Fax to: +4930/82 78 765-751

Waltraud Klaudius
Springer-Verlag GmbH & Co. KG, Berlin

From:
Re: **GPS Solutions DOI 10.1007/s10291-003-0053-7**
Degradation of GPS performance in geomagnetically disturbed conditions
Authors: **Afraimovich · Demyanov · Kondakova**

I. Permission to publish

Dear Waltraud Klaudius,

I have checked the proofs of my article and

☐ I have **no corrections.** The article is ready to be published without changes.

☐ I have **a few corrections.** I am enclosing the following pages:

☐ I have made **many corrections.** Enclosed is the **complete article.**

II. Offprint order

☐ Offprint order enclosed ☐ I do not wish to order offprints

Remarks:

Date / signature ______________________________

III. Copyright Transfer Statement (sign only if not submitted previously)

The copyright to this article is transferred to Springer-Verlag (for U.S. government employees: to the extent transferable) effective if and when the article is accepted for publication. The copyright transfer covers the exclusive right to reproduce and distribute the article, including reprints, translations, photographic reproductions, microform, electronic form (offline, online) or any other reproductions of similar nature.

An author may make his/her article published by Springer-Verlag available on his/her home page provided the source of the published article is cited and Springer-Verlag is mentioned as copyright owner. Authors are requested to create a link to the published article in Springer's internet service. The link must be accompanied by the following text: "The original publication is available at http://link.springer.de or at http://link.springer-ny.com." Please use the appropriate URL and/or DOI for the article. Articles disseminated via SpringerLink are indexed, abstracted and referenced by many abstracting and information services, bibliographic networks, subscription agencies, library networks, and consortia.

The author warrants that this contribution is original and that he/she has full power to make this grant. The author signs for and accepts responsibility for releasing this material on behalf of any and all co-authors.

After submission of this agreement signed by the corresponding author, changes of authorship or in the order of the authors listed will not be accepted by Springer-Verlag.

Date / Author's signature ______________________________

Journal: GPS Solutions
DOI: 10.1007/s10291-003-0053-7

Offprint Order Form

- To determine if your journal provides free offprints, please check the journal's instructions to authors.
- You are entitled to a PDF file **if you order offprints.**
- Please checkmark where to send the PDF file:

☐ afra@iszf.irk.ru

☐ ____________________

- If you do not return this order form, we assume that you do not wish to order offprints.
- If you order offprints **after** the issue has gone to press, costs are much higher. Therefore, we can supply offprints only in quantities of 300 or more after this time.
- For orders involving more than 500 copies, please ask the production editor for a quotation.

Please enter my order for:

	Copies	Price EUR	Price USD
☐	50	350.00	340.00
☐	100	400.00	390.00
☐	200	550.00	535.00
☐	300	700.00	680.00
☐	400	850.00	825.00
☐	500	1,000.00	975.00

Prices include surface mail postage and handling. Customers in EU countries who are not registered for VAT should add VAT at the rate applicable in their country.

VAT registration number (EU countries only):

____

I wish to be charged in
☐ Euro
☐ US-Dollar

If not specified, invoices are made out in Euro.

Please indicate your institutional purchase order number (if any) here

____

and send the purchase order, with all information about the article, via regular mail. The author will be billed for orders without a purchase order number. The title of the journal and the manuscript number of the article must be stated on the purchase order.

☐ Please charge my credit card
  ☐ Eurocard/Access/Mastercard
  ☐ American Express
  ☐ Visa/Barclaycard/BankAmericard

Number (incl. check digits):

_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Valid until: _ _ / _ _

Signature: ____________________

Send invoice to:

☐ E. L. Afraimovich
Inst.of Solar Terr.Physics
Siberian Div.of the
Russian Acad. of Sciences
P.O.Box 4026
Irkutsk
664033, Russian Federation

☐ ____________________

____

____

____

____

Ship offprints to:

☐ E. L. Afraimovich
Inst.of Solar Terr.Physics
Siberian Div.of the
Russian Acad. of Sciences
P.O.Box 4026
Irkutsk
664033, Russian Federation

☐ ____________________

____

____

____

____

Date / signature: ____________________

GPS Solutions

© Springer-Verlag 2003

DOI 10.1007/s10291-003-0053-7

Original Paper

Degradation of GPS performance in geomagnetically disturbed conditions

E. L. Afraimovich (✉) · V. V. Demyanov · T. N. Kondakova

E. L. Afraimovich · V. V. Demyanov · T. N. Kondakova
Institute of Solar-Terrestrial Physics SD RAS, P.O. Box 4026, 664033 Irkutsk , Russia

✉ E. L. Afraimovich
Fax: +7-3952-511675
E-mail: afra@iszf.irk.ru

Received: 17 January 2003 / **Accepted:** 24 February 2003

Abstract During geomagnetically disturbed conditions, the accuracy and quality of GPS performance is impaired. Unlike geomagnetically quiet conditions, magnetic storm conditions are accompanied by an increase in the spherical standard deviation of the position determination for all types of GPS receivers. In magnetic storm conditions there is an increase in the number of slips of the one-frequency mode of coordinate determination. We have identified an unambiguous tendency of the slip density of the one-frequency mode to increase for the ASHTECH and TRIMBLE GPS receivers. For the AOA receivers this tendency was not observed in any of the cases considered. The slip density in the two-frequency mode of coordinate determination in magnetic storm conditions increases most dramatically for the ASHTECH receivers. Regarding the TRIMBLE receivers, there is a similar, but less clearly pronounced, picture. No slips of the two-frequency mode were detected for the AOA receivers in the cases under consideration.

Introduction

The satellite navigation GPS system (Hofmann-Wellenhof et al. 1992) has become a powerful factor of scientific and technological progress worldwide, and enjoys wide use in a great variety of human activity. In this connection, much attention is given to continuous perfection of the GPS system and to the widening of the scope of its application for solving navigation problems, as well as for developing higher–precision systems for time and position determinations. Even greater capabilities are expected in the near future through the combined use of the GPS with a similar Russian system GLONASS (Kharisov et al. 1998).

The geospace environment limits the performance of modern global satellite radio navigation systems that utilize the “Earth-Space” radio wave propagation channel. The main degradation comes from the systematic ionospheric effects of radio wave propagation: the group and phase delay and the frequency Doppler shift. In many instances, the degree of manifestation of the above effects has only a weak dependence on the local distribution of electronic density in the ionosphere but is directly correlated with the value of total electron content (TEC) along the radio signal propagation path (Goodman and Aarons 1990).

Under undisturbed geospace conditions, the main contribution to the formation of the above-mentioned ionospheric effects is made by the regular TEC component. It undergoes periodic regular variations (seasonal-diurnal, latitudinal, and longitudinal) and can be predicted relatively accurately. A variety of TEC models have been developed to date, which are intended to cancel out the ionospheric influence on the performance of the modern GLONASS and GPS under geomagnetically quiet and weakly disturbed conditions (Afraimovich et al. 2000a; Klobuchar 1986).

