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ORIGINAL ARTICLE

Studies of storm-enhanced density impact on DGPS using IGS reference station data

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Abstract DGPS services are provided in support of land and marine applications by many government agencies worldwide. Horizontal positioning accuracies in the order of several metres are typically achieved for these systems. Under high levels of ionospheric activity, however, significant degradations in DGPS positioning accuracies can occur. In particular, gradients of up to 50 ppm are associated with a feature known as storm-enhanced density (SED). This feature is a localized enhancement of total electron content (TEC) extending north through the mid-latitudes into the polar region. DGPS positioning errors of 20 m or more can persist for hours during such events. In this paper, archived IGS data from GPS reference stations are used to derive high-resolution TEC maps for two SED events. The impact of SED effects on DGPS horizontal positioning accuracies is then quantified using data from select IGS reference stations in North America and Europe. Results indicate that positioning accuracies may be degraded by factors as large as 10–20 during such events.

Keywords IGS · GPS · GNSS · Differential ionosphere · Positioning and navigation

1 Introduction

Users worldwide rely on differential GPS (DGPS) systems for a variety of marine and land applications. These include hydrographic surveying applications, and exploration/exploitation of marine resources, assistance to vessel traffic management services, search and rescue operations, environmental assessment and clean-up, and underwater mine detection and disposal in the marine side. Marine horizontal positioning accuracy requirements are 2–5 m (95%) and 8–20 m (95%) for safety of navigation in inland waterways and harbour entrances/approaches, respectively; horizontal positioning accuracies of 1–100 m (95%) are required for benefits of resource exploration in coastal regions (DOD/DOT 2001). Typical integrity values are 10 s TTA (time to alarm), as adopted from those determined for aviation navigation (Volpe NTSC 2001). As for land applications, DGPS systems are employed in the automotive industry, at construction sites, for farming needs, and even for recreational purposes. Land accuracy requirements are specific to the application but in many cases positioning errors less than a few metres are expected.

The ionospheric range error is a function of the signal frequency and the electron density along the signal path. The majority of the ionospheric effect (greater than 99.9%) can be described by low-order terms in the ionospheric index of refraction equation and the following expression is derived for the ionospheric range error:

$$I = \pm 40.3 \frac{\mathrm{TEC}}{f^2} \quad \text{(in metres)} \tag{1}$$

where TEC denotes the total electron content integrated along the signal path (in el/m^2), f is the signal frequency (in Hz), and + (±) denotes the group delay (phase advance). The ionospheric range error can dominate the single frequency DGPS error budget under high levels of ionospheric activity. Additional effects of ionospheric scintillation can cause degradation of receiver tracking performance and, in extreme

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cases, loss of navigation capabilities entirely (Ledvina et al. 2002; Rodrigues et al. 2004).

For the most part, DGPS services offer satisfactory performance in terms of accuracy, reliability and availability. For example, the Canadian and United States Coast Guard specify the DGPS horizontal tolerance to be 10 m (95%) for their marine systems and, under normal operating conditions, accuracies fall well within this bound. During high levels of ionospheric disturbance, however, considerable degradations in DGPS positioning accuracy can occur. In the years following solar maximum, large ionospheric gradients have been observed in North America during geomagnetic storm events. GPS differential ranging errors are a direct function of such gradients, and very large positioning errors (which are dependent on both the differential ranging errors and the satellite geometry) have been observed in both Canada and the United States.

An ionospheric feature of particular importance for DGPS applications is called storm-enhanced density (SED) (Foster 1993). An example of the ionospheric TEC distribution characterizing this effect is shown in Fig. 1. The SED is observed as a plume of enhanced TEC extending north through the United States into Canada, and over the pole into Europe (Coster et al. 2003; Foster et al. 2005). This feature develops in the afternoon local time sector and can persist into early evening. In Eq. 1, GPS ionospheric range errors are directly proportional to TEC values. Large differential range errors arise when severe gradients in TEC are present. Some of the largest gradients on Earth, in the range 50–70 ppm, are observed at the edges of the narrow SED plume shown in Fig. 1.

