Weighted Quasi-optimal and Recursive Quasi-optimal Satellite Selection Techniques for GNSS

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Outline

- Introduction
- Dilution of Precision (DOP)
- Fast satellite selection techniques
- Quasi-optimal technique
- Recursive Quasi-optimal technique
- Weight functions
- Results and Discussion
- Conclusion

Introduction

- Global Positioning System (GPS) –gives 3D user position.
- GPS was approved for flight operations in 1993.
  - It could not meet the safety and reliability requirements of aviation.
- Therefore, GPS is augmented to improve Required Navigation Performance (RNP).
- ICAO standardized three augmentation system – SBAS, GBAS and ABAS.
- At present the SBAS systems such as WAAS (U.S.A), EGNOS (Europe), GAGAN (India), Beidou (China), and MTSAT (Japan) are operational.
- The performance of these systems are effected by several errors.

GPS Errors

Positional accuracy is limited by several factors :

- **Ionospheric time delay**
- **Tropospheric time delay**
- **Multipath effects**
- **Ephemeris error**
- **Receiver measurement noise**
- **Instrumental biases**
- **Satellite and Receiver clock errors**

Dilution of Precision

- **Accuracy of navigation solution depends not only on mitigation of GNSS errors but also on visible satellite geometry.**
- **Measure of instantaneous geometry is DOP (Dilution of Precision) factor.**
- **A poor geometry amplifies position error.**

Relation of DOP with position Error

- **The effect of all the error sources on pseudorange measurement can be combined and this combined error is referred to as User Equivalent Range Error (UERE).**

$$\sigma_{UERE} = \sqrt{\sigma^2_{x_1} + \sigma^2_{x_2} + \sigma^2_{x_3} + \cdots\cdots\cdots \sigma^2_{x_n}}$$

- **where,** $\sigma^2_{x_1}, \sigma^2_{x_2}, \sigma^2_{x_3}, \cdots\cdots\cdots \sigma^2_{x_n}$ **contribute to various sources of errors.**
- **The error in the positional accuracy can be determined by using the parameter Dilution of Precision (DOP).**

$$Position\ Error = UERE \times DOP$$

Computation of DOP and DOP components

- User position in ECEF coordinates (xu, yu, zu).
- All visible satellites positions in ECEF coordinates (Xsi,ysi, zsi) ad respective pseudoranges.
- where, 'A' is information matrix. from which Covariance matrix is obtained.

$$A = \begin{bmatrix} \frac{x_u - x_{s_1}}{\rho_1} & \frac{y_u - y_{s_1}}{\rho_1} & \frac{z_u - z_{s_1}}{\rho_1} & 1 \\ \frac{x_u - x_{s_2}}{\rho_2} & \frac{y_u - y_{s_2}}{\rho_2} & \frac{z_u - z_{s_2}}{\rho_2} & 1 \\ . & . & . & . \\ . & . & . & . \\ \frac{x_u - x_{s_n}}{\rho_n} & \frac{y_u - y_{s_n}}{\rho_n} & \frac{z_u - z_{s_n}}{\rho_n} & 1 \end{bmatrix} = \begin{bmatrix} LOS_1 & 1 \\ LOS_2 & 1 \\ . & . \\ . & . \\ LOS_n & 1 \end{bmatrix}$$

$$\mathrm{cov}(x) = (A^T A)^{-1} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} & \sigma_{zt} \\ \sigma_{xT} & \sigma_{yT} & \sigma_{zT} & \sigma_{Tt} \end{bmatrix}$$

- Various DOP related parameters are calculated from the trace of the covariance matrix.
- Horizontal DOP (HDOP)= $\sqrt{\sigma_{xx}^2 + \sigma_{yy}^2}$ Vertical DOP (VDOP)=σ_{ZZ}
- Position DOP (PDOP)=$\sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2}$ Time DOP (TDOP)=σ_{Tt}
- Geometric DOP (GDOP)= $\sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2 + \sigma_{Tt}^2}$

- DOP Estimation techniques - Significance - Satellite selection.

