The North American Reference Frame (NAREF): An Initiative to Densify the ITRF in North America

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BIOGRAPHY

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ABSTRACT

In an effort to densify the International Terrestrial Reference Frame (ITRF), the International GPS Service (IGS) initiated a program of distributed regional processing to better manage the computational load. The North American Sub-commission of the International Association of Geodesy (IAG) Commission X (Global and Regional Geodetic Networks) has recently formed a North American Reference Frame (NAREF) Working Group to promote and coordinate such regional processing in North America. This coordination has involved the adoption of standards and guidelines for station selection, operation, data processing, archiving, redundancy, and the combination and integration of regional solutions within the ITRF and IGS global network. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by the European Reference Frame (EUREF) Technical Working Group, NAREF's sister group in Europe. Presently, two independent Canada-wide solutions from Natural Resources Canada's (NRCan) Geodetic Survey Division, a western Canada solution from NRCan's Geological Survey of Canada, Pacific Division, and a western U.S. solution from the Scripps Institution of Oceanography are being combined on a weekly basis into a single NAREF combination. Overlap among these regional networks provide redundancy checks and allow for the determination of correct relative weighting of the different solutions relative to each other. Solutions for new regional networks will be incorporated as they become available. Other solutions are also being actively sought for the rest of the U.S. and Mexico. These weekly solutions will soon be incorporated into the official IGS densification network on a regular basis and ultimately integrated into future realizations of the ITRF.

INTRODUCTION

The International Association of Geodesy (IAG) is undergoing growth and evolution, particularly in providing and coordinating geodetic services. The most prominent example of such services is the International GPS Service (IGS), which promotes international standards for GPS data acquisition and analysis, deploys and operates a global GPS tracking network, and distributes GPS data and data products, such as precise orbits, clock estimates and coordinate solutions in the International Terrestrial Reference Frame (ITRF) [Kouba et al., 1998; IGS, 2000]. In an effort to densify the ITRF, the IGS initiated a program of distributed regional processing to better manage the computational load [Kouba, 1996; Blewitt, 1996; Blewitt et al., 1998]. The North American Sub-commission of the International Association of Geodesy's Commission X has recently formed a North American Reference Frame (NAREF) Working Group to promote and coordinate such regional processing in North America (see http://www.naref.org/). This organizational 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. These data and results can then be used as additional IGS-type fiducial points for integrating surveys into ITRF and for scientific applications, such as studies of crustal motions.

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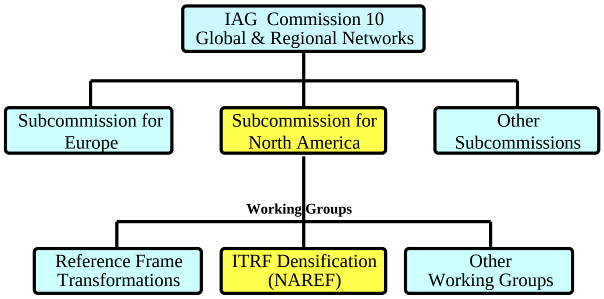

Figure 1: Organizational structure of the IAG Commission X Sub-commission for North America and its NAREF Working Group.

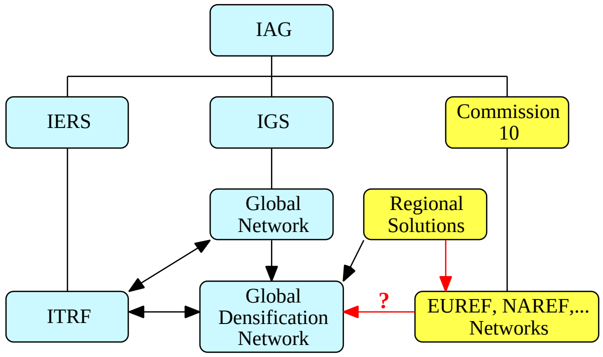

Figure 2: Data flow diagram of IGS distributed processing.

DISTRIBUTED PROCESSING APPROACH

The IGS densification of it's global network is based on so-called distributed regional processing, whereby different regional networks are processed separately and later combined with the global network. This is necessary to better manage the computation load required to handle hundreds of stations.

To further reduce the effort required to combine many small regional networks into a single global one, IGS Regional Network Associate Analysis Centers (RNAACs) are tasked with combining these smaller networks into a larger continental-scale networks. It's not yet clear whether the RNAACs will be responsible for integrating their combinations into the global network or whether this will be done by the IGS Global Network Analysis Centers or the IGS Reference Frame Coordinator. This process is illustrated in Figure 2.

STANDARDS

The selection of stations and solutions for NAREF combinations has involved the adoption of standards and guidelines for station monumentation, station operation, data processing, archiving and redundancy. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by the European Reference Frame (EUREF) Technical Working Group, NAREF's sister group in Europe. The following summarizes some of these standards we have employed.

The selection of stations has been limited to only dual frequency receivers that collect continuous 24 hr data at a 30 second data rate for a minimum of 5 days a week. These criteria have been determined primarily by the availability of CORS stations in the U.S. We prefer to have receivers collect data down to an elevation angle of 10° or less but this was not available for many CORS stations. We also limited our selection of stations to only those with reasonably stable, recoverable, geodetic-quality monumentation. We are considering include less stable monumentation, such as points on roofs or masts, but would need to classify stations accordingly. Finally, we also require complete and up-to-date station logs.

In order to provide some kind of quality check on the regional solutions to be combined, we would like to have all stations in more than one regional solution. This would allow for statistical compatibility tests for outlier detection. Any remaining differences would be reduced through averaging, thereby minimizing any anomalous effect one solution/software may have on the final result. Some people have referred to this as averaging out "software noise".

In order to ensure the best results possible, only solutions from state-of-the-art software have been considered for use in the combination. This includes software that is capable of estimating tropospheric zenith delays and horizontal gradients, modeling antenna phase center variations, resolving ambiguities on long lines and estimating solid Earth tides and ocean loading effects. Some examples of such software are GIPSY-OASIS II, GAMIT, Bernese GPS Software, MicroCosm and PAGES. These regional solutions should also follow, as much as possible, the processing strategies described in Rothacher et al. [1998]. In particular, fixed IGS precise orbits and Earth rotation parameters should be used for highest accuracy and reference frame consistency. The results must also be provided in the IGS SINEX format [IGS, 1996].

It has been difficult, if not impossible, to enforce such standards. Most regional solutions are performed by independent organizations with limited budgets and objectives that are often different from those of NAREF. We can only recommend these standards and use those meeting most of them.

REGIONAL SOLUTIONS

There are currently 4 solutions that are being contributed to NAREF since the beginning of 2001. Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD) presently provides two independent Canada-wide solutions. One is based on the Bernese GPS Software v4.2 with a total of 65 points, about half of which are in neighboring areas in the U.S. (see Figure 3). This solution is referred to here as "GSB". The other GSD regional network is based on the GIPSY-OASIS II software with a total of 27 points, mostly all in Canada (see Figure 4). This solution is referred to here as "GSG".

We have also obtained regional solutions from the Scripps Institution of Oceanography (SIO) based on the GAMIT software v9.72 for their Plate Boundary Observatory (PBO) consisting of about 300 points (see Figure 5). Only the 56 points in the northern half of the network were included in our NAREF combinations because of limitations in the number of stations our computer resources can presently handle. This will be rectified in the near future and the entire PBO will be included. This solution is referred to here as "PBO".

