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The Occurrence of Ionospheric Disturbances above Japan and Their Effects on Precise GPS Positioning

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Abstract

Dual-frequency GPS measurements can be combined to eliminate the ionospheric delay in the observations and therefore its effects on the coordinate estimation. However, precise applications require the resolution of the phase ambiguities, which can be prevented by severe ionospheric conditions. GPS measurements in Japan are, at times, affected by large-scale gradients in the ionospheric electron content, by equatorial small-scale irregularities, and also by medium-scale Travelling Ionospheric Disturbances. We processed one year of permanent GPS tracking data of the Japanese Station Usuda to produce a survey of the ionospheric conditions above Japan. The severest effects on double difference ambiguity estimation are caused by large-scale gradients which occur south of Usuda during day time hours of the winter months.

1. Introduction

It is widely believed that ionospheric corrections from dual-frequency GPS observations solve all GPS user problems which are due to ionospheric refraction. However, precise GPS positioning often requires the resolution of the double difference phase ambiguities. They cannot be resolved with the ionospheric-free linear combination directly. Techniques, which are not affected by first-order ionospheric effects (code-carrier comparison), require precise dual-frequency P-code observations, which are often not available. Other techniques use linear combinations of the phase observations which are less affected by the ionosphere than the original observation L_1 and L_2. With the exception of the widelane L_W, these signals have the disadvantage of short wavelengths of about 10cm (or even shorter) which complicates the ambiguity resolution (Wanninger and Jahn, 1991).

In order to define severe ionospheric conditions, which can prevent ambiguity resolution with most or even all existing post-processing software packages, we can say that, if the ionospheric effect on the double difference observable exceeds half a cycle of the widelane linear combination for a given baseline length and observation period, severe ionospheric conditions are present. These conditions are caused by large-scale horizontal gradients of the ionospheric electron content which mainly occur in the equatorial region (Wanninger, 1993b) and by Travelling Ionospheric Disturbances (Wanninger, 1993a) which are expected to occur in all world regions. Another kind of ionospheric effects on GPS is caused by small-scale irregularities which produce amplitude and phase scintillations of the signals. Under these conditions the receiver performance deteriorates: an increased number of cycle slips occurs (polar and equatorial regions) or it can even lead to the inability to perform measurements (equatorial region) (Wanninger 1993b).

Central Europe and the continental United States are located in the mid-latitude region of the ionosphere, where the least effects of the ionosphere on precise GPS positioning are observed. Japan, however, is situated at the boundary of the equatorial ionospheric region in the south and the mid-latitudes in the north (Figure 1). It can be expected that GPS measurements in Japan are, at times, affected by equatorial small-scale irregularities, by medium-scale Traveling Ionospheric Disturbances (TIDs), and by large-scale horizontal gradients. The occurrence of these ionospheric conditions is subject to daily variations, seasonal variations, and it varies due to the solar cycle.

We have developed algorithms which enable the detection and description of these ionospheric effects from single-station dual-frequency GPS phase observations. In order to demonstrate the usefulness of ionospheric monitoring with GPS and for GPS applications, we processed one year (September 1992 to August 1993) of permanent tracking data of the Rogue receiver at the Japanese station Usuda. Additionally, we used data of the Minimac receiver at the station Tsukuba to calculate the ionospheric effects on single-difference observations for this 155 km east-west baseline. The data were made available by Scripps Institution of Oceanography, California, which maintains an archive of GPS observation data of all major permanent tracking stations.

2. Detection of severe ionospheric conditions

In order to monitor and describe the ionospheric conditions which cause problems to the GPS user, GPS itself is very well

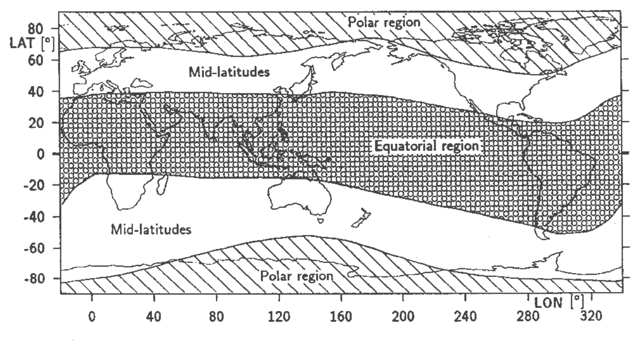

Fig. 1. Ionospheric regions of the world.

