International Civil Aviation Organization

THE SEVENTH MEETING OF THE ASIA/PACIFIC GBAS/SBAS IMPLEMENTATION TASK FORCE (GBAS/SBAS ITF/7)

(Bangkok, 14- 16 May 2025)

Agenda Item 4: Updates on GBAS/SBAS system and States' implementation status

Ionospheric Gradient Study for GBAS at Singapore Changi Airport

(Presented by Civil Aviation Authority of Singapore (CAAS), prepared by CDEC)

SUMMARY

This paper presents an ionospheric gradient study for future GBAS implementation at Singapore Changi Airport.

Key objectives of this paper are to describe:
1. Introduction
2. Layout of Ionospheric Monitoring Stations
3. Ionospheric Gradient Study
4. Way Forward

1. INTRODUCTION

1.1 Civil Aviation Authority of Singapore (CAAS) is planning to install a GBAS with minimally GAST-C capability to support CAT I GLS operations at Changi Airport.

1.2 One of the challenges associated with implementation of GBAS in low-latitude and equatorial regions is the uncertainty of ionospheric impact to Global Navigation Satellite System (GNSS) signals in these regions. Solar storm and equatorial plasma bubbles (EPB) activities may be characterised by steep gradients in the ionospheric delay over a relatively short distance (e.g. a few tens of kilometers). Ionospheric anomalies can produce position errors which have significant impact to (i.e. tens of meters) aircraft approach operations, and result in reduced availability and integrity of GBAS. To mitigate this ionospheric anomaly, CAAS has started to assess the impacts of ionospheric gradient (Iono Grad) on GBAS with the setup of GNSS ionospheric monitoring stations.

2. LAYOUT OF IONOSPHERIC GRADIENT MONITORING STATIONS

2.1 Layout of SGRS

2.1.1 The existing 4 Singapore GITM Reference Stations (SGRS) sites, setup by CAAS, are located at RWY1 and RWY3 in Changi Airport, as shown in Figure 1.

Figure 1- Layout of SGRS

2.1.2 The maximum separation is between 02L_LOC and 20L_LOC sites in the North-South direction with a distance of 7.18km and the minimum separation distance is 3.67 km, between 02L_LOC and 02R_LOC sites in the West-East direction. The SGRS sites are paired with short baseline which may not be ideal.

2.2 Layout of Temporary Iono Grad Monitoring Stations

2.2.1 CDEC and CAAS setup 4 temporary ionospheric monitoring stations in 2024 at 3 offshores islands (i.e. SINJON, UBIN and TEKONG) and 20L_LOC SGRS site in Changi Airport, as shown in Figure 2.

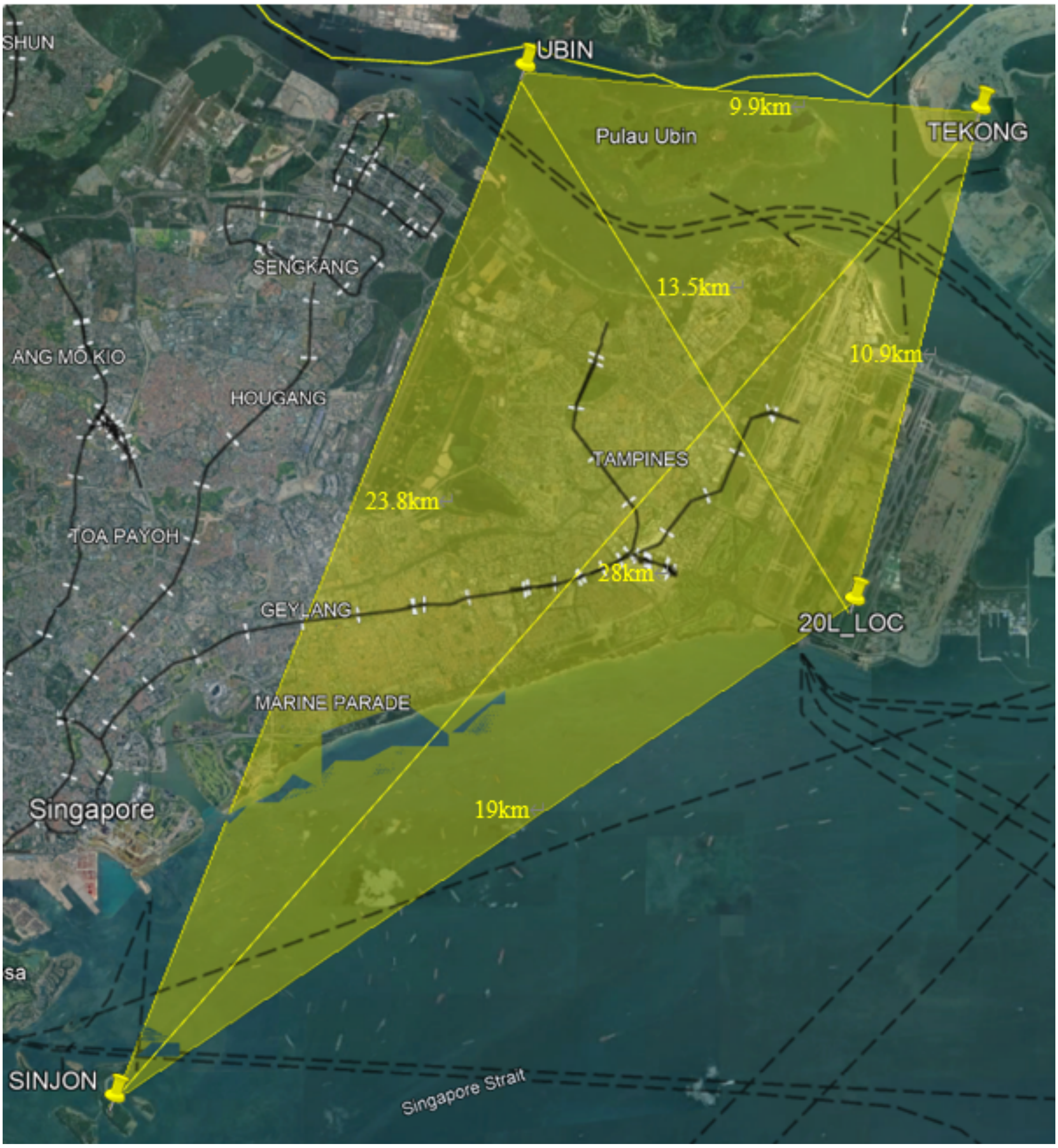

Figure 2- Layout of Temporary GNSS Stations

2.2.2 With this temporary setup, the minimum and maximum distance between stations is 10.9 km (TEKONG and 20L_LOC) and 28 km (SINJON and TEKONG) respectively. The increase in spacing could help to reduce the accumulation of errors in the monitoring results and improve overall monitoring accuracy. The baseline stations pair of SINJON+TEKONG, SINJON+UBIN and SINJON+20L_LOC are ideal, while other station pairs are still short.