Finally, NRCan's Geological Survey of Canada, Pacific Division, at the Pacific Geoscience Centre (PGC) also submits a western Canada regional solution based on the Bernese GPS Software v4.2 with a total of 17 points belonging to their Western Canada Deformation Array (WCDA), along the west coast of Canada and northwestern U.S. (see Figure 6). This solution is referred to here as "PGC".

A summary of the software and processing options used for all these solutions is given in Table 1.

The total NAREF network containing all these regional ones is displayed in Figure 7. There are a total of 114 points of which 20 are existing IGS global stations and 94 represent the NAREF densification stations. Obviously, this represents only a northern NAREF network. More solutions are need for the U.S. and Mexico. Coverage should improve significantly once the U.S. National Geodetic Survey is able to provide weekly solutions for their CORS network of about 150 stations across the entire U.S. We also hope to obtain solutions for the Mexican permanent GPS networks of about a dozen points and a few stations in Greenland, thereby making the NAREF network truly North American in scale.

COMBINATION PROCEDURE

The above regional solutions are combined on a weekly basis into a single NAREF solution. Overlap among these networks provides redundancy checks for outliers and allows for the determination of correct relative weighting of the different solutions relative to each other. Clearly, redundant solutions are needed for the PBO network. This would improve significantly if we are able to obtain a CORS solution covering the entire U.S.

The following step-by-step procedure used to combine the regional solutions into a single NAREF solution is modeled after that used to produce the official weekly IGS global combinations.

Alignment of Each Regional Solution

1. A priori datum constraints are removed.
2. Solution is aligned to the IGS weekly solution of the same week using 3 translations, 3 rotations and a scale change.
3. Covariance matrix is scaled by the weighted root mean square (WRMS) of the residuals from the above transformation.
4. Residuals are tested for outliers. If any outliers are found, they are removed and steps 2 to 4 are repeated.

Combination of Regional Solutions

5. Regional solutions are combined together by summation of the normal equations for the (scaled) regional solutions.
6. Combined solution is aligned to IGS weekly solution of same week using 3 translations., 3 rotations and a scale change.
7. Covariance matrix is scaled by the WRMS of residuals from the above transformation.
8. Residuals are tested for outliers. If any outliers are found, they are removed from their solution and steps 2 to 8 are repeated (only steps 2 to 4 for the regional solution with the outlier needs to be repeated).
9. A minimum constraint is applied to the combined solution for further testing and comparison with the IGS weekly solution. Presently, IGS station DRAO is constrained to it's IGS97 coordinates and weights at the epoch of date to facilitate comparisons among all the solutions (it's the only station common to all solutions).

The above combination procedure is implemented using the SINEX Software v1.0 by Remi Ferland, IGS Reference Frame Coordinator. This is the same software used to produce the weekly IGS global combinations. These weekly solutions will soon be integrated into the IGS global network on a regular basis and ultimately into future ITRF realizations. After a year of solutions, cumulative solutions will also be generated and submitted

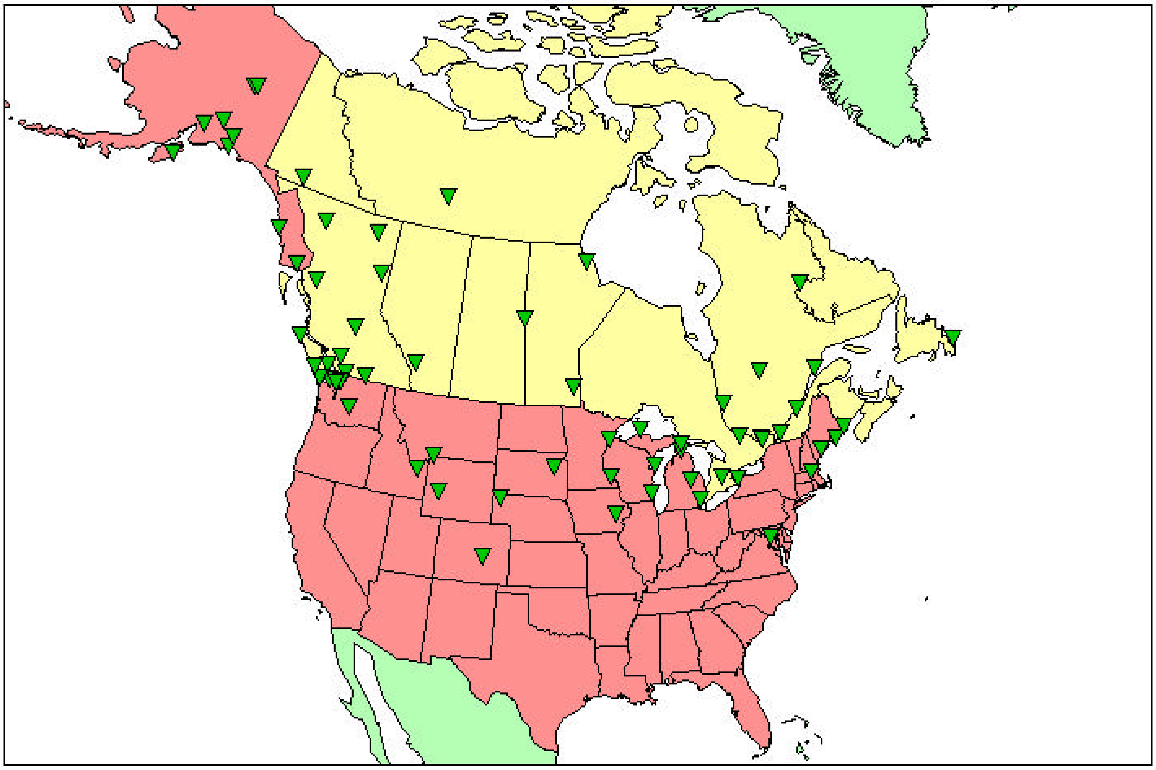

Figure 3: NRCan's Geodetic Survey Division Bernese regional network for Canada (GSB) – 65 stations.