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suited to observe both the total electron content and ionospheric disturbances. The total electron content (TEC) integrated along the signal path can either be derived from dual-frequency code observations (P_1, P_2 [m]) or from dual-frequency phase observations (Φ_1, Φ_2 [m]):

$$S_I \cdot (P_2 - P_1) = TEC + \underbrace{dH_P^j + dH_P^i}_{C_P} + \varepsilon_P \qquad (1)$$

$$S_I \cdot (\Phi_1 - \Phi_2) = TEC + \underbrace{dH_\Phi^j + dH_\Phi^i + S_I \cdot (N_1\lambda_1 - N_2\lambda_2)}_{C_\Phi} + \varepsilon_\Phi \qquad (2)$$

with

$$S_I = \frac{1}{40.3} \cdot \frac{f_1^2 \cdot f_2^2}{f_1^2 - f_2^2} = 9.52 \cdot 10^{16} m^{-3}. \qquad (3)$$

S_I converts the differences of GPS dual-frequency measurements from [m] into [electrons per m^2] with f_1 and f_2 being the signal frequencies. Both equations contain biases due to differential hardware delays in the satellite j (dH_P^j, dH_Φ^j [m^{-2}]) and in the GPS receiver i ($dH_{P,i}$ $dH_{\Phi,i}$ [m^{-2}]). In addition, equation (2) includes a phase ambiguity term with N_1 and N_2 [$-$] being the phase ambiguities and λ_1 and λ_2 [m] being the signal wavelengths. TEC determinations are also affected by random observation errors and multipath effects. The terms ϵ_P and ϵ_Φ [m^{-2}] comprise these additional errors. In general the term ϵ_P is larger than ϵ_Φ by a factor of about 100. If the biases C_P and C_Φ are fairly constant in time, they can be determined from the measurements (Lanyi and Roth, 1988; Wanninger, 1992). In the case of P-code measurements it is also feasible to use pre-determined values of the differential hardware delays of the satellites (Wanninger and Sardón, 1993) and the receiver.

The simplest way to convert slant range TEC into vertical total electron content (VTEC) is done by using a slant factor F which depends on the signal's incidence elevation angle e only:

$$TEC = F \cdot VTEC = \frac{1}{\cos z_I} \cdot VTEC \qquad (4)$$

with

$$z_I = \arcsin\left(r_e / (r_e + h_I) \cdot \cos e\right) \qquad (5)$$

and r_e being the earth's radius (6380km), h_I being the mean ionospheric height above the earth's surface (e.g. 400km) and z_I being the signal's zenith angle at a height of h_I. The slant factor F amounts to 1 for signals received from zenith direction and it increases to almost 3 for low elevation angles. Neglecting random observation errors and multipath effects, we obtain from equations (1), (2) and (4):

$$\begin{aligned} VTEC &= (S_I \cdot (\Phi_1 - \Phi_2) - C_\Phi) \cdot \cos z_I \\ &= (S_I \cdot (P_2 - P_1) - dH_P^i - dH_P^j) \cdot \cos z_I. \end{aligned} \qquad (6)$$

Relative GPS positioning is not only affected by the absolute electron content of the ionosphere but often even more by horizontal gradients in the electron distribution. Taking the difference of two VTEC-observations to one satellite at consecutive epochs t_1 and t_2 yields the gradient dVTEC which is normalized to a distance of 100km:

$$dVTEC = (VTEC(t_2) - VTEC(t_1)) \cdot \frac{100km}{l_I} \qquad (7)$$

with l_I [km] being the distance between the signal's intersection points at epochs t_1 and t_2 with a single-layer ionospheric model in a height of h_I ((sub-)ionospheric points). The distance l_I is mainly a function of the signal's elevation angle and amounts to about 3km/min at higher elevation angles and 30km/min at an elevation angle of 10°. An example of the sub-ionospheric points of the GPS signals received at the station Usuda on day 243/1993 is shown in Figure 2. The sub-ionospheric points were mapped in a coordinate system of local time (LT) and geographical latitude (LAT), which is appropriate for the presentation of ionospheric observations. The satellite flight direction and thus the direction of the gradients as given by dVTEC is approximately east-west for many satellite passes around the latitude of the station Usuda (35°-39°N). South of 33°N and north of 42°N all satellite passes proceed approximately in north-south direction. Thus, the gradients which can easily be obtained with GPS are restricted to certain directions. Gradients from differences of simultaneous observations to different satellites cannot be derived with sufficient accuracy because of difficulties in the determination of the biases C_Φ.

