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Construction of nominal ionospheric gradient using satellite pair based on GNSS CORS observation in Indonesia

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Abstract

Ground-Based Augmentation System (GBAS) is a GNSS augmentation system that meets International Civil Aviation Organization (ICAO) requirements to support precision approach and landing. GBAS is based on local differential GNSS technique with reference stations located around an airport to provide necessary integrity and accuracy. The performance of the GBAS system can be affected by gradient in the ionospheric delay between aircraft and reference stations. A nominal ionospheric gradient, which is bounded by a conservative error bound, is represented by a parameter σ_{vig}. The parameter σ_{vig} is commonly determined using station pair to GNSS Continuous Operating Reference Station (CORS) data. The station-pair method is susceptible to doubling of the estimation error of receiver inter-frequency bias (IFB) and is not suitable with the CORS conditions in Indonesia. We propose a satellite-pair method that is found to be more suitable for the CORS network over Indonesia which is centered in Java and Sumatra islands. An overall value of σ_{vig} (5.21 mm/km) was obtained using this method along with preliminary results of a comparison of σ_{vig} from Java and Sumatra islands.

Keywords: Ground-Based Augmentation System (GBAS), Ionosphere, Nominal ionospheric gradient

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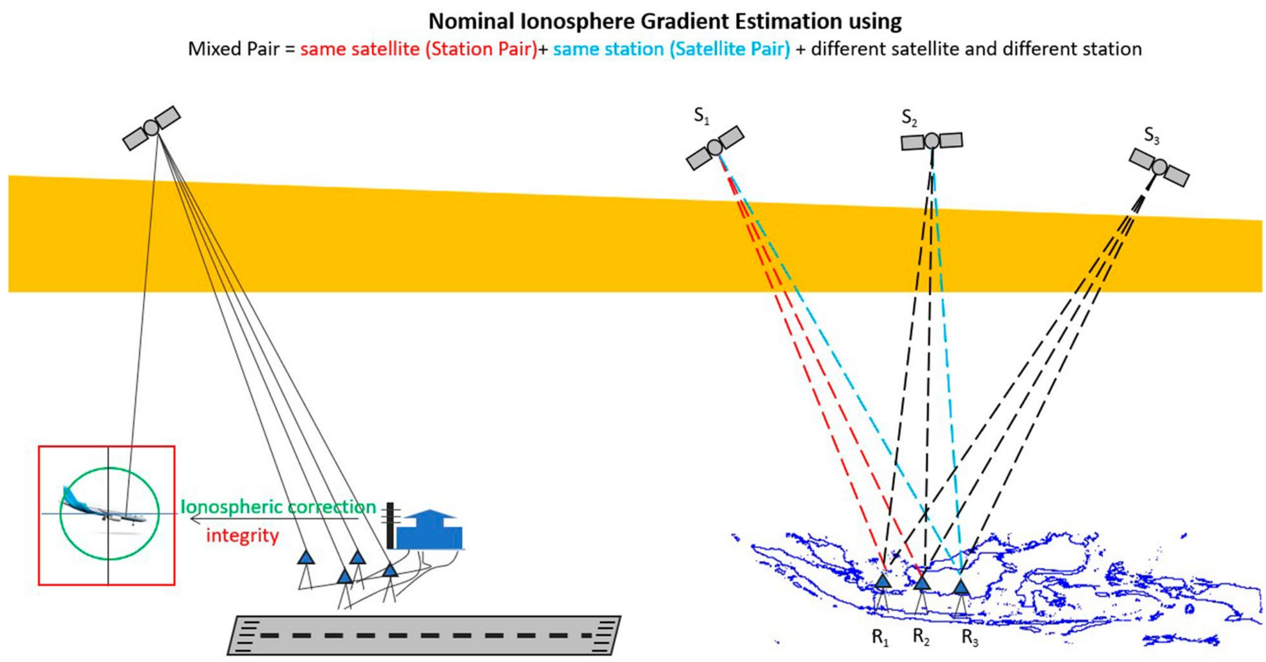
Graphical Abstract



Introduction

The use of Global Navigation Satellite System (GNSS) for positioning and navigation has begun to be accepted by various modes of transportation. GNSS needs an augmentation to meet performance requirements for air navigation to maintain passenger safety (International Civil Aviation Organization (ICAO) 2016). Ground-Based Augmentation System (GBAS) is a system that augments GNSS to support precision approach and landing of aircraft.

GBAS is based on the range-domain differential GNSS technique to correct pseudorange errors at the user by measurements of reference stations of which precise positions are known. When a GNSS signal propagates through the ionosphere, the propagation is delayed and this delay results in pseudorange error. The reference stations can estimate the error induced by the ionospheric delay together with other errors including tropospheric delay and satellite clock and ephemeris errors. The estimated errors are transmitted to users in the form of pseudorange correction. GBAS adds integrity information along with the corrections to assure that the level of integrity required for navigation systems on aircraft is met.

