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GPS CONTINUOUSLY OPERATING REFERENCE STATION (CORS) SELECTION TOWARDS REGIONAL GPS ORBIT DETERMINATION: A SIMULATED STUDY USING TRILATERATION TECHNIQUE

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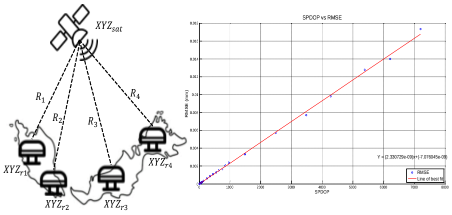
Graphical abstract



Expected accuracy of orbit determination = a*SPDOP + constant

Abstract

Global Positioning System (GPS) orbital error can be minimized using precise satellite orbit. These precise satellite orbits are calculated using GPS measurements from ground CORS. The distribution of the CORS involved in GPS satellite orbit determination is important, especially in the case of regional GPS orbit determination. A regional GPS orbit is an orbital product generated using locally distributed CORS network and is expected to improve the GPS measurement in the region. Satellite Position Dilution of Precision (SPDOP) is proposed as an indicator to measure the geometry of the CORS with respect to the GPS satellite. GPS measurements are simulated by calculating the range from GPS satellites to the CORS. The simulated measurement is then used to calculate the position of GPS satellite using trilateration algorithm. Results shows the SPDOP has a linear relationship with orbit determination accuracy. This study shows that SPDOP can be used as an indicator for a better CORS selection in GPS orbit determination.

Keywords: GPS orbit determination, regional GPS orbit determination, Satellite Position Dilution of Precision (SPDOP), trilateration, simulated GPS measurement, CORS selection

Abstrak

Ralat orbit Global Positioning System (GPS) boleh diminimumkan menggunakan orbit satelit yang tepat. Orbit satelit yang tepat ini dikira menggunakan pengukuran GPS dari CORS di darat. Pentaburan CORS yang terlibat dalam penentuan orbit satelit GPS adalah penting, terutamanya dalam kes penentuan orbit GPS serantau. Orbit GPS serantau ialah produk orbit yang dijana menggunakan jaringan CORS yang bertaburan dalam

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sesuatu kawasan dan dijangka dapat meningkatkan pengukuran GPS di rantau ini. Pencairan Ketepatan Kedudukan Satelit (SPDOP) dicadangkan sebagai penunjuk untuk mengukur geometri CORS daripada perspektif satelit GPS. Pengukuran GPS disimulasikan dengan mengira julat dari satelit GPS ke CORS. Pengukuran simulasi kemudiannya digunakan untuk mengira kedudukan satelit GPS menggunakan algoritma trilateration. Keputusan menunjukkan SPDOP mempunyai hubungan linear dengan ketepatan penentuan orbit. Kajian ini menunjukkan SPDOP boleh digunakan sebagai penunjuk dalam pemilihan CORS untuk tujuan penentuan orbit GPS.

Kata kunci: Penentuan orbit GPS, penentuan orbit GPS serantau, Pencairan Ketepatan Kedudukan Satelit (SPDOP), trilaterasi, ukuran GPS simulasi, pemilihan stesen

1.0 INTRODUCTION

Global Navigation Satellite System (GNSS) is a satellite-based positioning technique widely used throughout the world in various fields. GNSS has supported daily activities, such as navigation and surveying [1], to scientific activities, such as geodynamics monitoring and weather forecasting [2]. GPS is one such system under the bigger family of GNSS. Nevertheless, GPS or even GNSS are not perfect systems as they are prone to various errors such as orbital and clock error, atmospheric delays, and hardware errors [3]. Among these errors, orbital error refers to the error in satellite position which can contribute up to a root-mean-square (RMS) of 2 m error in GPS positioning [4] and 0.1 ppm in differential positioning [5].

Precise ephemerides have been developed to minimize the orbital error. Currently, final ephemerides, the highest accuracy ephemerides, promise an RMS of ±2.5 cm with a latency between 12 to 18 days [6]. This final ephemeris was generated using GNSS data from CORS located around the world. Various analysis centers associated with the International GNSS Society (IGS) use these GNSS data to determine the accurate satellite trajectory [7].

