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Agenda Item 2: Enhancements to existing GNSS SARP and guidance material:
Agenda Item 3: Development of SARPs for future GNSS elements and signals:

a) **Performance requirements for advanced GNSS applications (Cat II/III, advanced GNSS applications)**

Analytical results of spatial gradient of ionospheric delay

INFORMATION PAPER

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SUMMARY

This paper introduces the analysis results using GEONET in Japan corncering the spatial gradient distribution of ionospheric delay of GPS signal impacting on GBAS performance.

1. Background

The ionosphere activity effects on Ground Based Augmentation System (GBAS) for Global Navigation Satellite System (GNSS) became to be known generally among GBAS researchers by some observations. Electronic Navigation Research Institute (ENRI) has been developing and evaluating GBAS including VHF Data Broadcast (VDB) system and researching ionospheric effects on GBAS performance. One is an evaluation of the distribution function of the various spatial ionospheric delay gradients and its seasonal variations, and other is the observation of the deterioration of ionospheric delay caused by ionospheric scintillations with plasma babble phenomena at the ionospheric equatorial anomaly region. This paper introduces the summary of observation results concerning the spatial gradient distribution of ionospheric delay using GPS Earth Observation Network (GEONET) in Japan. The detail of this observation results was presented at ION (Institute of Navigation)-NTM (National Technical Meeting) in January 2004.

2. GEONET data analysis

GBAS is a system based on a differential GPS technique for aircraft precision approach using GNSS pseudoranges. In general, the ionospheric delay will be neglectable in local area using correction data set from the ground segment of GBAS. However, a large spatial gradient of ionospheric delay occurs between ground GPS monitoring stations, the position error of aircraft become large and the integrity risk will be increase.

Various ionospheric phenomena produced the both of spatial and time gradients of propagation delay on GPS signal. Specially, the geomagnetic latitude of Japan is lower than its geographic latitude, and ‘Equatorial anomaly’ of ionospheric phenomenon is often observed. It has the maximum peak of electron density of ionosphere at the both of geomagnetic latitude of 15 N and 15 S, and is larger gradient of ionospheric delay at the North-South direction than the East-West direction.

ENRI calculated spatial gradient for the both directions from South to North (the S-N direction) and from West to East (the W-E direction) using GEONET/TEC (Total Electro Content of ionosphere) database provided by Kyoto University with a correction of inter frequency bias. Firstly, nation-wide characteristic of spatial gradient of ionospheric delay over Japan was investigated using TEC data with 4 degrees grid in 2001. Secondly, we investigated local spatial gradient in the N-S and the W-E direction using each 4 stations co-located within several 10 km along the E-W and the N-S direction, respectively. .

GEONET, whose data was base of our analysis, is arranged by the Geographical Survey Institute (GSI) of Japan, and it has been operated with about over the 1,000 GPS dual-frequency receivers sites all over Japan. The primary purposes of GEONET are monitoring and detecting seismic deformation, but it is also useful for various geophysical observations, i.e. Precipitable water vapor (PWV) estimated from tropospheric delay, Total Electro Content (TEC) from dual-frequency observation, etc. In December 2001, 983 stations were available. A corresponding distance between two stations was about 20 km.

3. Nation-wide analysis

We used TEC data with a spatial resolution of 2-degrees-grid and a time resolution of 1-hour to investigate gradient variations with nation wide scale of Japan. This data set is called as ‘Hourly

TEC' estimated together with inter-frequency bias. To investigate dependence of ionospheric delay gradients on latitude, we selected three points, which are A (41 N, 141 E), B (37 N, 137 E) and C (33 N, 133 E), and defined 4 seasons, which were winter (DOY of 001-046), spring (047-137), summer (138-228) and autumn (229-319), to investigate seasonal variations of spatial gradient.

