International Civil Aviation Organization

THE EIGHTH MEETING OF THE ASIA/PACIFIC GBAS/SBAS IMPLEMENTATION TASK FORCE (GBAS/SBAS ITF/8)

(Melbourne, Australia, 12-14 May 2026)

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

Continued Ionospheric Gradient Study for GBAS at Singapore Changi Airport

(Presented by Singapore)

SUMMARY

This paper presents an ionospheric gradient study from Aug 2024 to Mar 2026 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. Conclusion

1. INTRODUCTION

1.1 The Civil Aviation Authority of Singapore (CAAS) is planning to install GBAS with GAST-C capability to support CAT I GLS operations at Changi Airport. A key challenge in implementing GBAS in low-latitude and equatorial regions is the uncertainty associated with ionospheric effects on Global Navigation Satellite System (GNSS) signals. Phenomena such as solar storms and equatorial plasma bubbles (EPB) are characterised by steep gradients in ionospheric delay over relatively short distance (e.g. tens of kilometers). These ionospheric anomalies can induce significant position errors – on the order of tens of metres – which may adversely affect aircraft approach operations and degrade the availability and integrity of GBAS. To address these challenges, CAAS, in collaboration with its appointed safety consultant, Chengdu ATM Engineering Construction Co., Ltd (CDEC), has carried out studies to assess the impacts of ionospheric gradient (Iono Grad) on GBAS performance. This includes the deployment of GNSS ionospheric monitoring stations to collect and analyse relevant data.

1.2 During ITF/7, CAAS presented the findings of the ionospheric gradient study conducted at Changi Airport for the periods August to December 2024 and January to March 2025. To deepen understanding of ionospheric behaviour in Singapore and support future GBAS implementation, CAAS and CDEC have continued the study, extending it to cover the second half of 2025 and first quarter of 2026. This information paper presents the findings.

2. LAYOUT OF IONOSPHERIC GRADIENT MONITORING STATIONS

2.1 CAAS and CDEC deployed 4 temporary ionospheric monitoring stations in 2024 at three offshores islands (i.e. SINJON, UBIN and TEKONG) and at the 20L_LOC SGRS site at Changi Airport, as shown in Figure 1.