The situation is more complicated under geomagnetically disturbed conditions of the space environment. The irregular TEC component makes a substantial contribution in this case. The amplitude of random TEC variations with a period from a few minutes to several hours in conditions of geomagnetic disturbances can make up as much as 50% of the background TEC value (Basu et al. 1988; Bhattacharrya et al. 2000; Ho et al. 1996; Warnart 1995). Furthermore, the range of amplitude and phase fluctuation of navigation satellites (NS) signals at the reception point can exceed the design level required for the uninterrupted operation of GPS receivers. Under these conditions, the accuracy to which the current location (CL) can be determined is degraded for both stationary and mobile users of GPS.

The study of deep, fast variations in TEC caused by a strong scattering of satellite signals from intense small-scale irregularities of the ionospheric F2-layer at equatorial and polar latitudes has a special place among ionospheric investigations based on using satellite (including GPS) signals (Aarons 1982; Basu et al. 1988; Aarons et al. 1996, 1997; Pi et al. 1997; Aarons and Lin 1999). The interest in this issue is explained by the fact that scattering causes severe amplitude fading the signal, which can lead to a phase slip at GPS frequencies (Skone and Jong 2000, 2001).

Recent years have seen extensive studies of mid-latitude phase fluctuations and phase slips of range measurements using GPS under conditions of geomagnetic disturbances (Afraimovich et al. 2000; 2001a, 2001b, 2002a, 2002b; Bhattacharrya et al. 2000; Skone and Jong 2000; Skone and Jong 2001; Coster et al, 2001; Shan et al, 2002; Conker et al. 2003). From the GPS user's point of view, however, the investigations into the influence of geomagnetic disturbances on the performance of GPS as a positioning system are of significantly greater interest

The objective of this paper is to estimate the CL determination accuracy and the failure density in determining the location in the one-frequency and two-frequency modes during conditions of geomagnetic disturbances for GPS receivers installed at permanent mid-latitude stations that are part of the global GPS network.

Experimental setup and data processing technique

The goal of our experiment for investigating GPS performance during conditions of geomagnetic disturbances was:

- to estimate the CL determination accuracy of the GPS user under conditions of geomagnetic disturbances and compare these estimates to undisturbed conditions;
- to establish the fact of presence (absence) of slips in the determination of the user's location in both the one-frequency mode of standard positioning and in the two-frequency mode of positioning during conditions of geomagnetic disturbances, and to obtain a numerical estimate of the slip density.

We used data from RINEX-files (Gurtner 1993) available through the Internet at http://lox.ucsd.cdu/cgi–bin/allCoords.cgi. Specifically, we concentrated on the data from the set of stations that are part of the global GPS network in the mid-latitude region (latitudes B–35...50°; longitudes L–120...90°) in North America where the distribution density of stations is the largest (the location map of GPS stations is presented in Fig. 1). We did not examine data collected from receivers in the equatorial and polar regions.

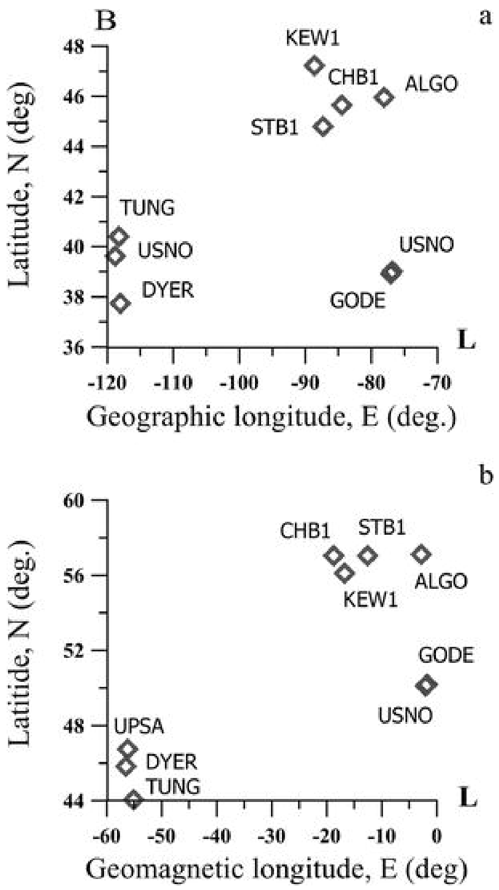

Fig. 1. Map showing the locations of the receiving GPS stations in the **a** geographic and **b** geomagnetic coordinates

---

Three days were examined in this analysis: one quiet day (12 July 2000; day number 194 in the year), and two magnetically disturbed days (15 July and 12 August 2000; day numbers 197 and 225, respectively) when strong magnetic storms occurred.

It is pointed out in (Afraimovich et al. 2000), 2001a, 2001b, (2002a, 2002b) that during geomagnetically disturbed conditions, two-frequency receivers manufactured by different firms show a different response. The lowest phase slip density of range measurements at the working frequencies f_1 and f_2 was observed for ASHTECH receivers, a moderate density for TRIMBLE, and the highest density for AOA. Hence our experiment was conducted with regards to GPS receivers of these types. Table 1 presents general information about the experiment: date; maximum level of geomagnetic disturbance characterized by the maximum values of the geomagnetic index $-Dst_{max}$, nT, and Kp index for 24 h; GPS station name and location (geographic and geomagnetic coordinates), and the name of the receiver installed at a given station.

[Table 1. will appear here. See end of document.]

The goal of the first stage of GPS data processing in this paper is to reconstruct the current location on the basis of available RINEX files using the software TEQC posted on the Internet at: http://tonga.unavco.ucar.edu/software/teqc/Microsoft/2000/Borland/5.0.
In order to carry out investigations into the above-mentioned issues, we developed a software package "Navigator" to perform the following functions:

- start software TEQC in batch mode by setting up a current command line of the form: $teqc.exe + qc - stYYmmddhhMMSS + dh\Delta t - navsitesddd0.YYnsitesddd0.YYo.,$ where $teqc.exe$ is the executable file; qc, *st*, and dh are the control options in the command line; YY, mm, dd, MM, and SS are the year, month, day, hour, minute, and second for which the coordinates of the object are calculated with a current start of TEQC; Δt is the time step of calculation of the coordinates on the interval of observation (in fractions of an hour); and *sites* is the abridged name of the GPS station, to which the RINEX-files of format "o" (observation) and "n" (navigation) refer; *ddd* is a day number.
- setting up of the output data file in the format: $t_i, X_i, Y_i, Z_i, L_i, B_i, H_i, \Delta X_i, \Delta Y_i, \Delta Z_i, \Delta L_i, \Delta B_i, \Delta H_i$, where t_1 is a current time (in hours and in fractions of an hour); X_i, Y and Z_i are current rectangular geocentric coordinates (in meters); L_i, B and H_i are current geographical coordinates; and $\Delta X_i, \Delta Y_i, \Delta Z_i, \Delta L_i, \Delta B_i, \Delta H_i$ are absolute current errors of determination of the corresponding rectangular and geographical coordinates
- detecting the slips of the one- and two-frequency modes of positioning, and determining the corresponding slip density;
- estimating the current and daily mean spherical standard deviations of CL determination for the GPS station.

The software package is controlled through the interactive file in which the following data are specified:

- name of GPS station sites;
- form of the command line (if necessary, the form of the command line can be changed);
- date (year, month, day);
- start and end time of the period of observation (in hours, minutes and seconds);
- size of the time step of calculation of the current coordinates (Δt: from 0.018–24 h);

- direction of count time increment - toward increasing (+dh) or decreasing (–dh), respectively;
- ON (OFF) option of analyzing the slip density and the standard of CL determination.

