plate motion.

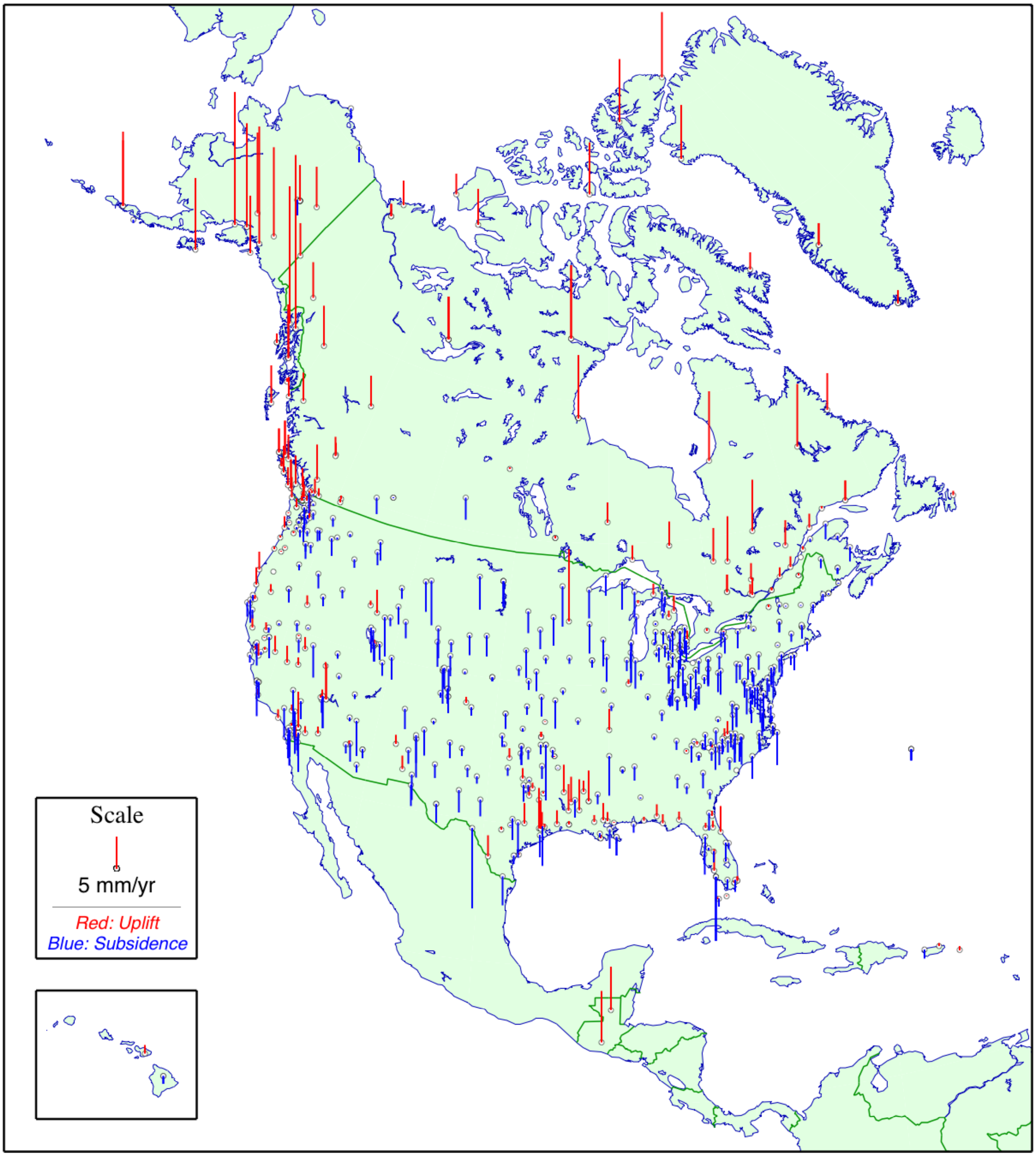

Figure 6: Vertical velocities from NAREF cumulative solution.