

Investigation of GDOP for Precise user Position Computation with all Satellites in view and Optimum four Satellite Configurations

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ABSTRACT

The advent of Global Positioning System (GPS) has revolutionized the field of navigation particularly in the field of civil aviation sector. The accuracy of GPS system is affected by several factors. One such factor is satellite Geometry, which represents the geometric locations of the GPS satellites as seen by GPS receiver. This plays a very important role in determining the total positioning accuracy. Better the geometry, better the position accuracy. The Satellite Geometry effect can be measured by a single dimensionless number called Geometric Dilution of Precision (GDOP). Lower the GDOP value, better the satellite Geometry. GPS requires minimum of four satellites to compute user position. When more number of satellites are in view, best four satellites are taken in order to reduce the redundancy. With four satellites, best geometry is obtained when one of the satellites is at the zenith and remaining three forms an equilateral triangle and all the four together forms a tetrahedron structure. The larger the volume of the tetrahedron, the better is the value of GDOP. Similarly, greater the number of satellites, better the value of GDOP. Practically, GDOP ranges from 2 to 6. Monitoring of GDOP is also an important aspect for high-precision applications such as surveying and Integrity monitoring in the GPS receivers. For making use of GPS for en-route and Precision Approach (PA) aircraft landings over the Indian subcontinent, the aspect of best GDOP value to be used in the user position computation is investigated which is obtained due to all the satellites in view or best four satellites in this paper. A new algorithm is proposed to compute various GDOP. Analysis is made by computing the best GDOP due to four optimum satellites as well as for all the satellites in view. The dual frequency GPS receiver data of IISC, Bangalore (13.02° / 77.57° Lat./Long.) is used for investigation of best GDOP configuration to be used in user position determination over the Indian subcontinent.

INTRODUCTION

Global Positioning System is a satellite based navigation system developed by US Department of Defense (DoD) to provide user with his position, velocity and time. It consists of Space segment, Control segment and User segment. Space segment consists of minimum of 24 satellites (Parkinson 1996). A GPS receiver computes its position using a technique called '3-Dimensional multilateration', which is the process of figuring out where a number of spheres intersect, with each sphere has a satellite at its center. The radius of the sphere is the distance between the receiver and the satellite. Ideally, these spheres intersect at one point, which is the possible

solution to the current position of the receiver. In reality, this intersection of spheres forms an area. In such case, the current position of the receiver may be at any point within the area, causing an uncertainty in the receiver position. Fig.1 represents the trilateration, in which the shaded part represents the possible area in which receiver would be located and the actual receiver position is represented by a small circle.

Several external sources introduce errors into GPS position estimated by a GPS receiver. One important source of error is the Geometry of the satellites from which signals are being received. The computed receiver position can vary depending on which satellites are used for the measurement. Different

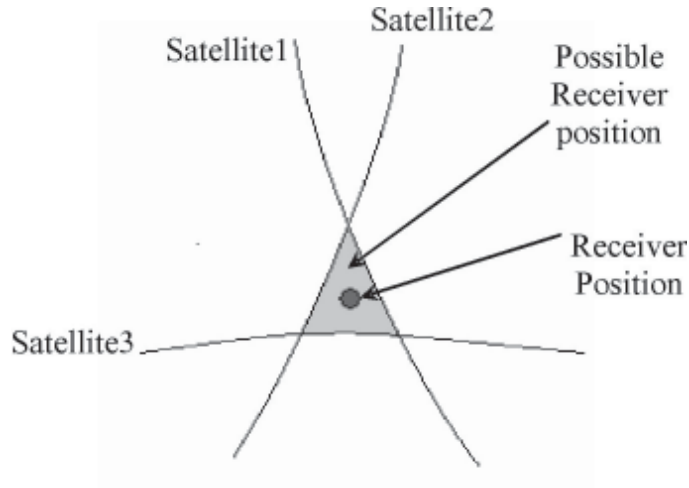


Figure 1. Trilateration.

satellite geometries can magnify or lessen the position error. DOP can be computed by selecting optimum four satellites or by using all satellites in view. Wider the angular separation between the satellites, lower the DOP. Lower the DOP, better the geometry. In this paper, DOP is computed for both cases i.e. for optimum four satellites and all satellites in view. Selection of optimum four satellites is based on the angular separation between the satellites.

Theoretical Back ground

Satellite navigation depends on accurate range measurements in order to determine the position of the receiver. Navigation solution of the receiver is nothing but the computation of receiver’s three-dimensional coordinates and its clock offset from four or more simultaneous pseudorange measurements. These are measurements of the biased range between the receiver’s antenna and the antennas of each of the satellites being tracked. The accuracy of the measured pseudoranges determines the overall accuracy of the receiver-derived coordinates.