Figure-1 shows the distribution of the wide area (more than a thousand km) spatial gradients of ionospheric delay in south-north (S-N) direction at the point 'B' (37 N, 137 E) in each season (winter, spring, summer and autumn). The distribution data divided for each magnitude with an interval of 0.08 mm/km in ionospheric delay gradient. The data number was represented in ratio to total numbers of each season with a log scale. The curved lines represent results of Gaussian distribution fitting. These Gaussian curves almost satisfied the observation results. The deviations of the distribution in spring and autumn were larger than in winter and summer, and the tail of the distribution expanded at the south direction. These phenomena were affected by the equatorial anomalies of ionosphere.

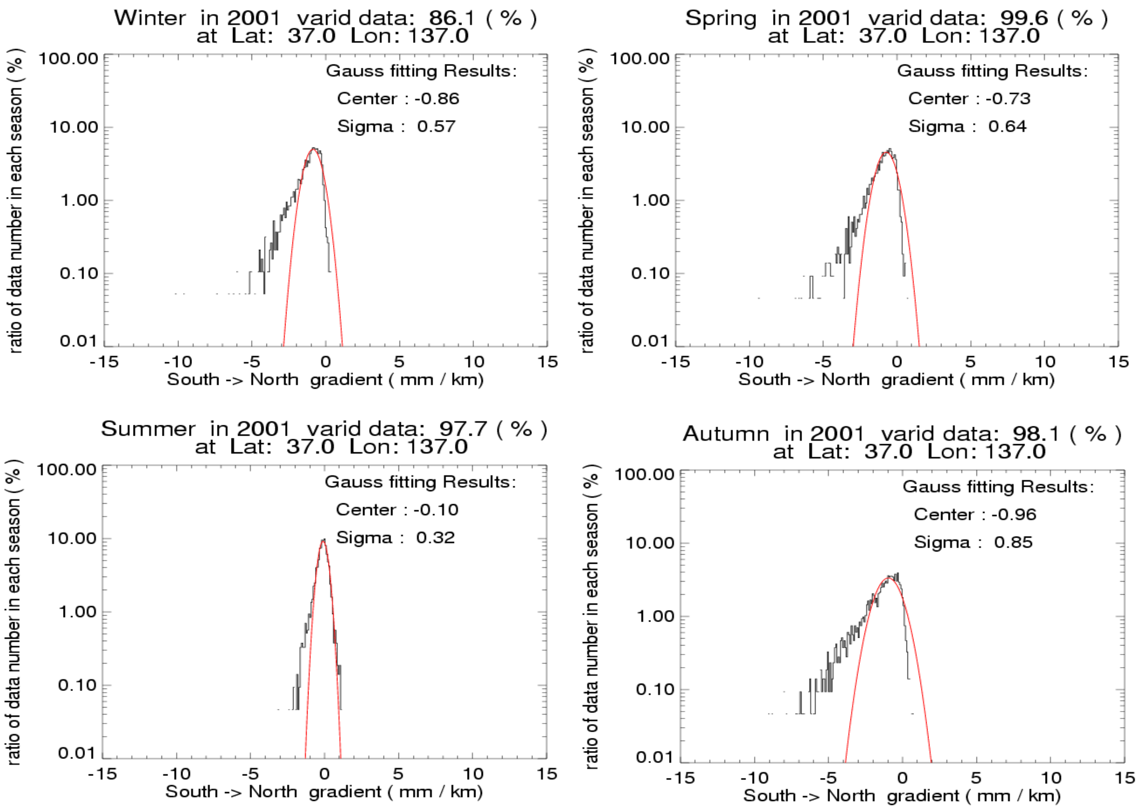

Figure-1: The distributions of the wide area spatial gradients of ionospheric delay in south-north direction at the point 'B' (37 N, 137 E) in each season. The distributions divided for each magnitude with an interval of 0.08 mm/km in ionospheric delay. The data number was represented in ratio to total numbers of each season with a log scale. Curved lines represent results of Gaussian distribution fitting.