Each analysis centers may use different software, parameters, or even CORS network in the process of generating their own version of final ephemerides [8]. In addition, no specific criteria are employed to select the CORS that will be used in the processing campaign. This can be understandable as the participation into IGS network is completely voluntary [9], thus limiting the realization of this 'ideal network distribution'. There is an indicator named SPDOP that measures the geometry of CORS with respect to the satellite position. Zhang *et al.* [10] experimented with orbit determination for BeiDou satellite and claimed that SPDOP can reflect the accuracy of the orbit determination. The SPDOP shows potential to be applied as an indicator in CORS selection for orbit determination.

Besides that, not all CORS available in the world are part of the IGS network. Some countries manage their own CORS network, and the data might or might not be publicly accessible. An example of publicly accessibly regional CORS network is Sumatran GPS Array (SuGAr) with regional coverage along the Sumatra fault line in Indonesia [11]. Malaysia has a few CORS network and the data are not publicly available as dictated by national security law [12].

Locally distributed CORS can contribute to the realization of regional GPS orbital product. A regional GPS orbital product is expected to improve the accuracy of GPS measurement. A regional GPS orbital product is generated using GPS measurement observed from local CORS with coverage that includes nearby area. It is also expected to support regional precise point positioning (PPP). This can be realized by the abundance of CORS in the local region.

Yet, the importance of CORS selection is elevated in the case of regional GPS orbit determination. For global orbit determination, CORS are located far apart over a wide area, thus is expected to have a relatively lower SPDOP and better geometry. On the other hand, CORS will be densely distributed in regional GPS orbit determination, resulting in a more challenging geometry.

This study aims to correlate SPDOP with the accuracy of orbit determination. GPS measurement will be simulated from real data and orbit determination will be done using trilateration formula. This paper is structured into four (4) section. After the introduction in Section 1, Section 2 discusses the methodology used in this study including GPS measurement simulation, orbit determination using trilateration, and SPDOP calculation. Section 2 also provides a brief introduction to the background of the dataset used. Section 3 presents the results and analysis of the study by presenting the result from orbit determination using trilateration and analyzing the SPDOP. Lastly, a brief conclusion is presented in Section 4.

2.0 METHODOLOGY

2.1 GPS Measurement Simulation

In this study, simulated GPS measurement is used. Raw GPS measurement contains errors such as ionospheric delay, tropospheric delay, receiver clock error, and satellite clock error. These errors cloud the accuracy of the range computed, necessitating a simulated GPS measurement which will be free of such errors. In addition, time offset due to signal travelling from satellite to receiver varies between receivers [13], thus satellite is referred to different position in the same epoch. Using simulated GPS measurement can ignore this time offset, simplifying the orbit determination algorithm.

A geometric range free of the errors is simulated by calculating the distance between a receiver and the satellite final ephemerides. The final ephemerides are originally referenced to the Center of Mass (CoM) and is translated to reference the antenna phase center (APC) using antenna phase offset values from IGS [14, 15]. Equation 2.1 shows the formula to calculate the simulated geometric range.

$$\rho_{sim} = \sqrt{(x_r - x^s)^2 + (y_r - y^s)^2 + (z_r - z^s)^2} \qquad (2.1)$$

whereby ρ represents the geometric range, subscript r represents receiver, subscript *sim* represents simulated, superscript s represents the satellite and x, y, and z represent the coordinates in an Earth centered, Earth fixed (ECEF) Cartesian coordinate system respectively. Geometric range for a satellite is only simulated if the receiver observed that satellite in the original measurement.

2.2 Orbit Determination Using Trilateration

Orbit determination is usually conducted through one of the three approaches: kinematic, dynamic, and reduced-dynamic orbit determination [16]. Trilateration algorithm falls under the category of kinematic orbit determination, but it is a more simplified version. A minimum of three (3) observation is required to calculate the satellite position using trilateration formula. Additional observation is preferred as it will introduce more redundancy to the solution thus the residual can be minimized using least-squares adjustment.