Satellite selection techniques

- GBAS applications : Geometry screening with MIEV as deciding factor play vital role to determine the satellite subsets that are safe to use for navigation solution.
- Geometry screening (nc4) - computational load.
- But the measure of instantaneous geometry (i.e. DOP) must be evaluated as well.
- DOP amplifies the position error.
- Lower the DOP values better the positional accuracy.

DOP Estimation Techniques

Prominent Conventional techniques - salient features and limitations

S.No.	DOP Estimation Technique	Salient features and limitations
1.	Combinations Method	• A minimum of 4 and maximum of 'n-1' visible satellites. • Huge computational load. • Long operation time and not practical in real-time applications.
2.	Highest Elevation Satellite Selection Technique	• A minimum of 4 Satellites Vehicles (SVs). • Selections of more than 4 SVs depends on elevation of total visible satellites. • Less computation load. • Only Satellites at higher elevation are used. • Satellites at low elevation that can contribute to better geometry are not included.
3.	Kihara's Maximum Volume Method	• Only Four satellites. • Selects only four SVs for DOP estimation. • Limited performance as technique is based on tetrahedron volume.
4.	Four Step Satellite Selection Technique	• Only Four satellites • Selects only four SVs for DOP estimation. • Limited performance as technique is based on tetrahedron volume.

Comparison of FLOPs for combinations method

Total no. of available satellites	No. of satellites in a subset=4	No of satellites in subset=5	No of satellites in subset=6	No of satellites in subset=7
9	$9c_4$=126 mul=360 Add=383 Tot=743	$9c_5$=126 mul=470 Add=497 Tot= 967	$9c_6$=84 mul=592 Add=621 Tot=1213	$9c_7$=36 mul=728 Add=759 Tot=1487
10	$10c_4$=210 mul=436 Add=463 Tot=899	$10c_5$=252 mul=565 Add=596 Tot=1161	$10c_6$=210 mul=706 Add=740 Tot=1446	$10c_7$=120 mul=861 Add=898 Tot=1759
11	$11c_4$=330 mul=520 Add=550 Tot=1070	$11c_5$=462 mul=670 Add=705 Tot=1375	$11c_6$=462 mul=832 Add=871 Tot=1703	$11c_7$=330 mul=1008 Add=1050 Tot=2058
12	$12c_4$=495 mul=612 Add=645 Tot=1257	$12c_5$=792 mul=785 Add=824 Tot=1609	$12c_6$=924 mul=970 Add=1014 Tot=1984	$12c_7$=792 mul=1169 Add=1217 Tot=2386

Necessity of fast satellite selection techniques

- **Geometry screening to determine the satellite subsets that are safe to use for navigation solution with less computational load.**
- **Due to interoperability of GNSS,**
  - **More no of GNSS satellites are available.**
  - **Receivers with more number of channels are being designed.**
- **In view of this, two fast satellite selection techniques:**
- ***Quasi-optimal***
- ***Recursive Quasi optimal***
- **These techniques are analyzed using suitable weight functions for GNSS.**

Quasi-optimal technique

- The method involves the computation of cost function based on the line-of-sight vectors.

$$R = \begin{pmatrix} los_1 \\ los_2 \\ los_3 \\ \vdots \\ \vdots \\ los_n \end{pmatrix} \qquad G = RR^T = \begin{pmatrix} \cos\alpha_{11} \cos\alpha_{12} \ldots\ldots \cos\alpha_{1n} \\ \cos\alpha_{21} \cos\alpha_{11} \ldots\ldots \cos\alpha_{2n} \\ \vdots \quad \vdots \quad \ddots \quad \vdots \\ \cos\alpha_{n1} \quad \cos\alpha_{n2} \ldots\ldots \cos\alpha_{nn} \end{pmatrix}$$

- Cost function - The cost function indicates that the cost is highest if the two vectors are nearly co-linear and lowest when perpendicular.

$$CF_i = \sum_{j=1}^{n} \cos 2\theta_{ij} = \sum_{j=1}^{n} (2\cos^2(\theta_{ij}) - 1) \qquad CF_i = \max\{CF_1, CF_2, \ldots\ldots, CF_n\}$$

- The row and column corresponding to the maximum cost are eliminated from direction cosine matrix. This will aid in removal of satellite with highest cost.

