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4. Radio Science Results

4.1 An Evaluation of Atmospheric Gradient Using Water Vapor Radiometers in Kashima, Japan

By

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ABSTRACT

With the aim of evaluating the effects of water-vapor atmospheric gradients on space geodesy technologies, observations of wet delay were performed using water vapor radiometers (WVR) over a period of about two years in Kashima, Japan. On comparing WVR gradient results with Global Positioning System (GPS) gradient results, a tendency for the gradient vector to be dominant in the southwest direction could be seen in both. On the other hand, the correlation coefficient between the two for gradient fluctuation was found to be only 0.2. This low correlation may be caused by gradients due to dry atmosphere and/or by the effects of mesoscale phenomena that are not simulated to reproduce in a gradient estimation model. In addition, for 1998 and 1999 GPS data, we examined the relationship between the use or non-use of atmospheric gradient estimation and positioning solutions and baseline-length solutions. It was found that repeatability of positioning solutions in the horizontal direction could be improved by 40% in the case of gradient estimation, but that seasonal changes were still evident.

Keywords: VLBI, GPS, Mapping function, Atmospheric gradient, WVR

1. Introduction

In space geodesy technologies like Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS) that use microwaves, removal of positioning error due to fluctuation of water vapor in the atmosphere is a critical issue in reaching three-dimensional sub-millimeter accuracy. A model that is now being put to use considers horizontal fluctuation of the atmosphere in a mapping function (called "azimuth-dependent mapping function" or "anisotropic mapping function") where the amount of atmospheric delay in the zenith direction (zenith delay) is multiplied by an elevation-angle-dependent coefficient[(1),(2)].

In this anisotropic mapping function, a simple model is used in which delay gradient is approximated as a linear plane. For Japan, however, where fluctuation in water vapor on mesoscale and local scale phenomena occur frequently on a horizontal scale no more than several tens of kilometers, it is not yet known whether this assumption is valid for eliminating these effects. In addition, the extent to which atmospheric gradients estimated from the model reflects actual water vapor fluctuation is not clear.

To therefore understand the dynamics behind water vapor fluctuation on these scales and to investigate the relationship with GPS and VLBI positioning error, we decided to perform observations using water vapor radiometers (WVR) in the Kashima, Ibaraki area of Japan beginning in May 1998. In these observations, we focused our attention on water vapor fluctuation originating in daily variation of land and sea breezes in the Kashima environs, on cumulus cloud convection phenomena that occur on the coasts of Chiba and Ibaraki prefectures, and the like. In this report, we describe in particular the observations performed at Kashima and compare atmospheric gradients obtained by WVR with that estimated by GPS.

2. Overview of Observations

We performed WVR observations at the Kashima Space Research Center from June 1998 to December 2000 (the time of this writing) with several periods of interruption. For these observations, we uses the Radiometrics™ WVR1100, which has an hardware option for determining amount of integrated water vapor along the line of sight by entering values for azimuth and elevation angle. As a consequence, it is also possible to track and observe a satellite by entering the broadcast orbit from a GPS satellite. As shown in Table 1, the observations have been performed by switching between line-of-sight observations (scanning mode), in which azimuth is rotated 30° at a time at an elevation angle of 20°, and tracking mode.

In addition to the above, we installed similar WVRs at GPS stations at the Meteorological Research Institute in Tsukuba, which is about 54 kilometers to the west of Kashima, and at the Lake Kasumigaura Water Research Station of the National Institute for Environmental Studies in Miho village, which is almost halfway between Kashima and Tsukuba. The satellite-tracking-mode observation data collected at Kashima and Tsukuba in the same time periods has been used for evaluating GPS analysis on the Kashima-Tsukuba baseline. The layout of these stations is shown in Fig. 1. Other data collected at Tsukuba and Miho are still being analyzed and are

Table 1 Overview of WVR observations in Kashima

Observation Period	Observation Mode	WVR Model No.	Observation Point
6/23/1998-9/15/1998	Tracking mode	WVR28	Roof of main office
10/4/1998-8/4/2000	Scanning mode	WVR28	Roof of main office
8/9/2000-9/29/2000	Tracking mode	WVR28	Roof of 34m office
10/3/2000-	Tracking mode	WVR26	Roof of main office