The basic pseudorange equation is given by

$$P = \rho + c (dT - dt) + d_{ion} + d_{trop} + e \quad (1)$$

in which ‘P’ denotes the pseudorange measurement; ρ is the geometric range between the satellite’s antenna at the time of signal transmission and the receiver’s antenna at the time of signal reception; dT and dt represent receiver and satellite clock bias respectively from the GPS time; d_{ion} and d_{trop} are the ionospheric and tropospheric propagation delays; ‘e’ represents measurement noise as well as unmodeled

effects such as multipath; ‘c’ stands for vacuum speed of light.

Assuming the receiver accounts for the satellite clock offset and atmospheric delays, Eq.1 can be simplified as

$$P = \rho + c.dT + e \quad (2)$$

With ‘M’ satellites in view, there are ‘M’ such equations that a receiver must solve using the M-simultaneous measurements. In order to determine the receiver coordinates, i.e receiver X,Y,Z position in Earth Centered Earth Fixed(ECEF)coordinate system and the receiver clock offset dt, pseudorange measurements from at least four satellites are required. As pseudorange measurement equations are nonlinear, they can be linearized by assuming initial estimates for the receiver’s position. By applying corrections to these initial estimates, receiver’s actual coordinates and clock offset can be estimated. By Grouping these equations and representing them in a matrix form, GPS measurement equation can be written as

$$\delta P = A\delta U + n \quad (3)$$

with ‘M’ satellites in view, ‘A’ represents M x 4 Line of Sight vector (LoS) matrix in which each term represents direction cosine vector between the receiver and the satellite.

δP represents Mx1 matrix of pseudo range measurements.

δU represents 4x1 navigation error state vector that includes receiver position and clock offset.

‘n’ represents Mx1 vector of Gaussian pseudo range measurement noise.

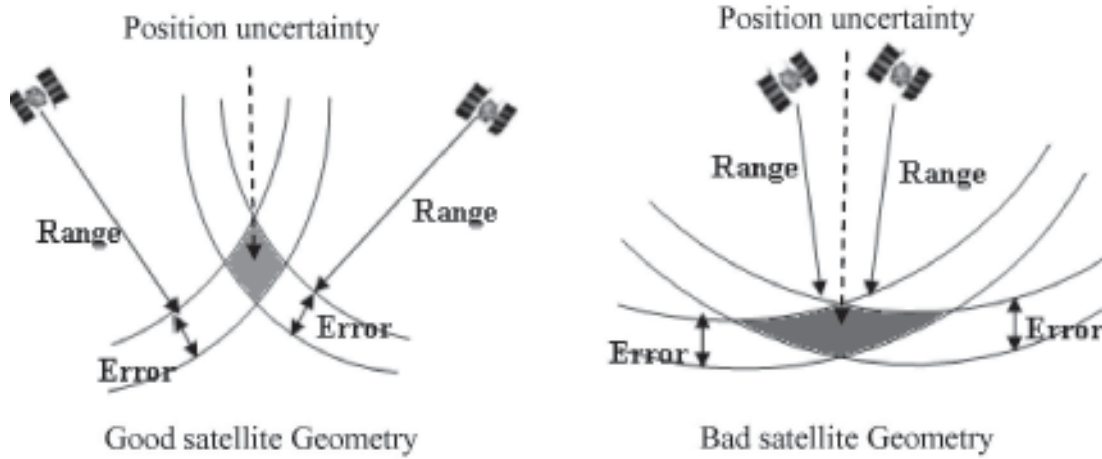


Figure 2a. Satellite Geometry Representation for two satellites.

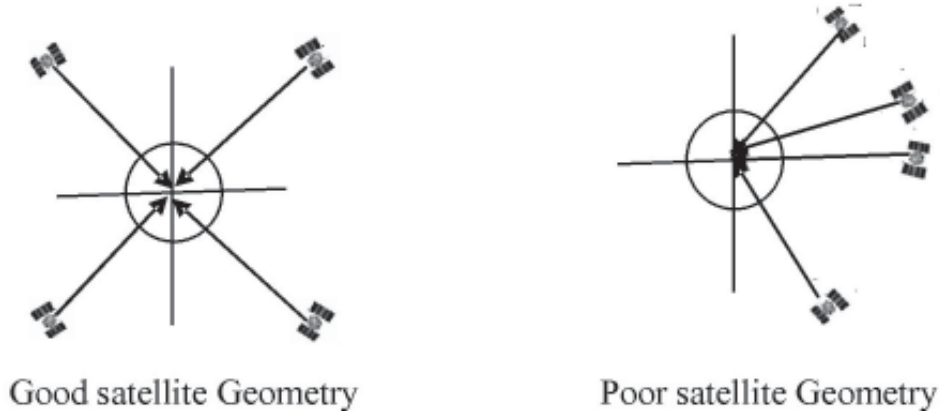


Figure 2b. Satellite Geometry representation.