An ionospheric GPS observable often used is derived from the slant range TEC values of consecutive epochs. Here, the bias C_Φ needs not to be determined because it cancels out. We define the observable Rate of TEC (RoT) as:

$$\begin{aligned} RoT(t_2) &= TEC(t_2) - TEC(t_1) \\ &= S_I \cdot (\Phi_1(t_2) - \Phi_2(t_2) - \Phi_1(t_1) + \Phi_2(t_1)) \end{aligned} \qquad (8)$$

with $\Delta t = t_2 - t_1 = 1min$.

Time series of RoT provide an excellent means to detect severe ionospheric conditions as phase scintillations and medium-scale TIDs. In contrast to irregularities detected in dVTEC time series, the apparent size of the irregularities detected in RoT time series corresponds to their effects on the single-difference phase observable.

A phase scintillations index I_{RoT} can be computed from RoT. In a first processing step the low-frequent changes of RoT are removed. They are a result of the absolute electron content and of large-scale horizontal gradients. The index is determined as RMS over the remaining parts of the RoT time series:

$$I_{RoT} = 10 \cdot RMS(\overline{RoT}_{\Delta t = 1\ min}). \qquad (9)$$

The actual effect of the ionospheric conditions on single-differences between stations and therefore also on double-differences is estimated with time series of single-difference TEC observations. Here, cycle slips have to be removed in order to yield continuous observations and a constant bias term $\Delta C_{\Phi,AB}$. From equation (2) we obtain the single-difference ΔTEC between the stations A and B with

$$\begin{aligned} \Delta TEC_{AB} &= TEC_A - TEC_B \\ &= S_I \cdot ((\Phi_1 - \Phi_2)_A - (\Phi_1 - \Phi_2)_B) - \Delta C_{\Phi,AB}. \end{aligned} \qquad (10)$$

Since we want to avoid the estimation of the bias term $\Delta C_{\Phi,AB}$, we cannot achieve absolute ΔTEC values, but we can only evaluate variations over time. If there are no considerable ionospheric effects, the ΔTEC values are fairly constant. If large variations occur, severe ionospheric condition exist, and we will have difficulties to resolve the double difference phase ambiguities. ΔTEC values can be converted into ionospheric effects ΔL on a certain

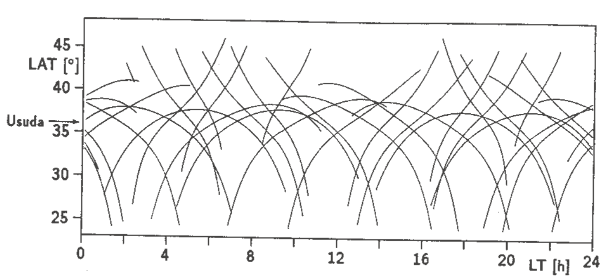

Fig. 2. Sub-ionospheric points of GPS satellite passes in geographic latitude and local time, h_I=400km, 10°-elevation mask, Usuda, day 243/1993.

signal with

$$\Delta L_{AB} = (1/S) \cdot \Delta TEC_{AB}. \qquad (11)$$

The conversion factor $1/S$ for ionospheric effects to units of cycles of L_1 amounts to 0.85, for full wavelength cycles in L_2 to 1.10, and for full wavelength cycle in L_W to -0.24. If the variations exceed half a cycle, ambiguity estimation can become impracticable with the selected signal.

Figure 3 compares four ionospheric conditions, their detection with one of the ionospheric GPS observables mentioned (VTEC, dVTEC, RoT), and their effect on the single-difference observable. The top panels show the geographic latitude of the sub-ionospheric points of the satellite passes over local time of the observation station. They enable us to localize in which latitude region certain ionospheric features occur. The examples are discussed in the following sections.