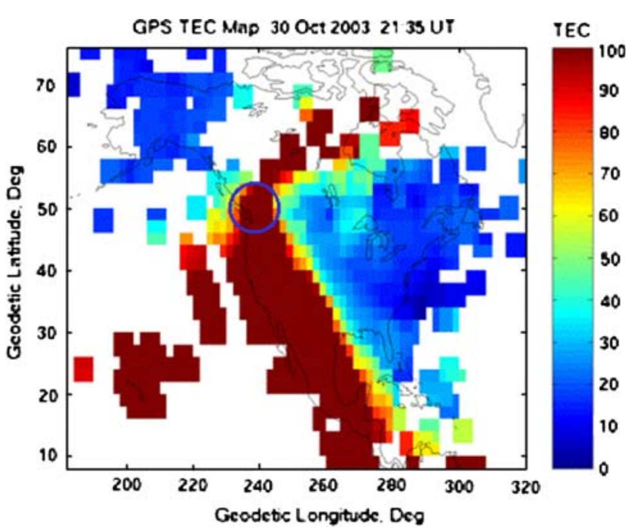

Fig. 1 An example of SED over North America during a geomagnetic storm event 2135 UT October 30, 2003. Region for DGPS processing is shown with a *blue circle*

This SED feature has been identified and studied in recent years, by generating high-resolution spatial maps derived from observations at hundreds of GPS reference stations made available by services such as the IGS (Rideout and Coster 2006), e.g. Fig. 1. Analyses of DGPS horizontal positioning accuracies during periods of SED are provided in this paper. The impact of SED on DGPS applications is quantified by processing archived data from IGS reference stations in Canada and Europe. The availability of IGS data in Canada has been particularly useful in this study. Data from Canadian Coast Guard DGPS reference stations are not archived on a regular basis and are not available for post-processing to study marine DGPS errors at Canadian latitudes.

2 North American region

A study of the effects of SED (and ionospheric gradients) on DGPS horizontal positioning accuracies in North America is conducted for a geomagnetic storm event which took place during October 2003 (Fig. 1). This analysis focuses on baselines of different lengths and orientations in western Canada.

2.1 Data set and processing

Extreme geomagnetic storms were observed during October-November 2003. Activity commenced with one of the most severe storm of the past 15 years, in late October 2003. A major solar flare and coronal mass ejection erupted 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 solar coronal mass ejections (which trigger ionospheric activity in the Earth's environment) at approximately 2100 UT October 29 and 1600 UT October 30.

The spatial distribution of SED over North America is shown in Fig. 1 at 2135 UT on 30 October 2003. Development of SED persisted during the period 1930–2300 UT on October 30, and very large gradients in ionospheric delay were observed (with values as large as 70 parts per million in the region indicated by the blue circle). A similar distribution of SED also occurred on October 29. The increased spatial decorrelation of ionospheric range errors had a direct impact on DGPS positioning accuracies.

For the purposes of this study, a network of eight reference stations in western Canada has been selected (see Fig. 2). This network is subdivided into two distinct networks for DGPS processing:

1. Network 1 includes reference sites ALBH, HOLB, WILL, and PRDS, with a simulated user at WSLR (blue triangles).

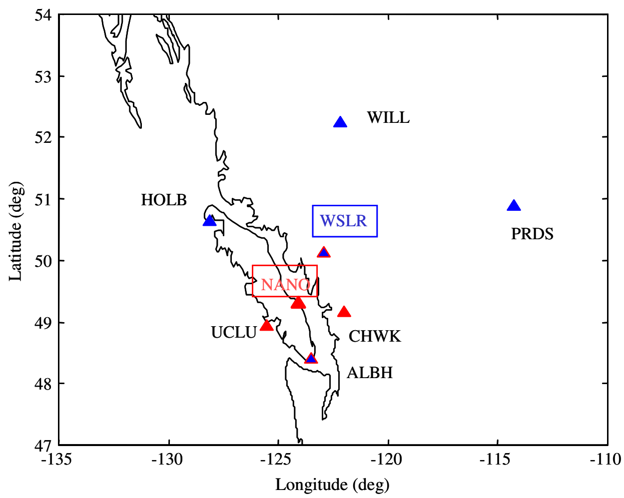

Fig. 2 Reference stations used for differential processing in western Canada. Simulated remote DGPS users are WSLR in Network 1 (*blue triangles*) and NANO in Network 2 (*red triangles*)