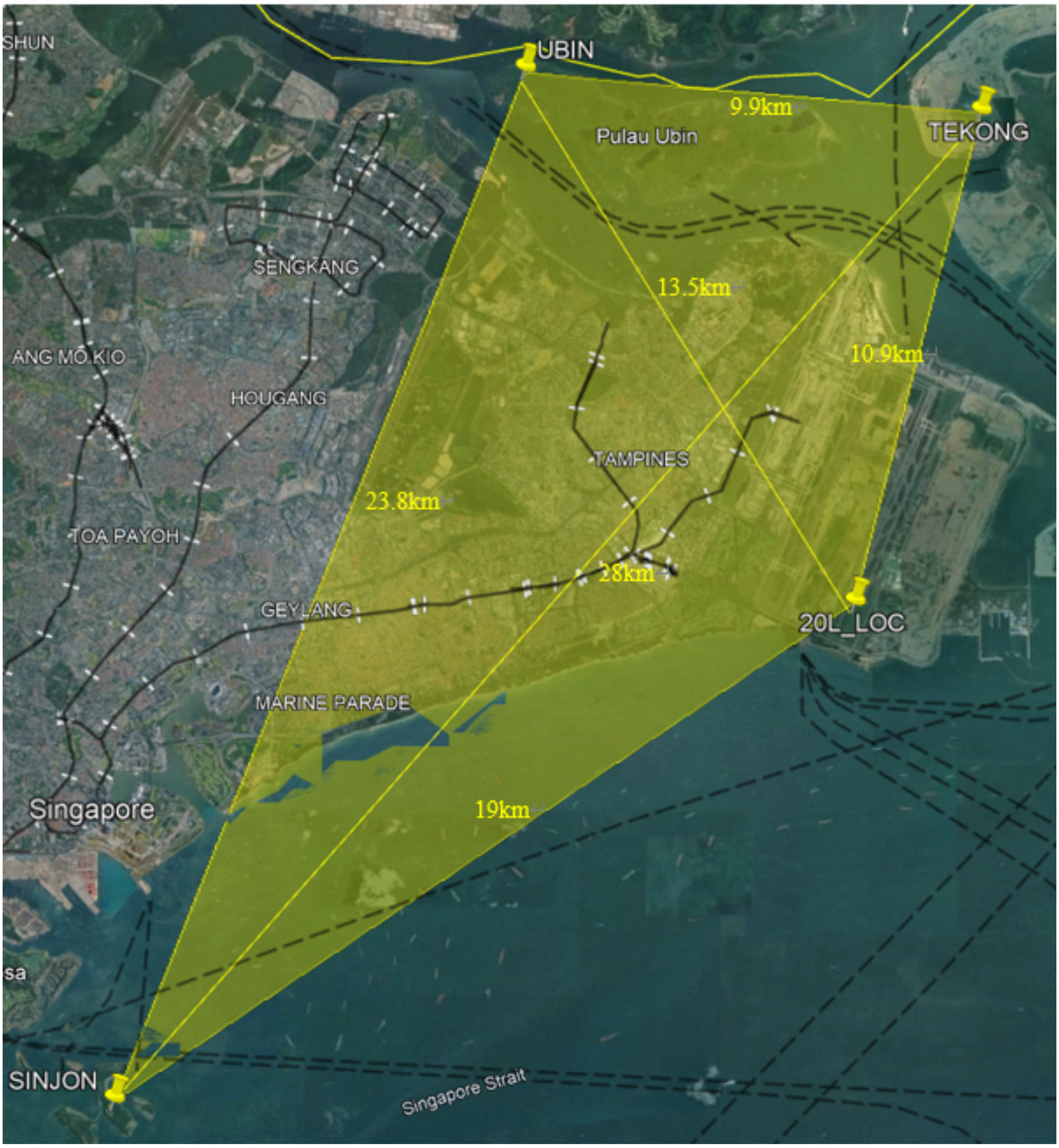

Figure 1- Layout of Temporary GNSS Stations

2.2 With this temporary setup, the minimum and maximum distances between stations are 9.9 km (TEKONG and UBIN) and 28 km (SINJON and TEKONG), respectively. With a shorter baseline, the noises were amplified significantly causing huge gradients and ultimately leading to false alarm events in the gradient values. The increased separation helps reduce the accumulation of errors in the monitoring results and improves overall monitoring accuracy, particularly as the station-pair method is used for this study. As such, the SINJON and TEKONG station pair is used for the Iono Grad analysis presented in this IP.

3. IONOSPHERIC GRADIENT STUDY

3.1 <u>Recap of Iono Grad Study Conducted in 2024 (presented at ITF/7)</u>

3.1.1 The Iono Grad observed in September and October 2024 exhibited notable instability, characterised by oscillating variation, as shown in Figure 2. This behaviour is likely attributed to seasonal effects associated with the period around autumnal equinox. The Iono Grad observed in August was lower than that in September and October, while values in November and December were comparatively small and stable, reflecting normal conditions.