2.3 Layout of SLA' SiReNT network

2.3.1 Singapore Satellite Positioning Reference Network (SiReNT) is a national reference network infrastructure, developed by Singapore Land Authority (SLA) to support real-time high precision Positioning, Navigation and Tracking (PNT). It supports multiple GNSS systems. SiReNT currently includes nine reference stations that provide differential GNSS correction data over Singapore, as shown in Figure 3.

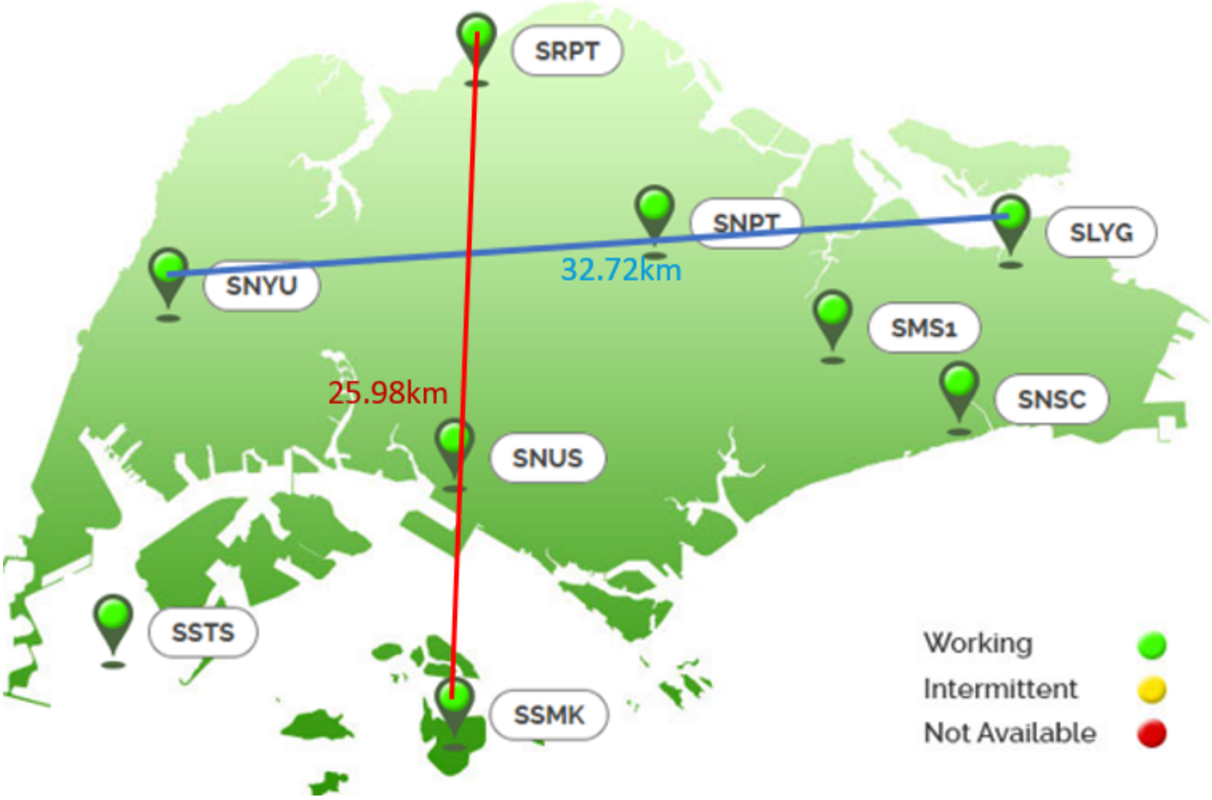

Figure 3-The Layout of SiReNT

2.3.2 The distance between the East-West pair of SLYG+SNYU is 32.72km, and the North-South pair of SRPT+SSMK is 25.98km. Although the stations are located away from Changi Airport, data from these two pairs can be used for a contrast analysis together with the SGRS and temporary GNSS monitoring stations.

3. IONOSPHERIC GRADIENT STUDY

3.1 Iono Grad Study Conducted in 2024

3.1.1 <u>Pair 1: SINJON + TEKONG</u>

3.1.1.1 The baseline of Pair 1 is 28.29km. The Iono Grad data from 1 August to 30 October 2024 indicated that some Iono Grad anomaly events occurred during the monitoring period (exceeding 200 mm/km). The maximum Iono Grad was -273 mm/km on 20 September 2024 as shown in Figure 4. The Iono Grad in September and October 2024 were not stable, i.e. oscillating up and down. The cause of this significant change was likely due to seasonal effect before and after the autumnal equinox.