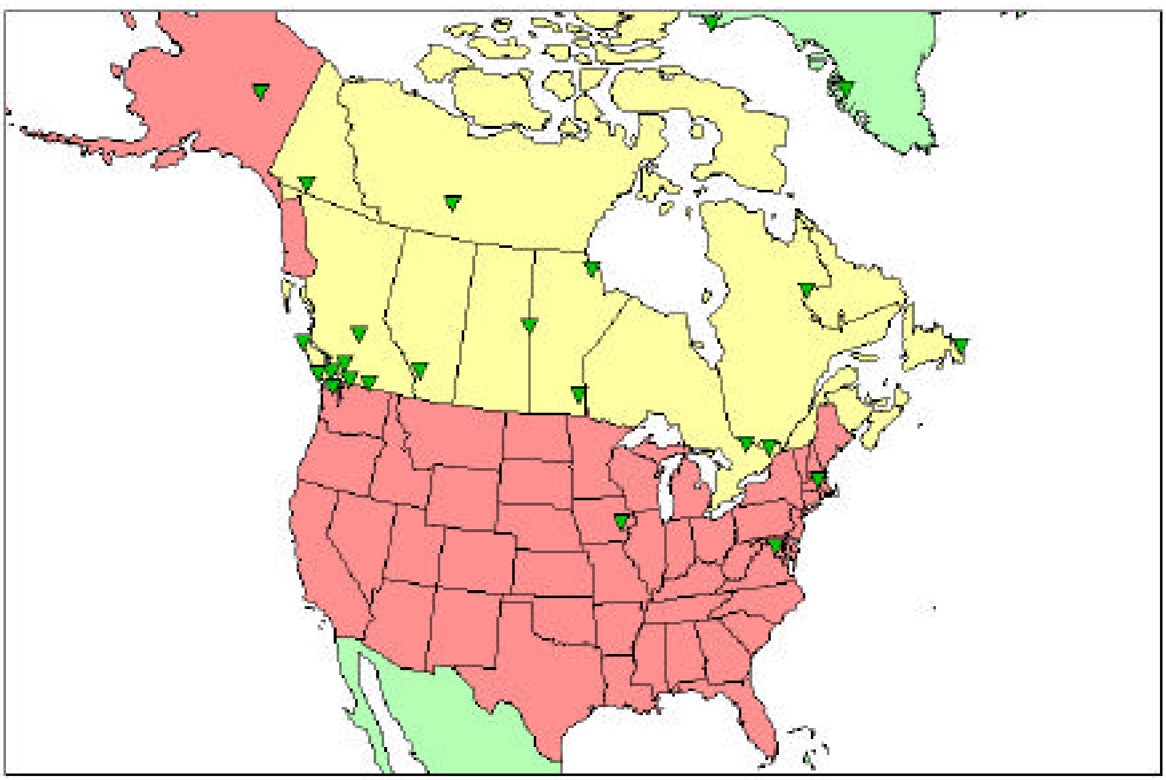

Figure 4: NRCan's Geodetic Survey Division GIPSY regional network for Canada (GSG) – 27 stations.

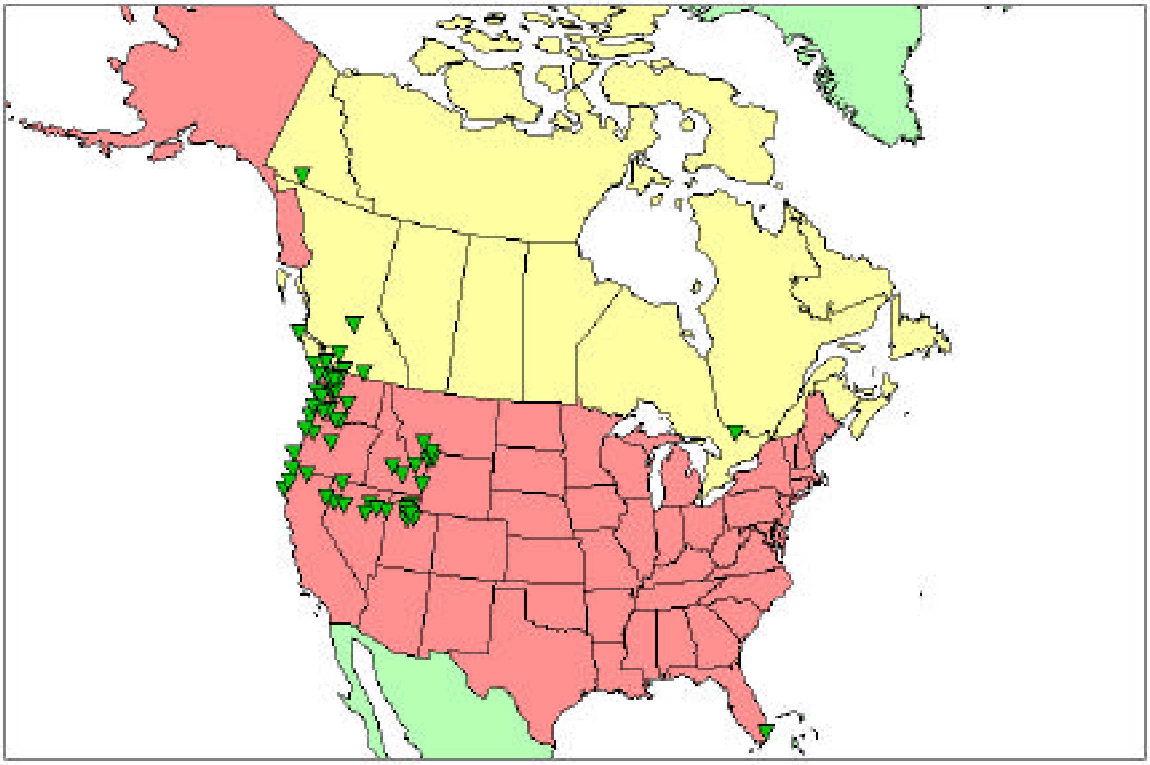

Figure 5: Scripts Institution of Oceanography Plate Boundary Observatory (PBO). Only the northern part (56 stations) of the total 300 station network is currently used by NAREF.

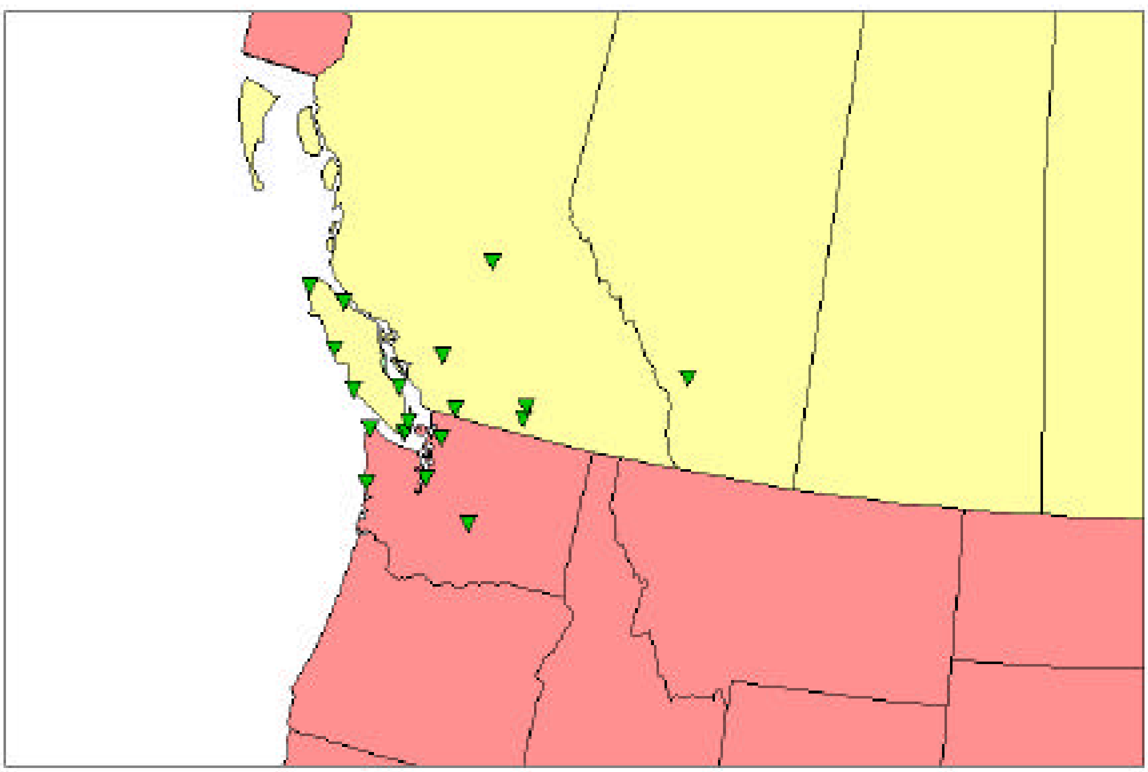

Figure 6: NRCan's Pacific Geoscience Centre (PGC) Western Canada Deformation Array (WCDA) – 17 stations.