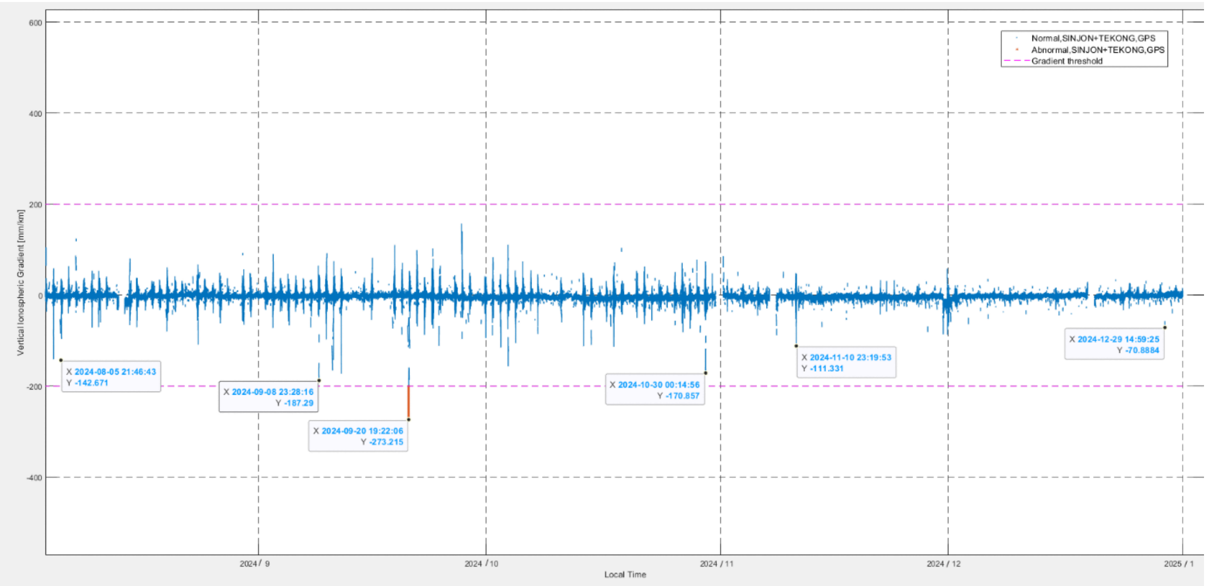

Figure 2-The Iono Grad Distribution from Aug to Dec 2024

3.1.2 On 20 September 2024, the Iono Grad exceeded 200 mm/km for 24 minutes and 38 seconds, and a maximum value of -273.215 mm/km recorded at 19:22:06 local time. This event was attributed to an equatorial plasma.

3.2 <u>Recap of Iono Grad Study Conducted in the First Half of 2025 (presented at ITF/7)</u>

3.2.1 The Iono Grad in February, March and April 2025 exhibited notable instability, characterised oscillating variations, as shown in Figure 3. This behaviour is likely due to seasonal effects associated with the vernal equinox. The Iono Grad observed in January was smaller than in February, while values in May and June were comparatively small and stable, reflecting normal conditions.