Recursive Quasi-optimal technique

- For 'n' visible satellites at an epoch, the GDOP is calculated for nC_{n-r} $(r = 1)$ combinations/subsets
- The co-factor matrix is defined only once at an epoch for the number of visible satellites 'n' and is given as, $Q_n = A^T A$
- nC_{n-1} subsets are generated
- Now the satellite which is not included in the subset out of 'n' satellites is identified and the corresponding satellite's LOS vector is given as, $L_i = \left[(x_i, y_i, z_i), 1 \right]$
- Now compute $L_i^T L_i$ and subtract from cofactor matrix Q_n , the trace of resultant matrix gives GDOP^2.
- The above two steps are implemented for all the subsets generated in nC_{n-1}
- The total number of iterations at an epoch in this technique are $n - k_{sb}$
- k_{sb} is the desired number of satellites in a subset.

Weight Functions

Elevation angle:

- **Cosine function of satellite elevation angle, which is widely used for calculation of accuracy of GPS measurements, is considered and given as (Jin et al, 2005),**

$$W_{EL_i} = \cos^2(\theta_{el})$$

Combination of elevation angle, signal strength and multipath:

- **Impact of atmosphere, multipath and orbit error can affect the signal strength and is given as (Wang et al, 2009),**

$$W_{ELCNR_i} = \frac{\theta_{el_i}}{\theta_{el_{\max}}} + \alpha_m \cdot \frac{CNR_i}{CNR_{\max}}$$

$\theta_{el_{\max}}$: Maximum elevation angle among the visible satellites at an epoch (deg.)

$CNR_{\max}$: Maximum signal strength among the visible satellites at an epoch

α_m : Multipath scaling factor

Multipath

- Fig. shows typical multipath scenario at antenna 'A1' due to reflector.

- Elevation and azimuth angles of direct signal are denoted as (θ_{eld}, ϕ_{azd} and for the reflected signal θ_{elr}, ϕ_{azr} are used.

- Signal power of multipath signal as a function of reflection coefficient and is given as,

$$R_{coef} = \frac{10^{\left(\frac{(C/N_0)_{\max}}{20}\right)}}{10^{\left(\frac{(C/N_0)_i}{20}\right)}}$$

Where, C/N_0: GPS signal strength in dB-Hz

- Typical GPS receiver,
  - *Minimum 'C/N_0' of 28-32 dB-Hz and*
  - *Maximum 'C/N_0' of 50-51 dB-Hz*