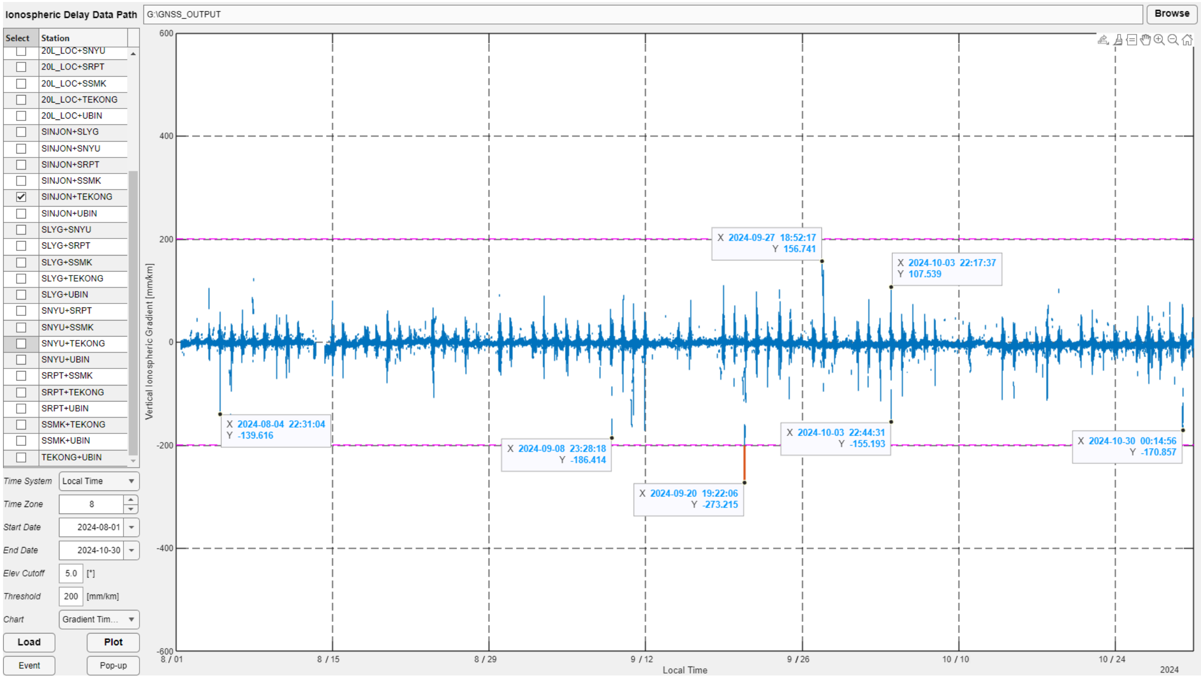

Figure 4-The Iono Grad Distribution for Pair 1 from Aug to Oct 2024

3.1.1.1.1 Further analysis revealed that the ionospheric gradient anomaly on 20 September 2024 was possibly caused by the G02 GPS satellite. Figure 5 shows the key parameters of G02, and the Iono Grad threshold reduced to 150 mm/km, as shown in the yellow area in the Figure 5. The blue and the red dotted line represent the key parameters of SINJON and TEKONG respectively. The key parameters are defined as follows:

Elevation: GPS elevation angle,

IODP: ionospheric delay from pseudo-range,

$$IODP = f_2^2 / (f_1^2 - f_2^2) \cdot (P_2 - P_1)$$

CMC: code-minus-carrier for GPS L1,

$$CMC = P_1 - \lambda_1 \Phi_1$$

IODL: carrier-phase linear combination, the ionospheric delay output by the Iono Grad calculation software after algorithm correction.

Note 1: f_1 and f_2 are the center frequency of the GPS L1 and L2 , P_1 and P_2 are pseudo-range observations for GPS L1 and L2 , λ_1 is the carrier wavelength for GPS L1 and Φ_1 is the carrier observation for GPS L1.

Note 2: IODP is compared with CMC, and CMC is more robust to outages and cycle slips. If both the IODP and CMC are in a good agreement, the gradient is declared to be a true anomaly.

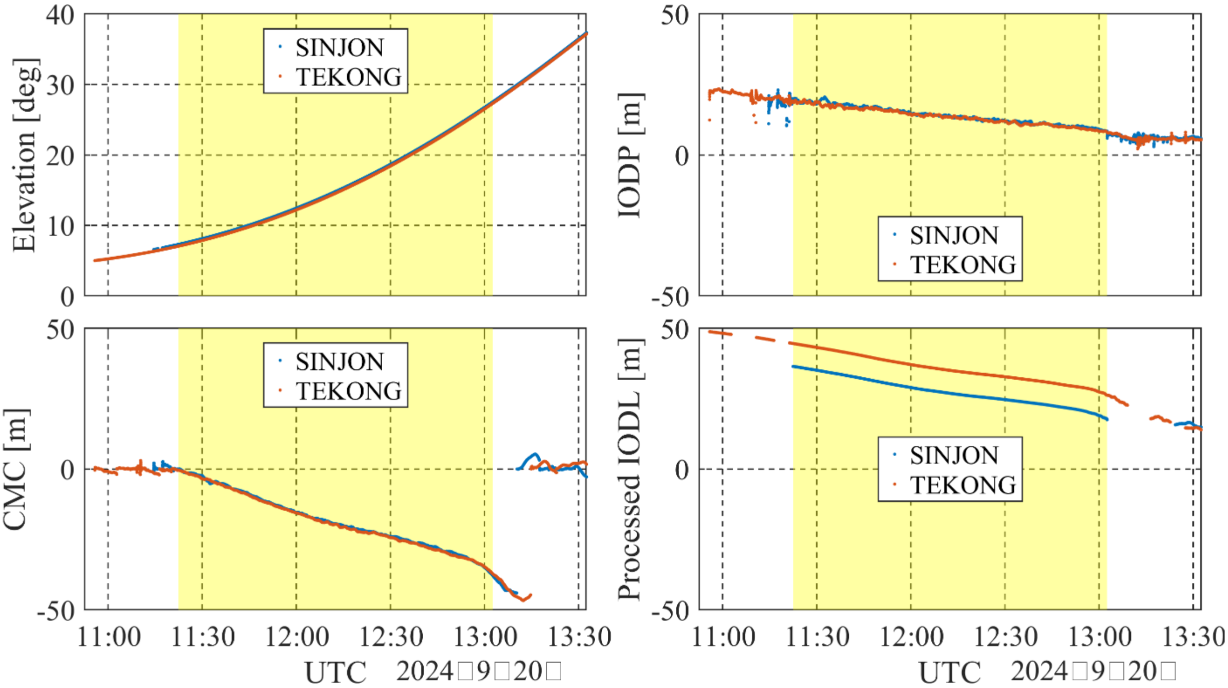

Figure 5-Key Parameters for G02

3.1.1.1.2 During the period when the Iono Grad exceeding 150 mm/km:

(a) the satellite elevation angle was about 8-28°;

(b) due to the large pseudo-range noise, there was a slight delay difference in IODP between the two stations, but the overall trend remains consistent;

(c) the overall trend of CMC at both stations is consistent, with a significant down-trend observed from 11:00UTC to 13:30UTC; and

(d) there was a significant difference in the IODL between two stations.

3.1.1.1.3 In this anomaly, the Iono Grad exceeded 200 mm/km, and the satellite elevation angle was relatively low. IODP, CMC and IODL showed a consistent downward trend, indicating a rapid decrease in the total electron density of the ionosphere which was caused by EPB.

3.1.1.2 The Iono Grad data from 1 November to 31 December 2024 showed no Iono Grad anomaly event occurred during the monitoring period. The maximum Iono Grad recorded was -111mm/km as shown in Figure 6. The Iono Grad was relatively smooth in November and December 2024 without any drastic changes.