Spatial variations of the ionospheric delay or ionospheric gradient may degrade GBAS performance. Ionospheric gradient causes a difference in the value of the ionospheric delay between the reference station providing the correction and the user receiving the correction so that the error in the user's position may increase. Ionospheric gradients that can interfere with GBAS performance are divided into nominal and anomalous. The nominal ionospheric gradient arises because the state of the ionosphere is constantly changing. Therefore, some difference in ionospheric delay between the reference station and the user always exists. The anomalous ionospheric gradient appears relatively infrequently and it is due to space weather activity which results in a very large gradient value far exceeding its normal value.

The nominal value for Contiguous United States (CONUS) is about 4 mm/km (Lee et al. 2006) and the anomalous ionospheric gradient is more than 400 mm/km (Pullen et al. 2009). Although small compared to anomalous gradient, the magnitude of nominal gradient needs to be determined for each region. In GBAS, the nominal ionospheric gradient is characterized by the σ_{vig} parameter which is a conservative bound of the spatial gradient in the vertical ionospheric delay.

Research on GBAS has largely been carried out in the mid-latitudes. But more recently, research on GBAS in low latitudes is being intensively carried out. GBAS implementation in Indonesia is still in the initial study stage of GBAS Category I (CAT I). GBAS CAT I is a GBAS that have the ability comparable to instrument landing system (ILS) CAT I which provides guidance information from the coverage limit of the ILS to the point at which the localizer course line intersects the ILS glide path at a height of 60 m (200 ft) or less above the horizontal plane containing the threshold (International Civil Aviation Organization (ICAO) 2016). To meet the requirements for the application of GBAS Category I, it is necessary to determine the nominal ionospheric gradient value (σ_{vig}).

The parameter σ_{vig} for CONUS was obtained by using ionosphere vertical delays data from pairs of GNSS CORS stations that are differenced (Lee et al. 2006). They used the ionospheric delay data obtained from the reference receivers of the Wide-Area Augmentation System (WAAS) which is an implementation of Satellite-Based Augmentation System (SBAS) in United States. The use of continuously operated reference stations (CORS) data for σ_{vig} was carried out in Germany (Mayer et al. 2009) and Japan (Yoshihara et al. 2010). The analysis of nominal ionospheric gradient in Japan was made for the east–west and north–south components of the gradients separately. The study concluded that there is a difference in the north–south direction with a larger southern ionospheric gradient as it is closer to low latitudes.

The distance between CORS stations is closer than the distance between SBAS reference stations so that it would better represent the gradient at a shorter distance relevant to GBAS. One of the software that can be used to calculate the ionospheric gradient using CORS data is the Long-Term Ionospheric Anomaly Monitoring (LTIAM) tool (Jung and Lee 2012; Lee et al. 2012).

Estimation of the ionospheric gradient in India has been carried out by using the Indian SBAS (GPS-Aided GEO Augmented Navigation: GAGAN) data (Ammana and Achanta 2016). India is located in the low-latitude region similar to Indonesia. The distance between the Indian SBAS reference stations is so far that the calculation of the ionospheric gradient is carried out using the temporal decorrelation method. The temporal decorrelation method is useful because errors in the ionospheric delay estimates related to the inter-frequency bias (IFB) estimation are canceled out. However, the results include the effects of relative motion between the gradient and the GNSS satellite. Research on ionospheric gradients in China was carried out using CORS data (Wang et al. 2017). The ionospheric delay is obtained by slightly modifying the LTIAM algorithm by placing the cycle slip detection earlier.

Another sigma value search was conducted in Bangkok, Thailand using the time-step method on single-frequency GPS (Budtho et al. 2020). The method is appropriate for Thailand's condition in which most reference station distances are more than 20 km. One of the weaknesses of the time-step method is that the gradient obtained is the result of the difference between two ionospheric pierce points (IPPs) with a north–south direction. The time-step method also gives rise to another source of error, namely temporal decorrelation errors. The drawback lies in the assumption of using the ionosphere at two different times to approximate the spatial differences. The ionospheric gradient as a result of the time-step method is a combination of temporal and spatial variations. Therefore, it is very difficult to separate the effects of temporal variation (Datta-Barua et al. 2002; Lee et al. 2006). In the case of Indonesia where the number of CORS is getting relatively denser (more than 15 km, though the distances may change over time), other techniques such as station pair could be applied. In addition, an appropriate technique may be different for different magnetic latitudes. Bangkok is located at 5° North of the geomagnetic equator which is in the equatorial trough, while most of CORS in Indonesia is installed at 20° South of the geomagnetic equator which is around the equatorial ionization crest.