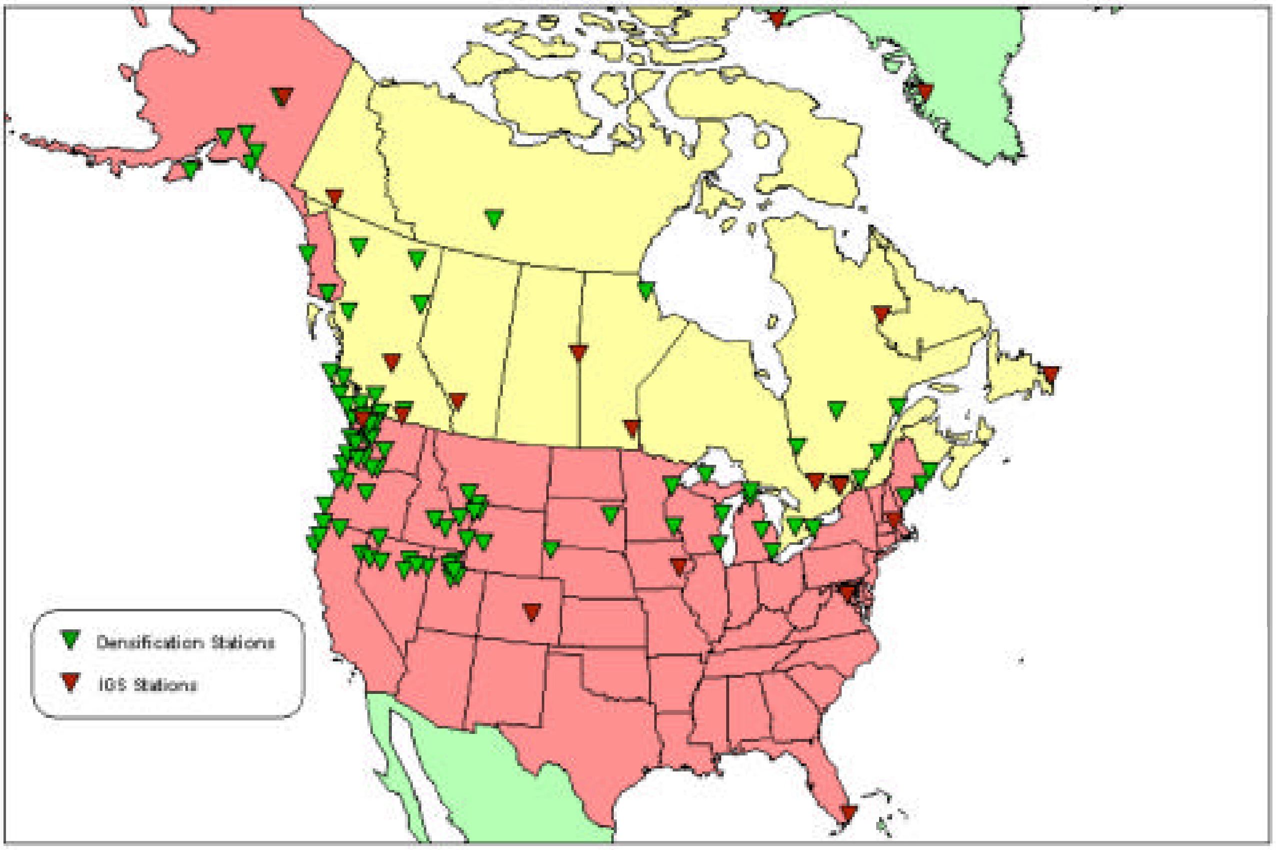

Figure 7: Entire NAREF densification network. Red symbols represent the 20 stations in IGS global solution and green symbols the 94 NAREF densification stations.

Table 1: Summary of regional GPS processing methodologies.

Solution	**GSB**	**GSG**	**PBO**	**PGC**
Software	Bernese v4.2	GISPY-OASIS II	GAMIT v9.72	Bernese v4.2
Observations	Double differenced	Undifferenced	Double differenced	Double differenced
Sampling rate	3 min.	7.5 min.	2 min.	30 sec.
Elevation cut off	10 deg.	15 deg.	10 deg.	10 deg.
Elevation weighting	Yes	Yes	Yes	Yes
Orbits & ERP	Fixed IGS	Fixed IGS	Fixed SIO	Fixed IGS
Trop. zenith delay	Every 2 hr.	Random walk	Random walk	Every 2 hr.
Mapping function	Niell (dry)	Niell (wet)	Niell (dry+wet)	Niell (dry)
Trop. gradient	1/day	Random walk	1/day	4/day
Ambiguity resolution	Yes	No	Yes, <500 km	Yes
Ocean loading	No	IERS 96	IERS 96	LOADSDP v5.02*
Datum constraints	Minimum constraint: DRAO to IGS97	Minimum constraint: ALGO to IGS97	Overconstrained: IGS sites to IGS97	Minimum constraint: DRAO to ITRF96

***** See Pagiatakis [1992] and Lambert et al. [1998]

to the International Earth Rotation Service for integration into future realizations of the ITRF.

COMBINATION RESULTS

Using the regional solutions described earlier for the first 12 weeks of 2001 (GPS weeks 1095 to 1106), NAREF combinations were computed using the above procedure. The results are described in terms of (i) residuals for each of the regional solutions (differences between each aligned regional solution and the final minimally constrained NAREF combination), and (ii) the differences between the NAREF and IGS weekly combinations.

Plots of the residual vectors for each regional solution for the first week of 2001 (GPS week 1095) are given in Figures 8 through 11. Summary statistics for the horizontal and vertical components of the residual vectors of each plot are given in terms of the average ± standard deviation, maximum and root mean square (RMS) in the accompanying Tables 2 through 5. The RMS of residuals are plotted for all 12 weeks for each regional solution in Figure 12.

It is important to realize that it is difficult to compare RMS values between different weeks and different regional solutions. This is due to the fact that different stations are used in different regional solutions and even from week to week for the same regional solution. For example, the GSB solution includes many more stations with poorer quality (noisier) data and much longer baselines than the others. In particular, IGS station ALGO was suffering from a bad external clock the first few weeks of 2001. After the clock was replaced, the solutions returned to a level more compatible with the other weeks. On the other hand, the PGC solutions included only stations with very high quality data and much shorter baselines. Consequently, the horizontal RMS of these solutions was much better.

Overall, the RMS of the residuals are less than 3 mm horizontally and 5 mm vertically. Over the first 12 weeks of 2001 the average horizontal RMS of these solutions varied from 0.5 mm for the PGC solutions to about 2 mm for the other two solutions. The average vertical RMS of the solutions varied from about 2 mm for the PBO and PGC solutions to about 3 mm for the GSB and GSG solutions.