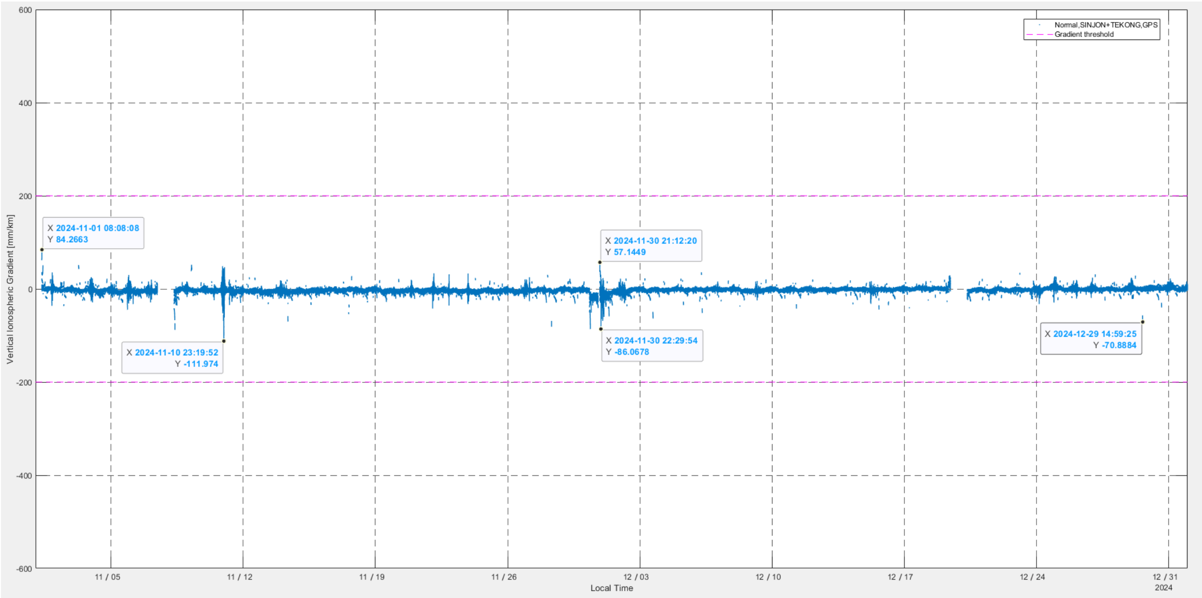

Figure 6-The Iono Grad Distribution for Pair 1 from Nov to Dec 2024

3.1.1.3 A contrast analysis was performed with the SiReNT data during the same period. The blue curve is the SINJON+TEKONG pair, the red curve is the SLYG+SNYU pair and the yellow curve is the SRPT+SSMK pair as shown in Figure 7. The profiles of these 3 curves were similar, though the maximum value for each pair did not occur on the same day.

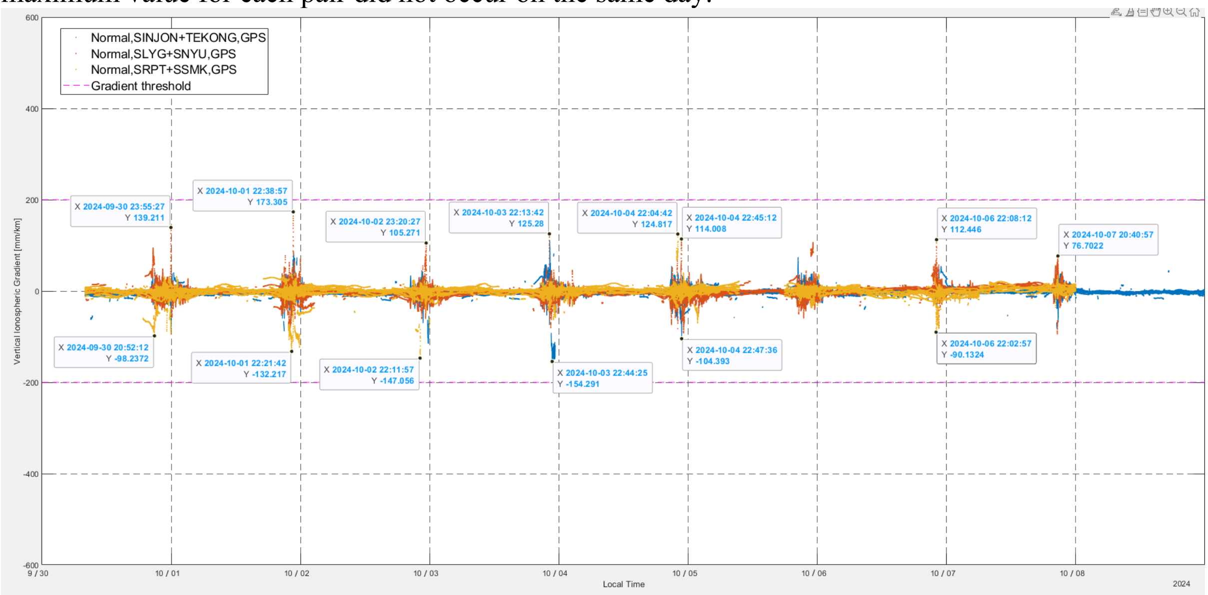

Figure 7-The Iono Grad Distribution Contrast with SLA in Oct 2024

3.1.2 <u>Pair 2: 02L_GP + 20L_LOC</u>

3.1.2.1 The baseline of Pair 2 is 4.28km. The Iono Grad data from 1 to 15 October 2024 indicated several Iono Grad anomaly events occurred during the monitoring period. The maximum recorded Iono Grad was 1619 mm/km as shown in Figure 8. The STD of Iono Grad was huge, and the dot race was discrete. The Iono Grad was disordered in October 2024, with many drastic changes. Similar analysis was conducted on Pair 1 during the same period, but no anomaly was found.