As a result of the first stage of processing, for each GPS station from Table 1, we reconstructed for 3 days (194, 197, and 225) of the year 2000 the diurnal series of rectangular geocentric coordinates X_i; Y_i;Z_i at time step of 1.2 min (the minimum possible steps when using the TEQC package), and the corresponding absolute errors:

$$\Delta X_i = X_i - X_0; \Delta Y_i = Y_i - Y_0; \Delta Z_i = Z_i - Z_0$$

where X_0, Y_0, Z_0 are the known coordinates of the GPS station, and i is the time count number.

The second stage of data processing involved estimating the current CL determination accuracy as the value of the spherical standard deviation (SD) of the coordinates $\sigma(t_i)$:

$$\sigma(t_i) = (\sigma_{Xi}^2 + \sigma_{Yi}^2 + \sigma_{Zi}^2)^{0.5}$$

where $\sigma_{Xi}, \sigma_{Yi}, \sigma_{Zi}$ are the SD of the rectangular geocentric coordinates. Values of $\sigma(t_i)$ were calculated for each 3.6-min interval over the length of the entire diurnal series.

In addition, as an overall estimate of the accuracy of the coordinates of each station, in particular geomagnetic conditions, we calculated the daily mean values of the spherical SD, denoted by $\bar{\sigma}$. Results of this processing are plotted as $\sigma(t_i)$ in Figs. 2, 3, 4, 5, 6 and 7 and are presented as histograms for $\bar{\sigma}$ in Fig. 8.

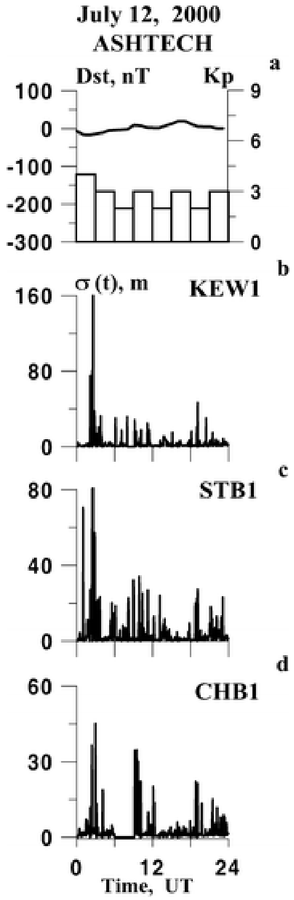

Fig. 2. a The magnetic disturbance index *Dst* and Kp index as a functions of time of day for the magnetically quiet day of 12 July 2000 (day 194). The standard σ(t_i), m in the position determination as a function of time of day, inferred using the data from the ASHTECH receivers installed at **b** KEWl, **c** STBl, and **d** CHBl

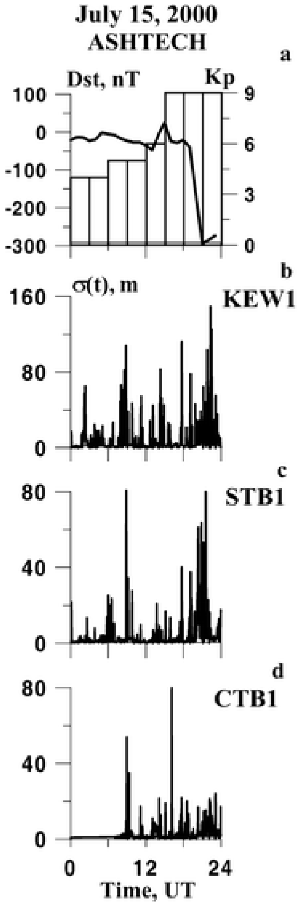

Fig. 3. The same as in Fig. 2, but for the magnetically disturbed day of 15 July 2000 (day 197)

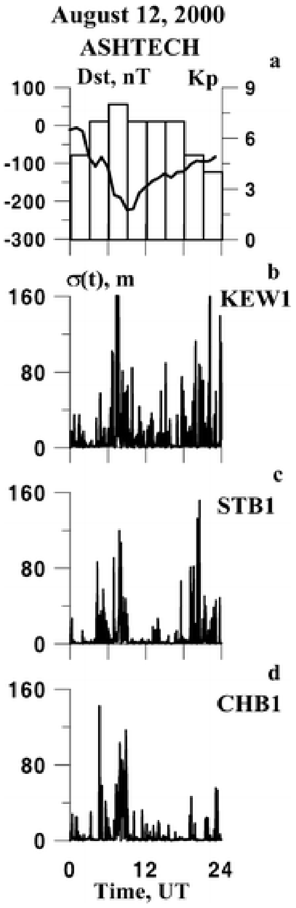

Fig. 4. The same as in Fig. 2, but for the magnetically disturbed day of 12 August 2000 (day 225)

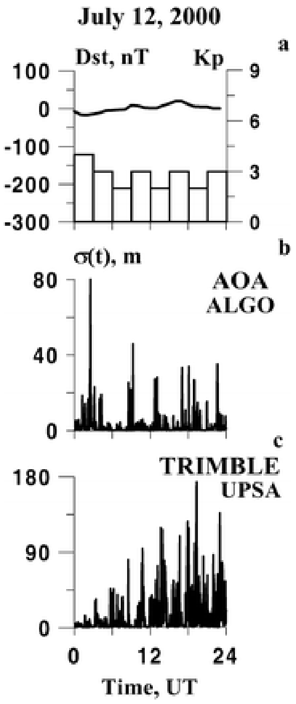

Fig. 5. a The magnetic disturbance index *Dst* and Kp index as a functions of time of day for the magnetically quiet day of 12 July 2000 (day 194). The standard $\sigma(t_i)$, m in the position determination

as a function of time of day, inferred using the data from the AOA receiver installed at **b** ALGO and from the TRIMBLE receiver installed at **c** UPSA

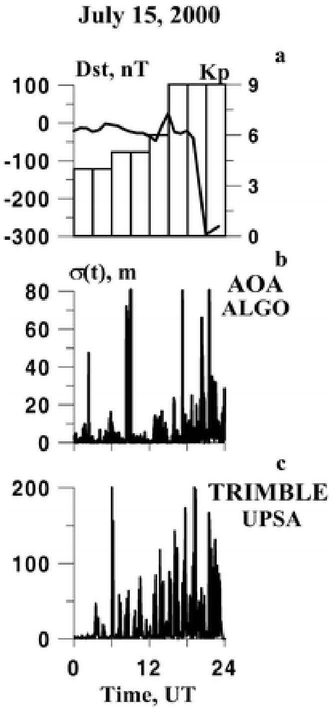

Fig. 6. The same as in Fig. 5, but for the magnetically disturbed day of 15 July 2000 (day 197)