In order to compute satellite position using trilateration, equation 2.1 must be linearized using Taylor's theorem [17]. The position of the satellite is first divided into an initial approximation (x_o, y_o, z_o) and unknown position $(\Delta x, \Delta y, \Delta z)$ as shown in equation 2.2. The linearized geometric range is given in equation 2.3.

$$\begin{aligned} x^s &= x_o + \Delta x \\ y^s &= y_o + \Delta y \\ z^s &= z_o + \Delta z \end{aligned} \qquad (2.2)$$

$$\rho_{com} = \rho_0 - \frac{x_r - x_0}{\rho_0}\Delta x - \frac{y_r - y_0}{\rho_0}\Delta y - \frac{z_r - z_0}{\rho_0}\Delta z \qquad (2.3)$$

whereby subscript *com* represents computed range. Broadcast orbit is used as the initial approximation for the position of the satellite. Equation 2.3 is then rearranged into matrices form as in equation 2.4. The least-squares solution is solved using equation 2.5. New approximated satellite position is then obtained using equation 2.2 and the solution is iterated for several times until it converges.

$$A = \begin{bmatrix} -\frac{x_{r1}-x_0}{\rho_0} & -\frac{y_{r1}-y_0}{\rho_0} & -\frac{z_{r1}-z_0}{\rho_0} \\ -\frac{x_{r2}-x_0}{\rho_0} & -\frac{y_{r2}-y_0}{\rho_0} & -\frac{z_{r2}-z_0}{\rho_0} \\ -\frac{x_{r3}-x_0}{\rho_0} & -\frac{y_{r3}-y_0}{\rho_0} & -\frac{z_{r3}-z_0}{\rho_0} \\ \vdots & \vdots & \vdots \\ -\frac{x_{rn}-x_0}{\rho_0} & -\frac{y_{rn}-y_0}{\rho_0} & -\frac{z_{rn}-z_0}{\rho_0} \end{bmatrix} \qquad (2.4)$$

$$L = \begin{bmatrix} \rho_{sim_r1} - \rho_{com_r1} \\ \rho_{sim_r2} - \rho_{com_r2} \\ \rho_{sim_r3} - \rho_{com_r3} \\ \vdots \\ \rho_{sim_rn} - \rho_{com_rn} \end{bmatrix}$$

$$X = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix}$$

$$X = (A^T A)^{-1}(A^T L) \qquad (2.5)$$

2.2 SPDOP Calculation

Dilution of precision (DOP) is an indicator that describes the geometry of the satellite [18]. It can be further detailed into position DOP (PDOP), vertical (VDOP) and geometric DOP (GDOP) [2]. SPDOP is a concept that builds similarly on the concept of DOP, but the calculation is inverted in order to quantify the geometry of the receiver with respect to the satellite. Commonly, SPDOP uses a 4x4 matrices, with the fourth element representing time. In the context of this study, SPDOP is calculated using a 3x3 matrices as the time element is not considered when simulated range measurement is used. Equation 2.6 to equation 2.7 shows the steps to calculate SPDOP in the context of this paper.

$$Q = (A^T A)^{-1} = \begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{bmatrix} \qquad (2.6)$$

$$SPDOP = \sqrt{q_{11} + q_{22} + q_{33}} \qquad (2.7)$$

2.3 Background of the Dataset

GPS observation data are taken from IGS network, Malaysia Real Time Kinematic Network (MyRTKnet) and National Research & Development CORS Network (NRC-net). MyRTKnet and NRC-net are both CORS network located in Malaysia. A total of seven (7) days data are collected from 20 August 2019 to 26 August 2019. The minimum requirement for the data is that the data must have 2880 epoch of 30 seconds interval data and must be available for the whole duration. The coordinates of both the CORS above are in Malaysia local geocentric datum named Geocentric Datum of Malaysia 2000 (GDM2000) [19, 20]. Thus, the coordinates are first preprocessed into International Terrestrial Reference Frame 2014 (ITRF2014) to be consistent with coordinates declared by IGS CORS.

There are a few extra requirements implied on the IGS network. First, daily coordinate solution from Center of Orbit Determination (CODE) is used as a reference for IGS CORS selection [21]. Only CORS that are present in the solution is considered in the dataset. Next, the IGS CORS is sorted according to distance from a reference point in Malaysia with a maximum distance of 8000 km. Lastly, if two IGS CORS are located close to each other, only one of them is selected.

After a rough filtering of all the available data, a total of 55 CORS are selected which consist of 24 IGS CORS, 27 MyRTKnet CORS and 2 NRC-net CORS. The CORS are then divided into three (3) designs. The first design (D1) consists of local CORS only, with a total of 29 CORS. The second design (D2) consists of 38 CORS from local CORS and IGS CORS within 4000 km from a reference point in Malaysia. The third design (D3) covers all the 55 CORS selected in the study. Figure 1, 2 and 3 shows the first, second, and third design respectively.