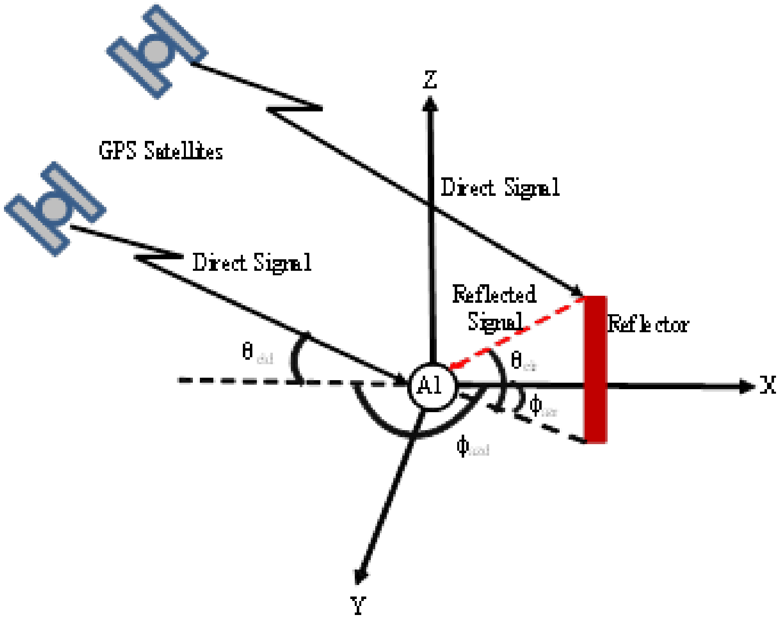


Fig. Illustration of multipath scenario

- **Multipath scaling factor as a function of reflection coefficient**

$$\alpha_m = \frac{\sqrt{R_{coef}} - 1}{\sqrt{R_{coef}} + 1}$$

Weighted Quasi-optimal and Recursive-quasi optimal techniques

- **Two weight functions -** W_{EL_i} **and** W_{ELCNR_i}
- **The weighted quasi-optimal technique is given as,**

$$WCF_i = W_i \sum_{j=1}^{n} \cos 2\theta_{ij} = W_i \sum_{j=1}^{n} (2\cos^2\left(\theta_{ij}\right) - 1)$$

- **The weighted Recursive quasi-optimal technique is given as**

$$Q^w_{k-1,i} = Q^w_k - W_g L_i^T L_i$$

- **Modified the weight function, which is a combination of elevation angle, signal strength and multipath** (W_{ELCNR})

$$W_{ELCNR_i} = \frac{\theta_{el_i}}{\theta_{el_{\max}}} + (1+\alpha_m).\frac{CNR_i}{CNR_{\max}}$$

- *Reflection coefficient will be '1' for multipath free signal, then* α_m *becomes zero, this will not affect the generality of Eq.*

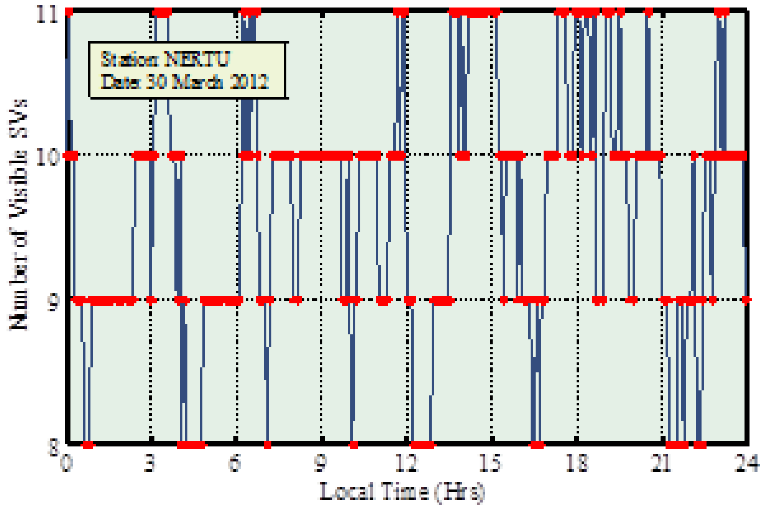
Data acquisition and processing

- The weighted quasi-optimal and recursive quasi-optimal techniques are evaluated for GPS constellation and also for combined GPS and GLONASS constellations.
- The GPS data is obtained from the receiver (make: Novatel, model: DL4 plus) located at Research and Training Unit for Navigational Electronics (17.29° N, 78.51° E), Hyderabad, India.
- GPS and GLONASS data is obtained from the receiver (make: Leica, model: GRX1200GGPRO) located at National Geophysical Research Institute (17.30° N, 78.55° E), Hyderabad, India.
- Two days typical data one corresponds GPS only receiver (30th March 2012) and the other one corresponds to GPS plus GLONASS data (20th April 2012) are used for the analysis.