The same analysis was performed at the points of A (41 N, 141 E and C (33 N, 133 E), in order to investigate dependence of gradient in S-N direction on latitude. The results observed in autumn are shown in Figure-2 and we recognized that the characteristics of seasonal variation at the both A point and C point ware similar to B point. The characteristics of the distribution and deviation were similar as each characteristic at the point A, point B and point C, except slightly larger at the point C, which was at lower latitude than the point A. Because the activity range of equatorial anomaly is up to about 40 N, it is expected that the distribution were more similar to Gaussian distribution curve in the Northern area than South area.

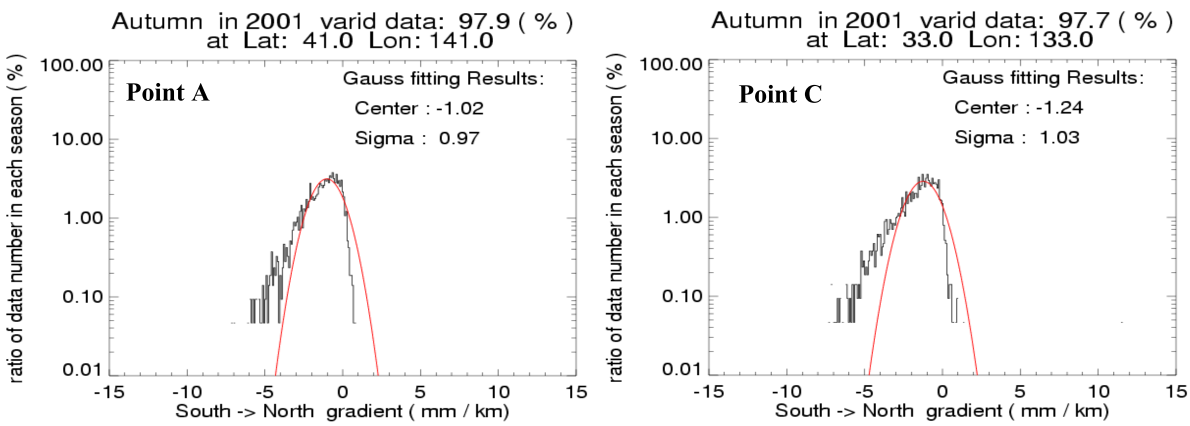

Figure-2: The distributions of the wide area spatial gradients of ionospheric delay in south-north direction at the point 'A' (41 N, 141 E) and point 'C' (33 N, 133 E) in 2001 autumn season. .

Additionally, we investigated the ionospheric gradient in W-E direction. We recognized that the seasonal variation in sigma of Gaussian curve was characterized that the maximum was in autumn and that the minimum was in summer as the same as the results in the S-N direction. Therefore, we show the results only in autumn. Figure-3 shows spatial gradient in W-E direction at the point 'A', point 'B' and point 'C' in autumn. In these figures, the deviation of Gaussian fitting curve was wider in the lower latitude. Because absolute TEC was larger in the lower latitude, it seemed that daily variation was represented on gradient in the W-E direction. It looks like the distribution of the wide area spatial gradients of ionospheric delay were almost similar to Gaussian distribution curve.

