Combating the Perfect Storm

Improving Marine Differential GPS Accuracy with a Wide-Area Network

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UNDER NORMAL OPERATING CONDITIONS, MARINE DIFFERENTIAL GPS (DGPS) HORIZONTAL POSITIONING accuracies on the order of several meters are achieved in North America. Such accuracies are well within the tolerance of 10 meters (95 percent confidence level) specified by the Canadian and United States Coast Guards, but under high levels of ionospheric activity, significant degradations in DGPS positioning accuracies can occur. Marine DGPS operations in North America are particularly susceptible to such effects, where a feature known as storm enhanced density is observed during ionospheric storm events.

It was previously thought that the mid-latitude North American ionosphere was reasonably benign, with minimal storm effects of relevance for marine DGPS users. However, during ionospheric storms in May and October, 2003, marine DGPS horizontal position accuracies were degraded by factors of 10–30. These degraded accuracies persisted for hours and were well beyond system tolerances specified for marine DGPS users. Such ionospheric activity is not unusual during the years following solar maximum, and is expected to persist for several years.

In this month's column, we examine the impact of ionospheric storms on marine DGPS users and look at a proposed wide-area approach for mitigating large storm-induced positioning errors. — R.B.L.

In differential GPS (DGPS), range errors are calculated at a reference site with known coordinates and transmitted to remote users. The errors remaining after DGPS processing are the residual atmospheric effects (both tropospheric and ionospheric errors), multipath, and, to a lesser extent, GPS satellite orbit errors. Proper antenna selection and placement can mitigate multipath errors. Atmospheric errors, on the other hand, can be rather large depending on the weather conditions (in the case of the troposphere) and ionospheric activity.

The ionospheric range error depends on both the frequency of the signal and the electron density along the signal path:

$$I = \pm 40.3\,\frac{TEC}{f^2} \qquad (1)$$

where *TEC* denotes the total electron content, which is the electron density integrated along the signal path (in electrons per meter squared), *f* is the signal frequency (in hertz), and the rounded value 40.3 is a function of the electron mass and charge values and the permittivity of free space. The sign, positive or negative, depends on the measurement. The ionospheric group delay is positive, contributing a positive range error to pseudorange measurements whereas the phase of a carrier is advanced by the ionosphere, contributing a negative range error to carrier-phase measurements. The ionospheric range error can dominate the DGPS error budget under high levels of ionospheric activity. Additional effects of ionospheric scintillation can cause degradation of GPS receiver tracking performance and, in extreme cases, loss of navigation capabilities entirely.

Mariners worldwide rely on DGPS systems for safety of navigation, hydrographic surveying applications, and exploration/exploitation of marine resources. Marine horizontal position accuracy requirements are 2–5 meters (at a 95 percent confidence level) and 8–20 meters (95 percent) for safety of navigation in inland waterways and harbor entrances/approaches, respectively; horizontal position accuracies of 1–100 meters (95 percent) are required for benefits of resource exploration in coastal regions. Marine DGPS currently assists a diverse range of government, industrial and military applications — these include hydrographic surveying, assistance to vessel traffic management services, search and rescue operations, environmental assessment and clean-up, and underwater mine detection and disposal.

The Canadian Coast Guard (CCG) currently offers marine radiobeacon DGPS services along the Pacific and Atlantic coasts of Canada, in addition to the Great Lakes and St. Lawrence River regions. While DGPS horizontal error bounds are specified as 10 meters (95 percent), marine users typically experience much better accuracies — on the order of several meters (95 percent). However, DGPS operations in Canada and other regions of the world are susceptible to enhanced ionospheric effects associated with geomagnetic storms, which can cause degraded positioning accuracies. To mitigate the impact of such effects, one could use a number of reference stations to spatially model correlated GPS ranging errors. In this article, we describe an investigation of such a wide-area approach for applications to marine users in Canada.

In wide-area differential DGPS (WADGPS), GPS observations from a sparse network of reference stations help model correlated error sources over an extended region. WADGPS services allow consistent levels of positioning accuracy to be achieved at all locations within the coverage area. A growing demand for accurate and reliable DGPS positioning worldwide has spurred the development of several WADGPS services in recent years. Current operational WADGPS systems include the Wide Area Augmentation System (WAAS), a system designed by the U.S. Federal Aviation Administration (FAA) for aircraft precision approach and en-route navigation. Commercial WADGPS systems include the OmniSTAR service, which charges annual user fees.

In this article, we present a description of ionospheric effects on GPS, the theory of WADGPS, and an emerging wide-area

DGPS technique to mitigate the impact of large ionospheric gradients on positioning accuracies. Our analyses focus on differential positioning accuracies in the mid- to high-latitude region, where some of the largest TEC gradients in the Earth's ionosphere occur.

Storm Enhanced Density

The focus of our investigation was to evaluate the potential of employing a wide-area positioning algorithm for marine users — and ultimately to mitigate extreme ionospheric effects in the Canadian sector. Prior to presenting this technique and discussing our test results, we will review relevant phenomena in the Earth's ionosphere.