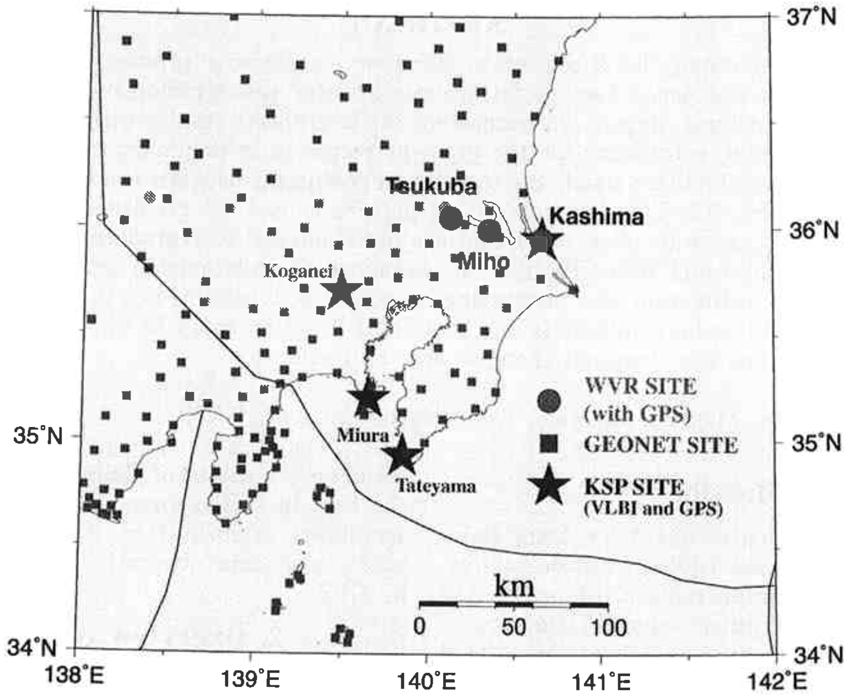

Fig. 1 Layout of WVR stations

therefore not presented at this time.

3. Analysis

The obtained WVR data was calibrated in the following way. The WVR1100 used in the observations measures brightness temperature by two-frequency receivers and estimates the amount of integrated water vapor and cloud moisture along the line of sight. First, WVR data was compared with radiosonde data obtained by the Meteorological Research Institute in the early summer of 1998, and on the basis of the following equation that relates brightness temperature and amount of integrated water vapor, coefficients were re-determined[3].

$$\Delta L_{wvr} = C_0 + C_1 * \tau_{23} + C_2 * \tau_{31} \quad \cdots (1)$$

The left side of this equation, ΔL_{wvr}, is the amount of wet delay, τ_{23} and τ_{31} are opacity at 23 and 31 GHz, respectively, and C_0, C_1, and C_2 are coefficients. By re-determining these coefficients, good agreement within RMS 5 mm could be ensured among WVR, radiosonde, and amount of zenith delay obtained from GPS[4]. We next applied these re-determined coefficients to WVR data of all periods and calibrated the data.

In addition, we determined water vapor gradients in the following way from WVR data. In a time period of about one minute, the WVR outputs one value each for amount of integrated water vapor and amount of cloud moisture. Three hours worth of this time-series data is treated as one set of data, and water vapor gradients for each data set are determined by the least-squares method. In this estimation, we use the gradient model of the anisotropic mapping function by Chen and Herring[4] as given by Eq. (2).

$$\Delta L_{wet} = \Delta L^z_w M_w(\varepsilon) + L_{az}(\varepsilon, \alpha), \quad \cdots (2)$$

Here, ΔL^z_w is amount of wet delay in the zenith direction and $M_w(\varepsilon)$ is the mapping function with respect to the amount of wet delay. In addition, $L_{az}(\varepsilon, \alpha)$ is a term of the atmospheric gradient model and is given as follows.

$$L_{az}(\varepsilon, \alpha) = L_{ns} m_{az}(\varepsilon) \cos\alpha + L_{ew} m_{az}(\varepsilon) \sin\alpha, \quad \cdots (3)$$