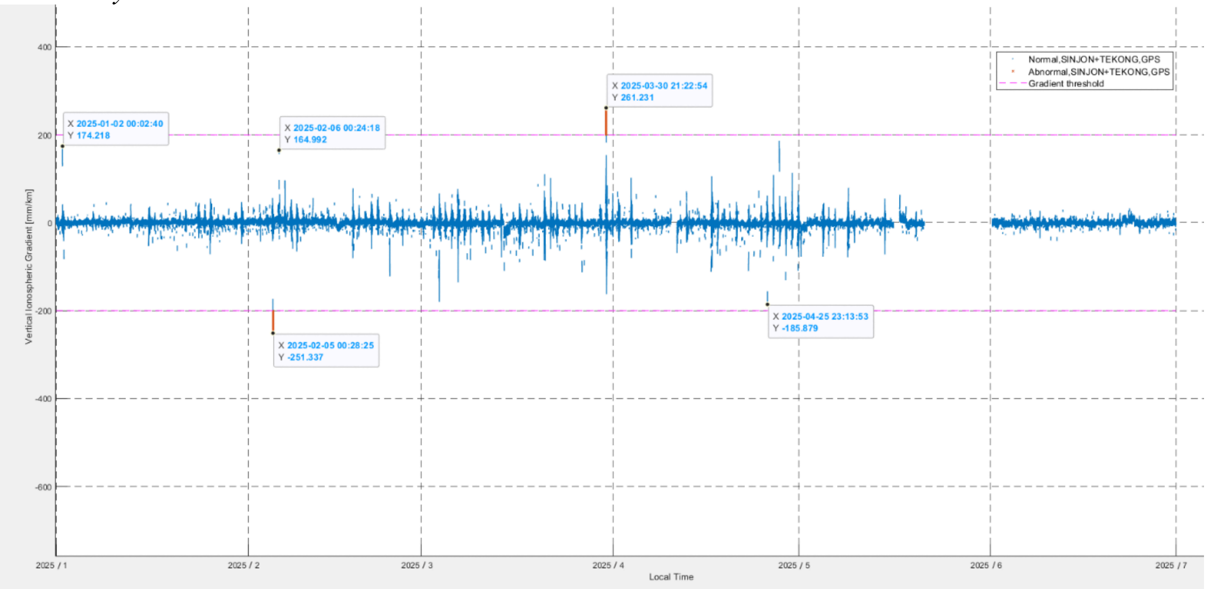

Figure 3-The Iono Grad Distribution in the First Half of 2025

3.2.2 On 5 February 2025, the Iono Grad exceeded 200 mm/km for 2 minutes and 13 seconds, with a maximum value of -251.337 mm/km recorded at 00:28:25 local time. This event was attributed to EPB.

3.2.3 On 30 March 2025, the Iono Grad exceeded 200 mm/km for 3 minutes and 11 seconds, with a maximum value of 261.231 mm/km recorded at 21:22:54 local time. This event was attributed to EPB.

3.3 Iono Grad Study Conducted in the Second Half of 2025

3.3.1 Due to limited GNSS data availability, the Iono Grad from 22 August to 3 September and from 1 to 31 October 2025 was unavailable. Nevertheless, the available data shows that Iono Grad values in September were substantially higher than in other months. The Iono Grad in July, August, November and December remained small and stable, as shown in Figure 4.

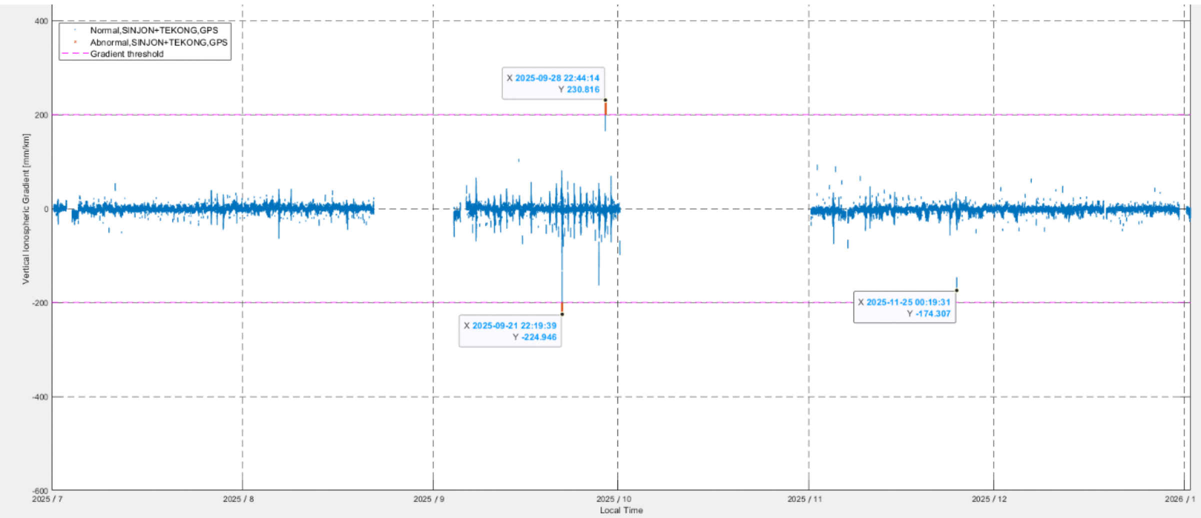

Figure 4-The Iono Grad Distribution in the Second Half of 2025

3.3.2 <u>Anomaly on 21 September 2025</u>

3.3.2.1 On 21 September 2025, the Iono Grad exceeded 200 mm/km for 46 seconds, with a maximum value of -224.946 mm/km recorded at 22:19:39 local time.