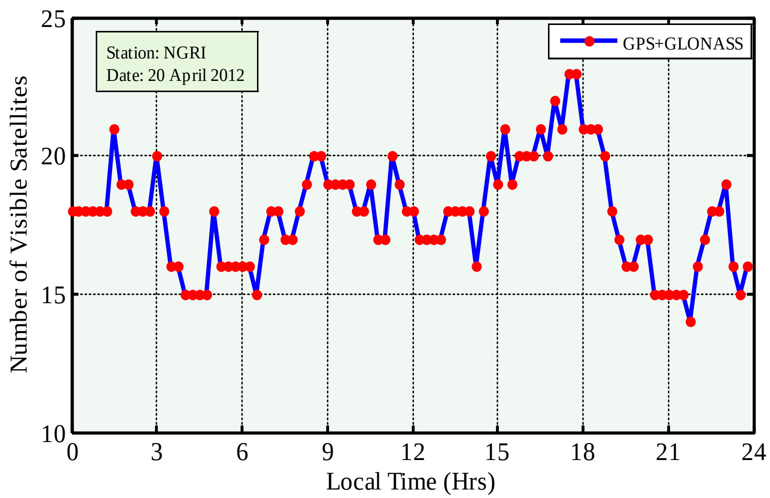
Results and Discussion

Satellite Visibility GPS and GLONASS

- Fig.2 shows the total number of satellites visible over NERTU and NGRI stations, Hyderabad.
- Number of SVs is varying from a minimum of 8 to maximum of 11 at NERTU (Fig.2a) and minimum of 14 to maximum of 23 at NGRI (Fig.2b).
- As the minimum number of SVs visible is 8, the subset with seven satellites is considered for DOP estimation (Fig.2a).
- As the minimum number of SVs visible is 14, the subset with thirteen satellites is considered for DOP estimation.



(a)



(b)

Fig.2 Number of visible SVs with respect to local time at a) NERTU and b) NGRI

Comparison of Quasi-optimal & Recursive Quasi-optimal (GPS Constellation)