In Eq. (2), $m_{az}(\varepsilon)$ can be given as follows.

$$m_{az}(\varepsilon) = 1/(\sin\varepsilon \tan\varepsilon + C) \quad \cdots\cdots (4)$$

Here, $m_{az}(\varepsilon)$ is elevation-angle dependency of delay at an angle of ε. Also, L_{ns} and L_{ew} and north/south component and east/west component, respectively, of the gradient vector. In this analysis, the assumption is made that $C = 0.0032$[5]. From Eq. (2), water vapor gradients averaged for each three-hour period could be obtained. We also estimated water vapor gradients from GPS data obtained from GPS equipment installed at Key Stone Project (KSP) stations, and we attempted to evaluate these by comparing them with fluctuation in integrated water vapor obtained from WVR.

4. Results and Discussion

Figure 2 shows the azimuth and size of water-vapor gradient vectors estimated by WVR observations in Kashima in a time series. Here, to remove short-term fluctuation and uncover overall tendencies, we show results with moving averages determined by 24 hours worth of data. Examining the figure, we can see that gradient vectors are large in early summer and that water vapor is remarkably non-uniform. Also, by taking note of gradient vector azimuth, we see a distribution in which water vapor is abundant to the southwest of Kashima.

In Fig. 3 we see that the length of the Kashima-Koganei baseline in the KSP observation network undergoes seasonal change for both GPS and VLBI and that the baseline is about 15 mm longer at maximum in summertime compared to wintertime[6]. According to simple water-vapor gradient simulations performed by Kondo et al. using the ray tracing method, water vapor gradients arise in the spring and summer due to the effects of paddy fields that abound to the southwest of Kashima, suggesting a link to seasonal changes of baseline length. These results concur overall with our results from WVR observations, but we went on to make further studies.

Recently, GPS analysis software has come to incorporate a model for estimating water vapor gradients. We therefore decided to reanalyze GPS data from January 1, 1998 to December 31, 1999 in an attempt to analyze the non-uniformity of water vapor distribution. The time series in Fig. 3 also shows results when estimating gradients. Figure 4, moreover, shows changes in horizontal displacement at the GPS Kashima station, and like Fig. 3, shows results when estimating water vapor gradients and when not estimating them. For results of either baseline length or horizontal positioning, dispersion becomes smaller when estimating atmospheric gradient and repeatability improves. With regard to the horizontal component of GPS positioning results in Fig. 4, we compared the RMS of data for all periods excluding primary trends (mainly crustal deformation due to plate motion) and found that repeatability could be improved by about 40% by estimating gradients.

Here, it is necessary to check whether the above results can actually be used to remove the effects of non-uniformity in the distribution of water vapor. Figure 5 shows a time series of north/south and east/west components of atmospheric gradient vectors at Kashima, with the solid line being observations by WVR (WVR gradients) and the broken line the results obtained from GPS analysis (GPS gradients). These gradients are shown as