3.3.2.2 Further analysis indicates that the Iono Grad anomaly on 21 September 2025 was likely caused by the G04 GPS satellite. Figure 5 shows the key parameters of G04, with the Iono Grad threshold of 200 mm/km indicated in the yellow area. The blue and red dotted lines represent the key parameters for SINJON and TEKONG stations, respectively.

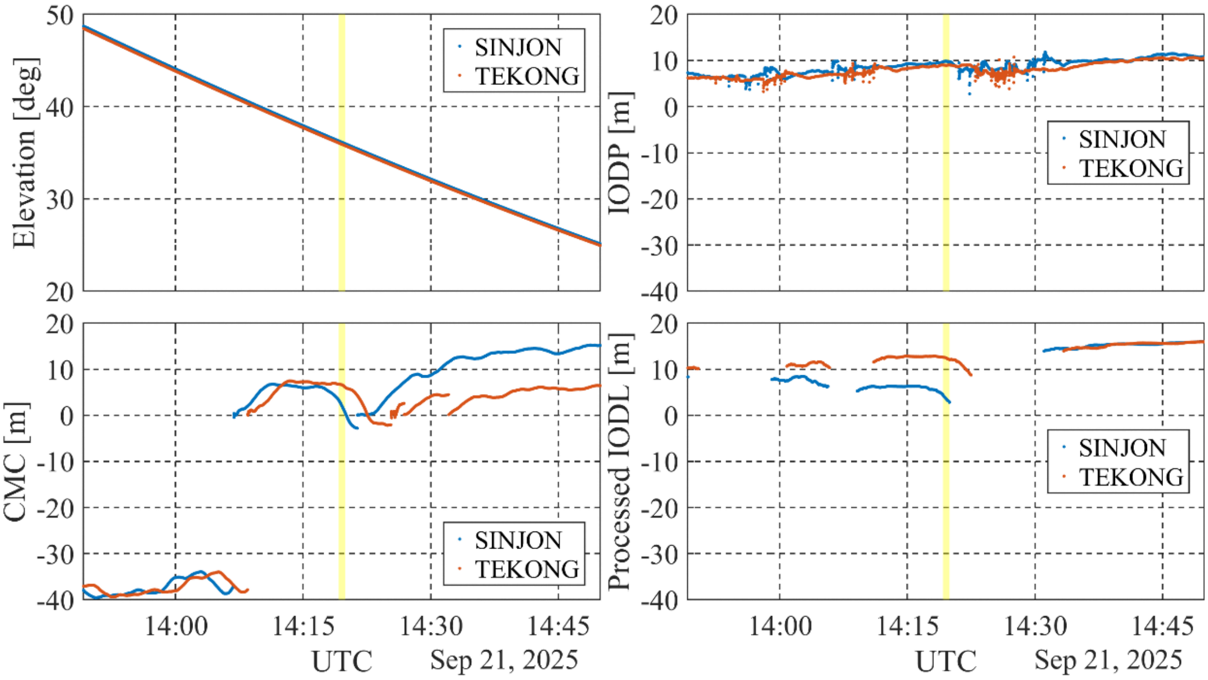

Figure 5-Key Parameters for G04

3.3.2.3 During the period when the Iono Grad exceeded 200 mm/km:

(a) the GPS satellite elevation angle ranged between 35.6° and 36°;

(b) the difference for ionospheric delay from pseudo-range (IODP) ranged between 0.7 m and 1.0 m;

(c) the difference for ionospheric delay from code-minus-carrier for GPS L1 (CMC) ranged between 1.735 m and 2.740 m, with a significant time offset observed between the corresponding times of the two stations; and

(d) the difference for ionospheric delay from carrier-phase linear combination (IODL) ranged between 1.735 m and 2.740 m.

3.3.2.4 Figure 5 clearly shows that both stations' CMC time-series exhibit fading and recovery patterns with similar amplitudes but different timings. The consistent fading amplitude suggests a stable ionospheric bubble structure, while the timing differences indicate significant drift motion of the bubbles. Therefore, this anomaly can be attributed to EPB.