Indonesia consists of many islands that are separated by the ocean where it is difficult to establish well distributed GNSS CORS network. Indonesia's CORS network at present consists of 280 CORS stations and is still not yet well distributed and mostly located on Java Island. The second center of the distribution is on Sumatra Island which is still near Java Island. Such distribution makes the station-pair methods could not be optimally applied in Indonesia. Additionally, Indonesia is located at geomagnetic low-latitude region which has highly inhomogeneous ionosphere which makes ionospheric delay estimation more challenging. This study investigates different methods to estimate σ_{vig} suitable for the less dense CORS networks. Determination of a suitable method will allow for further analysis of the difference in sigma values in the two CORS GNSS distribution centers.

Data and methodology

The location of CORS stations in Indonesia was mostly concentrated on the island of Java until 2018. Distributions of the CORS stations started to spread evenly across Sumatra Island by 2019. The distribution and corresponding IPPs at an altitude of 350 km are shown in Fig. 1. Data availability on 1 January 2009 was around 18 stations and on 1 January 2019, it had increased to 182 stations. We choose around 1 January for this study because outside of equatorial plasma bubbles and scintillation season in this region which are March and September equinoxes.

We processed data from first quiet day on January every year from 2012 to 2019. The processed data were obtained during quiet ionospheric condition, namely when the maximum Kp index is less than three. Kp index is an index that describes the geomagnetic activity in the earth's atmosphere. The data for 2009, 2010,