3. Small-scale irregularities

Small-scale irregularities in the electron content of the ionosphere, with spatial extents from a few meters to a few kilometers, can produce both refraction and diffraction effects on received GPS signals. Fluctuations in received signal level (amplitude scintillations) can cause the inability to track the GPS signal continuously and there-fore they can lead to significant data loss. In the case of the Rogue receiver at the station Usuda, no significant data loss could be justifiably attributed to scintillation activity.

The observed phase scintillations were not as severe as the ones which can be monitored closer to the magnetic equator. The detection of phase scintillation activity was performed with the help of the scintillation index I_{RoT}. Scintillation activity was observed in September 1992 and from June to August 1993. The mapping of $I_{RoT} \geq 3$ reveals that the activity was limited to the night-time sector. The main activity was observed before midnight and south of the observation station Usuda (Figure 4).

In the example given in Figure 3, the main scintillation activity takes place south of the observation station at the beginning of the satellite pass. With the satellite travelling northward and with the local time reaching early morning hours, scintillation activity decreases and later on it ceases. Whereas dVTEC and RoT show the change of ionospheric refraction in satellite flight direction (south-north), the single-difference over the 155km baseline

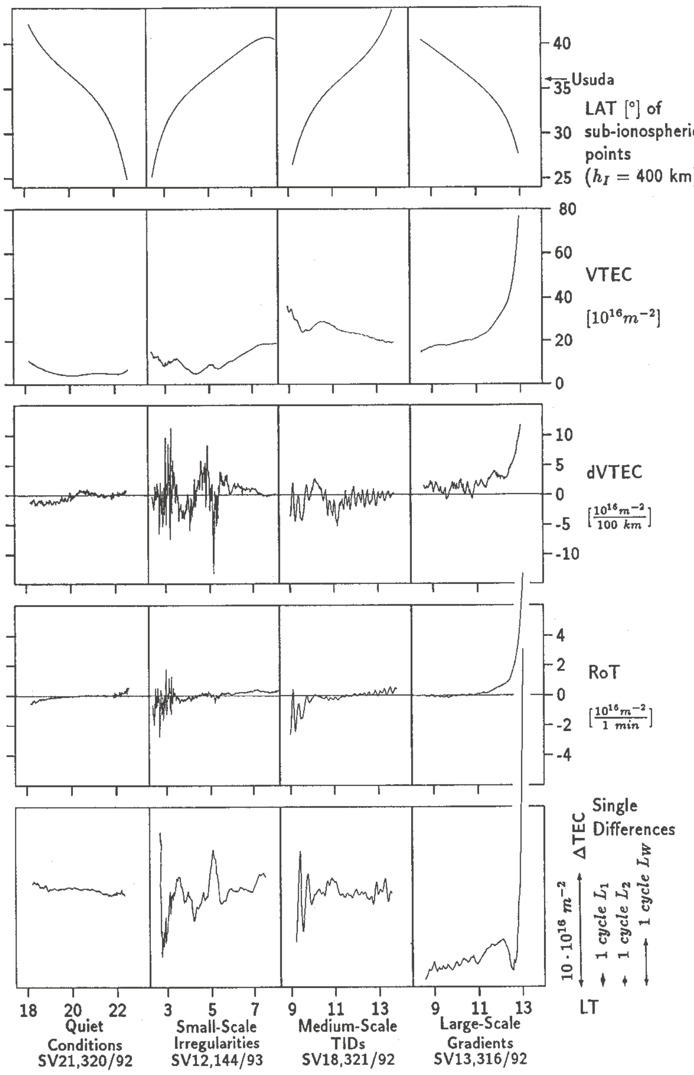

Fig. 3. Detection and description of severe ionospheric conditions shown by examples of GPS data from Usuda; corresponding single-differences of TEC of the 155km east-west baseline Usuda-Tsukuba.