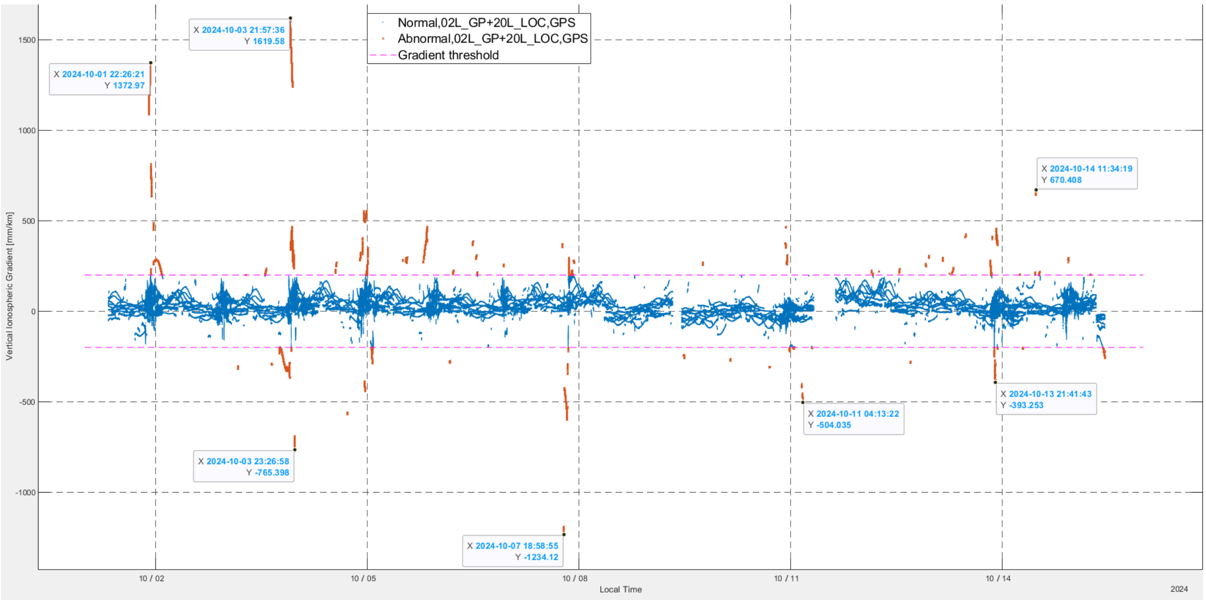

Figure 8-The Iono Grad Distribution for Pair 2 in Oct 2024

3.1.2.1.1 The maximum Iono Grad 1619 mm/km occurred on 3 October 2024 from 10:12 (UTC time) to 14:42 (UTC time), further analysis revealed that the ionospheric gradient anomaly on 3 October 2024 was possibly caused by the G04 GPS satellite.

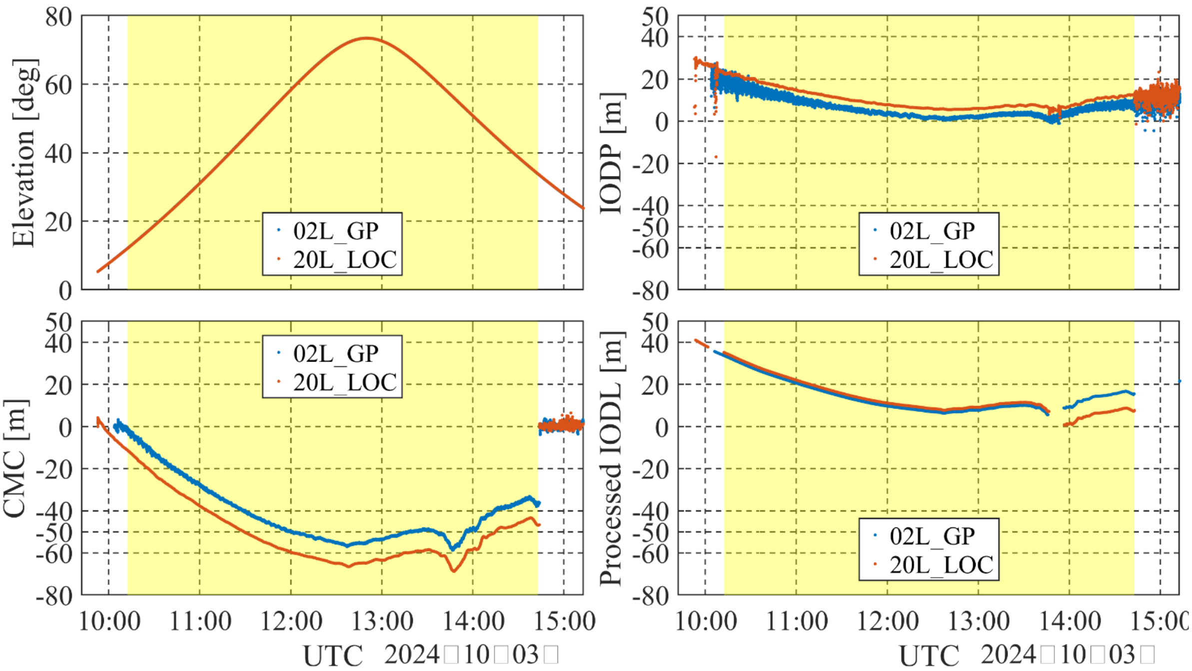

Figure 9-Key Parameters for G04

3.1.2.1.2 The yellow highlight indicates the period when the gradient value exceeded the 200mm/km threshold in Figure 9.

3.1.2.1.3 Observation shows that during abnormal periods, the satellite elevation angle remains high (15-70°).

3.1.2.1.4 Multi-source data analysis shows that although IODP/CMC/IODL all point to ionospheric disturbances, IODL results show that the delay difference between the two stations remained stable at the order of 1.5 meters before the data interruption occurred at 13:45:58 (UTC time) on 3 October 2024, resulting in a gradient of approximately -200 to -370 mm/km.

3.1.2.1.5 When the data was restored at 13:56:38 (UTC time) and continued until 14:42:50 (UTC time), with a duration of approximately 46.2 minutes, the software automatically estimated a significant deviation in the ionospheric delay. The delay difference between the two stations suddenly increased to over 8 meters, resulting in gradient values exceeding the upper limit of the existing model (1200 to 1600 mm/km).

3.1.2.1.6 This event does not reflect the true ionospheric gradient values and should be excluded as a false alarm.

3.1.2.1.7 After manual investigation, the anomaly of 1372.97 mm/km on 1 October 2024, -765.40 mm/km on 3 October 2024, and -1234.10 mm/km on 7 October 2024 were more than 600 mm/km which were taken as false alarms due to low-quality data or low cutoff angle of GPS.

3.1.2.2 The Iono Grad data of Pair 2 from 21 November to 30 November 2024 is shown in Figure 10, and that of data from 1 December to 25 December 2024 is shown in Figure 11. The calculated results were similar with some Iono Grad anomaly events occurred. The maximum Iono Grad in Figure 10 was -529 mm/km, and in Figure 11 was 671mm/km. The STD of Iono Grad was large and the dot race was very discrete. The Iono Grad was also disordered in November and December 2024, with many drastic changes. Similar analysis was conducted on Pair 1 during the same period, but no anomaly was found.

