THE NAREF INITIATIVE TO DENSIFY THE ITRF IN NORTH AMERICA

Mike Craymer
Mieczyslaw Piraszewski

Natural Resources Canada, Geodetic Survey Division,
615 Booth Street, Ottawa, Ontario, K1A 0E9, Canada
E-mail: craymer@nrcan.gc.ca, mpirasze@nrcan.gc.ca
Web: www.naref.org

ABSTRACT

Since the beginning of 2000, the Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) has been playing a leading role in the North American Reference Frame (NAREF) Working Group of the IAG Commission X Subcommission for North America in support of the International GPS Service (IGS) initiative to densify the International Terrestrial Reference Frame (ITRF) in North America. Following the IGS distributed processing approach, NRCan has been computing three weekly regional solutions for Canada following IGS guidelines. Two such solutions are now being generated by GSD on a regular basis for redundancy and quality control, one for a 27 station network using GIPSY-OASIS II software and the other for a 65 station network using the Bernese GPS Software. In addition to the two GSD solutions, we have obtained others from NRCan's Geological Survey of Canada – Pacific Division for the 17 stations Western Canada Deformation Array and from the Scripps Institution of Oceanography for their 300 station Plate Boundary Observatory. These different regional solutions are being combined on a regular basis into a single NAREF weekly combination beginning with the first week of 2001. Some stations are included in more than one solution thereby providing redundancy checks and allowing for correct weighting of the different solutions relative to each other and to the IGS solutions. All regional solutions agree with each other at the few mm level while their final NAREF combination agrees with the official IGS solutions at the 3 mm level horizontally and the 4 mm level vertically. This is within the expected accuracy of the IGS solutions. By the middle of 2001 we plan to begin submitting weekly NAREF combinations to the IGS for eventual incorporation into the official IGS densification network. Later in the year, we expect to receive more regional solutions in order to make the NAREF network truly North American in scope.

1. INTRODUCTION

When the IGS began official operations in 1994, there were only about 50 permanent stations. Since then, this global network has expanded significantly and now comprises over 200 stations. Moreover, the number of new permanent stations being deployed is increasing even more rapidly. Although this provides the IGS with the opportunity to produce a denser and more homogeneous reference frame, the large number of stations made it difficult to simultaneous process the data in an optimal manner.

In 1999 the IAG Commission X, Subcommission for North America established a North America Reference Frame (NAREF) Working Group to support the IGS initiative to densify International Terrestrial Reference Frame in North America. The organizational structure of the Subcommission is illustrated in Figure 1. The objectives of the NAREF Working Group are to:

- **Densify the ITRF reference frame in North America in both a spatial and temporal 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 continental-scale combinations of submitted regional solutions as well as cumulative solutions with velocity estimates.**

- **Provide public access to data and results 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.**

To provide a practical computational approach to such densification, the IGS instituted the distributed processing approach whereby the problem is partitioned into more manageable regional densifications (Kouba, 1996; Blewitt, 1997; Blewitt, 1998). The proposed approach was designed to be an extension of existing IGS operations. Global coordinate solutions are extracted from the products of the IGS Analysis Centers and combined in a global IGS network by the Global Network Associate Analysis Centers (GNAACs) and the IGS Reference Frame Coordinator. Regional solutions would then be added to the global network by the GNAACs to produce a densification network referred to as the IGS Polyhedron. This process is illustrated in Figure 2.

Because of the significant effort required to analyse and combine the many small regional solutions, it was proposed that these first be analyzed and combined on a continental level by by Regional Network Associate Analysis Center (RNAACs) prior to submission to the GNAACs. For example, this is the approach taken in Europe where the European Permanent Network is first combined together by the EUREF RNNAC prior to submission to the IGS GNAACs. It is not year clear, however, whether the RNAACs would be reponsible for integrating their densification networks into the global network to produce one official solution or whether this would be done by the GNAACs or Reference Frame Coordinator.