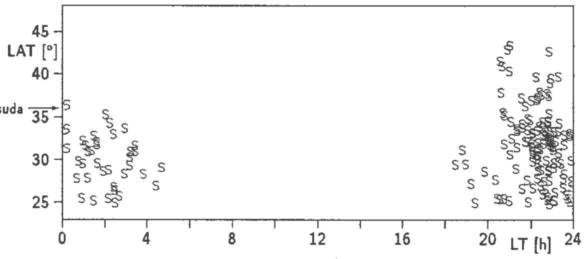

Fig. 4. Scintillation occurrence in September 1992 and from June to August 1993; data blocks of 15 minutes, $I_{RoT} \geq 3$.

displays the effects of east-west refraction differences. The bottom panel reveals that the scintillations do not only cause short-term variations in the single-difference observable of up to $10 \cdot 10^{16}$ electrons per m^2 but they are also an indicator of larger-scale variations. Due to the size of the irregularities, the observed effects are not proportional to the baseline length. Therefore, no conclusions can be drawn for medium-length baselines (20-50km). However, experiences with data from polar regions show that scintillations of this size can cause difficulties in cycle-slip fixing and ambiguity resolution (Wanninger and Jahn, 1991).

4. Travelling ionospheric disturbances

Travelling Ionospheric Disturbances (TIDs) are wavelike structures which may imply variations in the ionospheric electron density of several percent of the total electron content. Medium-scale TIDs have horizontal phase speeds of 100-300 m/s, periods from 12 minutes to about 1 hour and horizontal wavelengths of several hundred of km.

Medium-scale TIDs were observed from October 1992 to March 1993 almost only during day-time hours. Larger TIDs were mainly detected south of Usuda. The variation in vertical TEC could reach more than 5% (see VTEC-panel in Figure 3). Due to the size of the disturbances, the observed effects of up to $8 \cdot 10^{16}$ electrons per m^2 for the single-difference over the 155km baseline cannot be transferred to shorter baselines. Experiences with medium-scale TIDs twice as large as the ones in the example of Figure 3 show that even on short baselines ($\leq$10km) problems can occur with short observations periods (few minutes) and fast ambiguity resolution algorithms (Wanninger, 1993a). No significant effects on ambiguity resolution are expected for longer observation periods and smaller TIDs.

5. Large-scale gradients

Large-scale gradients result from differences in VTEC which are caused by latitudinal electron content differences (north-south gradients) or by local time dependent differences (east-west gradients). The largest gradients are found in the regions of the equatorial anomalies (±10-20°N magnetic latitude). But even GPS signals which are received at Usuda, located at 30°N magnetic latitude, can be affected by the high electron content of the northern equatorial anomaly, since the GPS-signals cross the ionosphere at a distance from the receiver of up to some 1000km. Electron content differences between the northern edge of the equatorial anomaly in the south and the mid-latitudes in the north lead to large gradients, which can affect the double difference ambiguity resolution of north-south baselines. Smaller gradients, caused by the diurnal cycle of the electron content, are found in east-west direction. They can cause difficulties in the resolution of the ambiguities of east-west baselines.

In the observation data of Usuda, high electron contents and corresponding large-scale gradients were found between October 1992 and April 1993. In the remaining months gradients did usually not exceed $5 \cdot 10^{16} m^{-2}/100km$. Figure 5 presents an example of VTEC derived from P-code observations (compare equation (1)). The differential hardware delays of the satellites dH_P^j were corrected according to the values given by Wanninger and Sardón, 1993. The differential hardware delay of the Rogue receiver at Usuda was estimated to be $-2 \cdot 10^{16} m^{-2}$. North of Usuda, the figure shows a very early daily maximum of some $30 \cdot 10^{16} m^{-2}$ at 9 LT, whereas south of the station the maximum exceeds $100 \cdot 10^{16} m^{-2}$ at 11 LT. Large gradients occur south of Usuda only. Their effect on single-differences is amplified for signals received under small elevation angles due to the slant factor F (see equations (4) and (5)).

All gradients $|dVTEC| \geq 5 \cdot 10^{16} m^{-2}/100km$ are shown in Figure 6. Remember that dVTEC represents the gradients in satellite flight direction only. East-west gradients can be detected in the latitude region of Usuda: They often exceed $5 \cdot 10^{16} m^{-2}/100km$ between 6 and 18 hours LT. No information can be extracted on east-west gradients south of Usuda. North-south gradients often exceed $10 \cdot 10^{16} m^{-2}/100km$ south of Usuda between 12 and 20 hours LT. North of the station no gradients greater $5 \cdot 10^{16} m^{-2}/100km$ were detected.