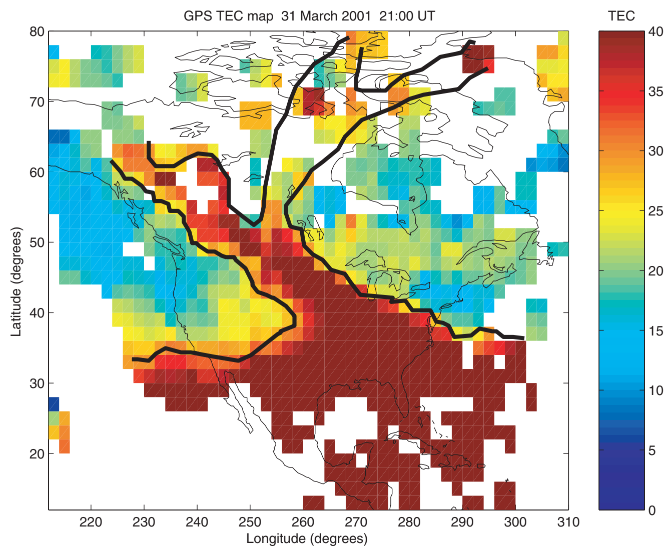
Enhanced ionospheric electric fields are present near the mid- to high-latitudes during geomagnetically disturbed periods, which can lead to depletions and enhancements of electron density in this region. The resulting gradients in TEC can cause large differential ionospheric range errors. Of particular interest is an effect known as storm enhanced density (SED). The Millstone Hill incoherent scatter radar in Massachusetts originally recognized SED in the early 1990s, and the phenomenon has been studied in detail ever since — most recently with satellite data from the Defense Meteorological Satellite Program (DMSP) and Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellites, and with TEC data collected from multiple GPS receivers located across the United States and Canada.

Analysis of the GPS TEC data shows that during geomagnetic disturbances, ionospheric electrons are transported from lower latitudes to higher latitudes, redistributing TEC across latitude and local time (see **Figure 1**). Gradients as large as 70 parts per million have been observed at geographic latitudes of 45°–50° in North America. SED effects can persist for several hours in this region, presenting a significant issue for the CCG DGPS service.

Wide-Area DGPS

For single-reference DGPS, range errors are calculated for each satellite observed at a single reference station and are transmitted as corrections to remote users. Corrections for spatially correlated errors (atmospheric and orbital effects) become less effective with increased baseline length, and DGPS positioning accuracies can be significantly degraded over longer baselines. Limitations therefore exist in both availability and positioning accuracy when using the single-reference DGPS approach.

In the wide-area approach, GPS observations from a sparse network of reference stations are used to model sources of correlated errors over an extended region. Such WADGPS services allow consistent levels of positioning accuracy to be achieved at all locations within the coverage area. Several different approaches and algorithms (including both state-space domain and measurement domain approaches) may be used to derive WADGPS corrections.



▲ **FIGURE 1** An example of storm enhanced density (SED) over North America during a geomagnetic storm event March 31, 2001. Total electron content (TEC) values are given in TEC units (1 TECU = 1016 electrons per meter squared). The thick lines denote the approximate SED boundaries.

In the state-space domain algorithms, different error models are computed for each individual source of error. Typically the satellite clocks, orbits, and ionosphere are modeled separately, and values of parameters describing these corrections are transmitted to users within the area of coverage. Vector corrections are then derived for each satellite observed at the user's location. This approach is mathematically complex and requires an adequate number of reference sites to resolve the various error components (for example, WAAS uses more than 20 reference stations throughout the United States).

In the measurement domain approach, DGPS range corrections are computed for each reference station within the network. A weighted mean of these corrections is computed to derive the optimal range corrections at a user's location within the network. In this approach, range corrections are scalar quantities — incorporating all error sources in a given correction value. Such algorithms are relatively simple and require only a limited number of reference sites (for example, the OmniSTAR system uses this approach with 10 sites in North America).

We have employed a measurement domain approach to derive optimal DGPS corrections at a given user location, based on DGPS corrections derived for all reference stations in the network. The combined DGPS correction for a given satellite at a given epoch is obtained as:

$$PRC' = \sum_{i=1}^{n} W_i PRC_i \qquad (2)$$

where PRC' is the optimal weighted-average pseudorange correction, n is the total number of reference stations, W_i is the weight for reference station i, and PRC_i is the pseudorange correction at reference station i. The weights are dependent on the distance d_i between the reference station and the user location and are computed as:

$$W_i = \frac{1/d_i}{\sum_{i=1}^{n} 1/d_i} \qquad (3)$$

The inverse-distance dependence allows lower weighting for reference stations farther from the user. This method models the known behavior of range corrections, where ranging errors are spatially decorrelated for increased distance from a given reference station. It must be noted, however, that other techniques could be employed to derive an optimal weighting scheme.

Data Set

To evaluate the implementation of a WADGPS approach at Canadian latitudes meaningfully, it is necessary to derive results for a network located in the region of operation for the CCG DGPS service. No archived long-term data set from CCG DGPS reference stations was available for this analysis. We therefore used a network of International GPS Service (IGS) reference stations from which representative results could be derived. The IGS data are freely available over the internet (*http://igscb.jpl.nasa.gov*), with no restrictions placed on their use for research purposes. The data are provided, along with the broadcast ephemerides from each station, in receiver independent exchange (RINEX) format. Dual-frequency observations are available with at least 30-second sample intervals. The coordinates of the reference stations are known to better than one centimeter.