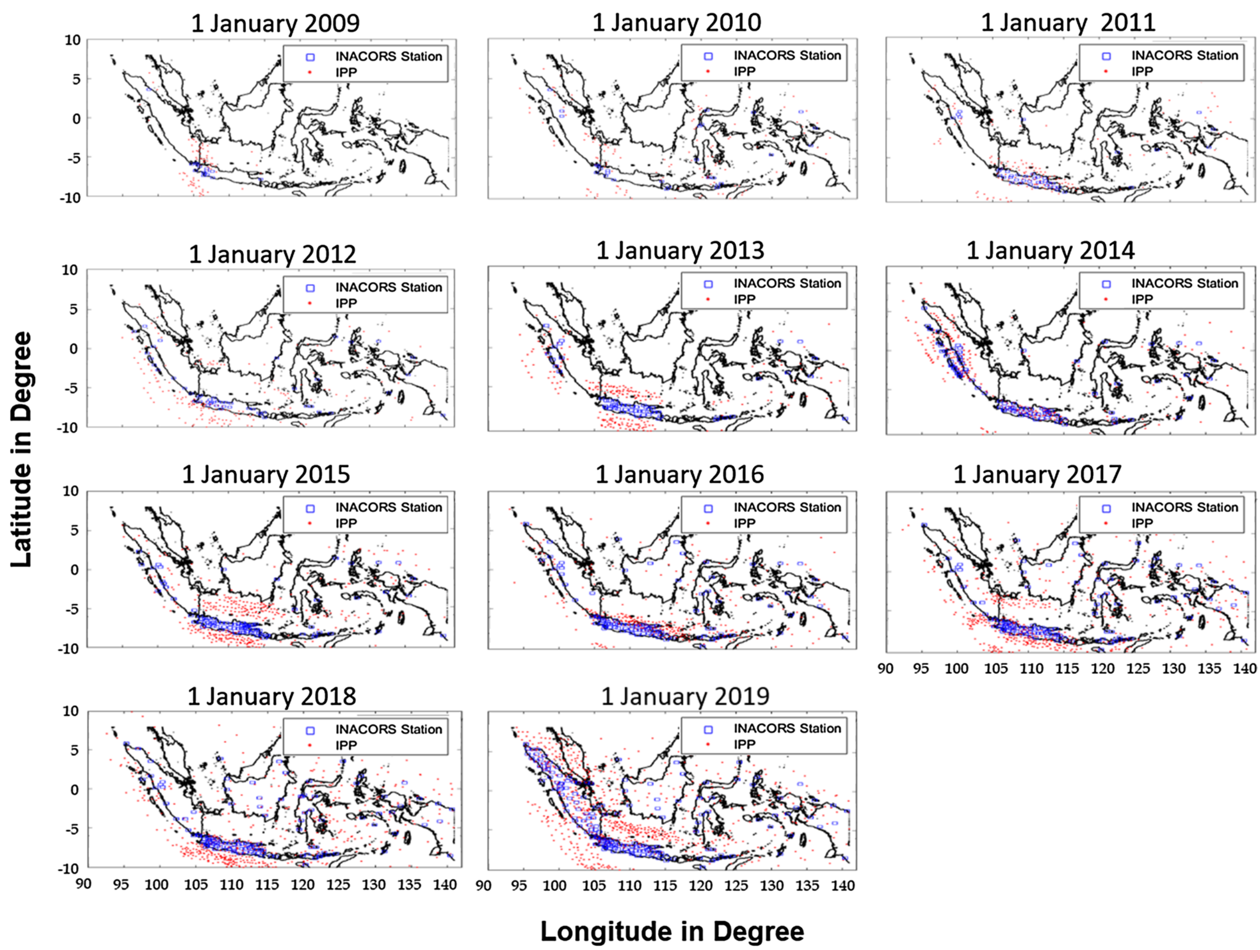


Fig. 1 Distribution of CORS stations (blue) from 2009 to 2019 and their IPPs with an elevation angle of 30° (red) at 0 UT or 7 local time on 1 January in each year

and 2011 were not processed because the number of data is not adequate for statistical analysis.

The distribution of CORS stations in Indonesia is becoming denser year by year. The data on 1 January 2019 are used to analyze spatial ionospheric gradient because it is dense enough for the analysis. Spatial gradient analysis was carried out for the north–south or west–east directions with the CORS stations on Sumatra and Java Islands, respectively (Fig. 2).

CORS data were processed using the LTIAM tool to calculate the slant ionospheric delay at the L1 frequency (1.57542 GHz) along the satellite–receiver path. The slant ionospheric delays calculated by using pseudorange measurements at two frequencies include IFB associated with frequency-dependent hardware delays of satellite and receiver circuits. The LTIAM tool requires IONEX data containing global ionospheric delay data calculated using the global GNSS network of the International GNSS Service (IGS). The IONEX data also contain the estimated satellite IFB (IFB_s) data that can be used to estimate the ionospheric delay values.

The slant ionospheric delay (SID) for each satellite observed by each station is obtained by LTIAM software. The SID observation (SID) generated from LTIAM is the result of a combination of carrier phase data that contains ambiguity (N) and has been leveled by pseudorange data. The measurement noise (w) will be included in the estimation as well. Although LTIAM produces reliable SID by estimating receiver IFB (IFB_r) at high latitudes geomagnetic, it will be difficult to obtain real *SID* (SID_real) that are completely free of real satellite IFB (IFB_sr) and real IFB (IFB_rr) at low-latitude:

$$\mathrm{SID} = \mathrm{SID\_real} + \mathrm{IFB\_sr} + \mathrm{IFB\_rr} + N + w. \quad (1)$$

LTIAM estimates a single receiver IFB using a simpler and faster method developed by (Ma and Maruyama

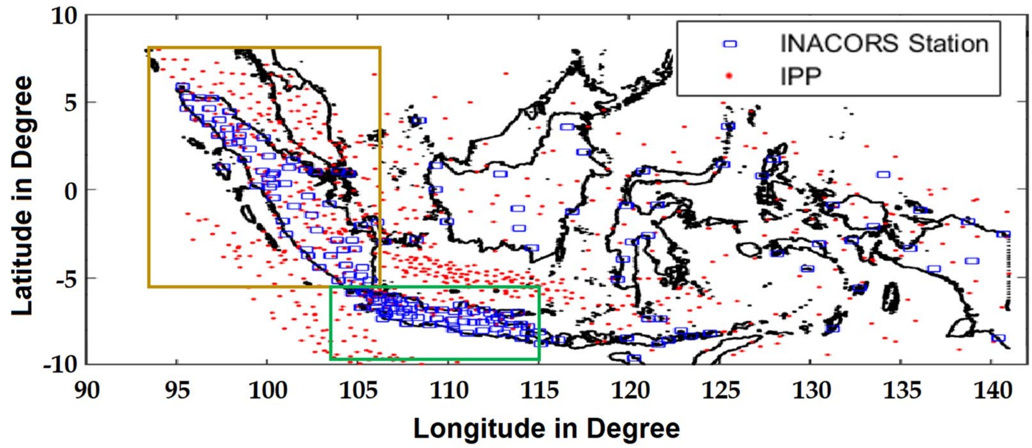


Fig. 2 Distribution of CORS station (blue) and their IPP (red) on January 1, 2019, for spatial analysis. Analysis of the Northwest–Southeast region using CORS data in Sumatra and Java

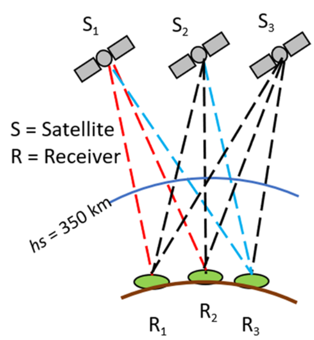


Fig. 3 Mixed-pair method (all colors) is a combination of station-pair method (red dashed lines), and satellite pair (blue dashed lines). hs is the height at which IPP is assumed (the figure is conceptual and not to scale)