3.3.3 <u>Anomaly on 28 September 2025</u>

3.3.3.1 On 28 September, the Iono Grad exceeded 200 mm/km for 4 minutes and 37 seconds, with a maximum value of 230.816 mm/km recorded at 22:44:14 local time.

3.3.3.2 Further analysis indicates that the Iono Grad anomaly on 28 September 2025 was likely caused by the G09 GPS satellite. Figure 6 shows the key parameters of G09, and the Iono Grad threshold of 200 mm/km indicated in the yellow area. The blue and red dotted lines represent the key parameters for SINJON and TEKONG stations, respectively.

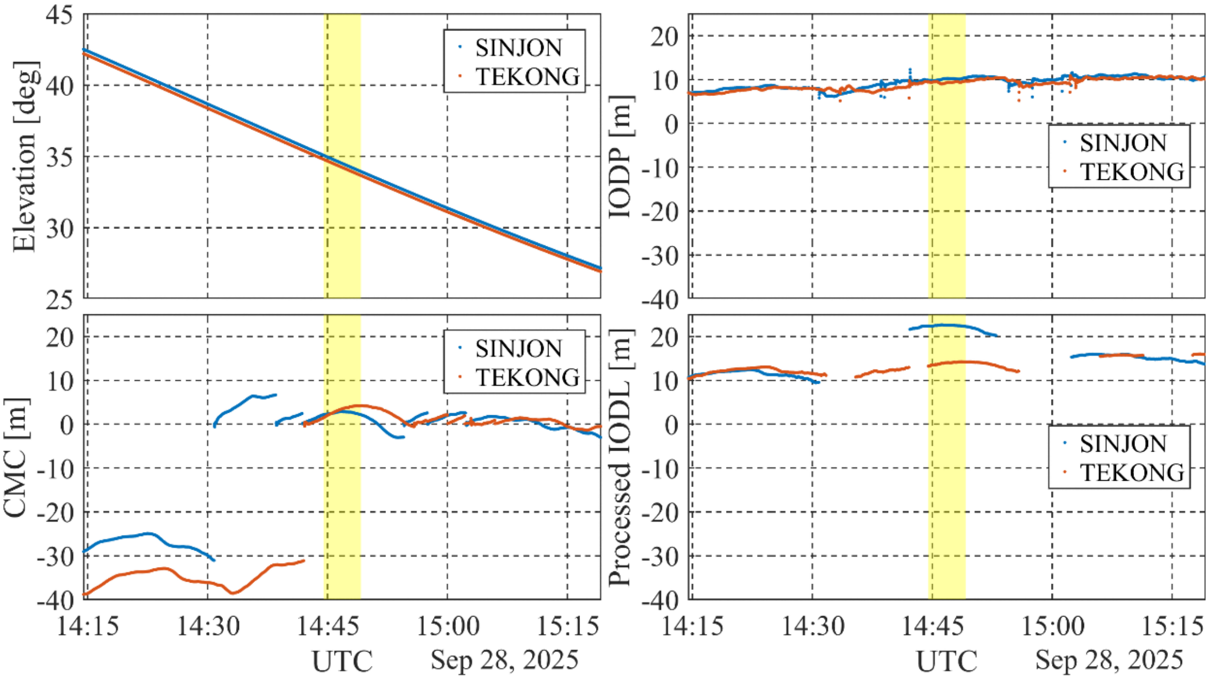

Figure 6-Key Parameters for G09

3.3.3.3 During the period when the Iono Grad exceeded 200 mm/km:

(a) the satellite elevation angle ranged between 34° and 35°;

(b) the ionospheric delay difference for IODP ranged between 0.278 m and 1.099 m;

(c) the ionospheric delay difference for CMC ranged between 0 m and 1.0143 m; and

(d) the ionospheric delay difference for IODL ranged between 8.0678 m and 9.1675 m.