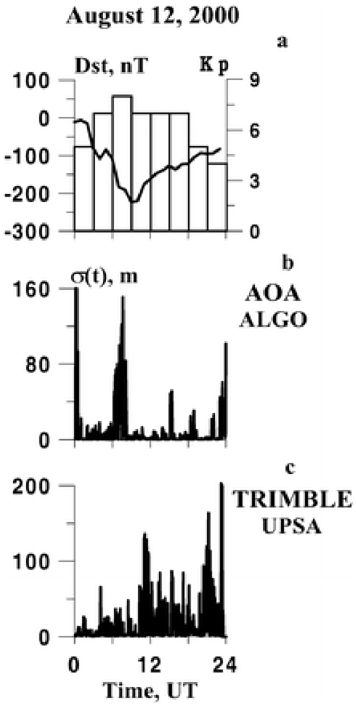

Fig. 7. The same as in Fig. 5, but for the magnetically disturbed day of 12,August 2000 (day 225)

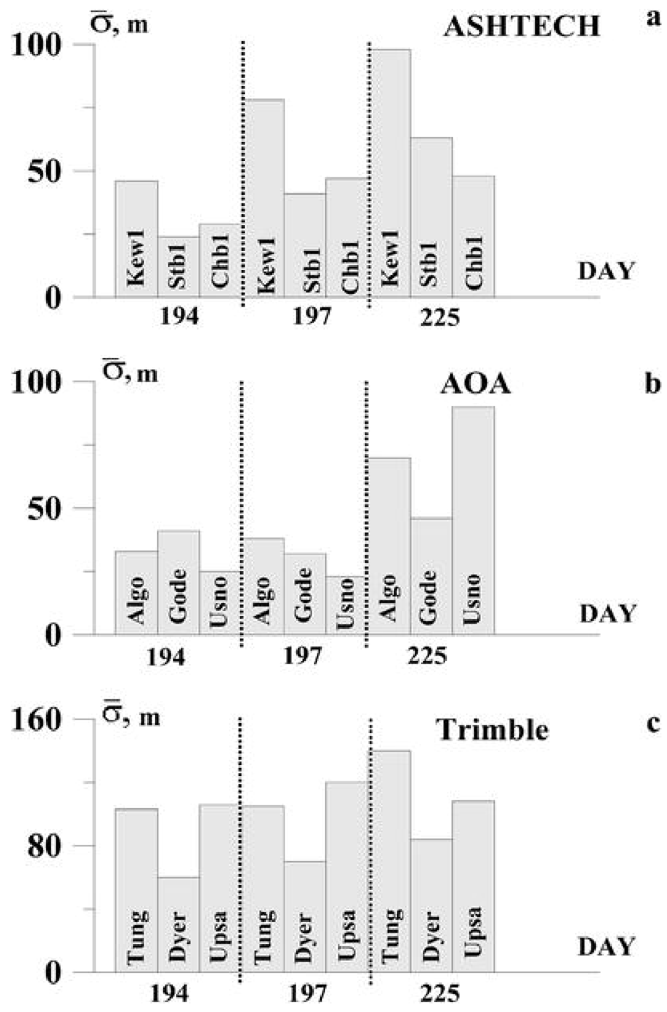

Fig. 8. Distributions of daily mean standard $\bar{\sigma}$, m in the position determination for one magnetically quiet (194) and two magnetically disturbed (197 and 225) days of 2000, obtained at three sites for each of the three types of receivers: **a** ASHTECH-KEWl, STBl and CHBl; **b** AOA-ALGO, GODE and USNO; **c** TRIMBLE-TUNG, DYER and UPSA

The third stage of data processing included estimating the slip density in the determination of the CL for receivers (ASHTECH, AOA, and TRIMBLE) in the one- and two-frequency modes. When analyzing the slip density in the one-frequency mode, the slip was considered to mean an event that satisfied the following condition:

$$\sigma(t_i) > \varepsilon = 500\mathrm{m}$$

We deduced empirically the value of the unacceptable error threshold ε=500 m due to the reason that better CL determination accuracy is required for the most practical purposes (see Skone and Jong 2000; Kharisov et al. 1998).

The slip in the mode of two-frequency determination of the coordinates implies the event where more than 30% of all observed NS of the constellation do not provide tracking at the auxiliary working frequency f_2. As the characteristic of the slip intensity, we calculated the current slip densities of the one- and two-frequency modes (N_1 and $N_{1,2}$, respectively). The current slip density N_1 and $N_{1,2}$ was determined as the total number of slips on each 0.5-h interval. Results of this processing are presented as plots of the diurnal slip density distribution for the one-frequency mode (Figs. 9, 10, 11), and for the two-frequency mode (Figs. 12, 13, 14).

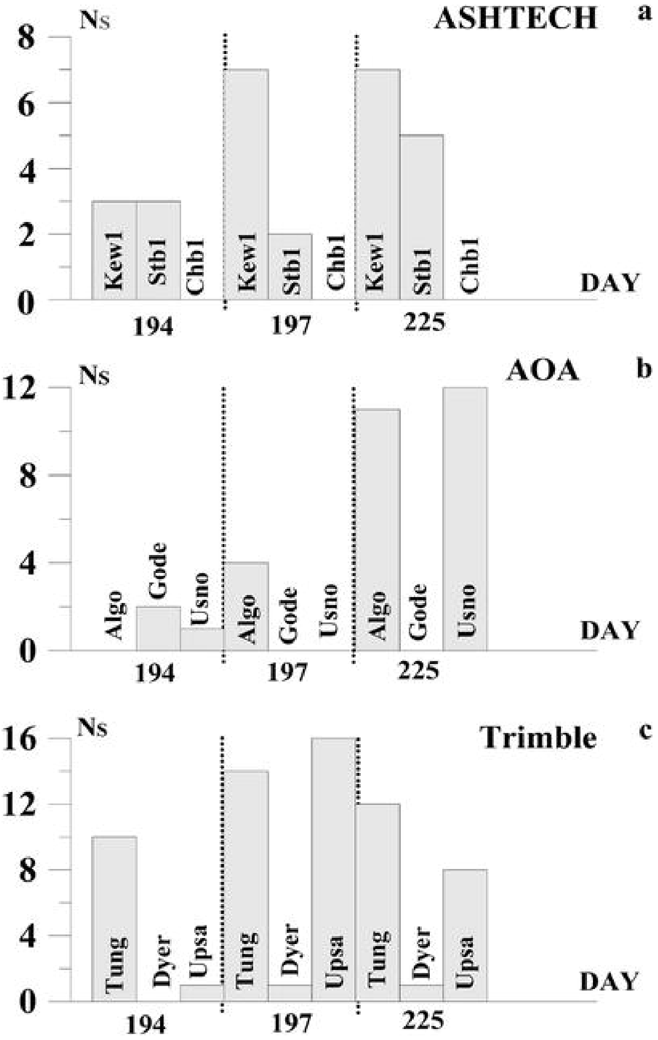

Fig. 9. a The magnetic disturbance index *Dst* and Kp index as a functions of time of day for the magnetically quiet day of 12,July 2000 (day 194). The current density of slips of the one-frequency operating mode as a function of time of day (N_1), recorded by the receivers: **b** ASHTECH (KEWl, STBl and CHBl); **c** AOA (ALGO) ; and **d** TRIMBLE (UPSA)