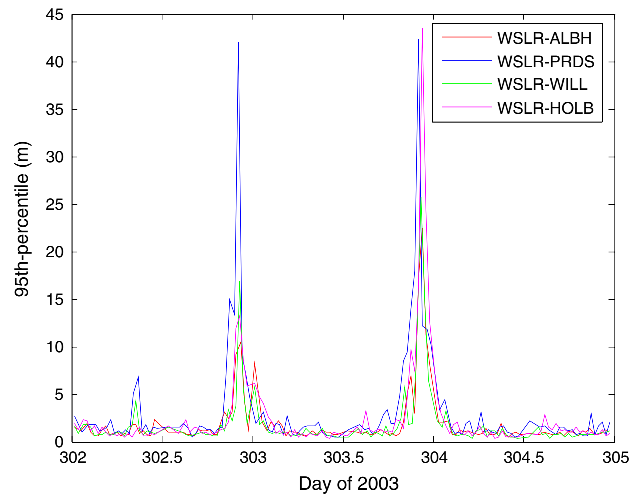

Fig. 3 The 95th-percentile DGPS horizontal positioning accuracies for all baselines in Network 1, for simulated user WSLR, October 29 (day 302) and 30 (day 303), 2003

Table 1 Baselines in Networks 1 and 2

Station pair (user-reference)	Baseline length (km)
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

2. Network 2 includes reference sites ALBH, UCLU, WSLR and CHWK, with a simulated user at NANO (red triangles).

The two networks have been chosen in order to investigate both longer baseline processing (Network 1) and shorter baseline processing (Network 2). Station spacings are similar to those for marine DGPS services in Canada. Baseline lengths within each network are given in Table 1.

For each network, DGPS horizontal positioning accuracies were computed for each of the four baselines. The remote users are assumed to be WSLR and NANO in Networks 1 and 2, respectively. An elevation cutoff angle of 10 degrees was used. For each baseline one station is designated as reference, and DGPS corrections generated for this site are applied at the user station. Positioning results are then compared with known truth coordinates at the user site to determine DGPS horizontal positioning accuracies. This DGPS post-processing was conducted using L1 code observations and a modified version of the C3NAV^{TM} software (Cannon et al. 1995). Horizontal DGPS positioning estimates were computed for each epoch at the user sites and the 95th-percentile horizontal positioning error statistics were generated at 30-min intervals. A horizontal dilution of precision (HDOP) threshold of 2.3 was applied for derivation of all results to ensure adequate satellite geometry. Less than one percent of the raw positioning solutions have HDOP values exceeding this threshold.

2.2 Results and analysis

Results are shown in Fig. 3 for all possible single-baseline DGPS solutions for Network 1. For this event, clear degradations in positioning accuracies are observed during the late hours UT on both October 29 and October 30. Typical 95th-percentile horizontal positioning accuracies (during ionospherically quiet periods) are on the order of several metres, even for the longer DGPS baselines in this network. During the storm periods, however, positioning errors larger than 20 m (95th-percentile) are observed for all DGPS baselines (which range in length from 200 to 750 km).