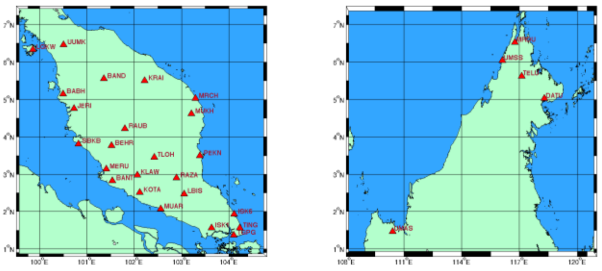

Figure 1 First design of CORS selection

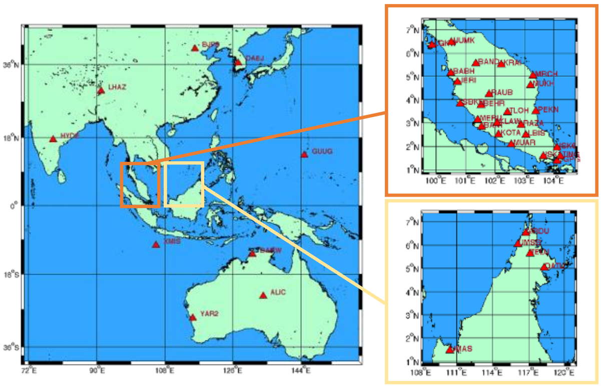

Figure 2 Second design of CORS selection

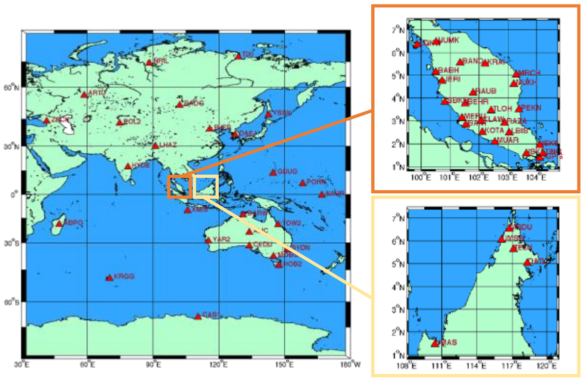

Figure 3 Third design for CORS selection

3.0 RESULTS AND DISCUSSION

3.1 Orbit Determination Using Trilateration

The orbit from orbit determination using trilateration is compared against final orbit. In general, the calculated orbit is consistent with final orbit at sub-millimeter level. Results from D1 is consistent at sub-millimeter level while D2 and D3 can achieve up to micrometer level. 3D error is calculated by taking the norm of the error in X, Y and Z direction. Figure 4 shows an example of the result of the orbit determination of D1, D2 and D3. PRN10 is selected for the demonstration and red, blue, and magenta represents D1, D2 and D3 respectively.

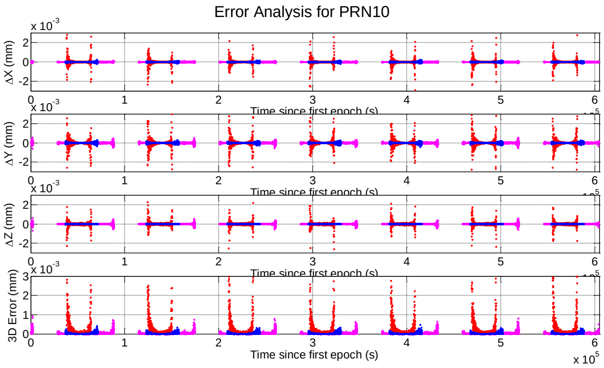

Figure 4 Error analysis for PRN10

Figure 4 illustrates two differences, in addition to the consistency of the calculated orbit. The first is the duration of the data. D3 has the longest time span, followed by D2, and D1 has the shortest time span. This can be explained by the fact that D3 covers a larger area, allowing it to track the satellite for a longer period of time.

The second difference shown from the figure is on the convergence and divergence of the error. This is especially obvious for D1 where the errors slowly converge and diverge before the tracking of the satellite is lost. Similar observation is available for D2 and D3, but the scale is a few levels smaller compared to D1. This observation is expected to be present only when the satellite is not tracked continuously.