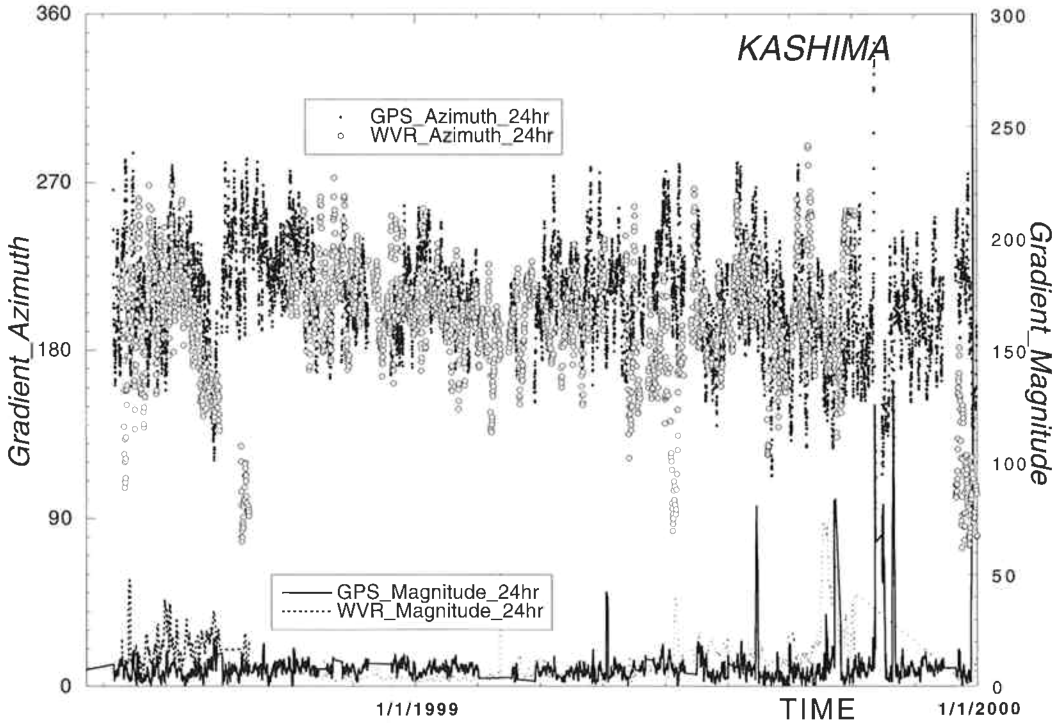

Fig. 2 Azimuth and magnitude of water-vapor gradient vectors estimated by WVR observations

values projected to 10°, the minimum elevation angle in GPS observations, to facilitate understanding of the relationship with GPS positioning solutions. Also on this figure are the results of estimating gradients with moving averages determined by 24 hours worth of data, plus the time series of daily GPS analysis results shown in Fig. 4.

In each figure, time change in the period indicated by the arrow suggests that, for this period only, estimation of atmospheric gradient by the model was performed effectively since (1) phase and amplitude of GPS gradients and WVR gradients are similar, and (2) the results of GPS positioning without gradient estimation exhibits an inverse correlation with the time series of WVR gradients. On the other hand, correlation between WVR gradients and GPS gradients for some of the data from summer to fall of this year was tentatively found to be 0.2, which is not necessarily a high value. Also, in the time-series comparison of Fig. 5, there are many cases in which change in atmospheric gradient behaves completely different between WVR and GPS, and in which a phase offset in gradient vector azimuth occurs despite similarity in time change.

The following reasons are given to explain the possibility that the two do not agree. To begin with, the cause of WVR gradients is completely different from that of GPS gradients. The former gradients are caused by spatial fluctuation of water vapor, while the latter gradients are caused by spatial fluctuation of the atmosphere in its entirety including dry atmosphere components in addition to water vapor. The contribution of water vapor gradient to total atmosphere gradient is about 70-90%. In winter, however, when water vapor is low, this contribution decreases accordingly, and it can be predicted that GPS gradients and WVR gradients do not agree. Furthermore, as the spatial fluctuation of water vapor is severe with respect to time, the two are likely not to agree even in the case that repeatability is difficult by the anisotropic mapping function. In actuality, some comparisons between water vapor gradients obtained by WVR observations performed at Tsukuba, which is about 54 kilometers from Kashima as mentioned earlier, and WVR gradients obtained at Kashima have revealed remarkable difference in the nature of atmospheric gradients[4]. This may be due to the effects of mesoscale phenomena on a horizontal scale less than 10 km. At present, we are still studying these possibilities and plan to report on our findings in a future paper.

In addition, there is still seasonal change in the GPS analysis results of Figs. 3 and 4 after gradient estimation. Since dispersion is small on a scale no greater than a few days, this seasonal change is plain to see. The cause of this seasonal change is not yet clear, but it has been pointed that it must be discussed and that more study should be given to the Niell mapping function[7] that is used when estimating hydrostatic water delay in addition to the effects of water vapor[8]. At the least, we can say that annual change in the results of GPS analysis cannot be explained solely by the effects of paddy fields.