The 95th-percentile horizontal positioning accuracies (HDOP $<$ 2.3) for the October storm event are shown in Fig. 4 for simulated user NANO in Network 2. Similar to Network 1, there are significant degradations in horizontal positioning accuracies during the late hours UT on both October 29 and October 30. DGPS horizontal positioning errors as large as 7 m (95th-percentile) are observed for the shortest baseline NANO-ALBH (110 km) and errors as large as 24 m (95th-percentile) are observed for the NANO-WSLR baseline (baseline length of 125 km) during the late hours UT on

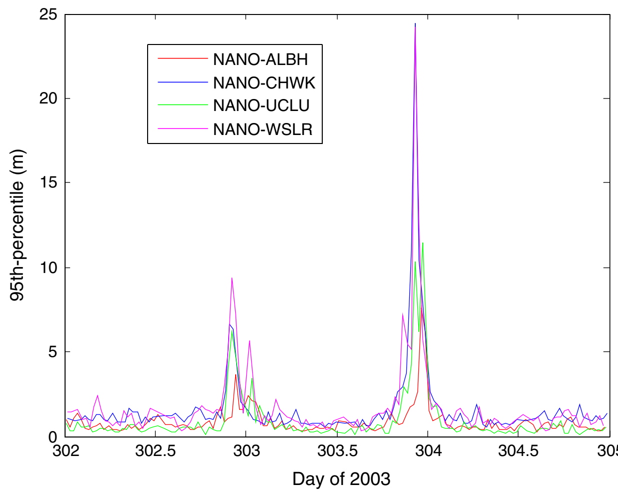

Fig. 4 The 95th-percentile DGPS horizontal positioning accuracies for baselines in Network 2, for simulated user NANO, October 29 (day 302) and 30 (day 303), 2003

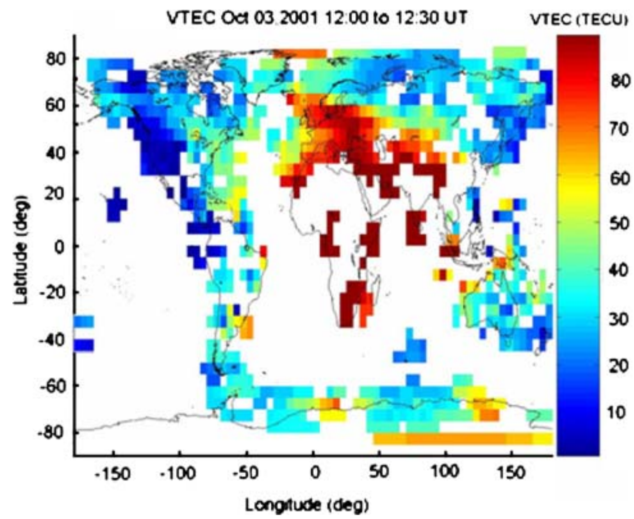

Fig. 5 Global distribution of vertical total electron content 1200–1230 UT October 3, 2001

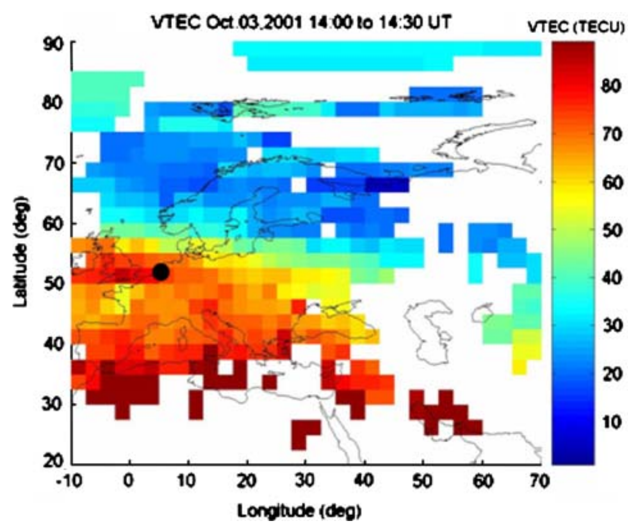

Fig. 6 Local distribution of vertical total electron content in Europe 1400–1430 UT October 3, 2001. The *black circle* indicates location of "user" BRUS for DGPS processing

October 30. These results are a factor of 10–20 times worse than typical positioning accuracies. For both Networks 1 and 2 the larger positioning errors persist for several hours.