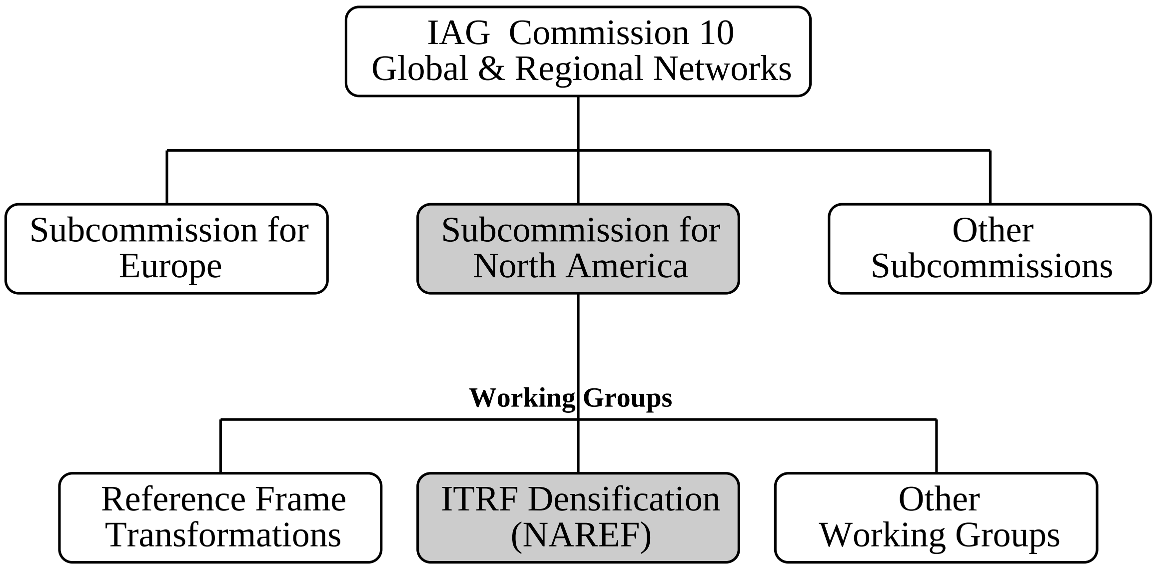

Figure 1. Organizational chart of Subcommission for North America

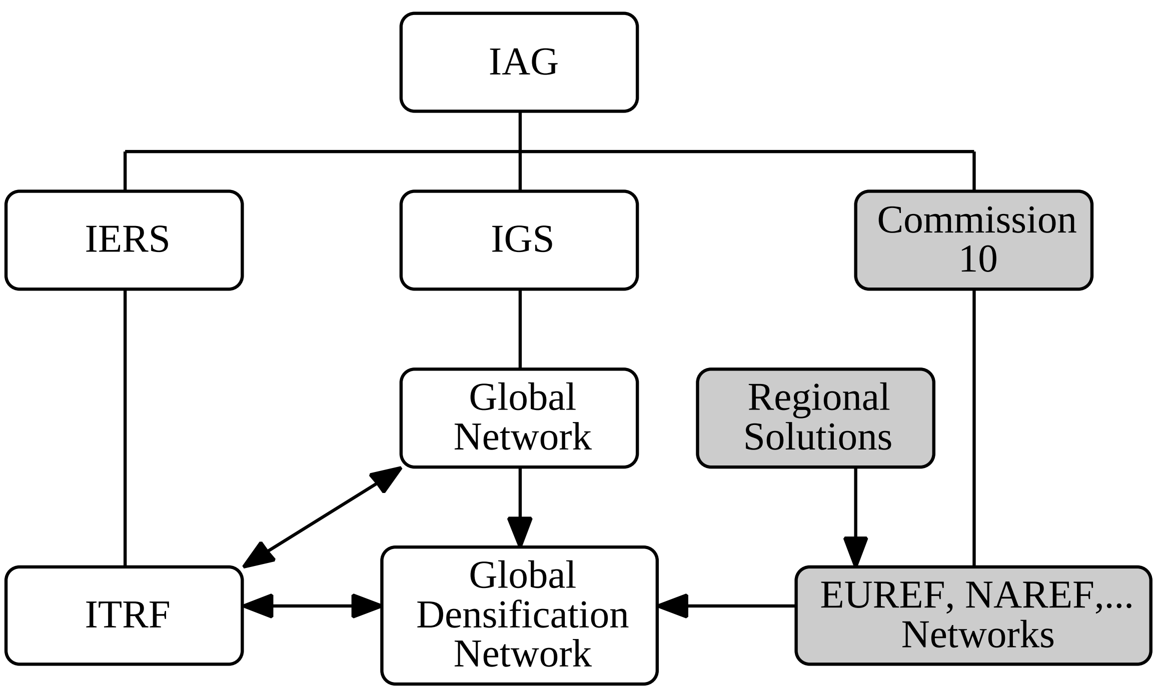

Figure 2. Organization and data flow of the IGS distributed processing approach.

2. NAREF REGIONAL SOLUTIONS

At the present time, the following four regional solutions are being contributed to NAREF:

Geodetic Survey Division Bernese (GSB) Solutions:
The Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) provides solutions for a network that spans the entire northern half of North America. The network is comprised of 65 stations from a variety of regional and local networks, including all IGS stations in the northern half of North America and all stations of the Canadian Active Control System, the Western Canada Deformation Array, and subsets of stations from the US Continuously Operating Reference Station (CORS) network, the Alaska Deformation Array, the Pacific Northwest Geodetic Array, the Eastern Basin Range Yellowstone Array, the British Columbia Active Control System and the Quebec Permanent GPS Network. The data from these stations are processed using the Bernese GPS Software v4.2.

Geodetic Survey Division GIPSY (GSG) Solutions:
GSD also provides solutions for a Canada-wide network of 27 stations that includes all IGS stations in Canada, Greenland, and the northern U.S. as well as all stations in the Canadian Active Control System and Western Canada Deformation Array. The data from these stations are processed using the GIPSY-OASIS II software.

Pacific Geoscience Center (PGC) Solutions:
NRCan's Geological Survey of Canada Pacific Division at the Pacific Geoscience Center provides a more local regional solution for the 17 stations in their Western Canada Deformation Array and the Pacific Northwest Geodetic Array. A few of these stations are also considered part of the IGS global network. The data from these stations are processed using the Bernese GPS Software v4.2.

SIO Plate Boundary Observatory (PBO) Solutions:
The Scripts Institute of Oceanography (SIO) provides solutions for their Plate Boundary Observatory (PBO), a network of more than 300 stations covering the west coast of the U.S. and Canada. It includes stations from both the Western Canada Deformation Array and the Pacific Northwest Geodetic Array and a few IGS stations, two of which are in the eastern part of North America. Only the northern part of this network is presently used because of limitations in the number stations our computer resources can accomodate. The data from these stations are processed using the GAMIT GPS software v9.72.