The fit of the final minimally constrained NAREF combination with respect to the IGS combination for week 1095 is given in Figure 13 and the summary statistics in Table 6. The RMS of the residuals for all 12 weeks are plotted in Figure 14. The horizontal RMS of these differences varied from about 2 to 3 mm with one exception (GPS week 1103 gave an RMS of 4.5 mm). The average was about 3 mm. The vertical RMS varied from about 3 to 5 mm with an average of 4 mm. 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.

FUTURE WORK

The most important task facing the NAREF Working Group is to incorporate more regional solutions in the NAREF weekly combination. More solutions are obviously needed for the U.S. and Mexico. We are hopeful the U.S. National Geodetic Survey will be able to contribute weekly solutions for their CORS network of more than 150 stations across the entire conterminous U.S. and Alaska. As well, we are following up with contacts in Mexico to obtain weekly solutions for their national GPS network of about a dozen stations.

Several new regional networks are also currently planned this year and next. These will be incorporated into our GSD regional solutions when they become available. The ones we know about include:

- The Western Arctic Deformation Network (WARDEN). During the Summer of 2001, two to three permanent GPS stations will be installed in the western Arctic around the Beaufort Sea by Natural Resources Canada.

- The Canadian post-glacial uplift monitoring network. During the Summer of 2001, six permanent GPS stations will be installed around Hudson Bay under a joint project between Natural Resources Canada and GeoForshungsZentrum of Germany.

- The Great Lakes CORS Network. During the Summer of 2001, fifteen permanent GPS stations will be installed on the Great Lakes together with water level gauges and meteorological instruments under a joint project lead by the Ohio State University and the U.S. National Geodetic Survey with participation by Fisheries and Oceans Canada and Natural Resources Canada.

- The Canadian Arctic Tide Gauge Project. During the Summer of 2002, four permanent GPS stations are being installed across the Canadian Arctic together with tide gauges and meteorological instruments under a joint project by Fisheries and Oceans Canada and Natural Resources Canada.

A few other permanent GPS networks are also being planned for the near future subject to funding.

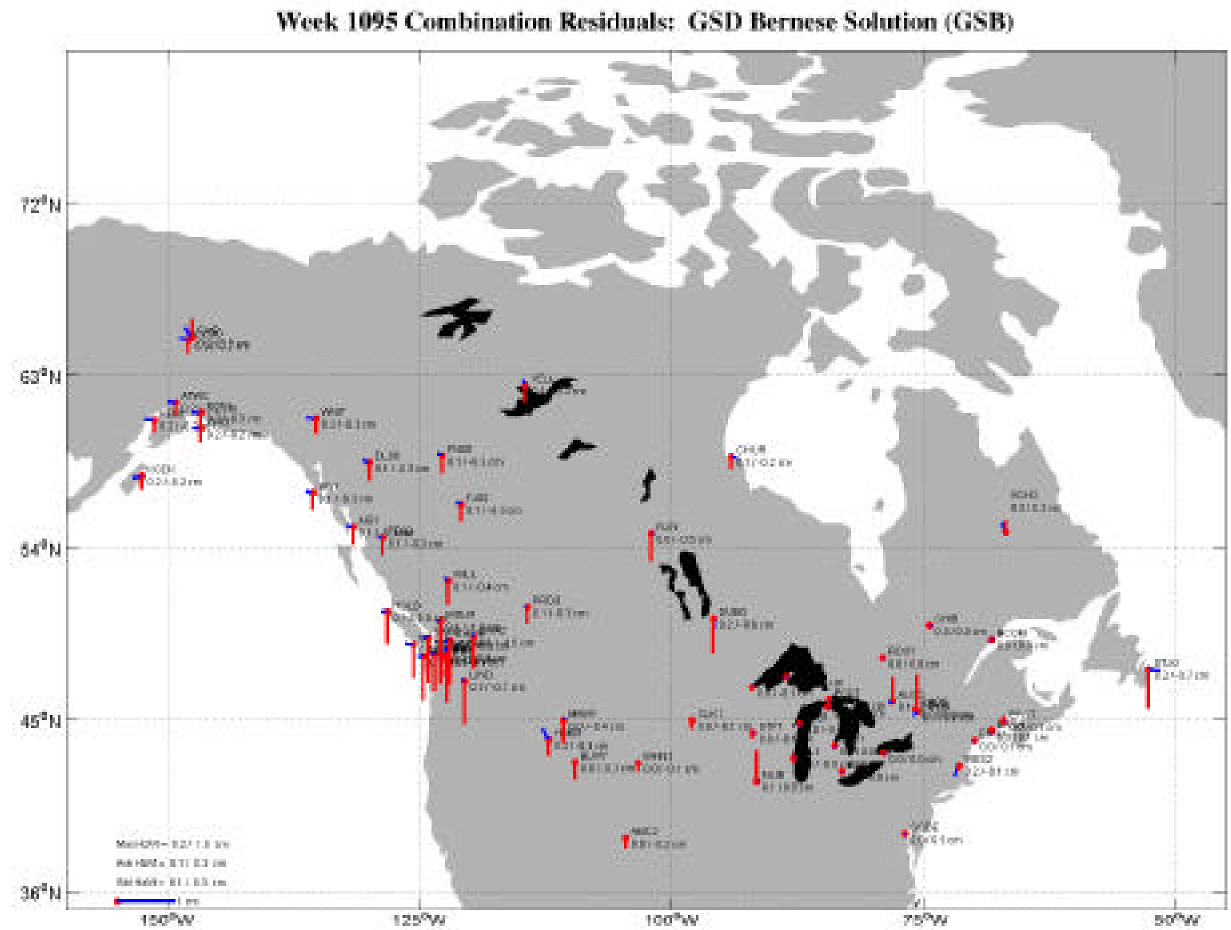

Figure 8: Horiztonal (blue) and vertical (red) vectors of NAREF combination residuals for GSD Bernese regional solution (GSB) for GPS week 1095 (residual fit with respect to the combined solution).

Table 2: Summary statistics of NAREF combination residuals for GSD Bernese regional solution (GSB) for GPS week 1095.