For the purposes of our research, we selected a network of eight reference stations in western Canada (see **Figure 2**). We subdivided this network into two distinct networks for WADGPS processing:

Network 1. Includes reference sites at Albert Head (ALBH), Holberg (HOLB), and Williams Lake (WILL) in British Columbia (B.C.), and Priddis (PRDS) in Alberta, with a simulated user at Whistler (WSLR), B.C. (all designated by the blue triangles in Figure 2).

Network 2. Includes reference sites ALBH, Ucluelet (UCLU), WSLR and Chilliwack (CHWK), with a simulated user at Nanaimo (NANO) all in B.C., (all designated by red triangles).

The geometries of these networks are similar to those for the CCG DGPS Atlantic region, where users may be located in the center of a network of several reference stations. We chose the two distinct networks to investigate both longer baseline processing (Network 1, with an average baseline length of about 400 kilometers) and shorter baseline processing (Network 2, with an average length of 125 kilometers). Baseline lengths within each network are given in **Table 1**.

We computed WADGPS horizontal positioning accuracies for each network using the measurement domain method, using L1 pseudorange observations from the four GPS reference stations surrounding the simulated user: ALBH, HOLB, WILL, and PRDS for user WSLR in Network 1; and ALBH, UCLU, WSLR and CHWK for user NANO in Network 2. We used an elevation cutoff angle of 10°. To conduct comparisons with standard single-baseline DGPS processing, the four single user-reference baselines in each network (Table 1) were processed in DGPS mode. Again, consistent with the WADGPS processing, we assumed an elevation cutoff angle of 10°.

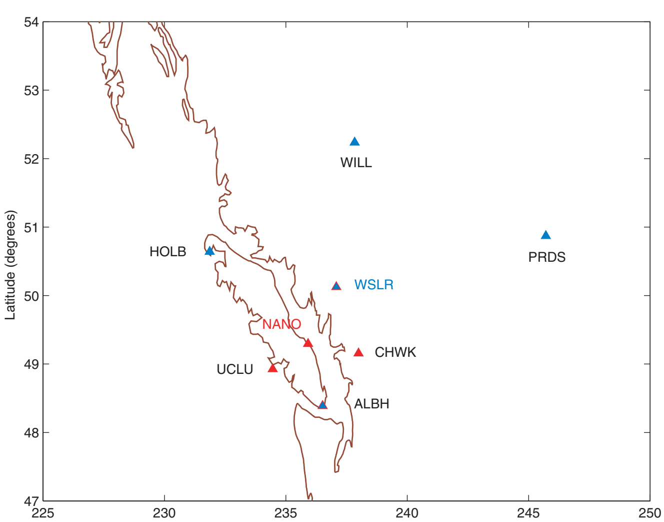


Figure 2 Reference stations used for differential processing in western Canada. Simulated users are WSLR in Network 1 (blue triangles) and NANO in Network 2 (red triangles).

We conducted the DGPS post-processing for all baselines using L1 code observations and a modified version of the C^3NAV software developed at the University of Calgary (U of C). We generated horizontal DGPS and WADGPS position estimates for each epoch at the user sites (WSLR for Network 1, and NANO for Network 2) as well as the 95th-percentile horizontal positioning error. We applied a horizontal dilution of precision (HDOP) threshold of 2.0 to ensure adequate satellite geometry.

Table 1 Baselines in Network 1 and Network 2

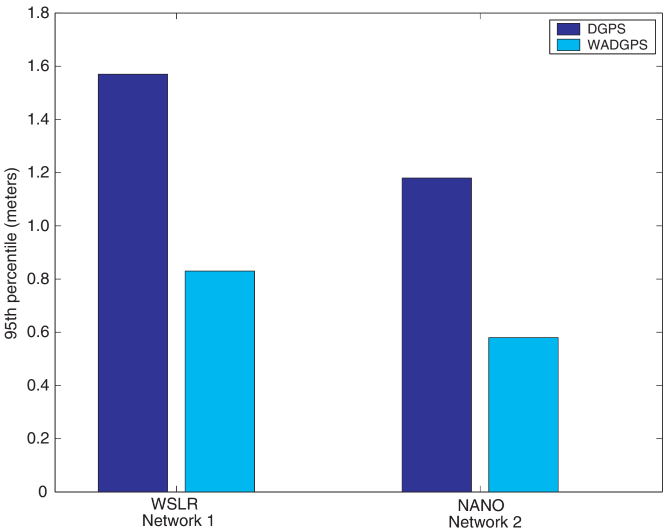
	Station Pair (user-reference)	Baseline Length (kilometers)
Network 1	WSLR-ALBH	198
	WSLR-WILL	241
	WSLR-HOLB	375
	WSLR-PRDS	750
Network 2	NANO-ALBH	110
	NANO-UCLU	114
	NANO-WSLR	125
	NANO-CHWK	152