A summary of the software and processing options used for all these solutions is given in Table 1. These processing procedures follow closely the strategies described in Rothacher et al. (1998). The station distribution for each regional network can be seen in the plots of the combination residuals in Figures 4 to 7. The entire NAREF network containing all the regional networks is displayed in Figure 3. There are a total of 114 points of which 20 are existing IGS global stations and 94 represent the NAREF

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 model	No	IERS 96	IERS 96	LOADSDP v5.02*
Datum constraints	Min. constraint: DRAO to IGS97	Min. constraint: ALGO to IGS97	Overconstrained: IGS sites to IGS97	Min. constraint: DRAO to ITRF96

* See Lambert et al. (1998) and Pagiatakis (1992)

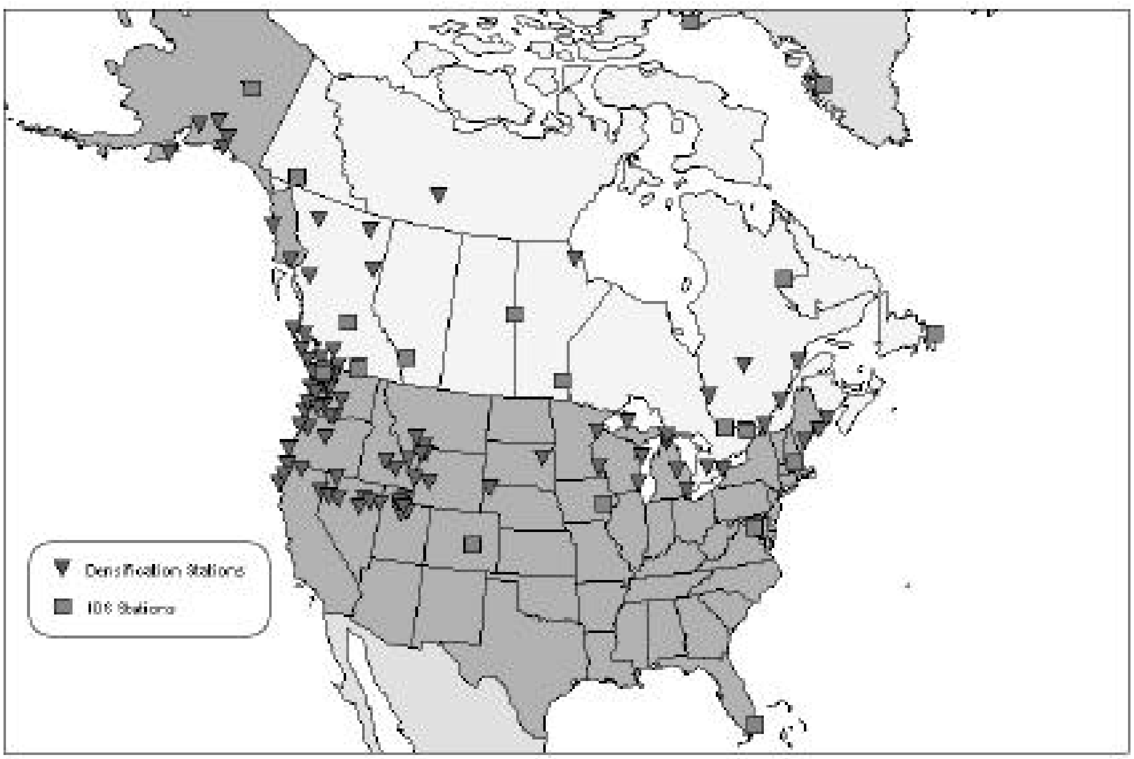

Figure 3. Entire NAREF densification network. Square symbols represent the 20 stations in IGS global solution and triangle symbols the 94 NAREF densification stations.

densification stations. Obviously, this represents only a northern NAREF network. More solutions are needed for the U.S. and Mexico. Coverage will improve significantly if the U.S. National Geodetic Survey could 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 network of about a dozen points and a few stations in Greenland, thereby making the NAREF network truly North American in scale.

3. NAREF COMBINATION PROCEDURE

The 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 allows for determination of correct relative weighting of the different solutions relative to each other and to the global IGS weekly solution. Redundant solutions are obviously needed for many of the U.S. stations but we expect this to be remedied if we are able to obtain a CORS solution for the entire U.S. Solutions are also available for the many smaller regional networks that make up the PBO network.

The combination strategy is modeled after the procedure used by the IGS Reference Frame Coordinator to produce the official weekly IGS global combination. It consists the following steps:

Alignment of Each Regional Solution

1. **Remove a priori datum constrains.**
2. **Align solution to the IGS weekly solution of the same week using 3 translations, 3 rotations and a scale change.**
3. **Scale the solution's covariance matrix by the weighted root mean square (WRMS) of the residuals from the above transformation.**
4. **Test the residual for outliers. If any outliers are found, they are removed and steps 2 to 4 repeated.**

Combination of Regional Solution

5. **Combine all (scaled) regional solutions by summation of the normal equations for each (sacled) regional solution.**
6. **Align the combined solution to the IGS weekly solution using 3 translation, 3 rotations and a scale change.**
7. **Scale the combined solution's covariance matrix by the WRMS of the residuals from the above transformation.**
8. **Test the residuals for outliers. If any outliers are found, they are removed from their respective solution and steps 2 to 8 repeated (only steps 2-4 for the regional solution(s) with the outlier need to be repeated).**
9. **Apply a minimum datum constraint for further testing and comparison with IGS weekly global solution. Presently, IGS reference frame station DRAO is constrained to its IGS weekly coordinates.**
10. **Integrate the NAREF combination solution into the IGS global network by removing the above minimum constraint and applying weighted constraints for all**

IGS stations using the fully populated covariance matrix from the weekly IGS solution.