	Horizontal	Vertical
Ave ± Std (mm)	1 ± 1	3 ± 3
Maximum (mm)	2	10
RMS (mm)	1	4

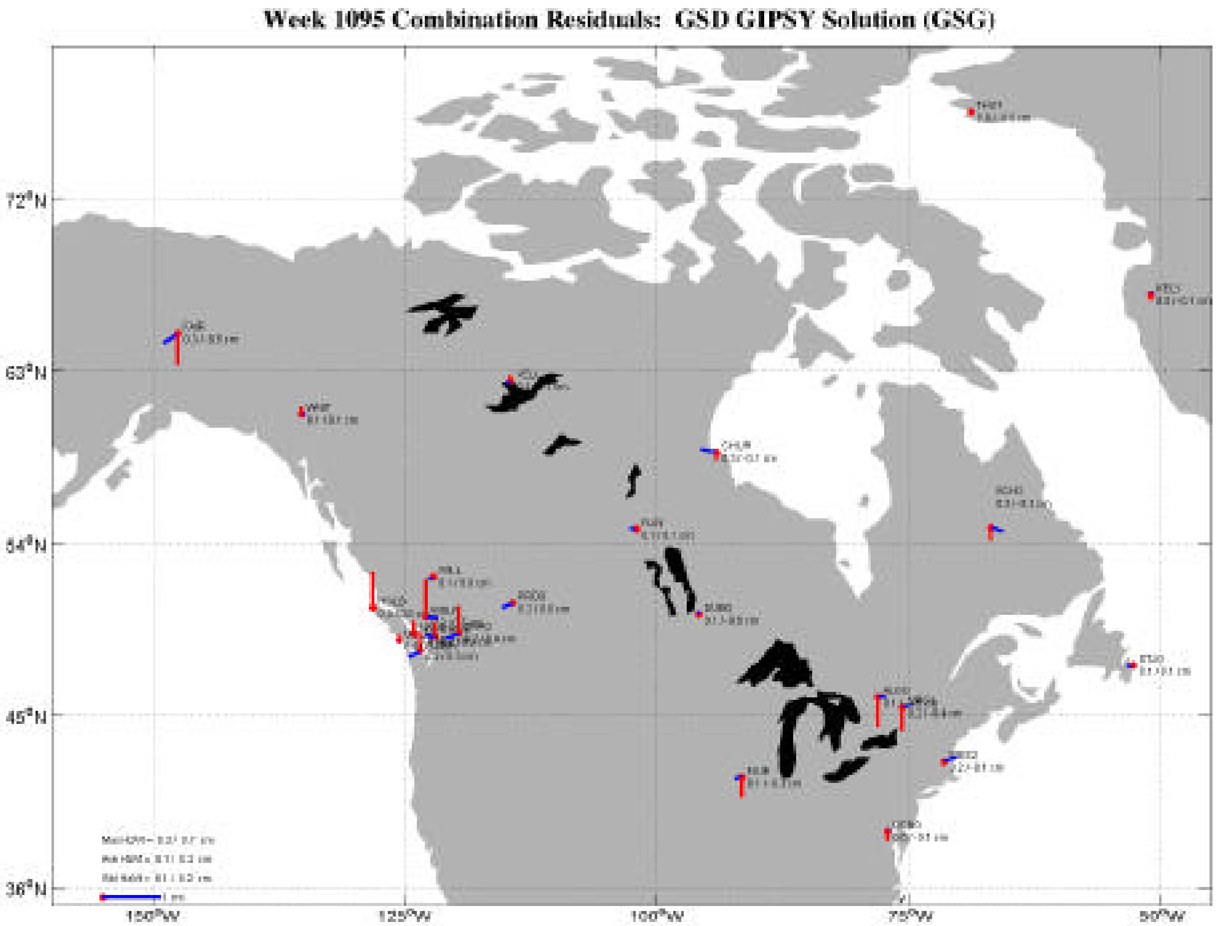

Figure 9: Horiztonal (blue) and vertical (red) vectors of NAREF combination residuals for GSD GIPSY regional solution (GSG) for GPS week 1095 (residual fit with respect to the combined solution).

Table 3: Summary statistics of NAREF combination residuals for GSD GIPSY regional solution (GSG) for GPS week 1095.

	Horizontal	Vertical
Ave ± Std (mm)	1 ± 1	2 ± 2
Maximum (mm)	3	7
RMS (mm)	1	3

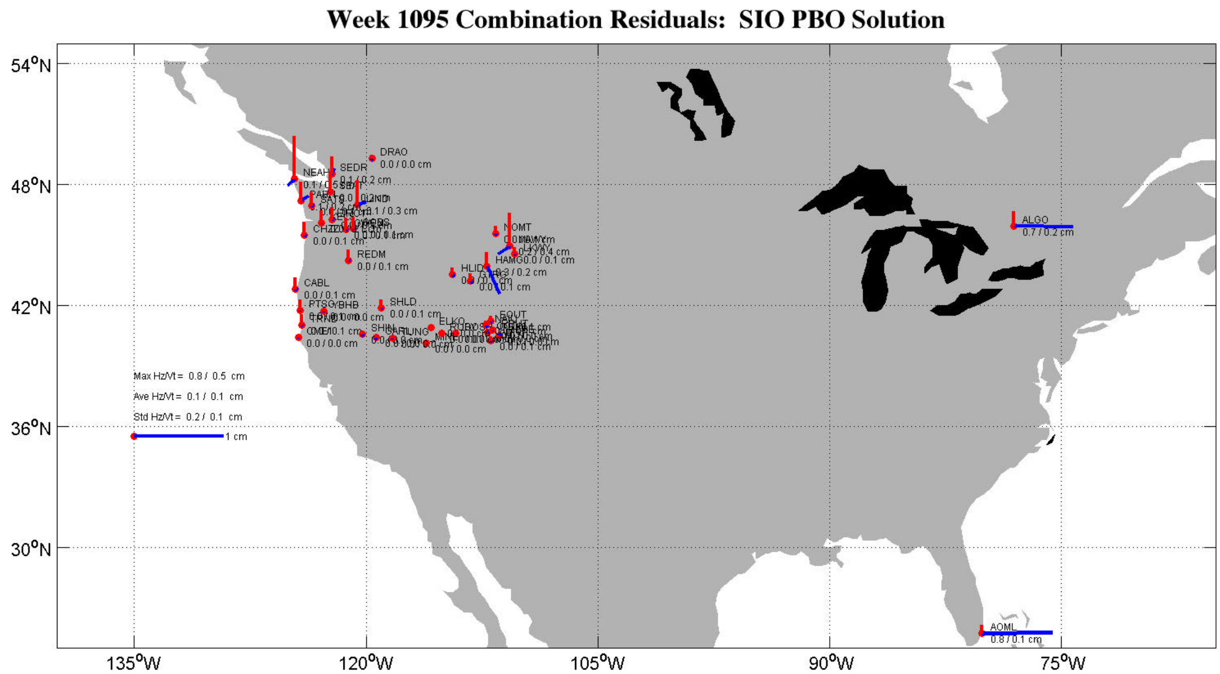

Figure 10: Horiztonal (blue) and vertical (red) vectors of NAREF combination residuals for SIO GAMIT regional solution (PBO) for GPS week 1095 (residual fit with respect to the combined solution).

Table 4: Summary statistics of NAREF combination residuals for SIO GAMIT regional solution (PBO) for GPS week 1095.