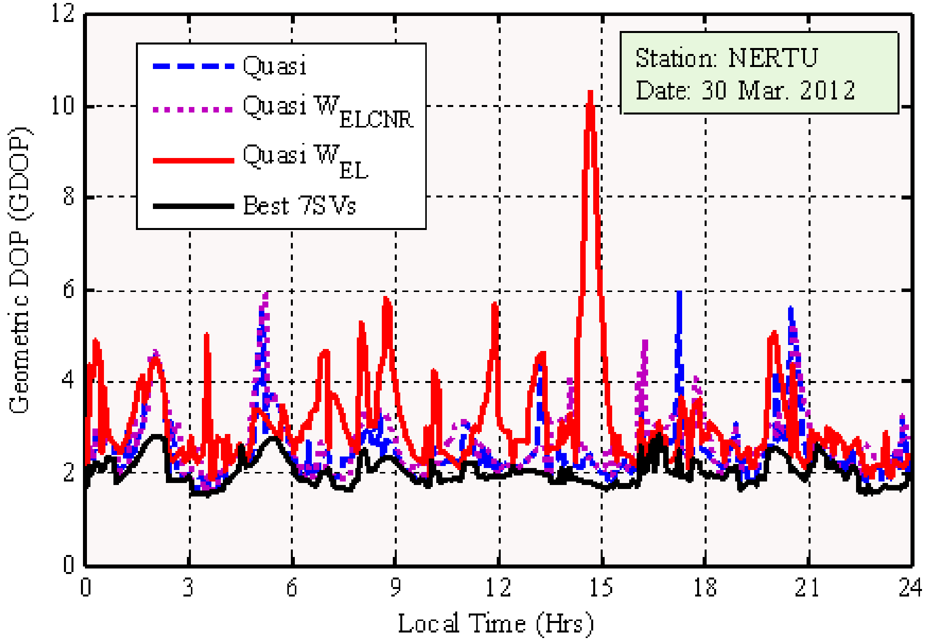
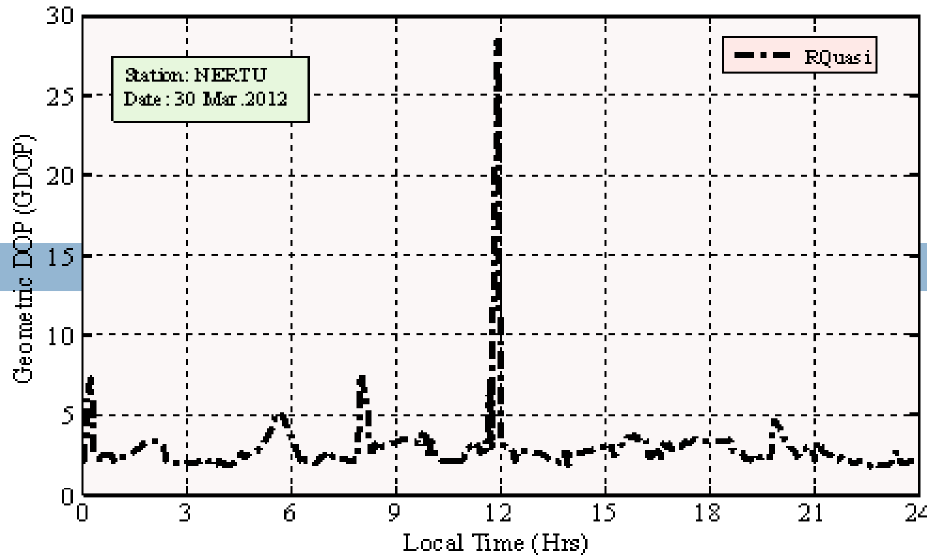
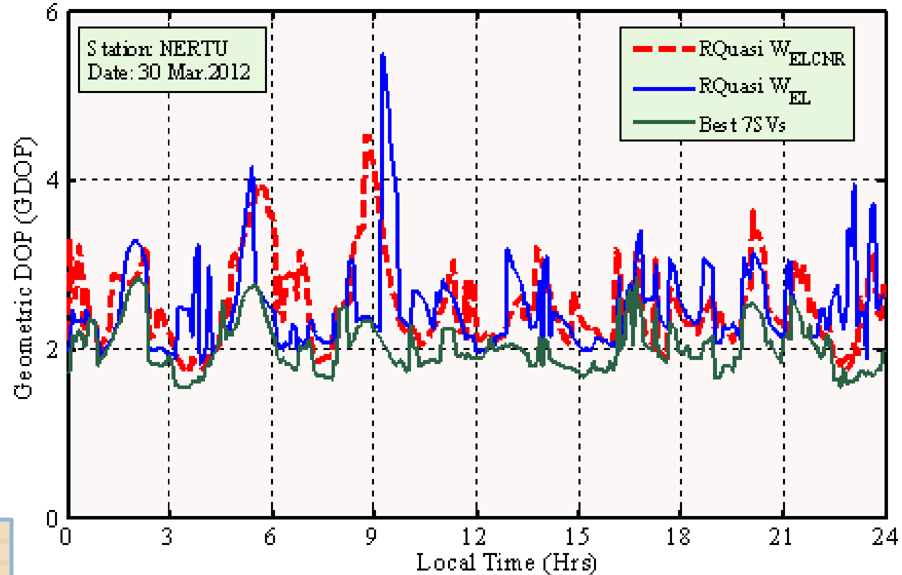


Fig. GDOP variations due to Best-7SVs, quasi-optimal and weighted quasi-optimal



(a)



(b)

Fig. GDOP variations due to (a) Recursive quasi-optimal (b) Weighted recursive quasi-optimal techniques and Best-7 SVs at NERTU

Recursive-quasi optimal - GDOP varies from a minimum of 1.72 to a maximum of 28.30 (11.92 Hrs) : W_{ELCNR} -(4.51);

Comparison of Quasi-optimal and Recursive Quasi-optimal (GPS constellation)

Table. Minimum, maximum, mean and standard deviation of GDOP for Quasi-optimal technique (30th Mar. 2012)