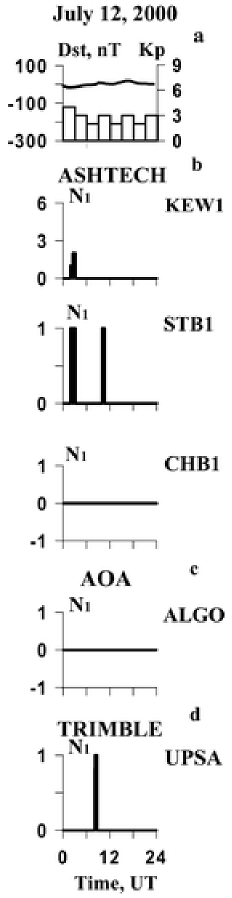

Fig. 10. The same as in Fig. 9, but for the magnetically disturbed day of July 15, 2000 (day 197)

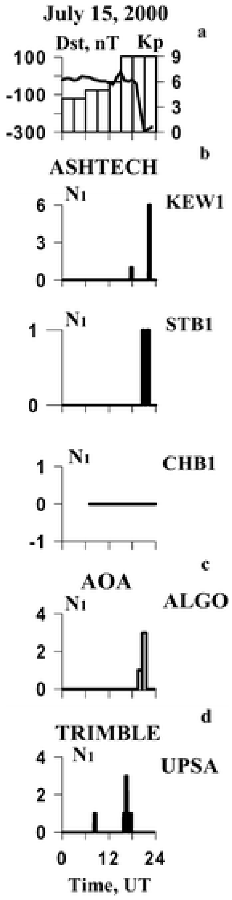

Fig. 11. The same as in Fig. 9, but for the magnetically disturbed day of 12 August 2000 (day 225)

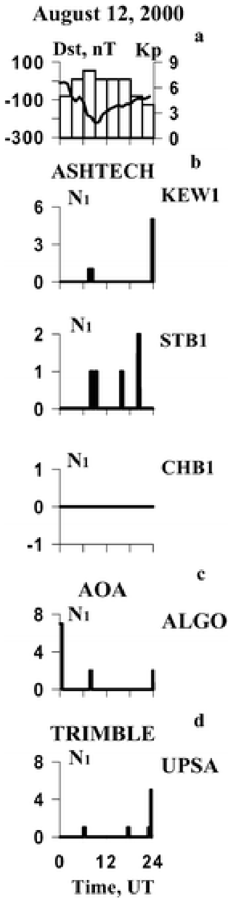

Fig. 12. a The magnetic disturbance index *Dst* and Kp index as a functions of time of day for the magnetically quiet day of July 12, 2000 (day 194). The current density of slips of the the two–frequency operating mode as a function of time of day ($N_{1,2}$) of the following receivers: **b** ASHTECH (KEWl, STBl and CHBl); **c** AOA (ALGO); **d** TRIMBLE (UPSA)

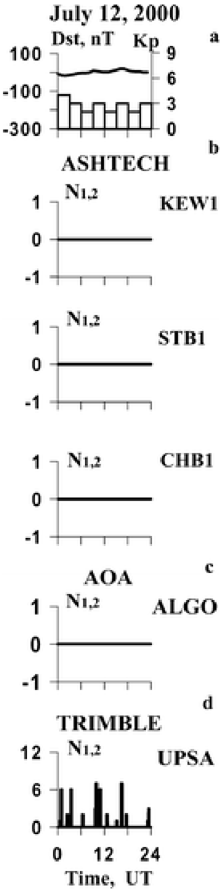

Fig. 13. The same as in Fig. 12, but for the magnetically disturbed day of 15 July 2000 (day 197)

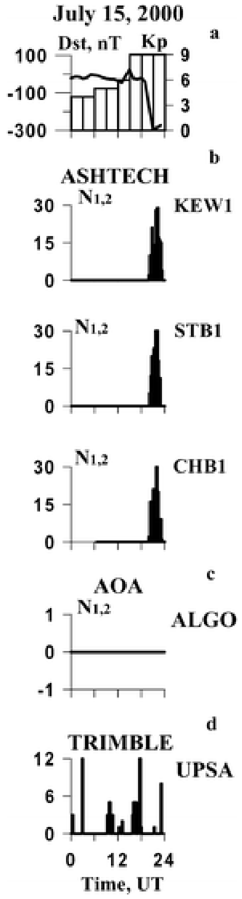

Fig. 14. The same as in Fig. 12, but for the magnetically disturbed day of 12 August 2000 (day 225)

Furthermore, we also determined the total diurnal slip density Ns for the one- and two-frequency modes, for each station and for each of the days listed in Table 1. Results of this processing are represented by the histograms in Figs. 15 and 16, respectively.

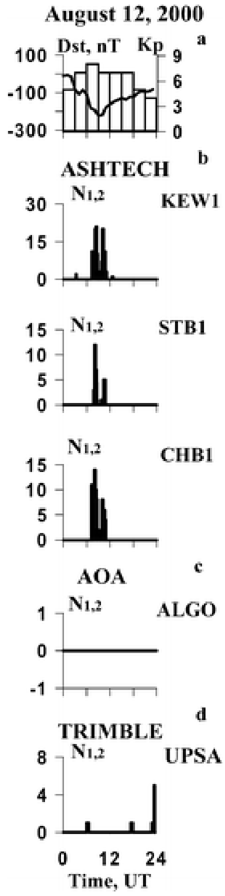

Fig. 15. Distribution of the daily mean number of slips *Ns* in the position determination in the one-frequency mode, recorded at the sites with receivers of the following types: **a** ASHTECH; **b** AOA; **c** TRIMBLE

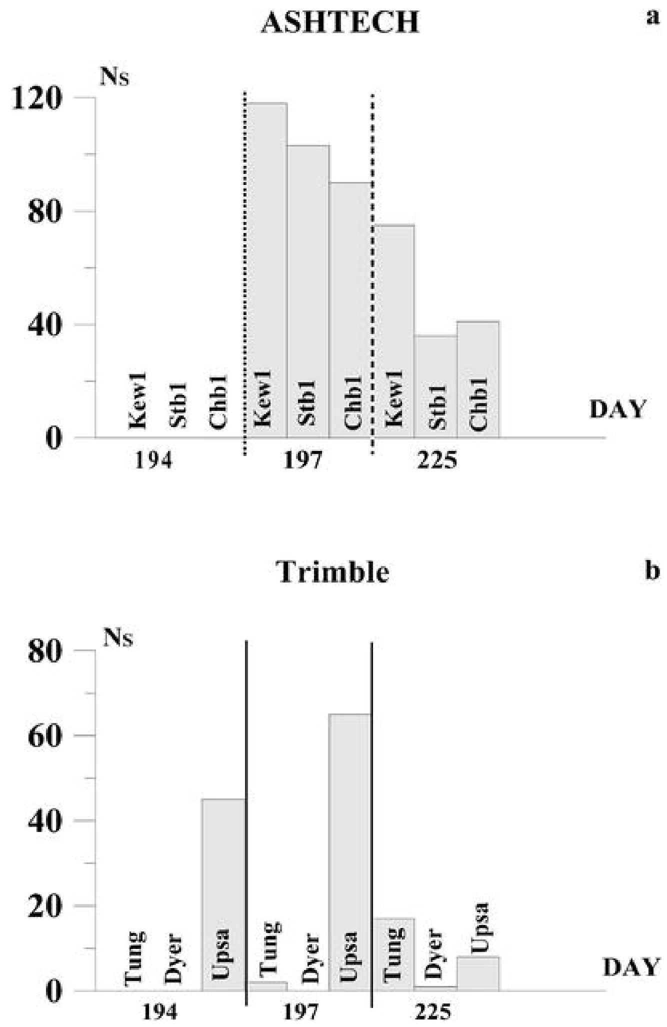

Fig. 16. Distributions of the daily mean number of slips *Ns* of the two-frequency operating mode, recorded at the sites with **a** ASHTECH receivers and **b** TRIMBLE receivers

Results and discussion

The magnetically quiet day of July 12, 2000

Figures 2b–d and 5b, c plot the time dependencies of the spherical standard deviations $\sigma(t_i)$ in the CL determination on the magnetically quiet day of 12 July 2000, obtained at three different sites: KEW1, STB1, and CHB1 with the ASHTECH receivers, and at sites UPSA (TRIMBLE) and ALGO (AOA). On some of the panels where the maximum values of standard deviations far exceeded the daily mean values, these values were included in Table 2 and excluded from the figures, for ease of viewing.