The accuracy of each design is also analyzed in terms of root-mean-squared errors (RMSE). The mean 3D RMSE of D1, D2 and D3 are 1.319e-06 mm, 6.711e-08 mm, 4.466e-08 mm respectively. Figure 5 shows the RMSE analysis of the calculated orbit. Figure 5 conclusively demonstrates that D2 and D3 have a smaller RMSE compared to D1. Mean 3D RMSE value also indicates that D3 is more accurate than D2, although individual comparison may vary depending on the trajectory of the satellite.

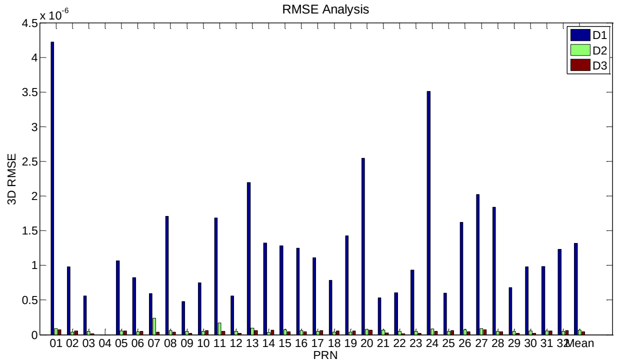

Figure 5 3D RMSE analysis for orbit determination using trilateration of all three designs

3.3 SPDOP Analysis

SPDOP is an indicator that measures the geometry of the satellite with respect to the available receiver. A lower value generally reflects a better geometry, hinting as a better design of CORS distribution for orbit determination. Figure 6 presents the result of SPDOP computation for PRN10.

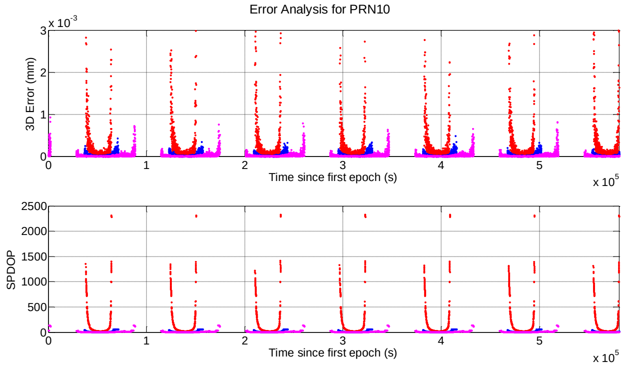

Figure 6 SPDOP analysis

Red, blue, and magenta points represent results from D1, D2 and D3 respectively. A general observation can be made from the example that 3D error is directly proportional to SPDOP. Among the three designs, D1's SPDOP has the largest range. This is due to the limited geometry offered by D1. The relationship between SPDOP and 3D error is presented in Figure 7.

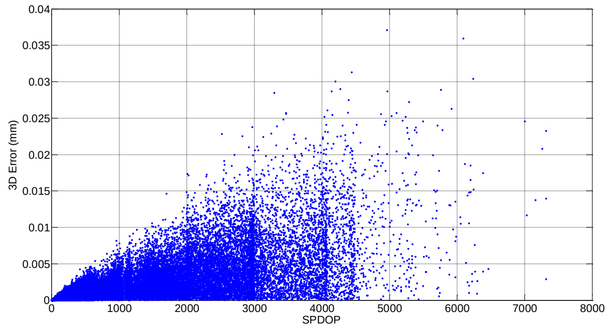

Figure 7 Analysis of SPDOP vs 3D error

From the result above, it is difficult to conclusively claim that 3D error is directly proportional to the SPDOP. In an ideal proportional relationship, the pattern should be a line with minimum variation. Yet, current result shows that the relationship between the two variables are not clearly defined and is corrupted by measurement noise. The relationship between SPDOP and 3D error is analyzed from another perspective whereby the RMSE of the 3D error is compared against a range of SPDOP. The range selected starts from 0 to 100, in steps of 10, followed by 100 to 1000, in steps of 100, and 1000 to 8000, in steps of 1000. Figure 8 shows the relationship between range of SPDOP and RMSE of 3D error.