	Horizontal	Vertical
Ave ± Std (mm)	1 ± 2	1 ± 1
Maximum (mm)	8	5
RMS (mm)	2	2

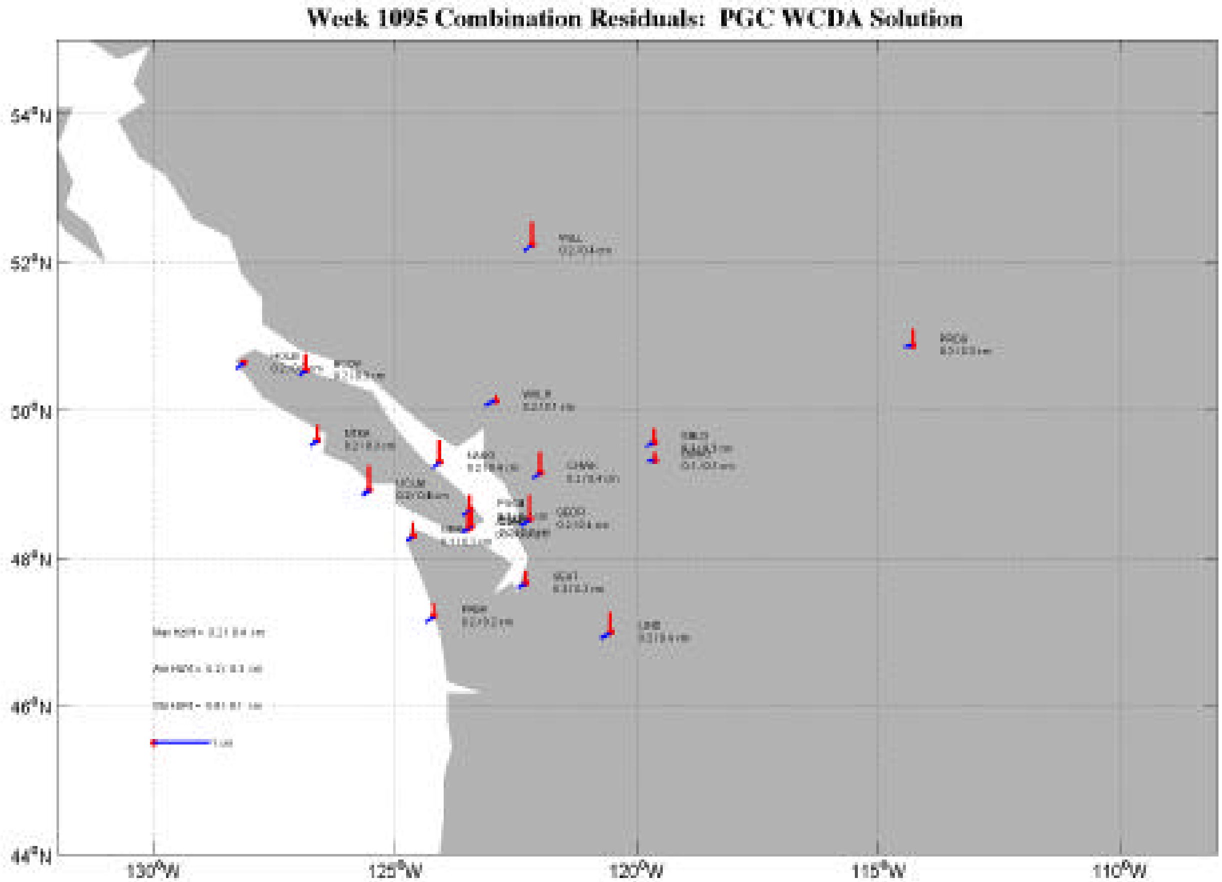

Figure 11: Horiztonal (blue) and vertical (red) vectors of NAREF combination residuals for PGC WCDA Bernese regional solution (PGC) for GPS week 1095 (residual fit with respect to the combined solution).

Table 5: Summary statistics of NAREF combination residuals for PGC WCDA Bernese regional solution (PGC) for GPS week 1095.

	Horizontal	Vertical
Ave ± Std (mm)	2 ± 0.3	3 ± 4
Maximum (mm)	2	4
RMS (mm)	2	3

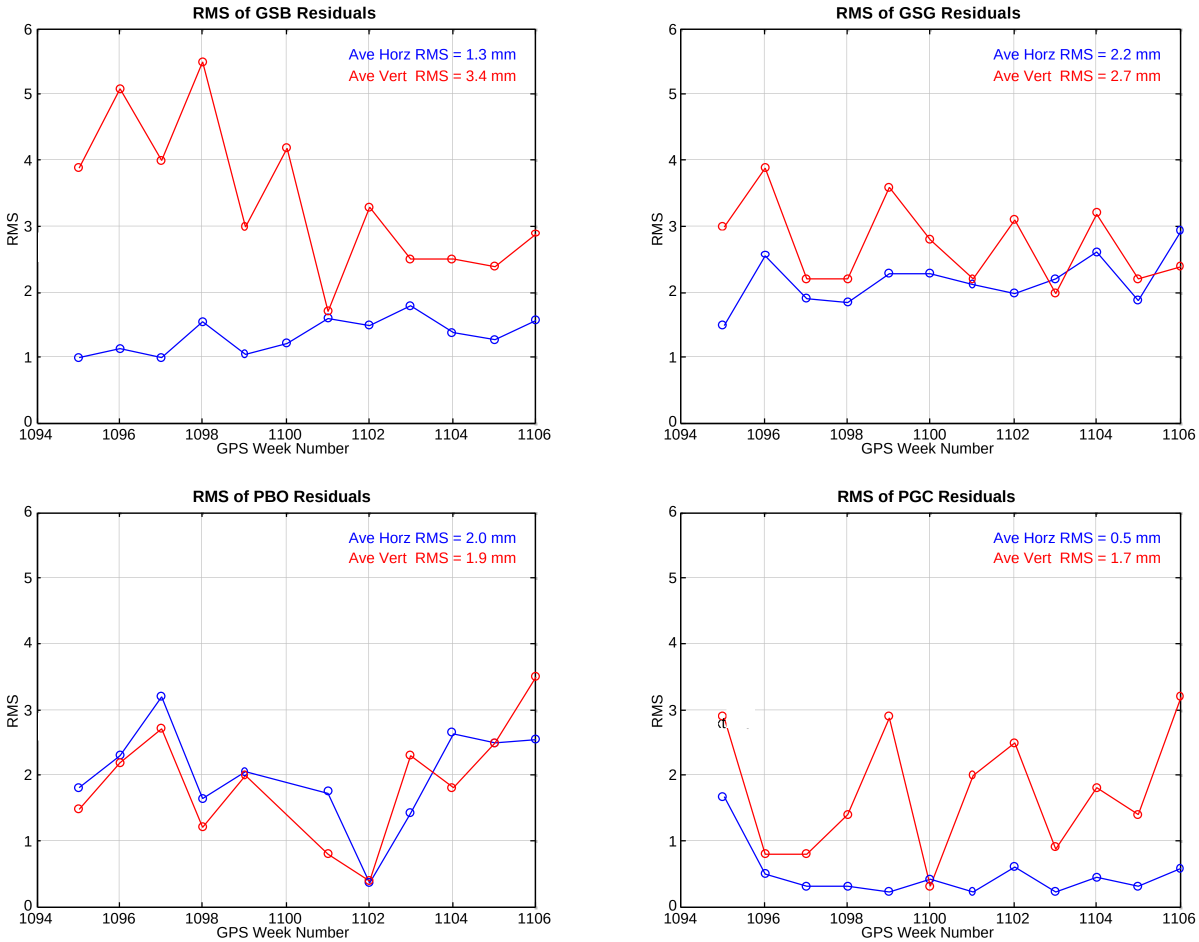

Figure 12: RMS of horizontal (blue) and vertical (red) NAREF combination residuals for each regional solution for GPS week 1095 (residual fit with respect to the combined solution).

Table 5: Summary of RMS of NAREF combination residuals for each regional solution for GPS weeks 1095 through 1106.