11. **Generated a SINEX file for integrated NAREF combined solution with the weighted constraints explicitly given in the "APRIORI" data blocks.**

The above weekly NAREF combinations are produced using using SINEX Software v1.0 from Remi Ferland, the IGS Reference Frame Coordinator. It is the same software used to produce the weekly IGS combinations and cumulative solutions.

The weekly NAREF solutions will soon be integrated into the IGS global network on a regular basis. After obtaining a year of weekly solutions, cumulative solutions with station velocity estimates will also be generated on a regular basis and submitted to the International Earth Rotation Service for inclusion in future ITRF realizations.

4. COMBINATION RESULTS

NAREF combination solutions were computed using above procedure for first 12 weeks of 2001 (GPS weeks 1095-1106). The results were analyzed in two ways. First, each aligned regional solution was compared to NAREF minimally constrained combination solution for each week; i.e., the residuals from the NAREF weekly combination. Then, the NAREF combination solution was compared to the IGS solution for each week. The differences were assessed in terms of the root mean square (RMS) of the horizontal and vertical components of the coordinate difference vectors.

Plots of the residual vectors from the NAREF combination solution for each regional solution are given in Figures 3 to 7. We used week 1095 as an example typical of the others. The RMS of the residuals for all 12 weeks are plotted as a time series for each regional solution in Figure 8. In general, the horizontal RMS of the residuals varied from an average of 0.5 mm for PGC to about 2 mm for GSG and PBO. The vertical RMS was an average of about 2-3 mm.

It is difficult to compare these residual RMS values between different solutions and even between different weeks for the same regional network. This is due to the fact that the different solutions and different weeks use different stations of varying quality (some stations have data that is significantly noisier than the others). In addition, some solutions cover only a relative small area and thus have very short baselines that are much more accuracy than the long, sometime continental-scale, baselines. For example, the GSB solution includes many more stations with noisier data than any of the other solutions. It also has some of the longest baselines. Similarly, the RMS values for the PBO solutions are slightly inflated because of the very long and less accurate baselines to the two IGS stations in the east. On the other hand, the PGC solution uses only high quality stations with some of the shortest baselines in our NAREF network.

The fit of the minimally constrained NAREF combination with respect to the IGS solution for week 1095 is given in Figure 9. Figure 10 provides the time series of the RMS of horizontal and vertical components of the coordinate differences. The RMS for

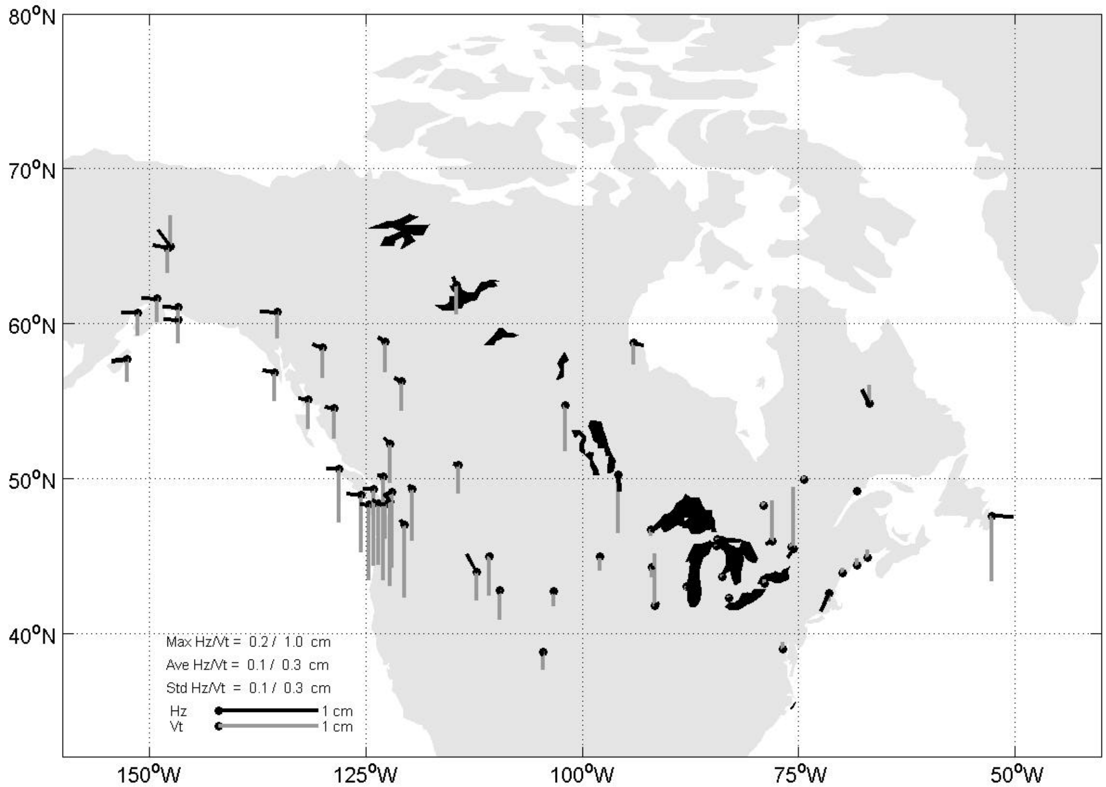

Figure 4. GSB residuals for week 1095.