2003). After IFBs are removed, the vertical ionospheric delay (VID) at a height of 350 km is then calculated by dividing SID by the slant factor (SF) as follows:

$$\mathrm{VID} = \mathrm{SID}/\mathrm{SF}, \tag{2}$$

$$\mathrm{SF(el)} = \frac{1}{\sqrt{1-\left(\frac{R\cos(\mathrm{el})}{R+\mathrm{hs}}\right)^2}}, \tag{3}$$

where el is the satellite elevation angle, R is the earth radius, and hs = 350 km is the altitude where the IPPs are assumed. The data obtained are filtered to exclude unsuccessful estimates of VID which is indicated by VID < 0. Vertical ionospheric gradient (VIG) is estimated by dividing the difference (dI) between a pair of vertical ionospheric delays (VID_1, VID_2) by the distance (d_{12}) between the IPPs of each ionospheric delay:

$$\mathrm{VIG} = \mathrm{dI}/d_{12} = (\mathrm{VID}_1 - \mathrm{VID}_2)/d_{12}. \tag{4}$$

In this study, we compare the results of σ_{vig} estimated by station pair, satellite pair, and mixed pair (Fig. 3). First is the station-pair method which takes differences between ionospheric delays observed by a pair of receivers at the same time with the same satellite. In this method, satellite IFB is canceled, but the error in receiver IFBs remains in the ionospheric delay differences with the measurement noise:

$$\mathrm{IFB\_r} = \mathrm{IFB\_rr} + w. \tag{5}$$

The second one, the satellite-pair method, takes differences between ionospheric delays of a pair of satellites observed by the same receiver. In this method, receiver IFBs are canceled out. Though the error in satellite IFBs remains because it contains measurement noise as well, the error of the satellite IFBs in IONEX data which are estimated by many receivers over the world would be smaller than that of the locally estimated receiver IFBs. The third one, the mixed-pair method, takes differences between ionospheric delays at any pairs of IPPs regardless of which receiver and satellite the IPP originates from.

The calculation of Indonesia's nominal ionospheric gradient differs from other regions for two reasons. First, the distribution of CORS which is concentrated on the island of Java means that the possible range of IPP distance is also limited. Second, the close CORS distance causes the ionospheric gradient at short distances to be susceptible to doubling of estimation error of receiver IFB because the IPP distance in the denominator is very small and the difference in ionospheric delay in the numerator still contains receiver IFB error.

The probability distribution function (PDF) of the *VIG* occurrence is obtained with the estimated *VIG* values. Since the normal distribution with the raw standard deviation usually cannot bound all of the observed PDF, especially the tail of it, an inflation factor is multiplied to the raw standard deviation so that the normal distribution with the inflated standard deviation bounds the PDF down to a sufficiently low probability. The inflated standard deviation is adopted as σ_{vig}.

Results and discussion

Figure 4 shows the number of occurrences of ionospheric delay differences estimated by the three methods as a function of the IPP distance by a two-dimensional histogram. The left column shows the results of the mixed pair on a quiet day in four days (01/01/2012, 01/01/2013,