With four visible satellites i.e. $M=4$, Eq.3 can be written as

$$\delta U = A^{-1} \delta P \quad (4)$$

With more satellites in view, i.e. $M>4$, receiver position is computed using least squares approach. In such case, Eq.3 can be written as

$$\delta U = (A^T A)^{-1} A^T \delta P \quad (5)$$

In general, the solution to the nonlinear problem is obtained by iterative process. Here also navigation solution is obtained by iterative process, in which δU is computed and with this user position is updated until the variation in is negligibly small.

SATELLITE GEOMETRY

Navigation solution accuracy can be degraded by satellite geometry which represents the geometric

locations of the satellites seen by receiver. As an example, Satellite geometry representation is illustrated for two satellites in Fig.2a. Two arcs are drawn from each satellite considering the satellite as the center. Inner arc is drawn considering true range as the radius and outer arc is drawn with pseudorange as the radius. Intersection area of these arcs of the two satellites represents the possible user location. When the two satellites are placed farther, intersection area is small which indicates low uncertainty of position, this in turn represents better satellite geometry. When the two satellites are placed closer, intersection area is large which indicates high uncertainty of position, this in turn represents poor satellite geometry. In the similar way, with many satellites in view, a good geometry is formed when the satellites are spread wider in space.

As GPS requires minimum of four satellites for user position determination, Fig.2b represents the satellite geometry with four satellites if the four satellites spread apart, GDOP obtained is minimum and this forms the good satellite geometry. When the

satellites are closer, GDOP obtained is maximum which indicates the Geometry is poor.

Dilution of Precision

Dilution of Precision (DOP) often called as Geometric Dilution of Precision (GDOP) is a dimensionless number, which is a measure of satellite geometry. Earlier days GPS receivers can track only some of the satellites in view and a subset of satellites (four satellites) are used for navigation solution even though more satellites are in view, which is called as optimum four GPS satellite positioning. In such case, GDOP computation is based on the optimum four satellites in view. Most of the new age GPS Receivers can track all the satellites in view and the navigation solution in such case is based on the signals from all satellites in view. In such case, GDOP is computed using all satellites in view. In this paper, GDOP is computed by selecting the four optimum (best) satellites in view as well as for all satellites in view. Selection of best four satellites is based on the Azimuth and Elevation angles of the satellites.

In Real time applications, quality of the overall navigation solution can be determined by examining the Dilution of Precision (Wells et.al., 1987). To examine the specific components such as three dimensional receiver position coordinates, horizontal coordinates, vertical coordinates or the clock offset, GDOP is resolved into various forms as

- a. Position Dilution of Precision (PDOP): It is a measure of the uncertainty in three dimensional position of the navigation solution (Eq.14).
- b. Horizontal Dilution of Precision (HDOP): It is a measure of uncertainty in Horizontal position (Longitude and Latitude) of the navigation solution (Eq.15).
- c. Vertical Dilution of Precision (VDOP): It is a measure of uncertainty in vertical position (Altitude) of the navigation solution (Eq.16).
- d. Time Dilution of Precision (TDOP): It is a measure of uncertainty in receiver clock (Eq.17)

GPS position accuracy is the combined effect of the measurement errors and satellite geometry. Measurement errors and biases can be represented by User Equivalent Range Error (UERE). UERE is defined as the root sum square of the various errors and biases. Multiplying UERE with GDOP gives expected accuracy of the GPS positioning at one-sigma (1-σ) level and is given in Eq.6.

$$\text{GPS Position accuracy} = \text{UERE} \times \text{GDOP} \quad (6)$$

DOP Ratings are listed in the Table 1.

Table 1. DOP Ratings [LANGLEY, R.B., 1999]

DOP Value	Ratings
1	ideal
2-4	excellent
4-6	good
6-8	Moderate
8-20	Fair
20-50	poor

Computation of Dilution of Precision (DOP)

The satellite geometry relates position errors to range measurement errors.