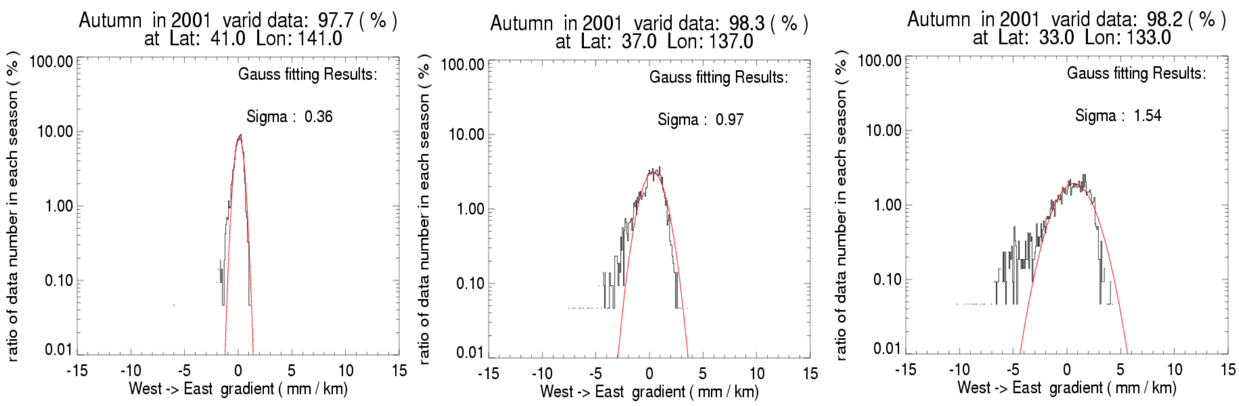

Figure-3: The distributions of wide area spatial gradients of ionospheric delay in west-east direction at the point 'A' (41 N, 141 E), 'point 'B' (37 N, 137 E) and 'point 'C' (33 N, 133 E) in 2001 autumn season.

4. Local scale analysis

We used slant TEC data obtained at each station in the densest area of GEONET to investigate ionospheric gradient within several 10 km. We selected 7 stations located along the N-S and the E-W directions. Using 4 stations aligned along each N-S and W-E direction, we calculated spatial gradient along these receivers' forming with a time averaging of 10 minutes from the original sampling rate of 30 seconds. Although we used the same satellite in local gradient analysis in each time interval, the satellite will be change at the other period. Therefore, it is expected that results are combinations of TEC observed using various GPS satellites. Namely, because ionospheric delay gradient of each satellite represents condition along own slant path, the results depend on satellite configurations. We used the one-year-data-set. The almost same satellite configuration repeated about 4-minute-earlier every day. Under the above condition, we calculated spatial gradient of ionospheric delay (mm/km) in the both directions of the S-N and the W-E using 4 stations along each direction. The distribution of the local area (less than a hundred km) spatial gradients of ionospheric delay in south-north direction are shown in Figure-4 and the distribution of the local area spatial gradients in west-east direction are shown in Figure-5. From two figure groups, general characteristics were similar each other in the both directions. Namely, ionospheric gradient was small in summer, and was large in spring and autumn. These Gaussian distribution curves did not satisfy the observation results, asymmetrical double exponential (DE) distribution was fitter than Gaussian distribution.