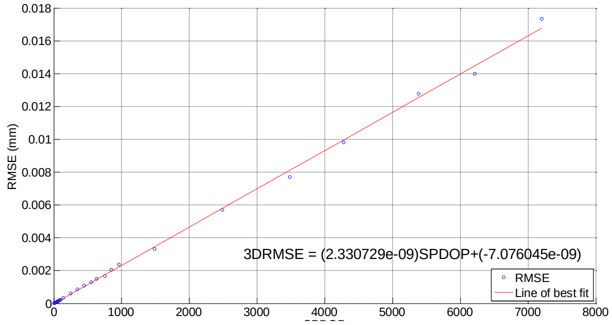

Figure 8 Relationship of range of SPDOP with RMSE of 3D error

The relationship between SPDOP and RMSE of 3D error shows positive linear relationship. The relationship can be approximated using a linear equation of *3DRMSE* = (2.2330729e-09)*SPDOP*+(-7.076045e-09), where *3DRMSE* is the RMSE of 3D error in mm. It should be highlighted that the coefficients are calculated using simulated GPS measurement, thus it might vary when real measurements are used, or when even more data is used. The accuracy of orbit determination is at cm-level when real measurements are used [6]. Real measurements are contaminated by errors such as ionospheric delay, tropospheric delay, and equipment noise. Furthermore, the type of measurement used will limit the accuracy, particularly in cases where code-based measurement is used. This further increases the uncertainties in the measurement, thus lowering the accuracy of orbit determination.

This study shows the theoretical achievable accuracy of orbit determination in different CORS distribution using simulated measurement. A smaller SPDOP value often promises a higher accuracy in orbit determination. This study would recommend a SPDOP upper limit of 4500 for orbit determination using simulated measurement which promises the 3D error to be below 0.01 mm. In a study that uses real measurement, Chen *et al.* [22] showed that cm-level accuracy in orbit determination is achievable with mean SPDOP below 100. On the other hand, Zhang *et al.* [10] result showed that BeiDou satellite with mean SPDOP of 208.6 can have an orbit accuracy of 34cm, the lowest orbit accuracy and second highest mean SPDOP value recorded in that study for middle earth orbit satellites. There will be a need to further investigate the suggested SPDOP when real measurement is used.

The current result is consistent with the claim that SPDOP is correlated with orbit determination accuracy, thus it can be used as a reference indicator when selecting the distribution design of CORS involved in orbit determination. Chen *et al.* [22] also showed that that there is a correlation between accuracy of orbit determination with the geometry of CORS distribution. They proved that SPDOP has a mild influence on orbit determination for medium earth orbit satellites such as GPS and part of the BeiDou constellation.

During CORS selection for orbit determination, it is recommended to select a design with a low SPDOP. The geometry of the CORS distribution is related to the distribution of the CORS; the wider apart the CORS are distributed, the lower the SPDOP, and thus the better the geometry of the CORS distribution. While this does not pose much effect on global orbit determination, this limitation will become one of the challenges in regional orbit determination.

Two solutions are proposed to lower the SPDOP value in regional orbit determination. The first proposed solution is to include CORS from nearby area during orbit determination. This can be seen as D3 that includes CORS 8000 km from Malaysia performs betters that D1 that only includes CORS in Malaysia.

The second proposed solution in realizing regional orbit determination is to perform global orbit determination with densification of regional CORS. This solution will overcome the design limitation, but will increase the computational expense and resources required for orbit determination. On the other hand, the product from this proposed solution will be able to be used globally, benefiting more users.

4.0 CONCLUSION

The relationship between SPDOP and orbit determination accuracy was discussed in this paper. The position of the satellite orbit is calculated using simulated GPS data and trilateration algorithm. The results show that the SPDOP can reflect orbit determination accuracy where a low SPDOP value is associated with high accuracy of orbit determination. Thus, SPDOP can be used as an indicator for CORS selection for orbit determination. This can be applied in the designing stage before orbit determination is performed. Moreover, trilateration algorithm is tested to be able to perform in orbit determination. Another point to note is that the results are based on simulated GPS measurement has no errors. Real GPS measurements are expected to give similar result but with more measurement noise, particularly for regional GPS orbit. For this matter, further research will be done using real GPS measurement in regional GPS orbit determination. Two solutions are also proposed to overcome the limitations of geometry of CORS distribution in regional orbit determination, namely, to include CORS from nearby area, and to involve more CORS in the region during global orbit determination.

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