Recalling the Eq.5,

$$\delta U = (A^T A)^{-1} A^T \delta P$$

in which, matrix 'A' represents the line of sight vectors from the receiver to satellites. If we consider δU as a zero-mean vector containing the errors in the estimated user state, then our interest is in the statistics of δU because that will characterize the expected position errors. Using the generalized inverse of A, we find the covariance of δU (Brown and Hwang 1992) :

$$\begin{aligned} \text{cov}(\delta U) &= E(\delta U \delta U^T) = E[(A^T A)^{-1} A^T \delta P \delta P^T A(A^T A)^{-1}] \\ &= (A^T A)^{-1} A^T dP dP^T A(A^T A)^{-1} \\ &= (A^T A)^{-1} A^T \text{cov}(dP) A(A^T A)^{-1} \quad (7) \end{aligned}$$

cov(δP) represents the pseudo range errors. These are assumed to be uncorrelated, Gaussian random variables. As such, they are statistically independent which results in a diagonal covariance matrix. Furthermore, the range measurement errors are assumed to have the same variance (σ_n) for each satellite. So, we have

$$\text{cov}(\delta P) = \sigma_n^2 \quad (8)$$

Using Eq.8, Eq.7 can be written as

$$\begin{aligned} E(\delta U \delta U^T) &= \sigma_n^2 (A^T A)^{-1} A^T A(A^T A)^{-1} \\ &= \sigma_n^2 (A^T A)^{-1} \quad (9) \end{aligned}$$

As (A^TA) is symmetric, transpose is not required.

$$\text{Therefore, cov}(\delta U) = \sigma_n^2 (A^T A)^{-1} \quad (10)$$

Let **G**=(A^TA)⁻¹ so that cov(δU)=σ_n²**G**

Expanding the Eq.10, we get

$$\begin{bmatrix} \sigma_x^2 & \text{cov}(x,y) & \text{cov}(x,z) & \text{cov}(x,b) \\ \text{cov}(y,x) & \sigma_y^2 & \text{cov}(y,z) & \text{cov}(y,b) \\ \text{cov}(z,x) & \text{cov}(z,y) & \sigma_z^2 & \text{cov}(z,b) \\ \text{cov}(b,x) & \text{cov}(b,y) & \text{cov}(b,z) & \sigma_b^2 \end{bmatrix} = \sigma_n^2 \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} & G_{xb} \\ G_{yx} & G_{yy} & G_{yz} & G_{yb} \\ G_{zx} & G_{zy} & G_{zz} & G_{zb} \\ G_{bx} & G_{by} & G_{bz} & G_{bb} \end{bmatrix} \quad (11)$$

The elements of \mathbf{G} give a measure of the satellite Geometry i.e. Dilution of Precision (DOP).

Various DOPs values can be calculated from the diagonal elements of \mathbf{G} .

$$\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_b^2 = (\mathbf{G}_{xx} + \mathbf{G}_{yy} + \mathbf{G}_{zz} + \mathbf{G}_{bb})\sigma_n^2$$

$$\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_b^2} = \sigma_n \cdot \text{GDOP} \quad (12)$$

There fore,

$$\text{GDOP} = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_b^2}}{\sigma_n} = \sqrt{\mathbf{G}_{xx} + \mathbf{G}_{yy} + \mathbf{G}_{zz} + \mathbf{G}_{bb}} \quad (13)$$

$$\text{PDOP} = \frac{\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}}{\sigma_n} = \sqrt{\mathbf{G}_{xx} + \mathbf{G}_{yy} + \mathbf{G}_{zz}} \quad (14)$$

$$\text{HDOP} = \frac{\sqrt{\sigma_x^2 + \sigma_y^2}}{\sigma_n} = \sqrt{\mathbf{G}_{xx} + \mathbf{G}_{yy}} \quad (15)$$

$$\text{VDOP} = \frac{\sigma_z}{\sigma_n} = \sqrt{\mathbf{G}_{zz}} \quad (16)$$

$$\text{TDOP} = \frac{\sigma_b}{\sigma_n} = \sqrt{\mathbf{G}_{bb}} \quad (17)$$

These DOP terms can be interrelated as

$$\text{PDOP}^2 = \text{HDOP}^2 + \text{VDOP}^2 \quad (18)$$

and

$$\text{GDOP}^2 = \text{PDOP}^2 + \text{TDOP}^2 \quad (19)$$

GDOP is computed by using Eq.13. Each of the DOP terms can be computed individually, and they are independent of each other. A high VDOP (Vertical Dilution of Precision), for example, signifies a large error in Altitude of receiver position.

- DOP Analysis for Best four satellites: When only four satellites are used for navigation solution,

GDOP analysis can be based on the volume of the tetrahedron, which is formed closing off the unit vectors from the satellites to the receiver. Larger the volume of the tetrahedron, smaller the GDOP. The largest possible tetrahedron is one for which one satellite is at zenith and the remaining satellites are below the earth's horizon at an elevation angle of -19.47° and equally spaced in azimuth. GDOP in this case is 1.581. But this is not practical as a GPS receiver on or near earth's surface cannot see three satellites below Horizon. Practically, Lowest GDOP (1.732) can be obtained with one satellite at zenith and the three satellites equally spaced on the horizon.