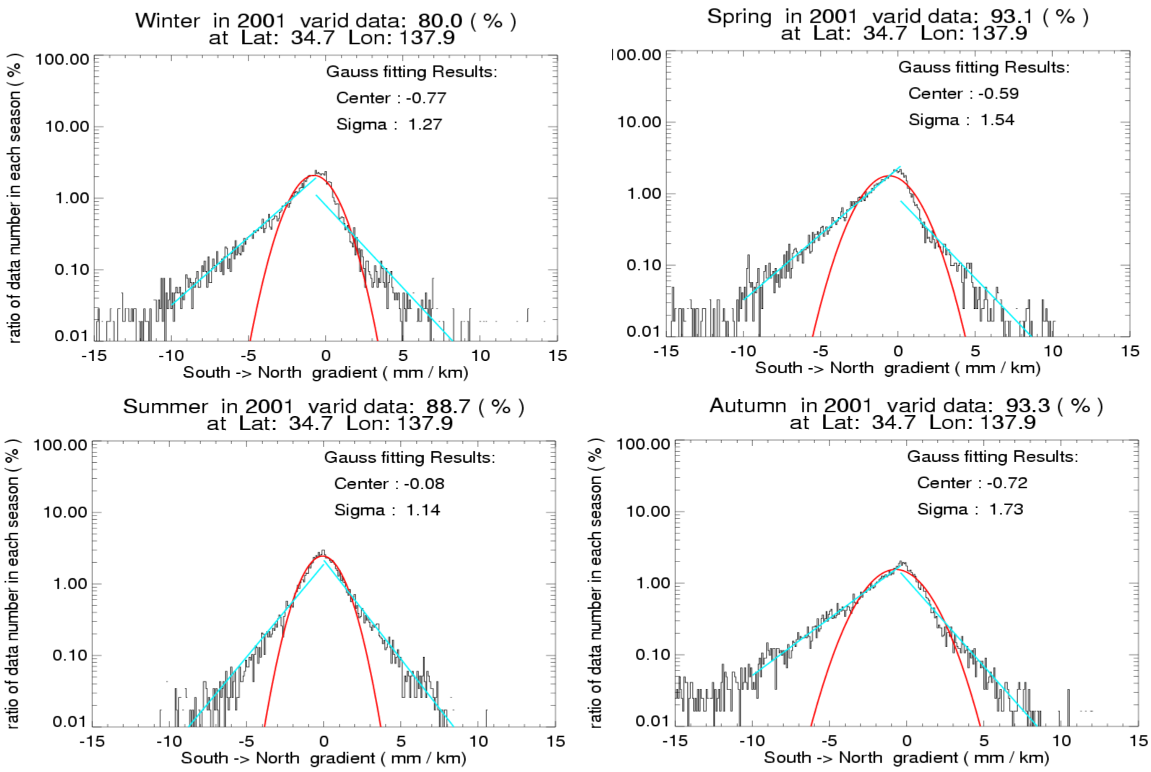

Figure-4: The distributions of local area spatial gradients of ionospheric delay in south-north direction using the 4 stations (34.7 N, 137.9 E). Each figure indicates the result of winter, spring, summer and autumn, respectively. Curved lines represent results of Gaussian distribution fitting. Straight lines represent results of asymmetrical DE distribution fitting.