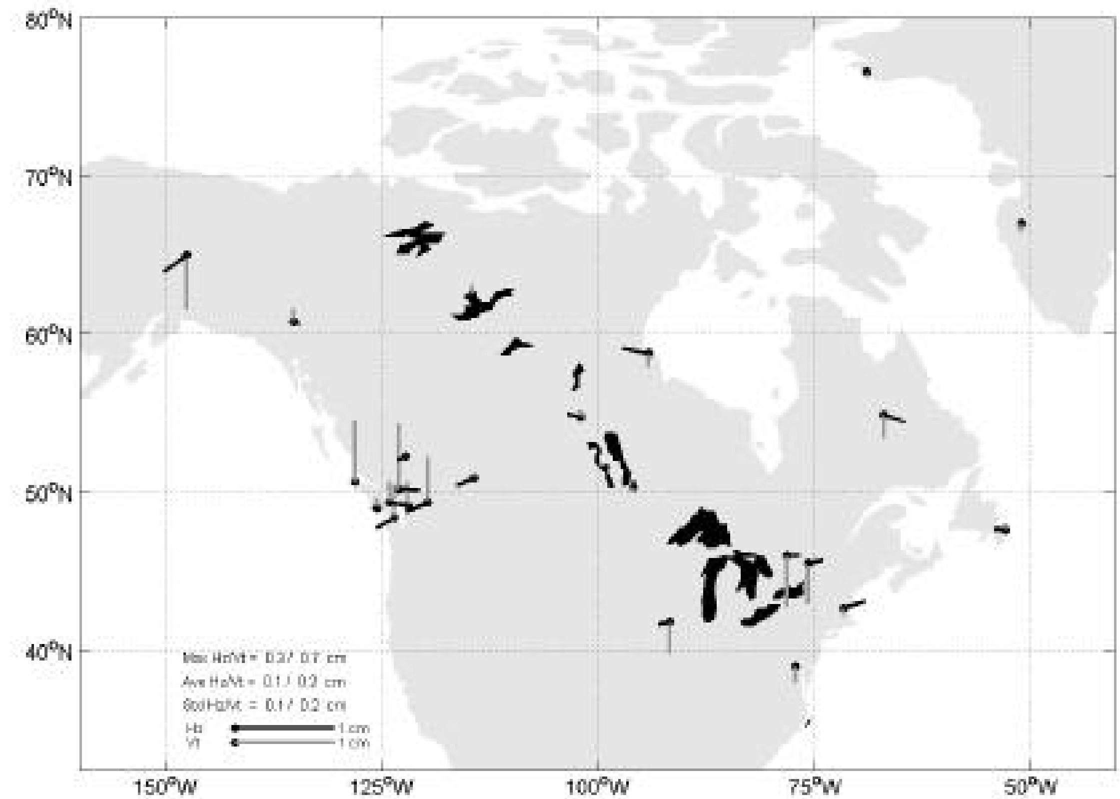

Figure 5. GSG residuals for week 1095.

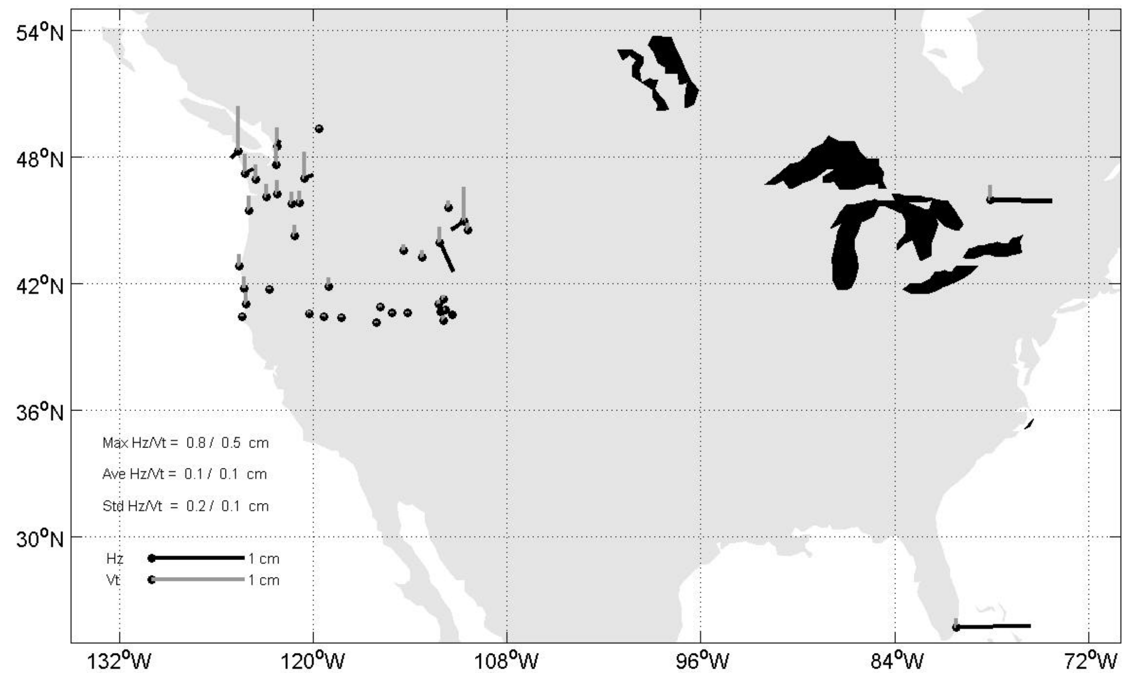

Figure 6. PBO residuals for week 1095.