3.3.3.4 Figure 6 shows that prior to the anomaly, both stations exhibited fading and recovery phenomena with similar amplitudes but different timings. Notably, the SINJON station's CMC displayed multiple jumps, with a maximum fading occurring earlier than at TEKONG station. The absence of jumps at TEKONG station suggests EPB drift motion, with disturbance level gradually stabilising.

3.4 <u>Iono Grad Study Conducted for first quarter of 2026</u>

3.4.1 GPS data was available up to 19 March 2026. The Iono Grad in March 2026 exhibited notable instability, characterised by oscillating variations, likely attributable to seasonal effect around the vernal equinox. The Iono Grad values in January and February were smaller than those observed in March, as shown in Figure 7.

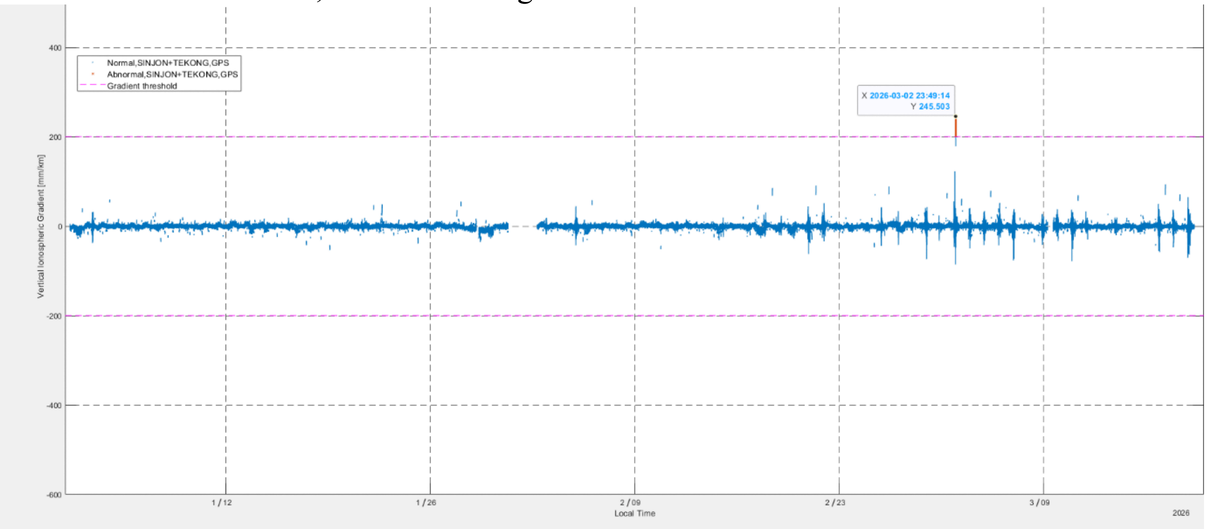

Figure 7-The Iono Grad Distribution in Q1 of 2026

3.4.2 <u>Anomaly on 2 March 2026</u>

3.4.2.1 On 2 March 2026, the Iono Grad exceeded 200 mm/km for 7 minutes and 53 seconds, with a maximum value of 245.503 mm/km recorded at 23:49:14 local time.

3.4.2.2 Further analysis indicates that the ionospheric gradient anomaly on 2 March 2026 was likely caused by the G28 GPS satellite. Figure 8 shows the key parameters of G28, and the Iono Grad threshold of 200 mm/km indicated in the yellow area. The blue and red dotted lines represent the key parameters for SINJON and TEKONG stations, respectively.