[Table 2. will appear here. See end of document.]

A more general picture of the daily mean values of standard deviations for all types of receivers for the days analyzed in this paper is provided by the Fig. 8 histograms. In this figure, each type of receiver under investigation is represented by a set of three stations. ASHTECH is represented on panel (a) by the sites KEW1, STB1, and CHB1; AOA is represented on panel (b) by the sites ALGO, GODE, and USNO; and TRIMBLE is represented on panel (c) by the sites TUNG, DYER, and UPSA.

It is evident from the figures and histograms presented here that in magnetically quiet conditions the CL determination accuracy that is provided by the ASHTECH and AOA receivers differs only slightly (for ASHTECH $\bar{\sigma} \leq 46\mathrm{m}$, and for AOA $\bar{\sigma} \leq 33\mathrm{m}$). Single abrupt changes of the current values ($\sigma_{\max}$) over the course of 24 h occur for the three types of receivers (Table 2). Furthermore, their maximum values do not differ greatly $\sigma_{\max} \leq 249\mathrm{m}$ for ASHTECH; $\sigma_{\max} \leq 256\mathrm{m}$ for AOA, and $\sigma_{\max} \leq 243\mathrm{m}$ for TRIMBLE.

Regarding the number of slips in the coordinate determination in the one–frequency mode under quiet geomagnetic conditions, ASHTECH and AOA receivers also showed about the same level. Thus, no more than three slips of the one-frequency mode and no more than two slips were observed for 24 h, respectively for ASHTECH (site KEW1) and AOA (site GODE). For the TRIMBLE receiver, this figure was worse and reached ten slips for 24 h (site TUNG). On the other hand, the three types of receivers at some of the sites did not show any slips of the one-frequency mode for 24 h (see Fig. 15). All observed slips occurred before 12 UT.

The performance of the TRIMBLE receivers in the two-frequency mode of coordinate determination in the magnetically quiet situation was also worse when compared with ASHTECH and AOA. Thus, for the receivers of the two last types, no slip of the two-frequency mode was recorded for all the sites under consideration (see Fig. 12).

The magnetic storms of 15 July and 12 August 2000

In general, the period of geomagnetic disturbances showed a degradation of the positioning accuracy and quality of GPS performance for the three types of receivers.

During the 15 July magnetic storm there was an increase in the value of the daily mean spherical standard deviation in the CL determination $\bar{\sigma}$. The corresponding maximum values were as follows: 76 m for the ASHTECH receiver (site KEW1); 39 m for AOA (site ALGO), and 120 m for TRIMBLE (site UPSA). Thus the value of $\bar{\sigma}$ increased (compared to geomagnetically quiet conditions) by a factor of 1.6–1.7 for ASHTECH, and by a factor of 1.1–1.2 for AOA and TRIMBLE (for the sites ALGO and UPSA, respectively). These estimates here and Figs. 3, 6 and 8 suggest that the ASHTECH receivers were the most sensitive to the effects of a geomagnetic storm. Values of the spherical SD in the CL determination using the AOA and TRIMBLE receivers do not increase as significantly and can, in some cases, also be lower than those in geomagnetically quiet conditions (Fig. 8a–c).

These results are in reasonably good agreement with data reported by Coster et al. (2001). These authors presented the regional GPS mapping of storm enhanced density during the 15–16 July 2000 geomagnetic storm and found, that the Millstone GPS receiver ASHTECH Z-12 lost (and then regained) lock on all satellites between 20.40 and 24.00 UT.

A similar picture is also observed during the magnetic storm of 12 August 2000; however, the effect is more fully manifested. There was an unambiguous increase in the values of $\bar{\sigma}$ for the three types of receivers and for all sites when compared with magnetically quiet conditions. Values of $\bar{\sigma}$ increased by a factor of 1.6–2.6, 1.3–2.1 and 1.02–1.4 for ASHTECH, AOA and TRIMBLE (Figs. 4b–d, 7b, c, 8), respectively.

Table 2 presents the maximum values of single abrupt changes of current values of the spherical SD in the CL determination $\sigma(t_i)$ for the 24 h that are analyzed. For the ASHTECH and TRIMBLE receivers, there is also a consistent tendency of the values of these abrupt changes to increase in geomagnetically disturbed conditions. Figs. 3b, c, 4b, c, d) induce us also to suggest that for ASHTECH the intervals with the largest number of abrupt changes of current values of $\sigma(t_i)$ correspond to the time period of the highest level of geomagnetic field disturbance. However, this assumption requires an extensive set of observations to be confirmed.

On the basis of studying the slip density of the one- and two-frequency modes in the CL determination, the following features were established. First, we identified an unambiguous tendency of the slip density of the one-frequency mode to increase in magnetic storm conditions for the ASHTECH and TRIMBLE receivers. Compared to magnetically quiet conditions, the slip density of the one-frequency mode increased by a factor of 2.5 and 1.4 to 8.0 for ASHTECH and TRIMBLE, respectively (Figs. 15, 9b, d; 10b, d; 11b, d).

Second, for the ASHTECH receiver the localization of slips of the one-frequency mode along the time axis corresponds to the time period of maximum geomagnetic field disturbance (Figs. 10b, 11b). The sole exception was the ASHTECH receiver at the site CHB1. No slips of the one-frequency mode were recorded for this site for any one of the days under consideration.

Third, we detected a clearly pronounced tendency of the slip density of the two-frequency mode in the CL determination to increase for the ASHTECH receivers in geomagnetically disturbed conditions. Thus, while no slips were observed for the magnetically quiet day of 12 July, at periods of geomagnetic disturbances their diurnal number varied from 40 (site STB1, 12 August) to 120 (site KEW1, 15July;Fig. 16). In addition, there was a clear localization of slip density of the two-frequency mode for the time interval corresponding to the maximum level of geomagnetic field disturbance (Figs. 13a, b, 14a, b). A similar, but less clearly pronounced, tendency of the slip density of the two-frequency mode to increase was also identified for the TRIMBLE receivers (Fig. 16b). We recorded no slips of the two-frequency mode in magnetic storm conditions for the AOA receivers in any cases that were considered.

Discussion

Our investigation has shown that disturbances of geospace environment due to geomagnetic storms are accompanied by a degradation of the accuracy and quality of GPS performance.