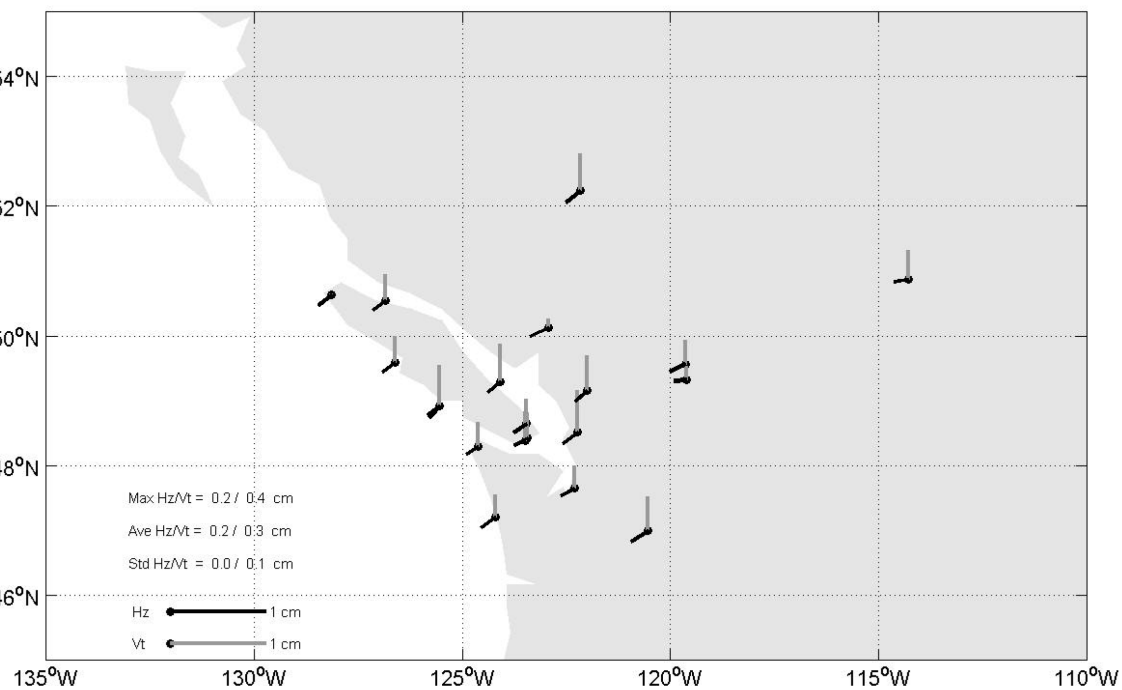

Figure 7. PGC residuals for week 1095.