Also, on the basis of results obtained from ongoing KSP and VLBI analysis, the dispersion in the time series of zenith delay estimated by the KSP/VLBI Kashima sta-

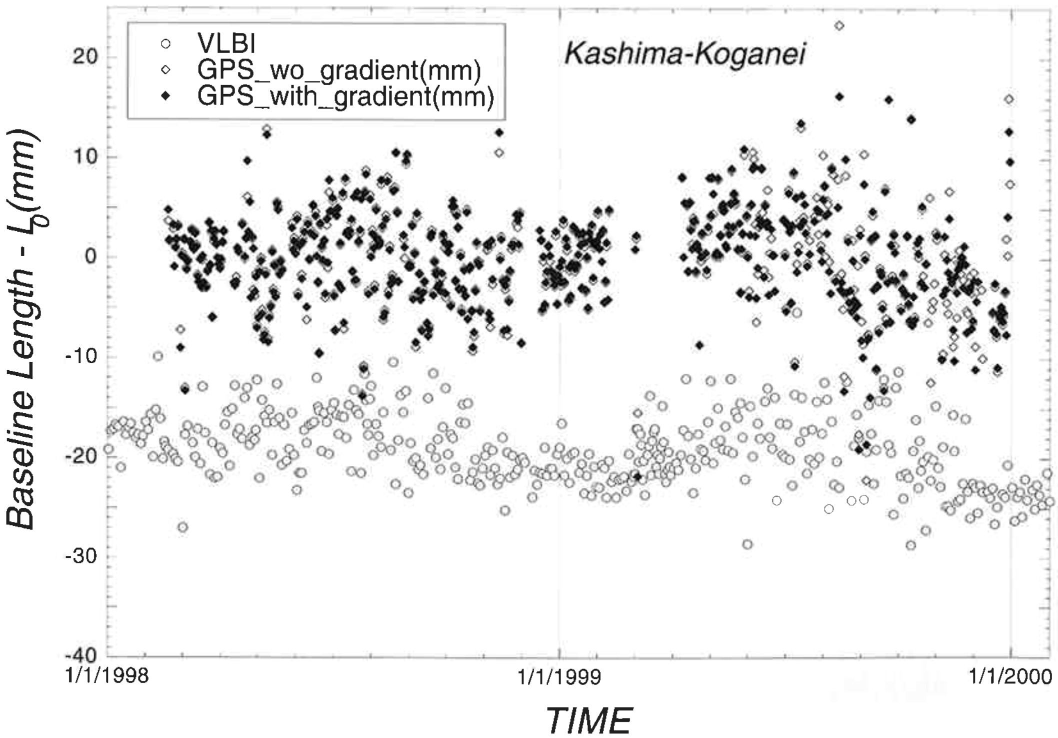

Fig. 3 Time-series change of baseline length