These results are in reasonably good agreement with data reported by Afraimovich et al. (2000, 2001b, 2001c, 2002a, 2002b). Phase measurements are more sensitive to equipment failures and to various interference affecting the GPS “satellite-receiver” channel when compared with group delay measurements that are directly used for navigation purposes.

Afraimovich et al. (2000, 2001a, 2001b, 2002a, 2002b) found that during strong magnetic storms, the relative density of phase slips at mid latitudes exceeds its mean value for magnetically quiet days at least by the order of one or two, and reaches a few percent of the total density of observations. Furthermore, the level of phase slips for the GPS satellites located at the sunward side of the Earth was five to ten times larger compared with the opposite side of the Earth. The level of slips of L_1 phase measurements at the fundamental GPS frequency is at least one order of magnitude lower than that in L_1–L_2 measurements. The slips of L_1–L_2 measurements are most likely to be caused by the high level of slips of L_2 phase measurements at the auxiliary frequency.

The deterioration of the signal/noise ratio with an increase of the level of geomagnetic disturbance is possible if this is accompanied by an enhancement of the proportion of the signal scattered from ionospheric electron density irregularities. This involves also an increase of the number of phase slips; for a more powerful f_1 signal, however, the density of slips is an order of magnitude smaller than that for the less powerful f_2 signal.

Under conditions of antispoofing (AS) the signal at the frequency f_2 is subjected to an additional special processing in the receiver. As a result, it is possible to ensure code range measurements at a given frequency, yet with a significantly worse signal/noise ratio. Depending on the receiver, the average power on the f_2 signal is 13 dB less (Interface Control Document: Langley 1998). Similar correlations of the effective radiated power of f_1 (30 W) and f_2 (21 W) signals are also characteristic for the Russian GLONASS system (Kharisov et al. 1998). It should also be taken into consideration that ionospheric effects of NS signal distortions are more pronounced at a lower auxiliary frequency f_2.

Karasawa et al. (1985) noticed from a long-term recording of the signal from the geostationary MARISAT satellite at 1.5 GHz frequency that, synchronous with scintillations of the signal amplitude, there occur similar-looking changes of the rotation angle of polarization plane that are proportional to a corresponding disturbance of TEC. Anomalous fluctuations, recorded during 13 months of observation, occur predominantly in the night-time and last from 5 s to 2 min. The maximum amplitude fade was 12 dB lower than the normal level.

The high positive correlation between the growth of the density of phase slips and the intensity of ionospheric irregularities during geomagnetic disturbances as detected by Afraimovich et al. (2000, 2001a, 2001b, 2002a, 2002b), points to the fact that the increase in slips is caused by the scattering of the GPS signal from ionospheric irregularities. Afraimovich et al. (2001c) found that the growth of the level of geomagnetic activity is accompanied by the growth of total intensity of TEC variations; however, it shows correlation not with the absolute level of D_{st}, but with the value of the time derivative of D_{st}.

It is evident from Table 1 that most of the stations under consideration are located within 50–58° of geomagnetic latitude. In magnetic storm conditions the auroral oval can reach these latitudes; for that reason, in this region the ionosphere should be regarded not as the mid-latitude ionosphere but as the auroral ionosphere, characterized by fast, profound fluctuations of the trans-ionospheric signal amplitude and phase (Afraimovich et al. 2001c, Coster et al. 2001).

Using the geomagnetic storm of 15 July 2000 as an example, Afraimovich et al. (2001a) investigated the dependence of GPS performance on the night side at mid-latitudes on the level of geomagnetic disturbance. It was shown that phase slips are correlated with *Kp* and that the phase slips depend on the aspect angle. *E* region coherent scatter is aspect angle sensitive. Therefore, GPS phase slips might be due to a mechanism rooted in two-stream Farley-Buneman instabilities (Foster and Tetenbaum 1991). Using simultaneous measurements of backscatter signal characteristics from the Irkutsk incoherent scatter radar (Kurkin et al. 1999) and existing models for such irregularities, Afraimovich et al. (2001a) estimated the order of magnitude of the expected phase fluctuations of the GPS signal.

As a result of our investigations, it has become clear that ionospheric disturbances during magnetic storms contribute to signal degradation and GPS system malfunctions not only at the equator and in the polar zone but also even at mid-latitudes. However, the question of the causes and the particular mechanisms of this influence remain largely open. The major objective of future research is to study the physical mechanisms of multi-scale total electron density variations in the ionosphere during geomagnetic disturbances of geospace that are accompanied by signal degradation and malfunctions of satellite radio engineering systems. Such investigations must have a comprehensive character, with the maximum possible involvement of experimental ionospheric monitoring facilities (digisondes, incoherent scatter radars, etc.).

An increase in slip density can also be caused by an inadequate response of GPS receivers of some types to fast changes in daytime TEC at the auxiliary frequency f_2. Unfortunately, we are unaware of any consistent investigation of this kind or published data lending support to such a point of view. As far as the differences between the responses of the particular types of GPS receivers, this issue still remains open and is beyond the scope of this paper. To elaborate on this question requires analyzing the design and functional features of receivers manufactured by different firms.

Conclusion

Main results of this study are as follows:

In geomagnetically disturbed conditions of geospace the accuracy and quality of GPS performance is impaired. Unlike geomagnetically quiet conditions, magnetic storm conditions are accompanied by an increase in the spherical standard deviation in the position determination for all types of GPS receivers. Furthermore, there was a maximum increase in the values of $\bar{\sigma}$ by a factor of 2.6, 2.1 and 1.4 for the ASHTECH, AOA and TRIMBLE receivers, respectively.

In magnetic storm conditions there is an increase of the number of slips of the one-frequency mode of coordinate determination. The slip density increased by factors of 2.5, 8 and 12 for the ASHTECH, TRIMBLE and AOA receivers, respectively (site USNO).

We have identified an unambiguous tendency of the slip density of the one-frequency mode to increase for the ASHTECH and TRIMBLE GPS receivers, respectively. For the AOA receivers this tendency was not observed in all cases that were considered.

The slip density in the two-frequency mode of coordinate determination in magnetic storm conditions increases most dramatically for the ASHTECH receivers (from 0 to 120 slips). As regards the TRIMBLE receivers, there is a similar, but less clearly pronounced, picture (the slip density increased by a factor of 1.5–2, on average). No slips of the two-frequency mode were detected for the AOA receivers in the cases under consideration.

Acknowledgments The authors are grateful to G.V. Popov and V.G. Eselevich for their encouraging interest in this study and active participation in discussions. The authors are also indebted to E.A. Kosogorov and O.S. Lesuta for preparing the input data. Thanks are also due V.G. Mikhalkovsky for his assistance in preparing the English version of the manuscript. Finally, the authors wish to thank the reviewers for valuable suggestions that greatly improved the presentation of this paper. This work was done with support from the Russian Foundation for Basic Research (grants 01-05-65374 and 00-05-72026) and from RFBR grant of leading scientific schools of the Russian Federation 00-15-98509.