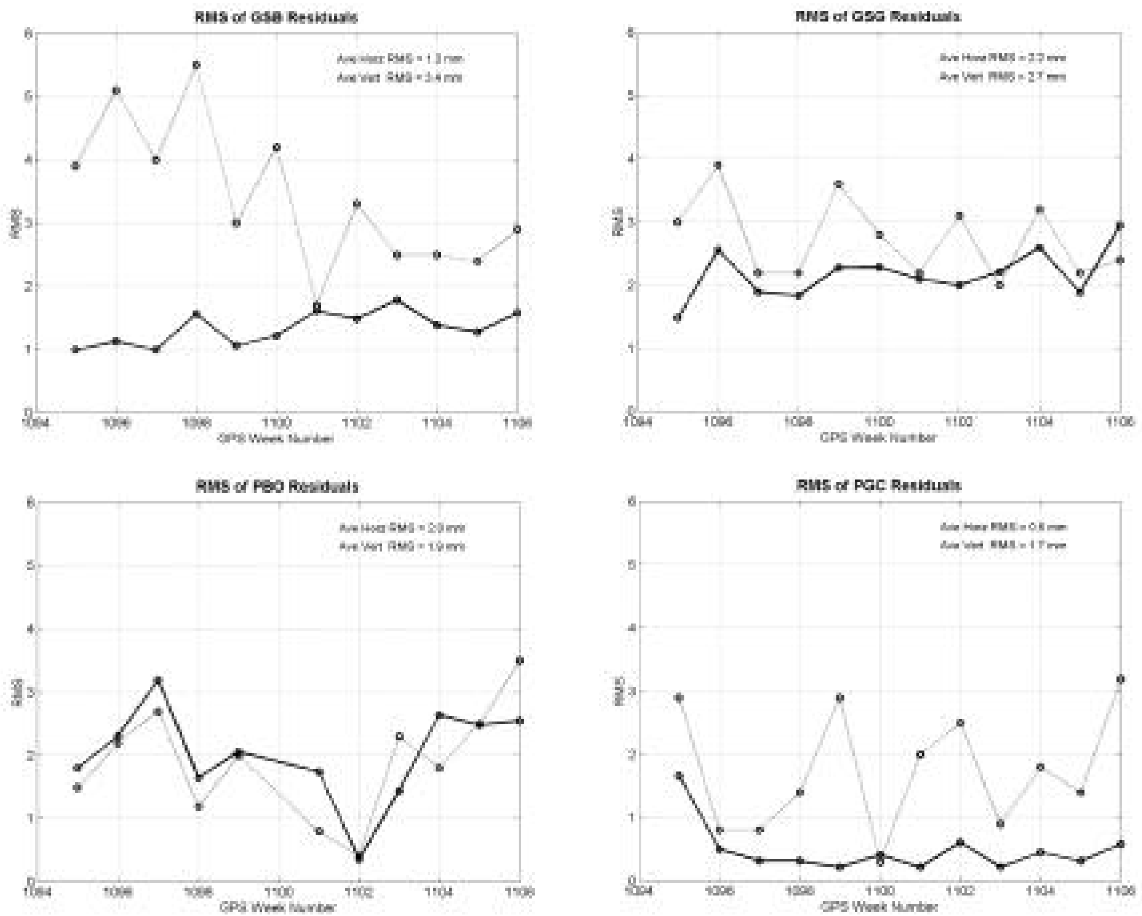

Figure 8. Time series of RMS of residuals of each individual solution. Solid lines represent the horizontal residuals and dotted lines the vertical residuals.

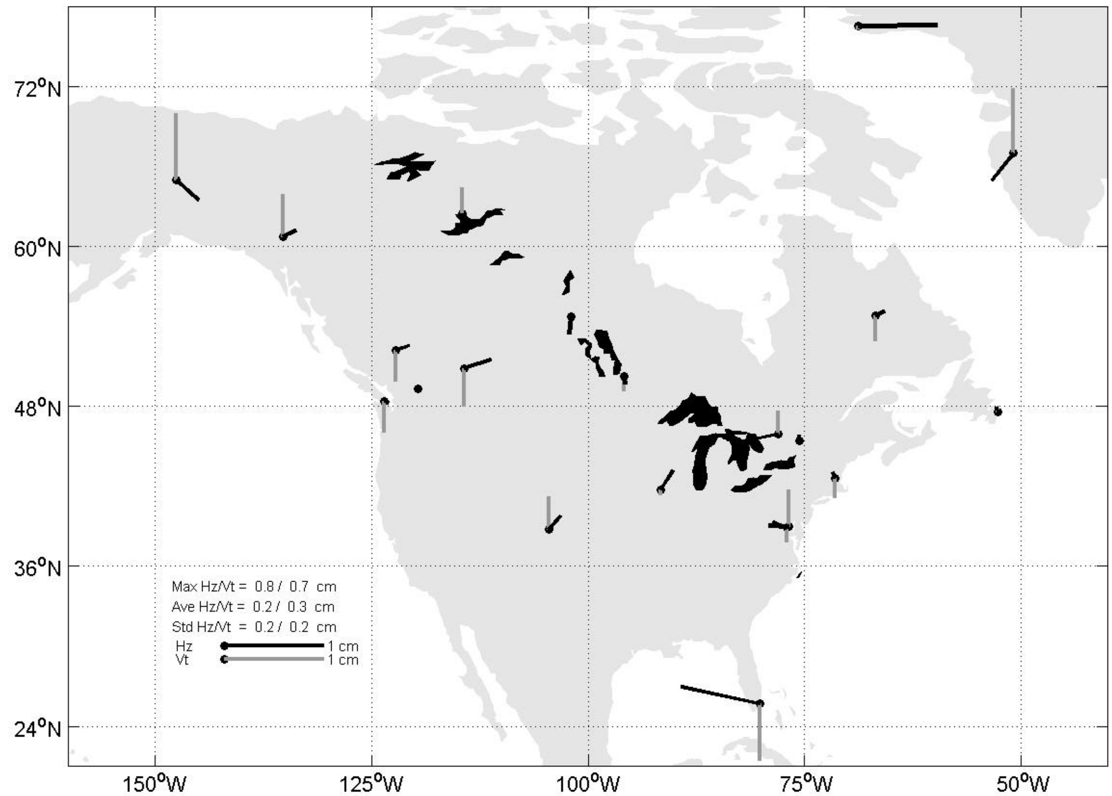

Figure 9. Differences between NAREF combination and IGS solution for week 1095.