- DOP Analysis with all satellites in view: The more the satellites used in the solution, smaller the DOP value and hence smaller the solution error. GDOP computed with all satellites in view is better than the one computed using best four satellites.

RESULTS AND DISCUSSION

The data due to IISC, Bangalore (IGS Station Lat/Lon: $13.02^\circ/77.57^\circ$) corresponding to a typical day (3rd January 2008) is sampled at a sampling rate of 30 seconds for the analysis. The Converter software tool of Novatel Make is used to convert receiver specific data format into Receiver Independent Exchange (RINEX) format. DOP values are computed for the day long data, for all satellites in view and for best four satellites as well.

At 2:00Hrs of GPS time, with 9 satellites in view, Line of sight vectors, azimuth angle and elevation angle for each of these satellites are calculated. Various DOP values are calculated for two cases i.e. with all satellites in view and for best four satellites and tabulated in Table.2 and Table.3 respectively. Geometry of the all satellites in view is represented as Sky plot in Fig.3

Table 2. DOP computation with all satellites in view.

SV PRN	Position (Unit Vector representation)			Azimuth Angle (in Deg.)	Elevation Angle (in Deg.)
	X	Y	Z		
4	0.316199210	0.435193118	-0.8429857	192.97	16.86
8	0.018343402	0.790366768	0.61235928	19.89	63.35
11	-0.604302232	0.647242197	0.46464645	65.046	36.42
13	0.001384195	0.57490726	-0.8182174	172.43	21.28
17	0.632049540	0.75145293	0.18929308	268.54	62.91
25	-0.361358908	0.923876856	-0.1259813	119.20	50.78
26	0.6998733785	-0.12472686	0.70329258	313.71	10.75
27	-0.185419649	0.961945654	0.20069905	91.05	67.14
28	0.3071187889	0.3359944443	0.89038519	343.73	35.79
Computed DOP values are: GDOP =2.0376; PDOP=1.805; HDOP=1.711					

Fig.4 represents the DOP values with all satellites in view plotted as function of time. We notice two spikes in the plot indicating large GDOP values. First spike is around 06:00:00Hrs and the second one around 17:40:30Hrs. At these times, number of satellites in view above the mask angle has dropped to four. Arrangement of the satellites is such that they yield poor GDOP. Arrangement of the satellites at 17:40:30Hrs is represented in Fig.5. If

the elevation mask angle is made 5° , several more satellites are available and good GDOP can be achieved.

Best four satellites are selected based on their Azimuth angles. These four satellites should spread apart such that each of the satellite's azimuth angles is in one of the four quadrants. Larger the volume of the Tetrahedron which is formed by the unit vectors from the user to the satellites, lower the DOP value.

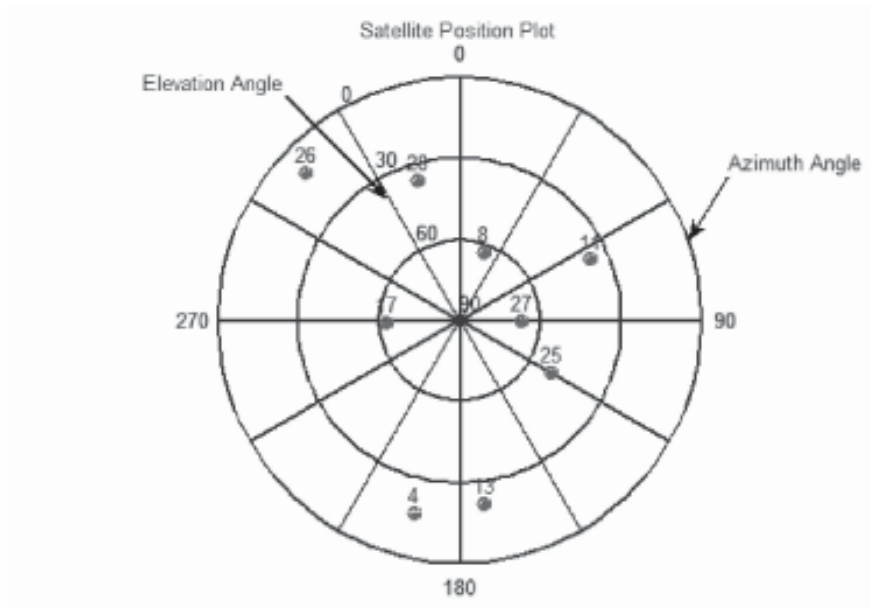


Figure 3. Sky plot of the all satellites in view GPS Time 02:00Hrs.