References

Aarons J (1982) Global morphology of ionospheric scintillations. Proc IEEE 70(4):360–378

Aarons J, Mendillo M, Kudeki E, and Yantosca R (1996) GPS phase fluctuations in the equatorial region during the MISETA 1994 campaign. J Geophys Res 101:26851–26862

Aarons J, Mendillo M, Yantosca R (1997) GPS phase fluctuations in the equatorial region during sunspot minimum. Radio Sci 32:1535–1550

Aarons J, Lin B (1999) Development of high latitude phase fluctuations during the January 10, April 10–11, and May 15, 1997 magnetic storms. J Atmos Terr Phys 61:309–327

Afraimovich EL, Lesyuta OS, Ushakov II (2000) Magnetospheric disturbances, and the GPS operation. LANL e-print archive, http://xxx.lanl.gov/abs/physics/0009027-

Afraimovich EL, Chernukhov VV, Demyanov VV (2000a) Updating the ionospheric delay model for single-frequency equipment of users of the GPS. Radio Sci 35(1):257–262

Afraimovich EL, Berngardt OI, Lesyuta OS, Potekhin AP, Shpynev BG (2001a) A case study of the mid-latitude GPS performance at nighttime during the magnetic storm of July 15, 2000. Proceedings of International Beacon Satellite Symposium, 4–6 June 2001, Boston College, Institute for Scientific Research, Chestnut Hill, MA, pp 408–412

Afraimovich EL, Lesyuta OS, Voeykov SV (2001b) GPS phase slips on L_1–L_2 and L_1 frequencies during geomagnetic disturbances. Proceedings of International Beacon Satellite Symposium, 4–6 June 2001, Boston College, Institute for Scientific Research, Chestnut Hill, MA, pp 191–195

Afraimovich EL, Kosogorov EA, Lesyuta OS, Yakovets AF, Ushakov II (2001c) Geomagnetic control of the spectrum of traveling ionospheric disturbances based on data from a global GPS network. Ann Geophys 19(7):723–731

Afraimovich EL, Lesyuta OS, Ushakov II (2002a) Geomagnetic disturbances, and the GPS operation. Geomagn Aeronomy 42(2):220–227

Afraimovich EL, Lesyuta OS, Ushakov II, Voeykov SV (2002b) Geomagnetic storms and the occurrence of phase slips in the reception of GPS signals. Ann Geophys 45(1):55–71

Basu Santimay, MacKenzie E, Basu Sunanda (1988) Ionospheric constraints on VHF/HUF communication links during solar maximum and minimum periods. Radio Sci 23:363–378

Bhattacharrya A, Beach TL, Basu S, Kintner PM (2000) Nighttime equatorial ionosphere: GPS scintillations and differential carrier phase fluctuations. Radio Sci 35:209–224

Conker RS, El-Arini MB, Hegarty CJ, Hsiao T (2003) Modeling the effects of ionospheric scintillation on GPS/Satellite–Based Augmentation System availability. Radio Sci 38(1):1001, DOI 10.1029/2000RS002604, 2003

Coster, AJ, Foster JC, Erickson PJ, Rich FJ (2001) Regional GPS mapping of storm enhanced density during the July 15–16 2000 geomagnetic storm. Proceedings of International Beacon Satellite Symposium, 4–6 June 2001, Boston College, Institute for Scientific Research, Chestnut Hill, MA, pp 176–180

Foster JC, Tetenbaum D (1991) High resolution backscatter power observations of 440 MHz E-region coherent echoes at Millstone–Hill. J Geophys Res 96:1251–1261

Goodman DM, Aarons J (1990) Ionospheric effects on modern electronic systems. Proceedings of the IEEE 78(3):512–528

Gurtner W (1993) RINEX: The Receiver Independent Exchange Format Version 2, http://igscb.jpl.nasa.gov/igscb/data/format/rinex2.txt

Ho CM, Mannucci AJ, Linqwister U J et al. (1996) Global ionosphere perturbations monitored by the worldwide GPS network. Geophys Res Lett 23(22):2219–2222

Hofmann-Wellenhof B, Lichtenegger H, Collins J (1992) Global positioning system: theory and practice. Springer, Berlin Heidelberg New York

Interface Control Document, ICD-GPS-200c; http://www.navcen.uscg.mil/pubs/gps/icd200/

Karasawa Y, Yasukawa K, Yamada M (1985) Ionospheric scintillation measurements at 1.5 GHz in mid-latitude region. Radio Sc 20(3):643–651

Kharisov VN, Perov AI, Boldin VA (1998) The Global Satellite Radio Navigation System—GLONASS. Russia, Moscow: IPRZhR

Klobuchar J (1986) Ionospheric time-delay algorithm for single-frequency GPS users. IEEE Trans Aerospace Electron Syst AES 23(3):325–331

Kurkin VI, Potekhin AP, Shpynev BG, Zarudnev VE, Zherebtsov GA (1999) Study of September 25, 1998 storm effects in the mid-latitude ionosphere using the Irkutsk Incoherent Scatter Radar. XXIV GA URSI (Abstracts). Toronto, Canada, 441

Langley RB (1998) GPS for Geodesy. Springer, Berlin Heidelberg New York

Pi X, Mannucci AJ, Lindgwister UJ, Ho CM (1997) Monitoring of global ionospheric irregularities using the world wide GPS network. Geophys Res Lett 24:2283–2286

Shan SJ, Lin JY, Kuo FS et al. (2002) GPS phase fluctuation observed along the American sector during low irregularity activity months of 1997–2000. Earth Planet Space 54(2):141–152

Skone S, de Jong M (2000) The impact of geomagnetic substorms on GPS receiver performance. Earth Planet Space 52:1067–1071

Skone S, de Jong M (2001) Limitations in GPS receiver tracking performance under ionospheric scintillation. Phys Chem Earth Part A, 26(6–8):613–621

Warnart R (1995) The study of the TEC and its irregularities using a regional network of GPS stations. IGS Worksh Proc, pp 249–263

Table 1. Statistics of experiments

Date	*Dst*, nT/K_p max. values	Station	Geographic coordinates		Geomagnetic coordinates		GPS receiver
			B°	L°	B°	L°	
12.07.2000 (194)	–17/3	KEW1	44.8	–87.3	56.11	–16.75	ASHTECH
		STB1	45.7	–84.5	57.04	–12.57	
		CHB1	47.2	–88.6	57.04	–18.73	
		ALGO	46	–78	57.11	–2.81	AOA
		GODE	39	–76.8	50.19	–1.76	
		USNO	38.9	–77	50.11	–2.05	
		TUNG	37.7	–118	44.05	–55.11	TRIMBLE
		DYER	39.6	–118.8	45.83	–56.52	
		UPSA	40.4	–118.3	46.75	–56.2	
15.07.2000 (197)	–295/9	The same					
12.08.2000 (225)	–223/8	The same					

Table 2. Data set of maxima rms of positioning error $\sigma_{max,}$(in meters)

GPS receiver	Stations	Date of 2000		
		194 (12 July)	197 (15 July)	225 (12 August)
		$\sigma_{max,}$ *m*	$\sigma_{max,}$ *m*	$\sigma_{max,}$ *m*
ASHTECH	KEW1	249	268	314
	STB1	103	91	152
	CHB1	45	92	142
AOA	ALGO	258	241	253
	GODE	190	125	114
	USNO	125	130	273
TRIMBLE	TUNG	243	231	361
	DYER	110	314	337
	UPSA	174	242	327