Analyses and Results

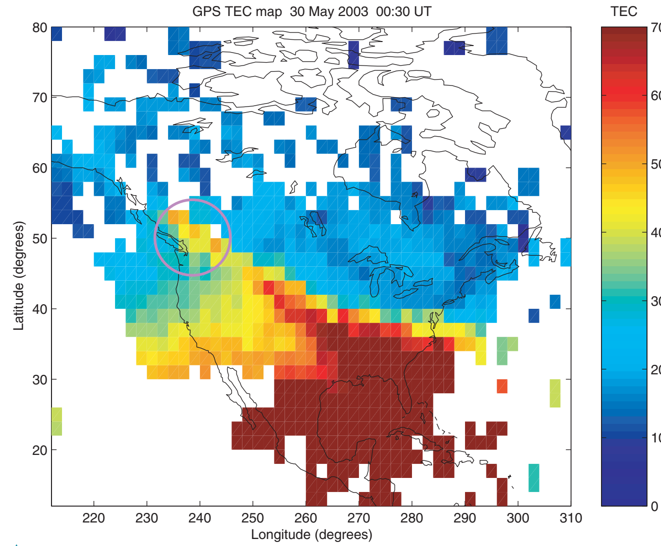
To investigate the performance of the wide-area algorithm on our two test networks, we analyzed a long-term data set covering a wide range of ionospheric activity as well as two shorter data sets obtained during two severe ionospheric storms.

Long-Term Data Set. We processed data from 1999–2003 for both Network 1 and Network 2 to derive representative statistics for a long-term data set. We derived positioning results for simulated user WSLR (Network 1) and NANO (Network 2) using the wide-area technique, and standard single-baseline DGPS results for the shortest baselines in each network: WSLR-ALBH (Network 1) and NANO-ALBH (Network 2). Afterward, we compared the DGPS and WADGPS results, which effectively demonstrated the difference between deriving positioning results using DGPS corrections from the closest reference station in a given network versus multiple reference stations for the WADGPS method. It is expected that an improved ability to model spatially correlated errors with the WADGPS method will result in improved horizontal positioning accuracies versus standard DGPS results.

Figure 3 shows the overall DGPS and WADGPS horizontal positioning accuracies for both networks. The largest horizontal positioning errors are approximately 1.5 meters (95th percentile), as observed for the WSLR-ALBH single-baseline DGPS approach in Network 1. The WSLR-ALBH baseline is 198 kilometers long. By employ-



▲ **FIGURE 3** Single baseline DGPS horizontal positioning accuracies (95th percentile) compared with WADGPS results, for Network 1 (user WSLR) and Network 2 (user NANO).



▲ **FIGURE 4** Storm enhanced density effect shown in GPS TEC map (0030 UT, May 30, 2003). The network of IGS stations (Figure 2) is indicated with a purple circle.

ing a wide-area approach in Network 1, positioning accuracies at WSLR are improved to 0.8 meters (95th percentile). Similarly, in Network 2, the larger positioning errors are observed for the single-baseline (NANO-ALBH) approach — where the baseline length is 110 kilometers. By employing a wide-area approach, horizontal positioning errors are reduced in Network 2 by a factor of two. Note that both the single-baseline DGPS and WADGPS positioning errors are larger for Network 1 than for Network 2. This is directly attributed to the larger station spacing for Network 1.

While these results demonstrate relative improvements in using WADGPS versus standard DGPS, the statistics in Figure 3 represent approximately 4 million processed positioning results for a given user and technique. A wide range of positioning accuracies may occur due to diurnal ionospheric variations and/or different levels of ionospheric activity.

To determine the relative accuracy improvement that may be obtained using WADGPS for higher levels of ionospheric activity, we studied two severe geomagnetic storm events.

May 29–30, 2003, Storm. A very severe geomagnetic storm was initiated on May 29, 2003, following two large solar coronal mass ejections (CMEs) at approximately 1200 UT and 1900 UT. Storm conditions persisted for a period of nine hours, with strong aurora observed in Europe, Canada and the United States. Development of SED was observed over North America for the period 1800 UT May 29–0100 UT May 30. This is illustrated in **Figure 4**.

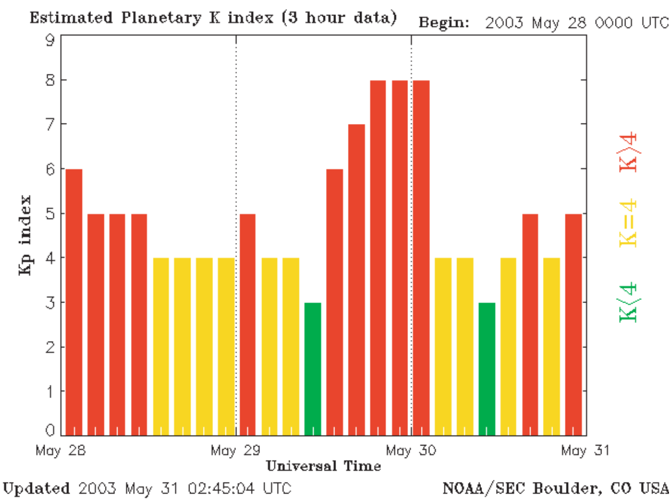
The level of global ionospheric activity during this event is quantified using the conventional space weather index Kp. This index is based on observations of magnetic field fluctuations at ground-based magnetometer stations (periods of enhanced ionospheric activity being characterized by strong electric currents that are observed as magnetic field perturbations at the Earth's surface). Measurements of magnetic field variations at 13 global stations at approximately equally spaced longitudes are combined to produce the planetary Kp index at three-hour intervals, with values ranging from 0 (quiet) to 9 (extreme). Such indices provide an approximate measure of global ionospheric activity at higher latitudes.