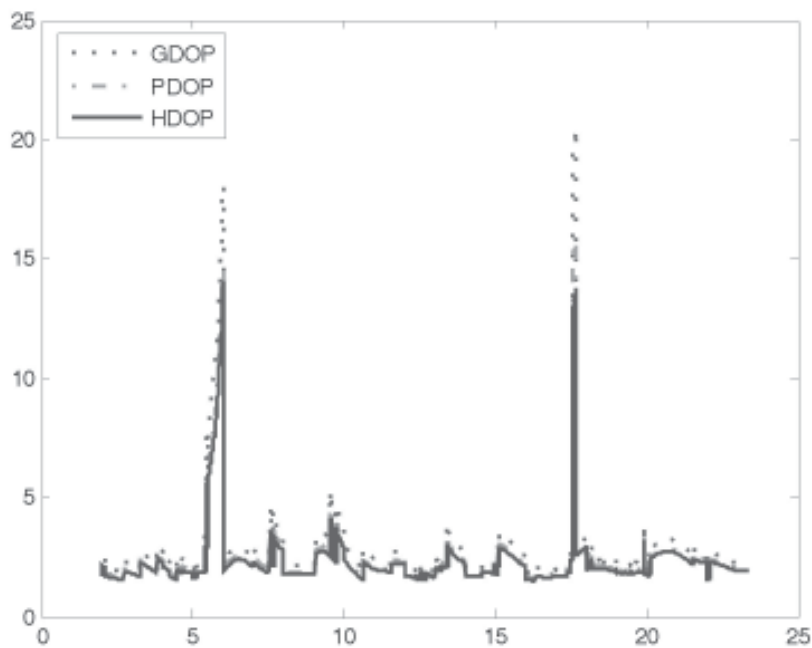


Figure 4. DOP value vs. GPS Time with all satellites in view.

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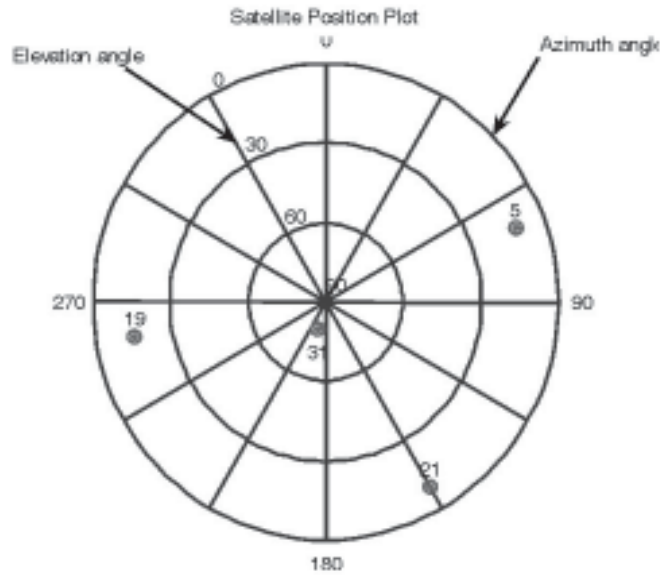


Figure 5. Arrangement of satellites at 17:40:30Hrs.

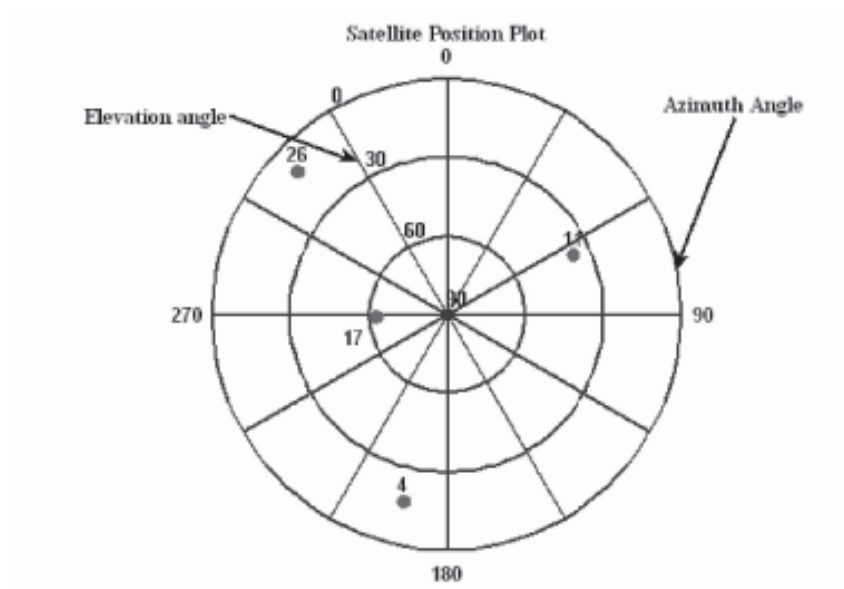


Figure 6. Sky plot of the best four satellites at GPS Time 02:00Hrs.