In comparing results for Networks 1 and 2 there is a clear dependence of positioning error on baseline length, with generally larger positioning errors in Network 1. Even for shorter baselines in Network 2 (e.g. 110–150 km), however, the DGPS positioning errors are significant. For several hours on October 30, the DGPS positioning errors within Network 2 exceed the 10-m bound (95%) specified by the Canadian Coast Guard for marine users. For the event studied here there is minimal dependence of positioning errors on baseline orientation. It is noted that vertical positioning errors for these studies were typically a factor of 1.5 larger than the horizontal positioning errors.

3 European region

Storm-enhanced density effects are local time dependent, typically developing near local noon and extending into the afternoon sector. In the previous section, analyses were conducted to quantify the impact of such effects on horizontal positioning accuracies in North America (Canada). For the North American study, an event was chosen (October 2003) in which North America was near local noon–afternoon as the SED plume developed. In this section, a second event is identified and studied—to assess impact in the European sector. For this event Europe in located in the afternoon region local time as the SED effects develop. DGPS positioning errors are computed for baselines near regions of large ionospheric gradients and horizontal positioning errors are investigated.

3.1 Data set and processing

A geomagnetic storm event took place on October 3, 2001 where SED development was observed in Europe. The global distribution of ionospheric TEC during this event is shown in Fig. 5. A plume of enhanced ionospheric TEC is observed to extend through the mid-latitudes into Europe 1200–1230 UT. During this time, Europe is located near approximately noon local time. Figure 6 shows the local distribution of TEC in Europe several hours later (1400–1430 UT) where the ionospheric gradients of magnitude 15 ppm persist over Europe.

DGPS horizontal positioning errors are evaluated for this event by processing data from two IGS (EUREF) stations:

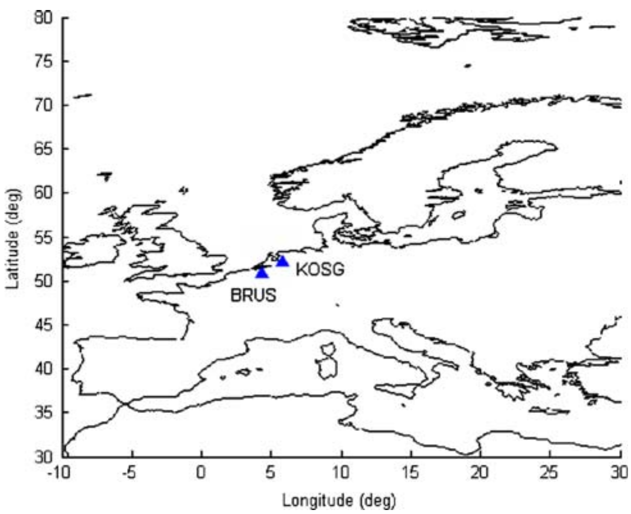

Fig. 7 IGS (EUREF) reference stations used for October 3, 2001 DGPS processing

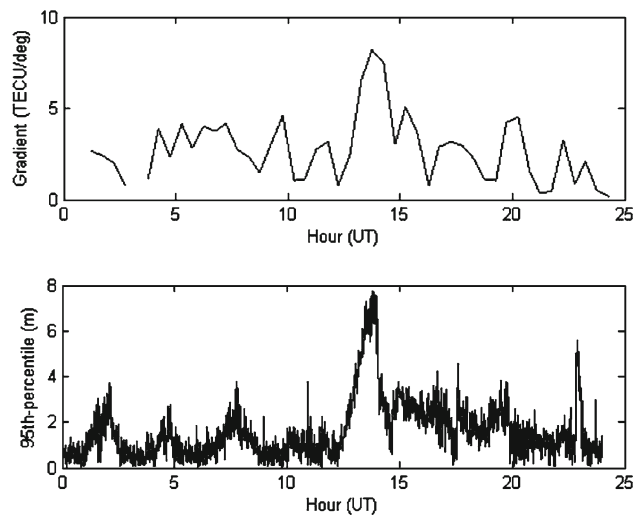

Fig. 8 Ionospheric gradients near BRUS (*top*) and 95th-percentile DGPS horizontal positioning errors for baselines BRUS-KOSG (*bottom*), October 3, 2001