Figure 5 shows the Kp indices for the period May 28–30, 2003. Limited intervals with Kp values of 4–5 are observed throughout this period — indicating moderate ionospheric activity. The Kp values reached 8 for the period 1800 UT May 29–0300 UT May 30, 2003. The impact of increased ionospheric activity was observed globally during this nine-hour period.

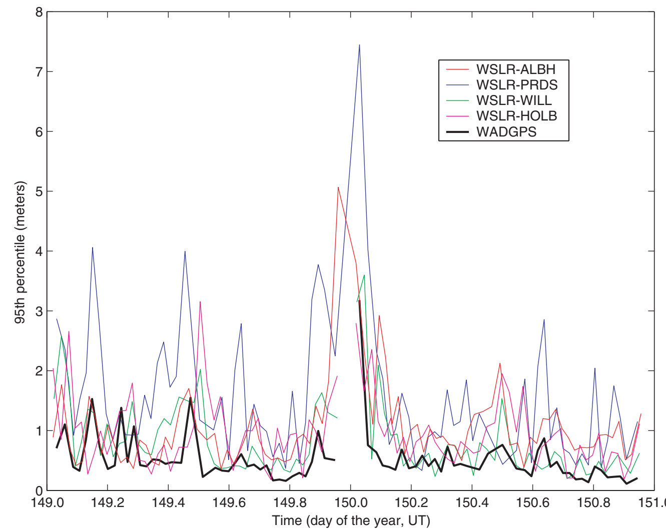
Network 1. We derived the 95th-percentile horizontal positioning accuracies (HDOP<2.0) for simulated user WSLR in Network 1, for each 30-minute time interval during May 29 (day 149)–May 30 (day 150). Results are shown in **Figure 6** for all possible single-baseline DGPS solutions (Table 1), in addition to WADGPS accuracies. Note that the WSLR-ALBH baseline is the shortest in the network, and results for this baseline represent DGPS horizontal positioning accuracies obtained for user WSLR using the closest reference station.

For the WSLR-ALBH baseline (with a length of 198 kilometers), DGPS horizontal positioning errors increased by a factor of 3–4 for a period of several hours during the storm event, compared to more-typical conditions. Unfortunately, we obtained corrupt observations from two of the reference stations (WILL and HOLB) such that WADGPS positioning solutions could not be computed for WSLR (using the four surrounding reference stations) during the most-severe portion of the storm event. In general, the WADGPS results are improved over all single-baseline DGPS results.

Network 2. We also generated the 95th-percentile horizontal positioning accuracies (HDOP<2.0) for simulated user NANO



▲**FIGURE 5** Kp values for May 28–30, 2003 (National Oceanic and Atmospheric Administration Space Environment Center).

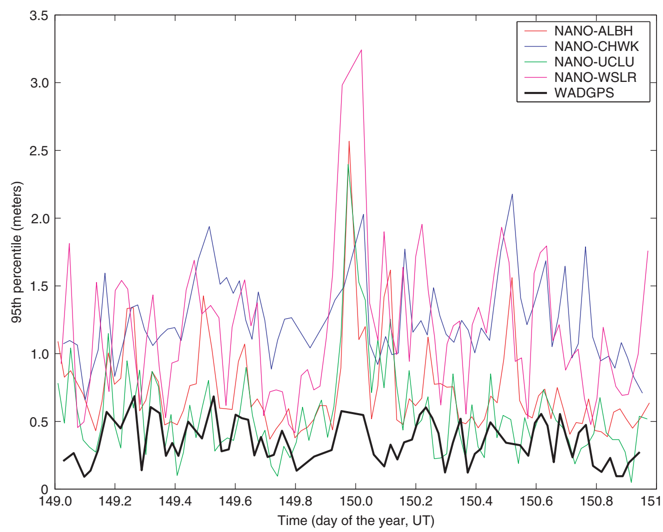


▲**FIGURE 6** 95th-percentile DGPS horizontal positioning accuracies for baselines in Network 1 versus WADGPS results, for simulated user WSLR.

in Network 2, again for each 30-minute time interval during May 29 (day 149)–May 30 (day 150). Results are shown in **Figure 7** for all possible single-baseline DGPS solutions (Table 1), in addition to WADGPS accuracies. For Network 2, the baseline NANO-ALBH (which is 110 kilometers in length) represents single-baseline DGPS positioning accuracies obtained using the closest reference station. Positioning accuracies for this baseline are degraded by a factor of 2–3 for the storm period, as compared with more typical results.

By employing a wide-area technique, horizontal positioning accuracies of better than 0.5 meter (95th percentile) are maintained for user NANO throughout the storm period — with no significant degradation compared to quiet ionospheric conditions earlier on day 149 or later on day 150. Note that positioning accuracies in Network 2 are generally improved over those for Network 1 due to the smaller station spacings in Network 2.

October 29–31, 2003, Storm. One of the highest-intensity storms of the past 15 years occurred in late October, last year. A major solar flare and associated CME developed at approximately 1100 UT on October 28. A severe geomagnetic storm commenced in the Earth's environment at 0600 UT on October 29. Activity continued for several days, with further CMEs at approximately 2100 UT October 29 and 1600 UT October 30.