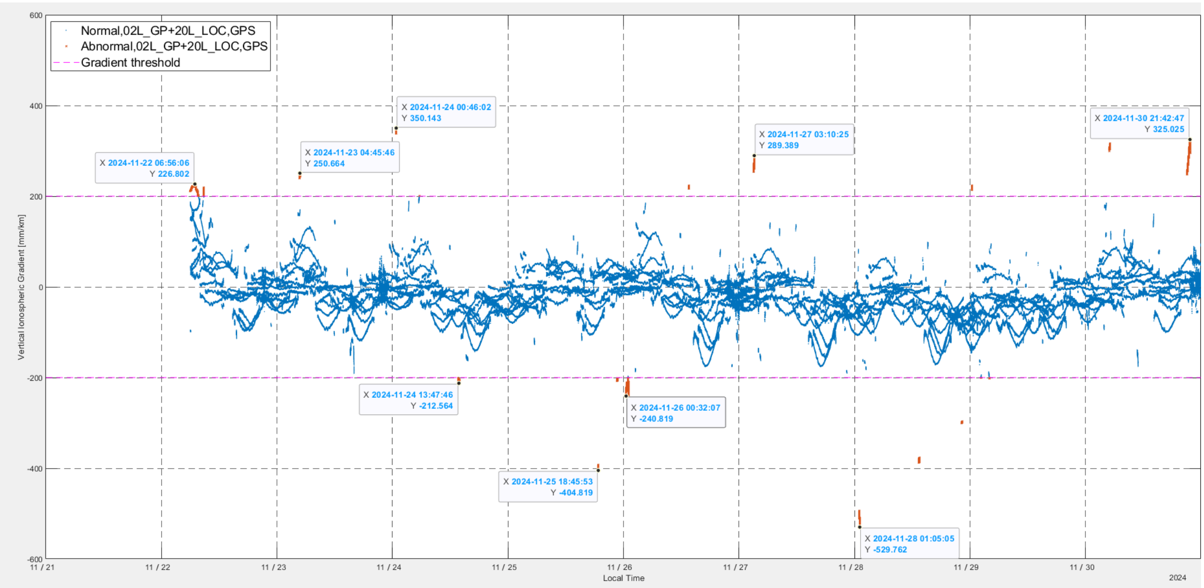

Figure 10-The Iono Grad Distribution for Pair 2 in Nov 2024

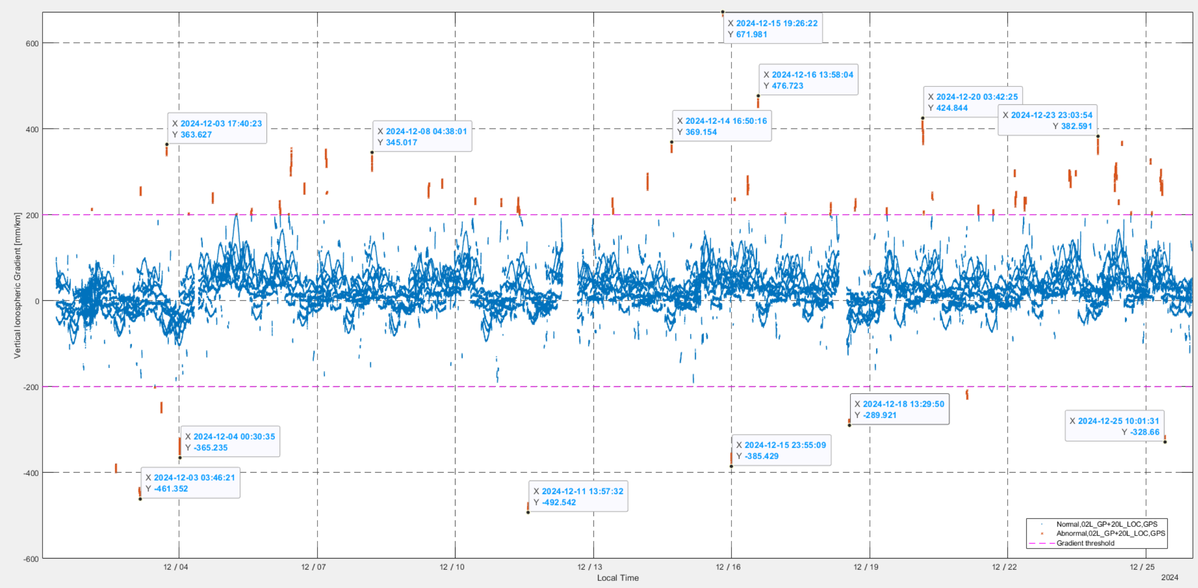

Figure 11-The Iono Grad Distribution for Pair 2 in Dec 2024

3.1.2.3 Therefore it was concluded that shorter baseline may cause bigger noise and resulted in high disordered Iono Grad and more false alarms.

3.2 Iono Grad Study conducted in 2025

3.2.1 <u>Pair 1: SINJON + TEKONG</u>

3.2.1.1 The Iono Grad data from 1 January to 31 March 2025 indicated that some Iono Grad anomaly events occurred during the monitoring period. The maximum Iono Grad was 261 mm/km on 30 March 2025 as shown in Figure 12. The Iono Grad from February to March 2025 was unstable, and large than those in January 2025. The cause of this significant change could be due to seasonal effects before and after the vernal equinox.

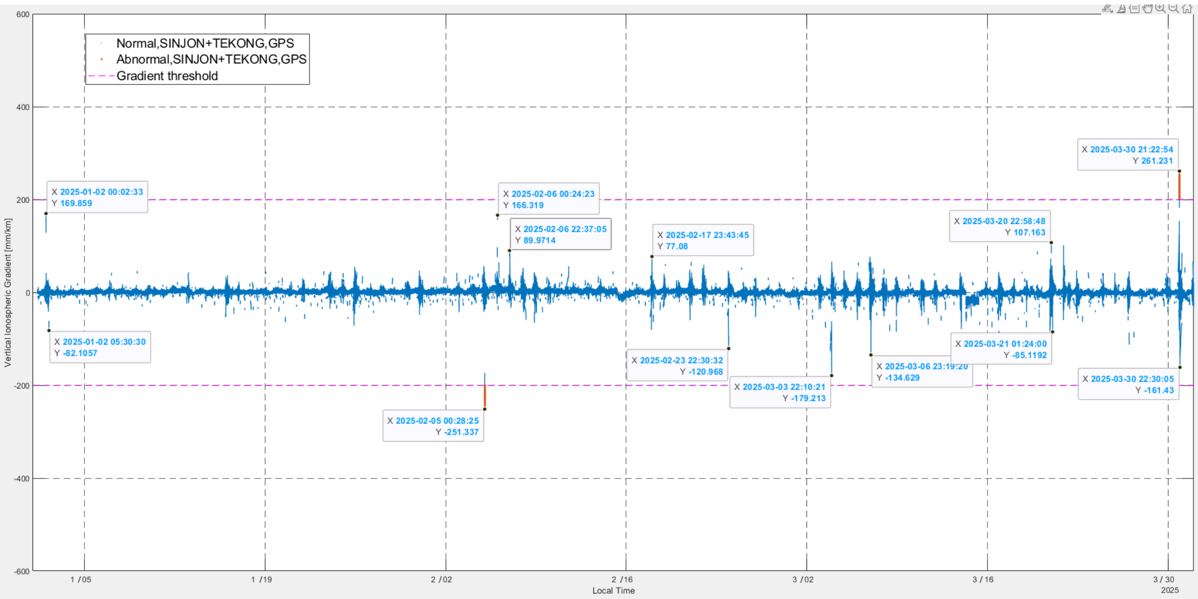

Figure 12-The Iono Grad Distribution for Pair 1 in Q1 2025

3.2.1.2 <u>Anomaly on 5 February 2025</u>

3.2.1.2.1 Further analysis revealed that the ionospheric gradient anomaly on 5 February 2025 was possibly caused by the G12 GPS satellite. Figure 13 shows the key parameters of G12, and the Iono Grad threshold was 150 mm/km, as shown in the yellow area in the Figure 13. The blue and red dotted lines represent the key parameters of SINJON and TEKONG respectively.