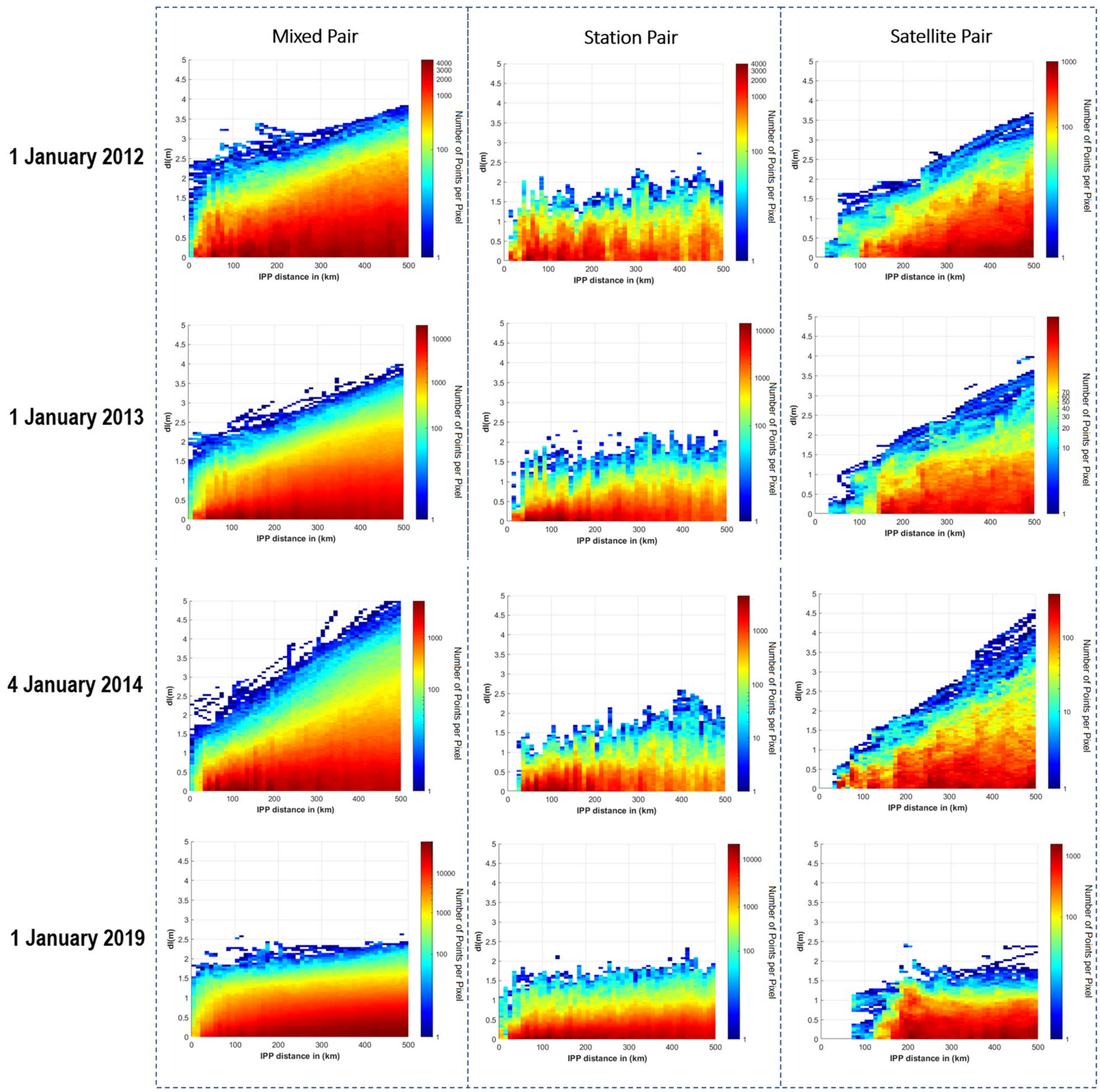


Fig. 4 Occurrences of ionospheric delay differences as a function of the IPP distance estimated by the mixed-pair, station-pair, and satellite-pair methods for 4 quiet days in different years

04/01/2014, and 01/01/2019). The two-dimensional histogram of observations number is a function of IPP separation and VID difference (dI). The x-axis and y-axis show the bin division of the IPP separation and dI, respectively. The ideal maximum IPP separation distance for all available data is 500 km. The color shows the number of observations per pixel.

The number of observations from the mixed-pair method is greater than the others because this method processes all IPP pairs. The dI value is very large at low IPP separation distances, and it is difficult to determine what factors influence this condition. The middle column which is the result of the station pair has almost the same dI value in every IPP separation. Ideally, the dI value should be very small at low separation distances and larger dI at long separation distances as in satellite-pair results (right column).

It can be seen that dI estimated by the satellite-pair and mixed-pair methods are correlated with the IPP distance, while dI estimated by the station-pair method is not. This less correlation between dI and the IPP distance can be explained by the short distances between the CORS stations which is centered on the island of Java. As mentioned in "Data and methodology" section, the receiver IFB error which does not depend on the distance between stations becomes dominant. It can be seen that large dI values with short IPP distances in the mixed-pair method are mainly contributed by IPPs of station pairs. This can be understood considering that the receiver IFB errors in the station-pair method become dominant in the short IPP distance cases. On the other hand, large dI values at long distances in the results of the mixed-pair methods are mainly contributed by IPPs of satellite pairs. This could be because large IPP distances cases can be obtained by the satellite-pair method.

Because dI values estimated by the satellite-pair method are well correlated with the IPP distance from short to long, the satellite-pair method is considered to provide reliable dI data down to short IPP distances. This is because the receiver IFB error is canceled in the satellite-pair method and satellite IFB values in IONEX data are well estimated. Thus, it is suitable for areas of Indonesia. On the other hand, the satellite-pair method would not be suitable in regions where the CORS distance is too far. The satellite-pair method can be applied in the region where a moderately dense CORS network is available.