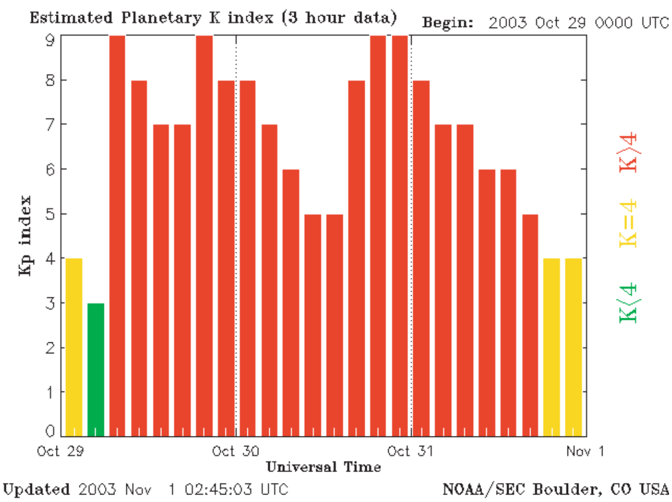


▲**FIGURE 7** 95th-percentile DGPS horizontal positioning accuracies for baselines in Network 2 versus WADGPS results, for simulated user NANO.

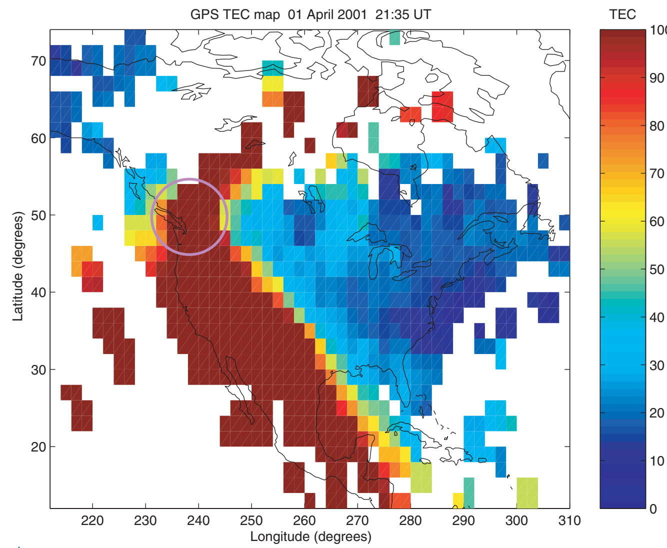
Figure 8 shows the Kp index for the full storm period. Kp values of 9 were observed October 29–30. This indicates severe storm events for extended periods on both days. Communications were disrupted for commercial aircraft operating in polar regions, and satellite instruments were shut down to mitigate the impact of enhanced radiation in the space environment. Similar to the May 29 event, aurora were observed at mid-latitudes — in both Europe and the United States. Development of strong SED was again observed in North America.

The gradients associated with SED were extremely large during this event. The spatial distribution of SED over North America for October 30, 2003, is shown in **Figure 9**. A similar distribution of SED also occurred on October 29. Note that the IGS stations being used for analysis are located near the edge of the SED, where the largest gradients exist. Development of SED persisted during the period 1900–2300 UT on October 30, 2003.

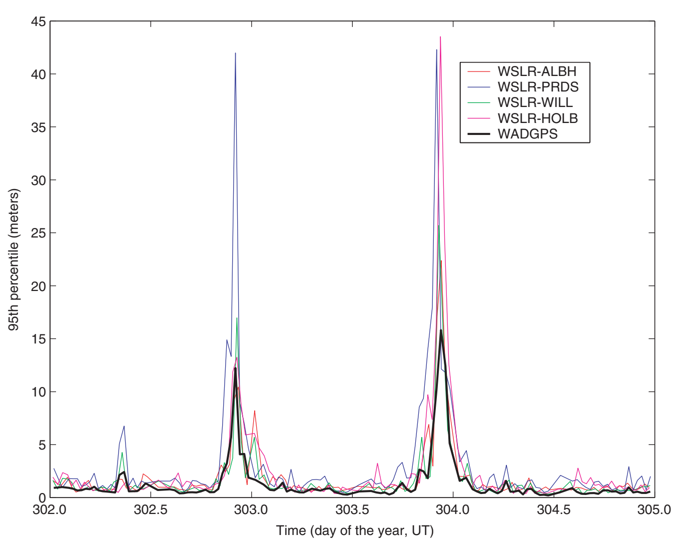
Network 1. As for the May 2003 storm event, 95th-percentile horizontal positioning accuracies (HDOP<2.0) were derived for simulated user WSLR in Network 1 during October 29–31 (day 302–day 304). Results are shown in **Figure 10** for all possible single-baseline DGPS solutions versus WADGPS accuracies. For this event, clear degradations in positioning accuracies are observed during the late hours UT on both October 29 and October 30. Typical 95th-