BRUS and KOSG. Locations of these stations are shown in Fig. 7 and the baseline length is 182 km. In this analysis BRUS is considered to be the DGPS user. DGPS corrections were computed at 30-s intervals for reference station KOSG. These corrections were then applied at remote user BRUS and 95th percentile positioning solutions were computed. As for the North American DGPS processing, an HDOP cutoff threshold of 2.3 is applied. Results are then compared with BRUS truth coordinates to determine the DGPS horizontal positioning errors.

3.2 Results and analysis

Results for the BRUS-KOSG baseline are shown in Fig. 8. The top plot shows the ionospheric gradients near BRUS, as computed from the ionospheric TEC distribution, e.g. Fig. 6. The lower plot shows the 95th percentile DGPS horizontal positioning errors. It is observed that errors in the range 4–8 m exist during the period 1300–1430 UT. This is consistent with the development of SED in Fig. 6.

Overall, degraded horizontal positioning errors (in excess of 5 m, 95th-percentile) were observed for a period of 90 min during this event (note that vertical positioning errors were approximately 40% larger than the horizontal positioning errors). These positioning errors are a factor of two larger than those for quiet ionospheric conditions. The horizontal positioning errors of 5–10 m observed in the European sector during this event are less than the 10–20 m observed in the North American sector for the October 2003 event. This is due to the severity of the event in October 2003, and the fact that gradients associated with SED tend to be smaller in the European sector. This is likely due to differences in the geomagnetic field in Europe versus North America, resulting in larger TEC values near the base of the plume in North America (Coster et al. 2007). Comparisons of SED effects in the North American and European sectors is an ongoing area of research, with implications for future WAAS and EGNOS implementation—in addition to the DGPS results presented here.

4 Conclusions

An ionospheric feature known as SED has been observed in North America and Europe during the years following solar maximum. This phenomenon is characterized by a plume of enhanced electron content extending through the mid-latitudes with dimensions of 1,000 km east-west. Near the edges of this plume very large ionospheric gradients can exist, and larger DGPS positioning errors are observed in these regions. Variations in SED effects exist, as a function of the geomagnetic field, with typically less impact (smaller gradients) in the European versus North American sectors. The evolution of SED can be observed in TEC maps generated from global GPS reference station data, as provided by services such as the IGS.

Archived data from IGS reference stations in western Canada were processed to evaluate DGPS horizontal positioning accuracies during a severe geomagnetic storm event in 2003. Baselines in the range of 200–750 km (Network 1) were processed, with positioning errors larger than 40 m observed for baselines longer than 400 km. Baselines in the range 110–150 km (Network 2) were also processed, to evaluate shorter baselines, and horizontal positioning errors of up to 25 m were observed to persist for several hours. These effects were associated with large gradients of up to 70 ppm near the edge of the SED plume.

An SED event was also studied for the European region, and DGPS horizontal positioning accuracies were derived in a region of large ionospheric gradients using archived data from IGS reference stations. DGPS horizontal positioning errors of 2–10 m (95%) were observed in Europe, with ionospheric gradients of 10–15 ppm. These DGPS errors are lower than those observed for the SED event in North America. This is attributed to lower severity of the European events studied, and the nature of the SED phenomenon—where geomagnetic fields in the North American sector tend to enhance the SED effect and cause higher TEC values (and gradients). The results derived in this paper do, however, establish the presence of degraded DGPS accuracies during SED events in Europe. This has not been studied or quantified previously, and it has been established here that SED effects have a global impact on DGPS positioning for land and marine users.

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