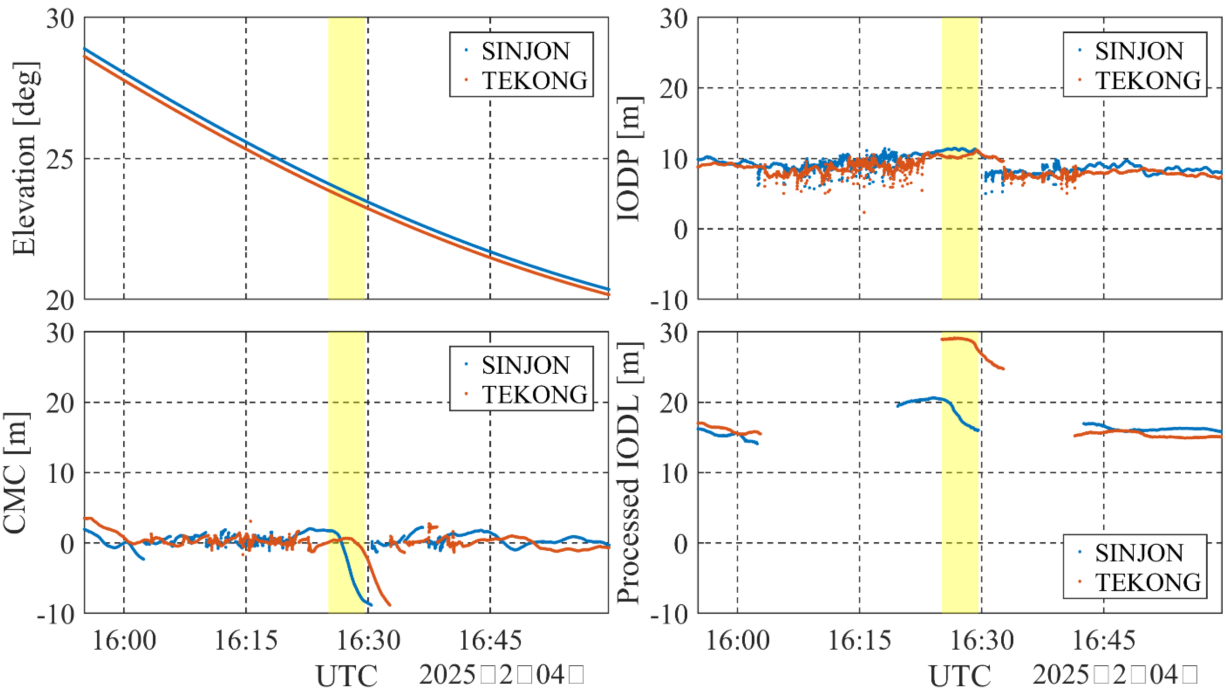

Figure 13-Key Parameters for G12

3.2.1.2.2 During the period when the Iono Grad exceeds 150 mm/km:

(a) the satellite elevation angle is about 21-24°;

(b) the IODP showed that there were significant rapid fluctuations before and after the abnormal period, and there was a clear trend separation for two stations in the period;

(c) from the CMC results, both stations experienced deep fading phenomena and showed significant time differences for 2-3 minutes;

(d) for IODL, the data before the abnormal period showed significant jitter and lock loss due to poor quality, resulting in the software removing a large number of "short arc segment" data. The remaining data arc segments were still relatively short, leading to excessive algorithm correction errors and causing ionospheric gradient anomalies.

3.2.1.2.3 In the anomaly event on 5 February 2025, the elevation angle of the satellite relatively high, there was a deviation in the IODP of the two stations, and a significant decrease in the CMC and IODL between the stations, indicating a rapid decrease in the total electron density of the ionosphere which can determine to be caused by EPB.

3.2.1.3 <u>Anomaly on 30 March 2025</u>

3.2.1.3.1 Further analysis revealed that the ionospheric gradient anomaly on 30 March 2025 was possibly caused by the G29 GPS satellite. Figure 14 shows the key parameters of G29, and the Iono Grad threshold was 200 mm/km, as shown in the yellow area in the Figure 14 The blue and red dotted lines represent the key parameters of SINJON and TEKONG respectively.