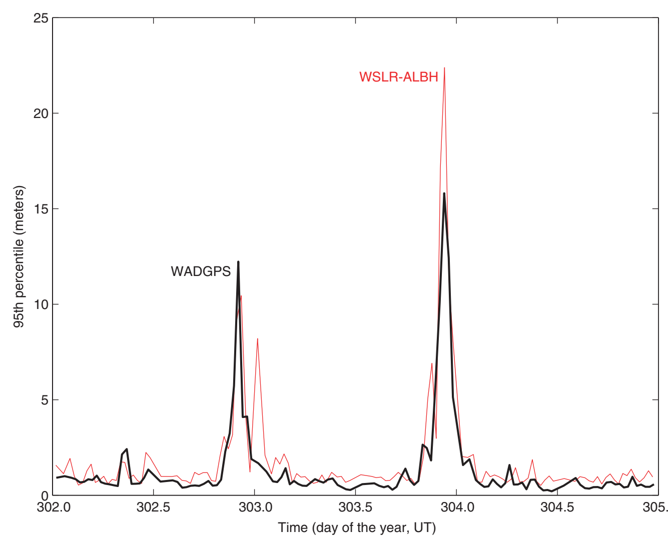
▲ **FIGURE 8** Kp values for October 29–31, 2003 (National Oceanic and Atmospheric Administration Space Environment Center).



▲ **FIGURE 9** Storm enhanced density effect shown in TEC map (2135 UT, October 30, 2003). The network of IGS stations (Figure 2) is indicated with a purple circle.



▲ **FIGURE 10** 95th-percentile DGPS horizontal positioning accuracies for all baselines versus WADGPS results in Network 1, for simulated user WSLR.



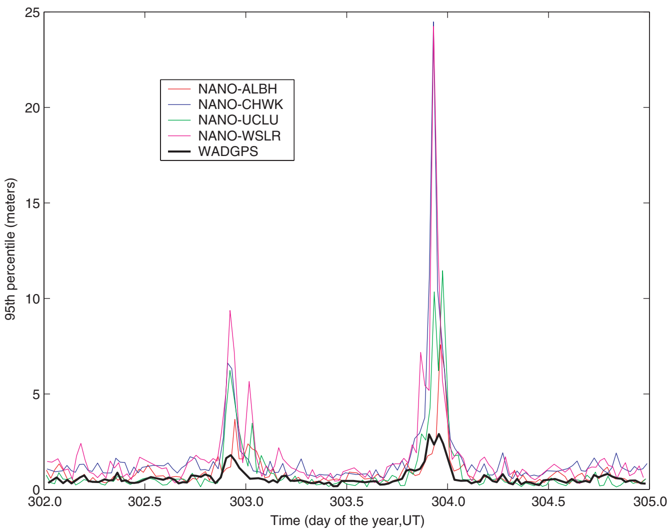
▲ **FIGURE 11** 95th-percentile DGPS horizontal positioning accuracies for the WSLR-ALBH baseline (red line) versus WADGPS results (black line) in Network 1, for simulated user WSLR.

percentile horizontal positioning accuracies (during ionospherically quiet periods) are on the order of several meters, even for the longer DGPS baselines in this network. During the storm periods, however, positioning errors larger than 20 meters (95th percentile) are observed for all DGPS baselines (which range in length from 200–750 kilometers).

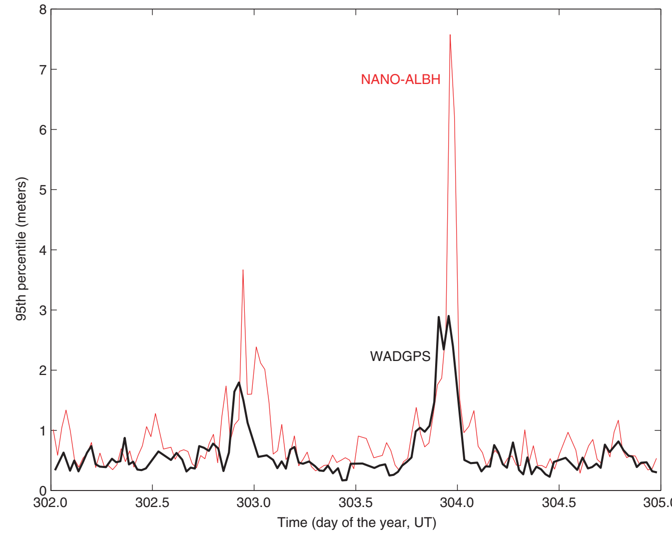
By employing the wide-area technique, some improvement in positioning accuracies is achieved for user WSLR. This is better illustrated in **Figure 11** — where the single-reference DGPS positioning accuracies are shown for the shortest baseline WSLR-ALBH versus WADGPS results.

If user WSLR were to select the closest reference station (ALBH) in a single-reference DGPS approach, maximum horizontal positioning errors of 22 meters (95th percentile) would occur. The wide-area technique would improve accuracies to better than 17 meters. While this represents an improvement of 5 meters, WADGPS does not successfully mitigate the ionospheric effects to a large extent — with the positioning errors still well beyond the typical accuracies or even desired accuracies of 10 meters (95 percent). Smaller station spacings are required to better resolve the ionospheric features.

Network 2. The 95th-percentile horizontal positioning accuracies (HDOP<2.0) for the October storm are shown in **Figure 12** for simulated user NANO in Network 2. Results include all possible single-baseline DGPS solutions, as compared with WADGPS accuracies. Similar to Network 1, there are significant degradations in horizontal positioning accuracies during the late hours UT on both October 29 and October 30. For the single-reference DGPS solutions, position errors as large as 7 meters (95th percentile) are observed for the shortest baseline NANO-ALBH (110 kilometers) and errors as large



▲ **FIGURE 12** 95th-percentile DGPS horizontal positioning accuracies for baselines in Network 2 versus WADGPS results, for simulated user NANO.