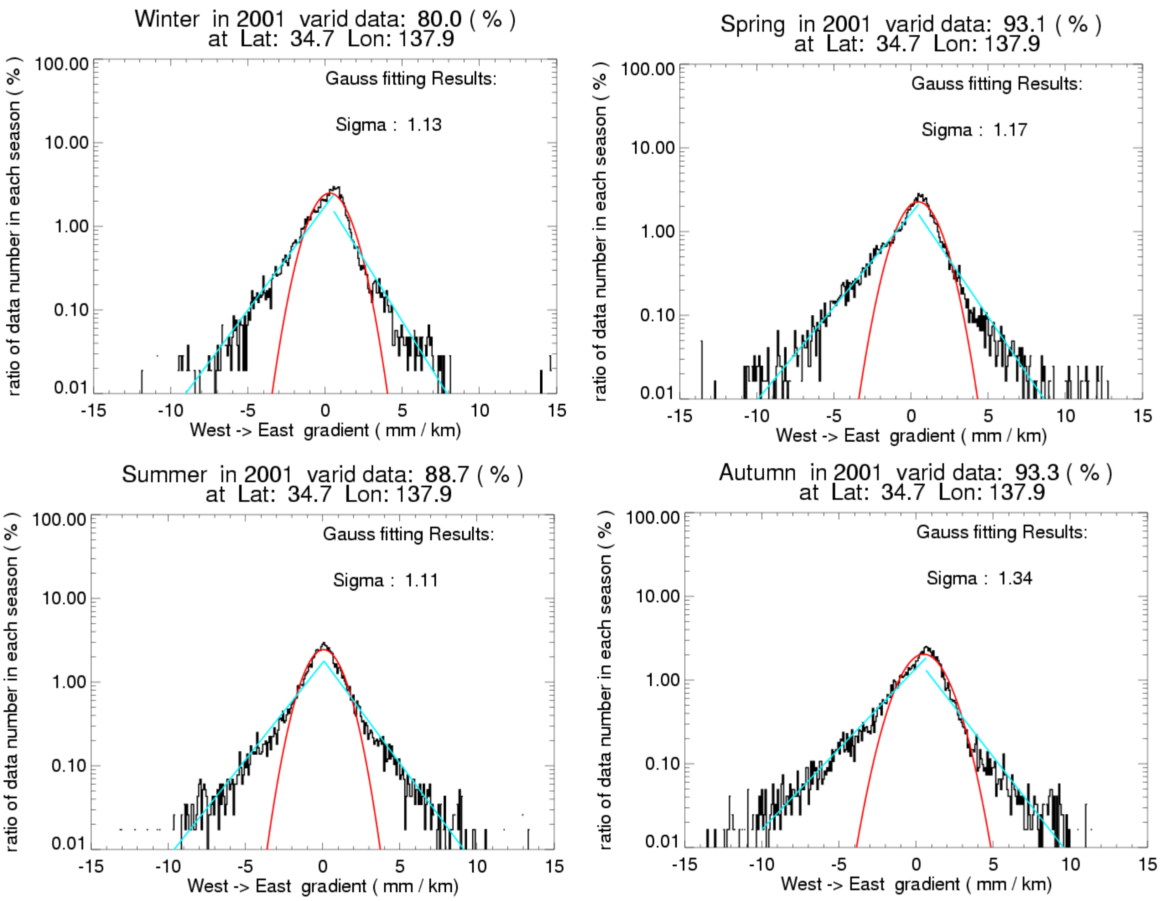

Figure-5: The distributions of the E). Each figure indicates the result of winter, spring, summer and autumn, respectively. Curved lines represent results of Gaussian distribution fitting. Straight lines represent results of asymmetrical DE distribution fitting.

The double exponential (DE) distribution is expressed below equation.

$$DE(y,\lambda) = \exp(-|y|/\lambda) / (2\lambda)$$

We also recognized that larger deviation in the S-N direction than the W-E direction. In the other word, the deviations of the distribution were larger in the S-N direction than E-W direction, and the deviations of the distribution were more symmetrical in the W-E direction. The maximum absolute of gradient value was observed as –26.8 mm/km in the S-N direction, and –31.6 mm/km in the E-W direction in spring. The distribution of the local area spatial gradients of ionospheric delay of this analysis was more similar to asymmetrical DE distribution curve than Gaussian distribution curve.

5. Plasma babbles phenomena observation experiment

The deterioration of ionospheric delay caused plasma babble phenomena at the ionospheric equatorial anomaly region often occur from midnight to dawn around the Spring Equinox Day and Autumn Equinox Day. Therefore, we carried out the observation campaigns for depletion phenomena of ionospheric delay at Okinawa Island near the ionospheric equatorial anomaly region on this spring and autumn, and will be carrying out in next spring. The analysis of this spring campaign has not finished yet in this spring. The plasma babble phenomena were observed more than 2 or 3 events every week in this spring campaign. These results will be presented at later working group meetings.

6. Conclusion

This paper introduces the observation results corncering the spatial gradient distribution of ionospheric delay of GPS signal impacting on Ground-Based Augmentation System (GBAS) performance. These results of our analysis using GEONET database showed that the distribution of the wide scale spatial gradients of ionospheric delay were fit to the Gaussian distribution curves, but the distribution of the local scale spatial gradients deeply related to GBAS performance were more similar to asymmetrical DE distribution than Gaussian distribution. The discussion of the GBAS integrity affected by the ionospheric delay gradients will make analyze carefully separating local area distribution and wide area distribution based on this result and other works. The data of the deterioration of ionospheric delay impacted on GBAS in the ionospheric equatorial anomaly region will be presented after finished our observation campaigns and analysis at the coming meetings.

Reference

(1) T. Yoshihara, N. Fujii and A. Saito; "A study of the ionospheric effect on GBAS (Ground-Based Augmentation System) using the nation-wide GPS network data in Japan", *Proceedings of the ION NTM 2004*, pp 502-511, Jan., 2004