Table 3. DOP computation with best four satellites.

SV PRN	Position (Unit Vector representation)			Azimuth Angle (in Deg.)	Elevation Angle (in Deg.)
	X	Y	Z		
4	0.316199210	0.435193118	-0.8429857	192.97	16.86
11	-0.604302232	0.647242197	0.46464645	65.046	36.42
17	0.632049540	0.75145293	0.18929308	268.54	62.91
26	0.6998733785	-0.12472686	0.70329258	313.71	10.75
Computed DOP values are: GDOP = 2.55; PDOP=2.294; HDOP=2.103 Volume of the Tetrahedron : 0.1295 (Cubic mts)					

Sky plot of the best four satellites at GPS time 02:00Hrs is shown in Fig.6. GDOP (2.0376) obtained with all satellites in view is better than the GDOP (2.55) obtained with best four satellites.

For few epochs, GDOP and the Volume of the tetrahedron are tabulated in Table.4. Figure.7 represents the relation between the volume of the tetrahedron and the GDOP, computed for the day long data.

Table 4. Values of GDOP and Tetrahedron volume for few epochs.

GPS Time	Best four Satellites	GDOP	Tetrahedron Vol.(m ³)
2:00Hrs	4,11,17,26	2.55	0.1295
3:00Hrs	8,11,25,26	2.83	0.1039
4:00Hrs	4,15,27,28	2.86	0.090
5:00Hrs	2,8,17,26	2.72	0.115

Tips of the four receiver-satellite unit vectors form the tetrahedron structure. Volume of the tetrahedron is inversely related to the GDOP. In Fig.7, this relation is clearly represented. Larger the volume of the tetrahedron, lower GDOP value is obtained.

DOP Values computed for best four satellites are represented as function of time in Fig.8. We notice a large spike in DOP values just before 06:00:00 Hrs. This large spike is the effect of poor Satellite geometry. At this time, Satellites in view are SV2, SV4, SV17, SV28

with azimuth angles 311.96°, 20.97°, 55.4°, 122.35° respectively. Volume of the Tetrahedron formed by the tips of the four receiver-satellite unit vectors is 0.00972 m³. If the satellites azimuth angles are spread in all four quadrants, best GDOP can be obtained. In this case, the azimuth angles are not spread in all four quadrants that results in poor satellite geometry.

Similarly, we notice a second spike around 17:40:30Hrs which is also due to poor satellite geometry. Satellites in view are SV1, SV14, SV22, SV31 with azimuth angles 12.56°, 44.761°, 108.48°, 9.36° respectively. Volume of the Tetrahedron formed by the tips of the four receiver-satellite unit vectors is 0.00521 m³.

For few epochs, GDOP comparison for all satellites in view and best four satellites is presented in Table 5.

Table 5. GDOP Comparison.

GPS Time (Hrs)	GDOP	
	Best Four Satellites	All satellites in view
2:00	2.55	2.04
3:00	2.83	2.28
4:00	2.86	2.46
5:00	2.72	2.26
6:00	2.75	2.35
7:00	2.80	2.46
8:00	2.87	2.09
9:00	2.94	2.15
10:00	3.95	3.02