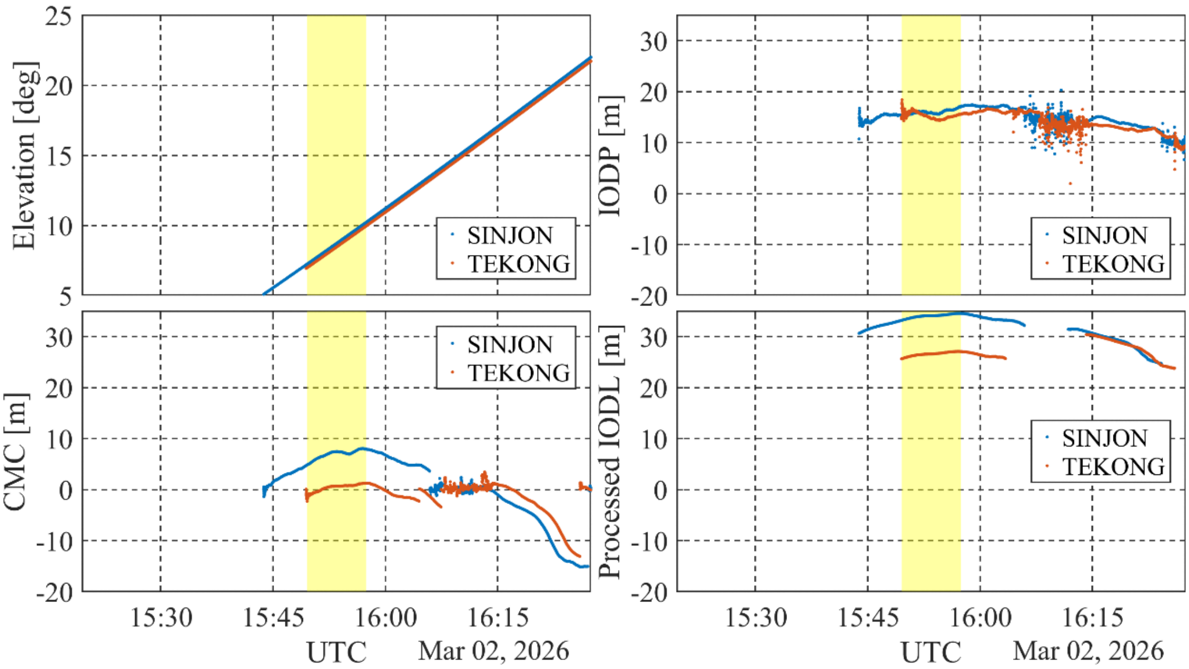

Figure 6-Key Parameters for G28

3.4.2.3 During the period when the Iono Grad exceeded 200 mm/km:

(a) the satellite elevation angle ranged between 7° and 10°;

(b) the ionospheric delay difference for IODP ranged between 0 m and 1.549 m;

(c) the ionospheric delay difference for CMC ranged between 3.0875 m and 3.424 m; and

(d) the ionospheric delay difference for IODL ranged between 7.4244 m and 7.4689 m.

3.4.2.4 This event occurred when G28 GPS satellite had just entered TEKONG station's field of view, with the signal not yet stabilised. Although the overall CMC trends at both stations were consistent, their change characteristics did not conform to typical ionospheric gradient model or EPB models. Given the satellite's low elevation angle, this event is not attributable to ionospheric disturbance. The ionospheric monitoring gradient result of 246.3921 mm/km is not credible, and this suspected anomaly should be excluded.

4. CONCLUSION

4.1 The Iono Grad anomaly events predominantly occurred in February, March, September and October.

4.2 These Iono Grad anomaly events frequently occurred between 20:00 and 02:00 local time.

4.3 The Iono Grad anomalies in September and October in 2025 decreased compared to 2024, while those in February and March 2026 decreased compared to 2025. This indicates that the solar maximum period has passed, with ionospheric activity gradually subsiding.

4.4 The Iono Grad anomalies exceeding 24 minutes were observed during solar maximum years, whereas duration remained under 10 minutes during solar minimum years at Changi Airport.

4.5 It is recommended to deploy multiple ionospheric monitoring stations to collect and analyse the variations in ionospheric gradient and scintillation effects, particularly in low latitude areas during GBAS implementation.

5. ACTION REQUIRED BY THE MEETING

5.1 The meeting is invited to:

a) note the information contained in this paper; and

b) discuss any relevant matters as appropriate.

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