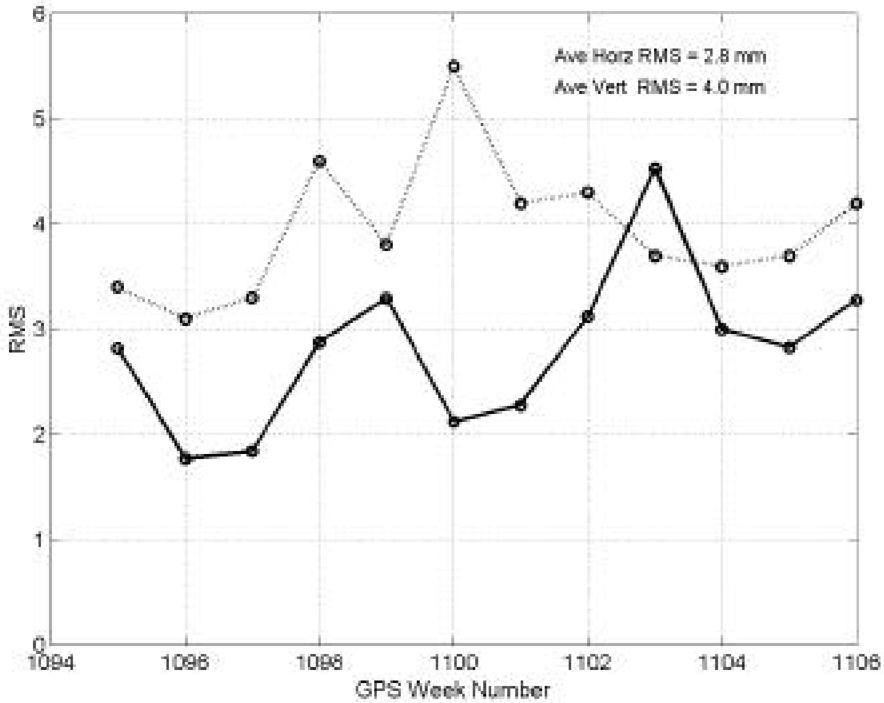

Figure 10. RMS of weekly NAREF combinations with respect to IGS weekly solutions. The solid line represents the horizontal residuals and the doted line the vertical residuals.

the horizontal differences was about 2-3mm while the vertical RMS was about 3-5 mm. Considering the fact that the accuracy of the IGS weekly solutions is of the order of a few mm (Ferland, 1999), we can conclude that the NAREF combined solutions are statistically compatible with IGS solutions.

5. FUTURE WORK

Although the present NAREF network gives good coverage of northern part of North America, we clearly need additional solutions in the southern part. We also need to include additional redundant solutions for many of the existing stations in the PBO solution. Weekly solutions from the U.S. National Geodetic Survey for their CORS network (approximately 150 stations) would help greatly in this regard, as would solutions for stations in Mexico and Greenland.

Several new regional networks in Canada are also currently planned this year and next. These will be incorporated into our GSB and GSG 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 by Natural Resources Canada in the western Arctic around the Beaufort Sea.

- 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.

Finally, there are a significant number permanent GPS stations with less stable monumentation that are being used for meteorological applications. If we decide to include these stations in NAREF to improve our spatial coverage, we would need to classify these stations according to their monument stability.

Once we have a truly North America-wide network and have begun to submit our NAREF solutions to the IGS, a consistent strategy will need to be developed for integrating NAREF and the other regional network into the IGS global network. It is not yet clear how this will be done or who will be responsible for doing this. Nevertheless, after producing year of weekly solutions we will begin to perform regular cumulative solutions for the NAREF network, in order to provide estimates of station velocities.

6. ACKNOWLEDGMENTS

The NAREF project is based on the work performed by a number of different agencies. We would especially like to acknowledge the following current contributors of regional solutions:

- Brian Donahue and Caroline Huot of NRCan’s Geodetic Survey Division for contributing the GSD GIPSY (GSG) solutions.
- Herb Dragert of NRCan’s Geological Survey of Canada – Pacific Division at the Pacific Geoscience Centre, for contributing the WCDA (PGC) solutions.
- Matthijs van Domselaar of the Scripps Institution of Oceanography for contributing their Plate Boundary Observatory (PBO) solutions.

We also thank Remi Ferland of NRCan’s Geodetic Survey Division, and current IGS Reference Frame Coordinator, for providing this SINEX combination software and explaining his combination procedure for producing the official IGS solutions.

Finally, we appreciate very much the help and support Dr. Jan Kouba has provided since the beginning of this project.

7. REFERENCES

Blewitt, G. (1997). IGS Densification Program. IGS 1996 Annual Report, International GPS Service, pp. 24-25.

Blewitt, G., Boucher, C., Davies, P.B.H., Heflin, M.B., Herring, T.A., Kouba, J. (1998). ITRF Densification and Continuous Realization by the IGS. In F.K. Brunner (ed.), Advances in Positioning and Reference Frames, IAG Scientific Assembly, Rio de Janeiro, Brazil, September 3-9, 1997, International Association of Geodesy Symposia, Vol. 118, Springer-Verlag, Berlin, pp. 8-17.

Ferland, R. (1999). IGS Reference Frame Pilot Project. IGS 1999 Technical Reports, International GPS Service, pp. 257-261.

IGS (1996). SINEX - Solution (Software/technique) INdependent EXchange Format, Version 1.00. International GPS Service, June 30. Internet URL <ftp://cddisa.gsfc.nasa.gov/pub/formats/sinex1.format>.

Kouba, J. (1996). Status of the IGS Pilot Project to Densify the ITRF. IGS 1996 Annual Report, International GPS Service, pp. 101-116.

Lambert, A., Pagiatakis, S.D., Billyard, A.P., Dragert, H. (1998). Improved ocean tide loading corrections for gravity and displacement: Canada and northern United States. Journal of Geophysical Research, Vol. 103, No. B12, pp. 30231-30244.

Pagiatakis, S.D. (1992). Program LOADSDP for the calculation of ocean load effects. Manuscripta Geodaetica, Vol. 17, pp. 315-320.

Rothacher, M., Springer, T.A., Schaer, S., Beutler, G. (1998). Processing Strategies for Regional GPS Networks. In F.K. Brunner (ed.), Advances in Positioning and Reference Frames, IAG Scientific Assembly, Rio de Janeiro, Brazil, September 3-9, 1997, International Association of Geodesy Symposia, Vol. 118, Springer-Verlag, Berlin, pp. 93-100.