Table 1 shows the σ_{vig} values estimated by the three methods in each year. The results of the satellite-pair method show that the largest σ_{vig} of 5.21 mm/km is obtained in 2014. The peak solar activity was from 2013 to 2015. The small sigma value in 2019 was possible because it is in a period of solar minimum.

Figure 5 shows the probability density functions of VIG obtained by the three methods on 1 January 2013. These results show the advantages of the satellite-pair method (Fig. 5c) which has smaller tails because receiver IFB is canceled out in the satellite-pair method. The tails of PDFs could be attributed to the large receiver IFB and multipath. To prove this hypothesis, dI and VIG values are simulated by the NeQuick model for the CORS over the Java region (Nava et al. 2008). As expected, dI values are well correlated with the IPP distance (Fig. 6). The PDF of the VIG is smooth and the tail of the PDF is narrow. This is expected from a model which is free from measurement errors such as the IFB error or multipath errors as well as because the model represents the mean state of the ionosphere which is free from random day-to-day variability.

Table 2 shows the σ_{vig} values at Sumatra and Java regions for data obtained in 2019 using the satellite-pair

Table 1 Comparison of the value of the inflation factor (*f*) and σ_{vig} in the unit of mm/km

Year	Mixed-pair		Station-pair		Satellite-pair		Kp index	Data
	f	σ_{vig}	*f*	σ_{vig}	*f*	σ_{vig}		
01/01/2009	–	–	–	–	–	–	2.7	Insufficient
01/01/2010	–	–	–	–	–	–	1	Insufficient
01/01/2011	–	–	–	–	–	–	2	Insufficient
01/01/2012	1.6	6.65	2.2	4.55	1.3	4.38	1.7	Sufficient
01/01/2013	1.7	5.91	1.8	4.35	1.3	4.48	0.7	Sufficient
04/01/2014	2.0	7.10	2.3	6.27	1.2	5.21	2.3	Sufficient
01/01/2015	1.6	4.73	2	4.51	1.7	3.75	2.3	Sufficient
03/01/2016	1.5	5.64	2.6	4.45	1.7	3.33	2.7	Sufficient
02/01/2017	1.9	5.60	2.0	4.23	2.0	3.37	2.3	Sufficient
03/01/2018	1.4	4.46	1.8	4.42	1.3	4.18	1.0	Sufficient
01/01/2019	1.8	5.56	2	4.18	1.4	3.78	2.7	Sufficient

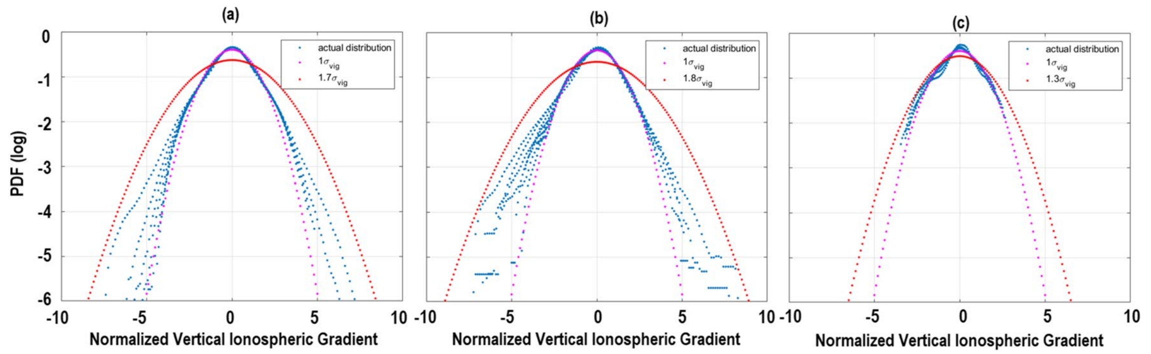


Fig. 5 Probability density of the occurrence of the ionospheric gradients normalized by the raw standard deviation for the data on 1 January 2013 as a result of **a** mixed-pair, **b** station-pair, and **c** satellite-pair