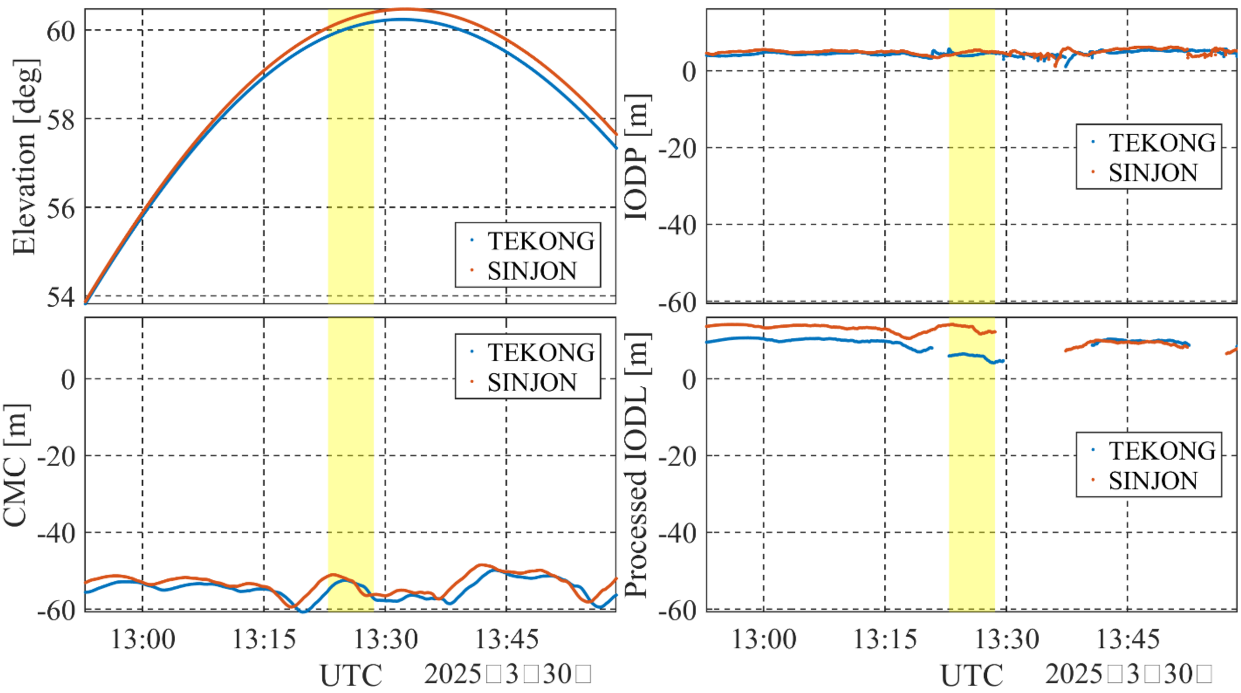

Figure 14-Key Parameters for G29

3.2.1.3.2 During the period when the Iono Grad exceeds 200 mm/km:

(a) the satellite elevation angle is about 60°;

(b) comparing the IODP of the two stations, the changes were relatively minimal. There was a noticeable jitter phenomenon after the abnormal period;

(c) it can be seen that during the abnormal period, both stations experienced fluctuations in CMC, and there was a significant time difference between the corresponding times of the two stations; and

(d) from the IODL perspective, the delay difference between the two stations was increasing during the abnormal period.

3.2.1.3.3 In the anomaly event on 30 March 2025, the elevation angle of the satellite was about 60 °, and the IODP trend of the two stations was gentle, while the CMC shows significant fluctuations and response time differences, indicating a rapid decrease in the total electron density of the ionosphere which can determine to be caused by EPB.

3.2.2 <u>Pair 2: 02L_LOC + 20L_LOC</u>

3.2.1.2 The pair 2 was 02L_LOC and 20L_LOC pair, with a baseline of 7.18km as shown in Figure 1. The Iono Grad data from 1 January to 31 March 2025 indicated several Iono Grad anomaly events occurred during the monitoring period. The maximum recorded Iono Grad was 582 mm/km as shown in Figure 15. The STD of Iono Grad was huge, and the dot race was discrete. The Iono Grad was disordered in Q1 2025, with many drastic changes. Similar analysis was conducted on Pair 1 during the same period, and with 2 anomaly events occurred on 2 February and 30 March 2025.

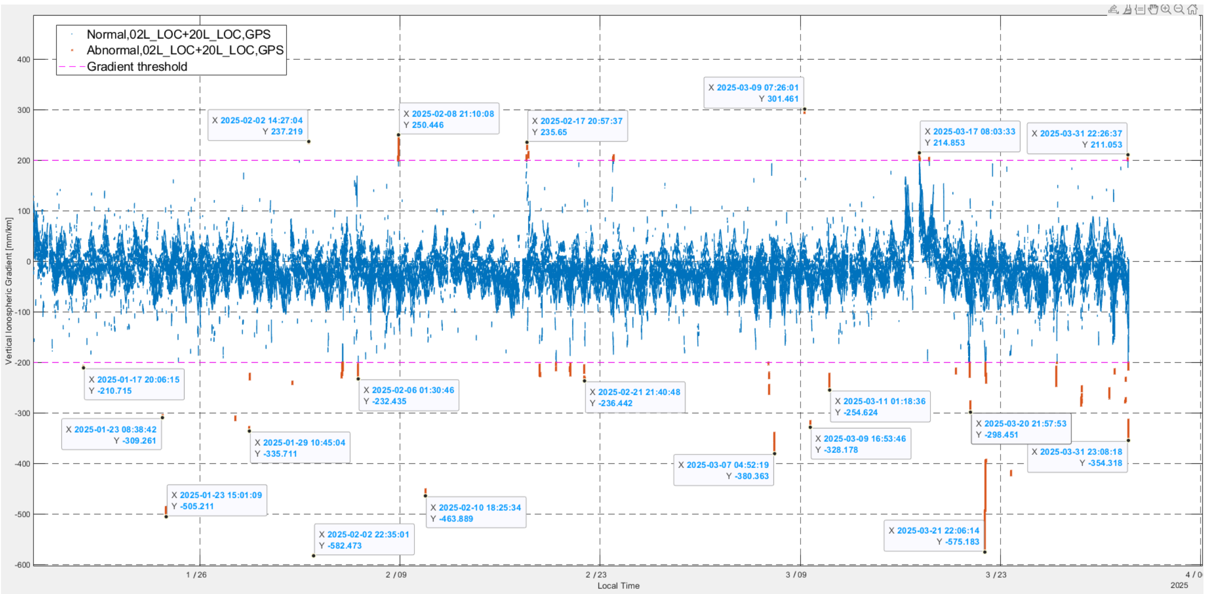

Figure 15-The Iono Grad Distribution for Pair 2 in Q1 2025

3.2.2.2 The result of Iono Grad for 02L_LOC+20L_LOC pair is better than that of 02L_GP+20L_LOC pair due to a longer baseline.

3.3 Conclusion on Analysis of Iono Grad in low latitude area during monitoring period

3.3.1 With a shorter baseline, the noises were amplified significantly causing in huge gradients and ultimately leading to false alarm events in the gradient values. If possible, the baseline distance between GNSS station pair should be longer than 10km and less than 50km. Ideally, a 30km baseline is preferred.

3.3.2 The Iono Grad of Pair 1 (SINJON + TEKONG) was very similar to SLA SiReNT data (SLYG + SNYU) which has a long baseline.

3.3.3 The Iono Grad anomaly events occurred more in February, March, September and October of the year.

3.3.4 The Iono Grad anomaly events occurred often between 20:00 local time (LT) and 02:00LT.

3.3.5 The maximum values recorded Iono Grad for a short baseline were much higher than a longer baseline, hence they should be investigated manually to exclude false alarms.

3.3.6 As the anomalies are generally caused by the EPB, it may be necessary to implement a dedicated scintillation receiver to record scintillation situations.

4. WAY FORWARD

4.1 CAAS will continue working on the impact of the Iono Grad and EPB as well as other research activities leading to safe implementation of GBAS in Singapore.

5. ACTION REQUIRED BY THE MEETING

5.1 The meeting is invited to:

a) note the Iono Grad analysis performed in Singapore;

b) note the importance of the Iono Grad research affecting availability and integrity of GBAS in low-latitude and equatorial regions;

c) note that Singapore will continue to study and share pertinent information, and welcome information shared by other States / Administrations;

d) supplement the ICAO GBAS guidance material and GBAS manual with the ionospheric monitoring station setup requirements; and

e) discuss any relevant matters as appropriate.

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