▲ **FIGURE 13** 95th-percentile DGPS horizontal positioning accuracies for the NANO-ALBH baseline (red line) versus WADGPS results (black line) in Network 2, for simulated user NANO.

as 24 meters (95th percentile) are observed for the NANO-WSLR baseline (baseline length of 125 kilometers) during the late hours UT on October 30. These results are a factor of 10–20 times worse than typical positioning accuracies.

By employing the wide-area technique, position errors are significantly improved, even during the most-severe period of the storm.

This is better illustrated in **Figure 13**, where the single-reference DGPS positioning accuracies are shown for the shortest baseline NANO-ALBH versus the WADGPS results. If user NANO were to select the closest reference station (ALBH) in a single-reference DGPS approach, maximum horizontal positioning errors of 7.5 meters (95th percentile) would occur. The WADGPS approach improves horizontal positioning accuracies to better than 3 meters (95th percentile).

Conclusion

We have demonstrated the potential of employing a wide-area differential GPS approach to mitigate the differential positioning errors seen by marine users of DGPS services. It is intended that such a technique might be implemented using existing Canadian or United States Coast Guard reference stations. Archived data were not available from Canadian Coast Guard stations and so we generated comparable WADGPS results using observations from Canadian IGS stations. We evaluated two networks: Network 1 with station spacings of 200–750 kilometers, and Network 2 with station spacings of 110–150 kilometers.

For the larger-baseline network, some improvements were observed for WADGPS versus single-reference DGPS during the storm events. The WADGPS method did not improve horizontal positioning errors

Further Reading

For marine navigation system requirements, see

2001 Federal Radionavigation Plan, DOD-VNTSC-RSPA-01-3/DOD-4650.5, U.S. Department of Defense/ Department of Transportation, Washington, D.C., 2001.

For further information on wide-area DGPS algorithms, see

"Performance Overview of Two WADGPS Algorithms" by M.A. Abousalem in *GPS World*, Vol. 8, No. 5, May 1997, pp. 48-58.

"Wide Area Differential GPS" by C. Kee in *Global Positioning System: Theory and Applications*, Vol. II, eds. B.W. Parkinson, J.J. Spilker Jr., P. Axelrad, and P. Enge, American Institute of Aeronautics and Astronautics, Washington, D.C., 1996, pp. 81–115.

For discussions of space weather and ionospheric storm effects, see

"GPS, the Ionosphere, and the Solar Maximum" by R.B. Langley in *GPS World*, Vol. 11, No. 7, July 2000, pp. 44–49.

"Ionospheric Signatures of Plasmaspheric Tails" by J.C. Foster, P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich in *Geophysical Research Letters*, Vol. 29, No. 13, 10.1029/2002GL015067, 2002.

For further information on the effect of the ionosphere on GPS, see

"A Comparison of Predicted and Measured GPS Performance in an Ionospheric Scintillation Environment" by M. Knight, M. Cervera, and A. Finn in *Proceedings of ION GPS-99*, the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation, Nashville, Tennessee, September 14–17, 1999, pp. 1437–1450.

"Limitations in GPS Positioning Accuracies and Receiver Tracking Performance During Solar Maximum" by S. Skone, M. El-Gizawy, and S.M. Shrestha in *Proceedings of KIS 2001*, the International Symposium on Kinematic Systems in Geodesy, Geomatics, and Navigation, Banff, Canada, June 5–8, 2001, pp. 129–143.

For an introduction to the use of GPS for monitoring space weather, see

"Space Weather: Monitoring the Ionosphere with GPS" by A. Coster, J. Foster, and P. Erickson in *GPS World*, Vol. 14, No. 5, May 2003, pp. 42–49.

to within the 10 meters (95 percent) threshold, however, and the lack of significant overall improvement for WADGPS within this network is attributed to the large station spacing — which does not allow adequate resolution of ionospheric features.

For the shorter-baseline network, significant improvements were observed for WADGPS versus single-reference-station DGPS during the storm events. Horizontal positioning errors were decreased by a factor of two for the WADGPS approach during the most-severe stages of the storms. This demonstrates the potential of using multiple reference stations in a combined approach for networks with reference-station spacings of around 100 kilometers.

Marine GPS users also have access to public and commercial WADGPS corrections from systems such as OmniSTAR, the Canada-wide Differential GPS Service, WAAS or EGNOS (European Geostationary Navigation Overlay Service). While these systems were not evaluated for this article, we can comment on potential improvements in using such systems during ionospheric storm events. The WADGPS solutions demonstrate a strong dependence on station spacing within the reference network. For systems such as OmniSTAR, with only a sparse network of reference stations throughout North America, the resolution required to resolve storm enhanced density would not be achieved. Only with dense networks (with station spacings less than about 150 kilometers) would significant benefit be gained in employing a multiple-reference-station WADGPS approach. Further benefits could be gained with a more complex wide-area algorithm, through which a spatial model of the ionospheric corrections is derived using dual-frequency observations from all reference stations. We are currently investigating this more complex approach.

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"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by **RICHARD LANGLEY** of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 2 of this issue.