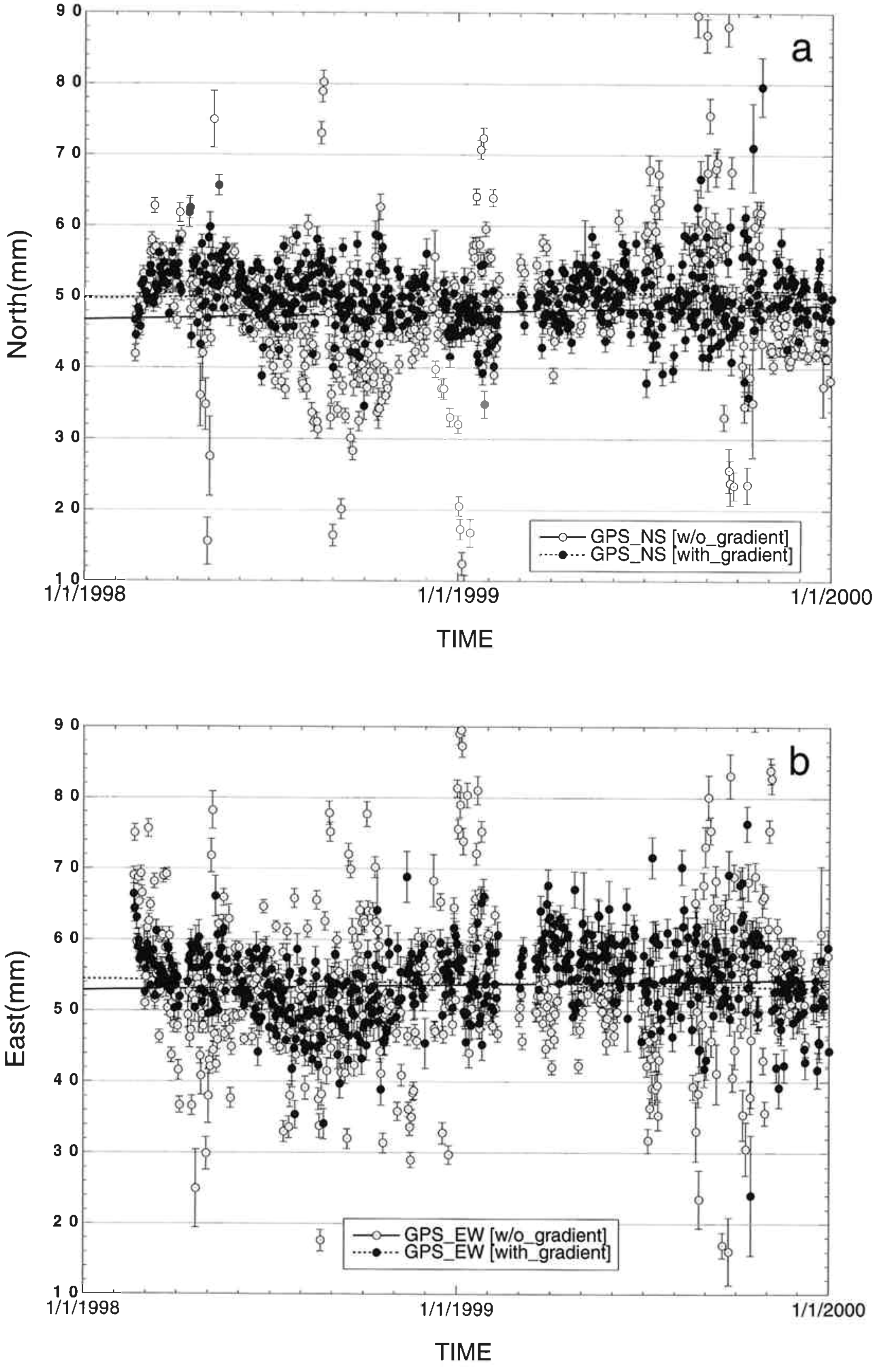

Fig. 4 Time-series position solutions in the horizontal direction by GPS; upper results are north/south components (a) and lower results are east/west components (b)