	Horizontal RMS (mm)	Vertical RMS (mm)
GSB	1.3	3.4
GSG	2.2	2.7
PBO	2.0	1.9
PGC	0.5	1.7

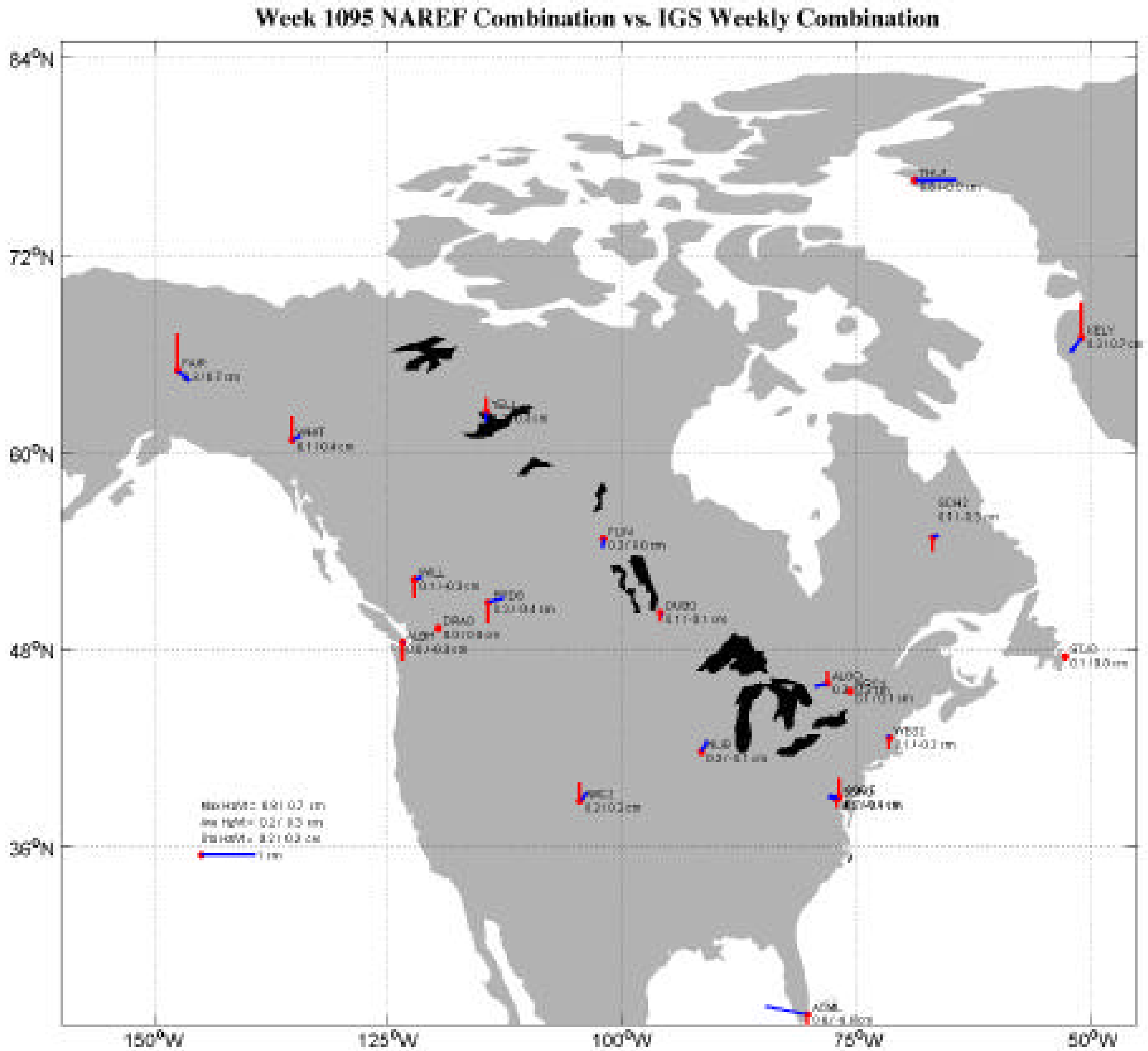

Figure 13: Horizontal (blue) and vertical (red) discrepancy vectors between NAREF combination and IGS weekly combination for GPS week 1095.

Table 6: Summary statistics of differences between NAREF combination and IGS weekly combination for GPS week 1095.

	Horizontal	Vertical
Ave ± Std (mm)	2 ± 2	3 ± 2
Maximum (mm)	8	7
RMS (mm)	3	3

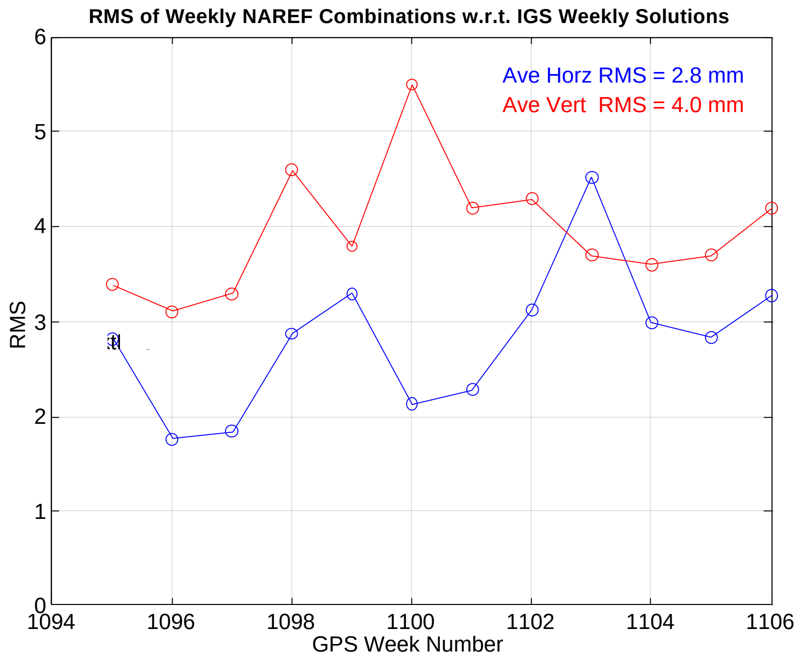

Figure 14: RMS of horizontal (blue) and vertical (red) coordinate differences between NAREF weekly combinations and IGS weekly solutions for GPS weeks 1095 to 1106.

As we seek to obtain more stations to add to NAREF, the quality of monumentation becomes more of an issue. We are therefore considering including more networks but would need to classify stations according to their monumentation and stability.

Once we have a truly North America-wide network and have begun to submit our solutions to the IGS, a strategy will need to be developed for integrating NAREF into the IGS global network. It is not yet clear who will be responsible for producing the final ITRF coordinates.

Finally, after completing a year of regular weekly solutions, it is planned to combine these into a cumulative solution where coordinate velocities will be estimated. These solutions will also be submitted to the IERS for incorporating into future ITRF solutions.

ACKNOWLEDGEMENTS

This work would not have been possible without those people and agencies submitting their weekly regional solutions to us. They include:

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- Dr. Matthijs van Domselaar of the Scripps Institution of Oceanography for their Plate Boundary Observatory (PBO) solutions.

We also wish to thank Remi Ferland of NRCan's Geodetic Survey Division for the use of his SINEX Software and for explaining his procedure for combination IGS solutions.

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