The large-scale gradients in the example in Figure 3 can also be detected in the RoT time series. The north-south gradient causes a maximum dVTEC of $12 \cdot 10^{16} m^{-2}/100km$. The east-west gradient can be derived from the single-difference observable in the bottom panel ($\Delta TEC = 28 \cdot 10^{16} m^{-2}$, 155km baseline length, elevation angle $15° \rightarrow F = 2.4$) : it amounts to $7.5 \cdot 10^{16} m^{-2}/100km$. It can be assumed that the effect of large-scale gradients are proportional to the baseline length. A gradient of $10 \cdot 10^{16} m^{-2}/100km$ corresponds to a single-difference over a 10km baseline and for a signal's elevation angle of 15° ($F=2.4$) of 2.0 cycles L_1, 2.6 cycles L_2 and 0.6 cycles L_W. Thus, even for short baselines the ionospheric effect can exceed half a cycle of the widelane linear combination. These ionospheric conditions can prevent ambiguity resolution

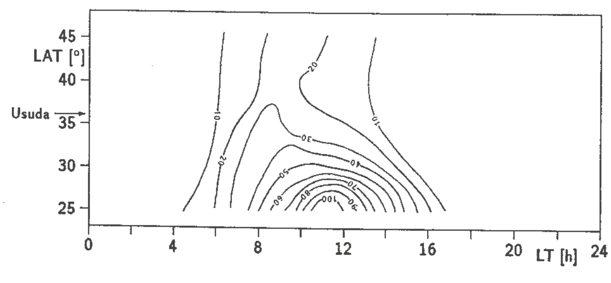

Fig. 5. Vertical TEC derived from P-code observations, Usuda, day 40/1993, in $10^{16} m^{-2}$.

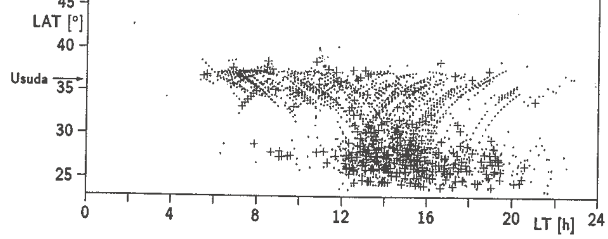

Fig. 6. Large-scale gradients from October 1992 to April 1993; observable dVTEC was calculated from data with an epoch rate of 8 minutes, two symbols: dot (・) if $5 \leq |dVTEC| \leq 10 \cdot 10^{16} m^{-2}/100km$, cross (+) if $|dVTEC| \geq 10 \cdot 10^{16} m^{-2}/100km$.

Table 1. Occurrence of severe ionospheric conditions above Japan

Ionospheric Conditions	Time of Year	Time of Day	Latitude Region
small-scale irregularities	June-September	night-time	mainly south of Usuda
medium-scale TIDs	October-March	day-time	mainly south of Usuda
large-scale gradients:			
east-west	October-April	6-18 hours LT	above and south of Usuda
north-south	October-April	12-20 hours LT	south of Usuda

which is essential for many precise applications of relative GPS positioning.

6. Summary and outlook

One year of permanent GPS tracking data of the Japanese station Usuda were processed in order to provide a survey of the occurrence of severe ionospheric conditions above Japan. The results are summerized in Table 1. We can assume that the temporal distribution in 1994 and also in subsequent years will be similar to that of 1992/1993.

No data loss could be justifiably attributed to scintillation activity. Thus, the main effects of severe ionospheric conditions relate to the ambiguity resolution in relative GPS positioning. Especially the north-south large-scale gradients south of the observation station Usuda can prevent the ambiguity resolution even on short baselines. If precise results are obtained by long observation sessions of many hours without ambiguity resolution, the ionospheric effects described are of no concern. However, if ambiguity resolution is required, the occurrence of severe ionospheric conditions should be carefully considered in the planning stage of a GPS campaign in order to avoid difficulties in the data processing.

High ionospheric electron content and disturbances depend on the solar activity. The maximum of the last solar cycle lasted from about 1989 to about 1992. In the next years, smaller ionospheric effects on GPS positioning can be expected. At the end of this decade, solar activity will increase again.

Acknowledgements

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