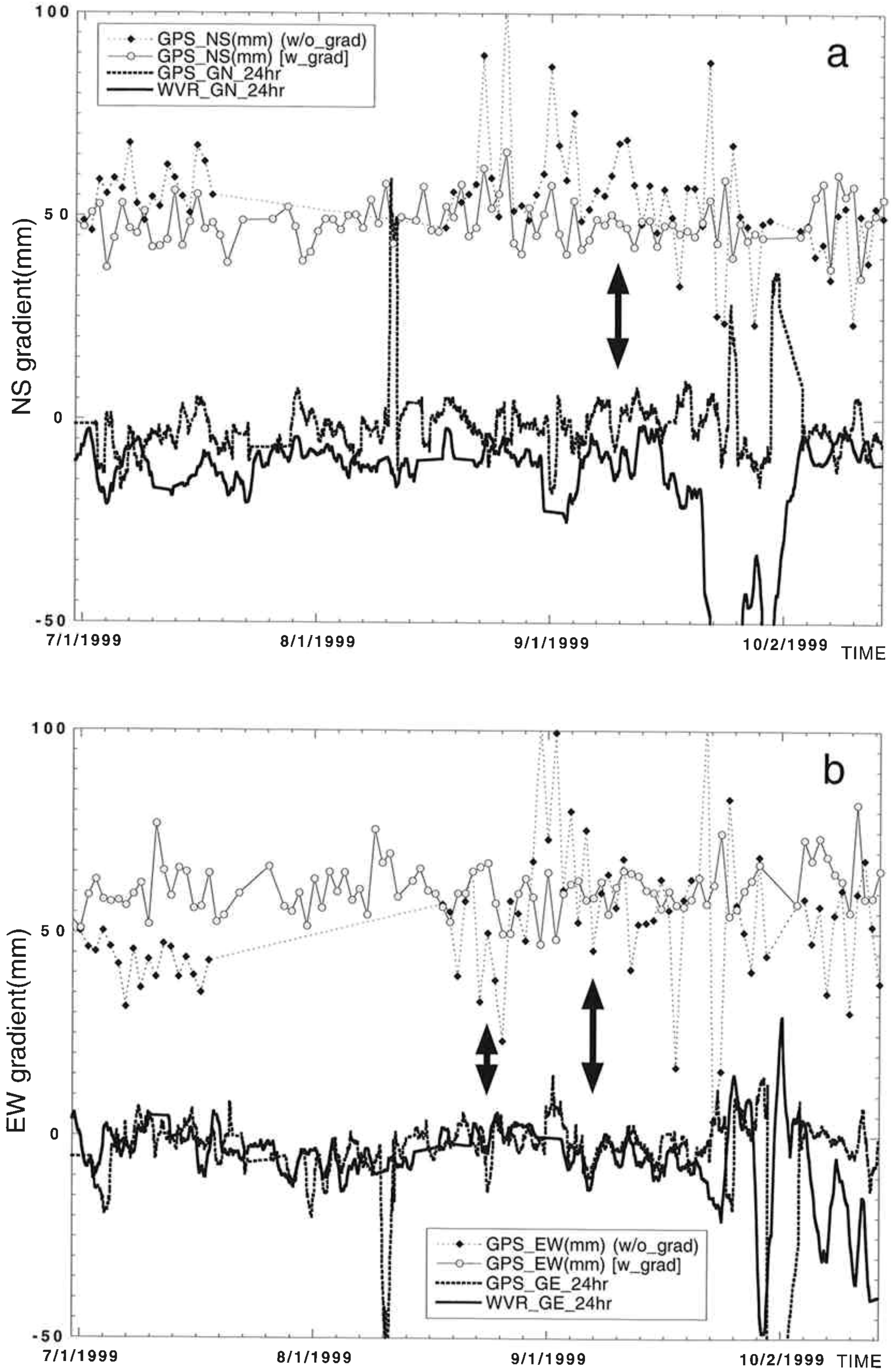

Fig. 5 Comparison of atmospheric gradient vectors; upper results are north/south components (a) and lower results are east/west components (b)

tion is quite large compared to WVR and GPS results. This is thought to be due to the relatively short baselines (about 150 km at maximum) of the KSP observation network that in turn produce poor estimates of zenith delay at each observation station. For this reason, it cannot be denied that the effects of zenith delay are included in seasonal change of baseline length appearing in regular VLBI observations. To uncover the cause of such seasonal changes will require another study of the atmospheric estimation model including both zenith delay and gradients.

5. Summary

With the aim of evaluating the effects of water vapor gradients on space geodesy technologies at Kashima, we performed WVR observations of wet delay over a period of about two years. We also attempted to compare 1998 and 1999 GPS data analysis when and when not estimating atmospheric gradients. First, in the results of GPS analysis, it was found that repeatability improves by 40% when estimating gradients. Next, comparing the results of WVR and GPS gradients, both showed that gradient vectors tend to be dominant in the southwest direction. On the other hand, completely different behavior in gradient fluctuation and shift in gradient vector phase despite similar time changes could often be seen between the two. In addition, the correlation coefficient was tentatively determined to be 0.2. The reason for this low correlation is thought to be consideration or not of gradients caused by dry atmosphere or the effects of mesoscale phenomena that are difficult to reproduce in a gradient estimation model. Furthermore, in comparing changes in GPS baseline length, dispersion was found to be small in the case of gradient estimation for a time scale no longer than a few days, although seasonal changes are clearly evident. The cause of these seasonal changes is not clear at present.

Acknowledgments

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