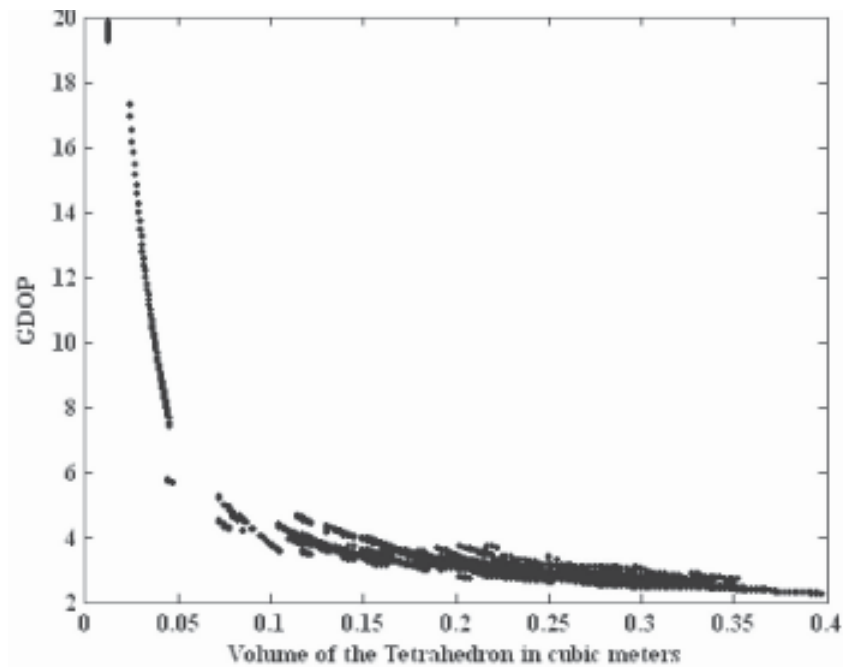


Figure 7. Relation between Tetrahedron volume and GDOP.

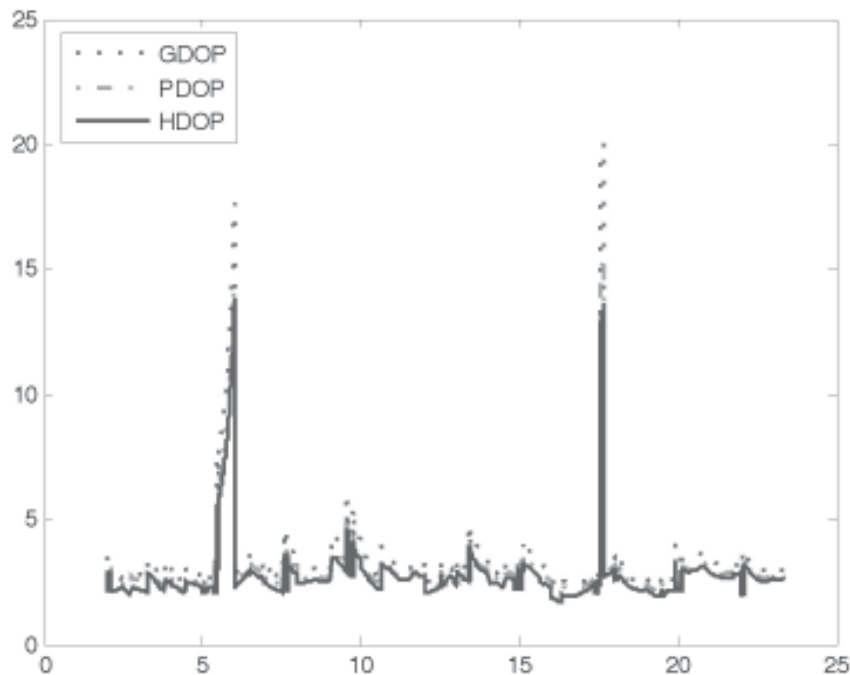


Figure 8. DOP value vs. GPS Time with best four satellites.

It is observed that, GDOP computed using all satellites in view is better than the GDOP computed by using best four satellites. There fore it is proposed that all the satellites in view can be used for GPS Navigation solution, which avoids the troublesome computation of selecting four satellites

CONCLUSIONS

The satellite geometry seen by the user from the Indian subcontinent is different from the higher latitude regions such as U S, Europe etc. The position accuracy of GPS system is affected by satellite geometry, which represents the geometric locations of the satellites as seen by GPS receiver. GPS requires minimum of four satellites to compute user position. Usually, when more number of satellites is in view, best four satellites are taken in user position computation in order to reduce the redundancy. However, with four satellites, best geometry is obtained when one of the satellites is at the zenith and remaining three forms an equilateral triangle and all the four together forms a tetrahedron structure. In this paper, the number of satellites to be used for the best position computation is investigated by comparing the best GDOP value obtained with two different configurations i.e best four satellites configuration and all satellites in view configuration. This analysis is particularly useful for precise user position computation over the Indian subcontinent. It is found that, GDOP computed using all satellites in view is better than the GDOP computed

using best four satellites. There fore it is proposed that all the satellites in view can be used for GPS navigation solution, which avoids the troublesome computation of selecting four satellites. With best four satellites, minimum GDOP value obtained is 2.234 compared to GDOP obtained with all satellites in view is 1.89. From the daylong observations, it is found that for the civil aviation applications and precise surveying purposes, the GDOP obtained due to all satellites in view configuration is suggested.

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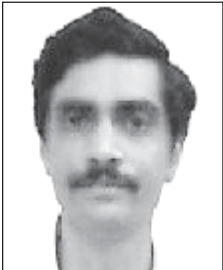
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