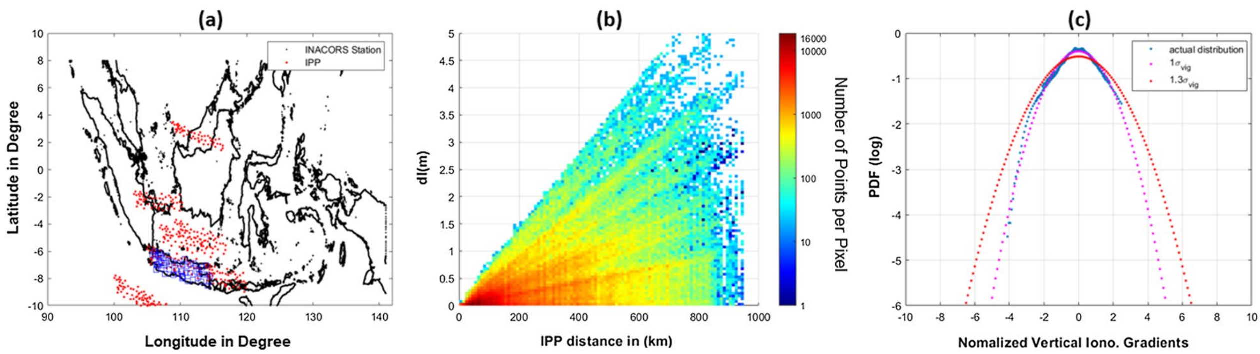


Fig. 6 **a** CORS location (blue) and their IPPs (red) on Java island used in the NeQuick model; **b** ionospheric delay difference as a function of the IPP distance; **c** PDF of the normalized ionospheric gradient generated by the NeQuick model

Table 2 The inflation factor (*f*) and σ_{vig} values in Sumatra and Java regions

Region	*f*	σ_{vig} (mm/km)
Sumatra	1.2	3.8
Java	1.5	3.75
Indonesia (Sumatra and Java)	1.3	3.78

method. The distributions of stations are different for Sumatra and Java regions. Note that Sumatra region has a wider range of latitudes and gradients may have more variability. σ_{vig} in the Sumatra region has a slightly larger value than Java region. At first glance, this shows that there are no significant differences between the two regions. However, the range of latitude in Java region is narrower than in Sumatra. So, smaller variability is expected. But on the other hand, it is closer to the southern crest of the equatorial ionization anomaly (EIA), and the gradient may be larger. With these two competing effects, the resulting σ_{vig} of Java region may become similar to that of Sumatra region. Because only one day of data in 2019 is used for this comparison, this result is just one realization of the σ_{vig} characteristics which should be subject to the day-to-day variability of the background ionosphere. Therefore, further studies with more complete data must still be carried out to ensure whether the σ_{vig} value can be applied to every airport in Indonesia or not.

Conclusions

Three methods, station-pair, satellite-pair, and mixed-pair methods are used to evaluate the ionospheric delay gradients by using the data obtained by GNSS CORS networks over Indonesia on 8 quiet days in different years (01/01/2012, 01/01/2013, 04/01/2014, 01/01/2015, 03/01/2016, 02/01/2017, 03/01/2018, and 01/01/2019). The results of the station-pair method appear to be contaminated by the receiver IFB errors for short IPP distances, which also impacts the results of the mixed-pair method. The satellite-pair method is found to be suitable for the GNSS CORS network over Indonesia and those with similar station densities.

The VIG values obtained by the satellite-pair method had smoother PDF than those obtained by the other two methods. The largest σ_{vig} value obtained from available data by the satellite-pair method was 5.21 mm/km on 4 January 2014. A larger value of sigma may be found by adding more data and using a denser GNSS CORS network in the future. The value of σ_{vig} in Sumatra (3.83 mm/km) is slightly higher than that of Java region (3.75 mm/km). The small difference may be due to combined effects of different geographic distribution CORS stations (elongated in the east–west and north–south directions in Java and Sumatra regions, respectively) and different magnetic latitudes (closer to the southern EIA crest and magnetic equator for in Java and Sumatra regions, respectively) as well as the day-to-day variability of the background ionosphere. These results still require clarification with analysis by using more data.

Abbreviations
CAT I: Category I; CONUS: Contiguous United States; CORS: Continuous Operating Reference Station; EIA: Equatorial ionization anomaly; GBAS: Ground-Based Augmentation System; GNSS: Global Navigation Satellite System; GPS: Global Positioning System; ICAO: International Civil Aviation Organization; IFB: Inter-frequency bias; IGS: International GNSS Service; IONEX: Ionosphere map exchange; IPP: Ionosphere pierce point; LTIAM: Long-term ionospheric anomaly monitoring; PDF: Probability distribution function; RINEX: The receiver independent exchange; SBAS: Satellite-Based Augmentation System; SID: Slant ionospheric delay; SF: Slant factor; VID: Vertical ionospheric delay; VIG: Vertical ionospheric gradient.

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Author contributions
SS designed this study and performed the analysis. HA, DD, and PA supported SS to investigate spatial analysis and supervised the findings of this work. SS supported this analysis and contributed to the discussion. DU verified the analytical methods. All authors discussed the results and contributed to the final manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The IONEX data are available at the IGS website (https://www.igs.org). The analyzed TEC and VIG data can be obtained upon request to the corresponding author (asepslamet@yahoo.com).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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