S.No.	Quasi-optimal technique (Date:30th Mar. 2012)	GDOP			
		Minimum	Maximum	Mean	Standard deviation
1.	Quasi-optimal	1.60	5.93	2.50	0.69
2.	Quasi-optimal with W_{EL}	1.89	10.29	3.11	1.15
3.	Quasi-optimal with W_{ELCNR}	1.59	5.90	2.66	0.68

Table Minimum, maximum, mean and standard deviation of GDOP for recursive quasi-optimal technique (30th Mar. 2012)

S.No.	Recursive Quasi-optimal (RQuasi) technique (Date:30th Mar. 2012)	GDOP			
		Minimum	Maximum	Mean	Standard deviation
1.	Recursive Quasi-optimal	1.72	28.31	2.89	1.91
2.	Recursive Quasi-optimal with W_{EL}	1.83	5.47	2.50	0.52
3.	Recursive Quasi-optimal with W_{ELCNR}	1.72	4.51	2.51	0.52

Comparison of Quasi-optimal & Recursive Quasi-optimal (GPS constellation)

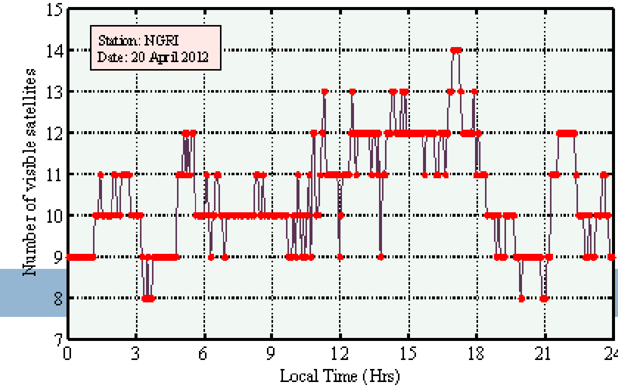


Fig. Illustration of Number of Visible SVs on 20th Apr. 2012

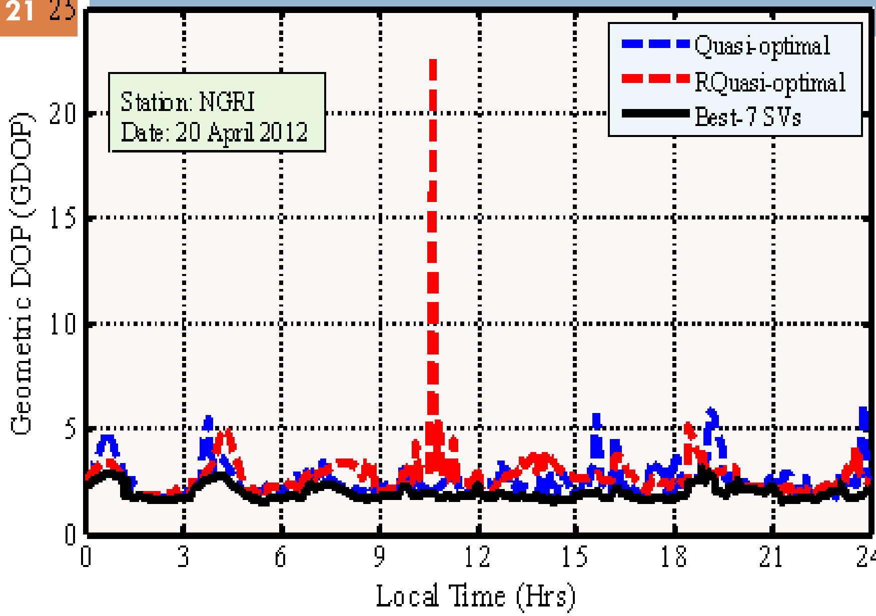


Fig. Variations in GDOP with respect to local time due to (a) Best-7 SVs (b) Quasi-optimal and (c) Recursive Quasi-optimal for GPS constellation on 20 Apr.2012

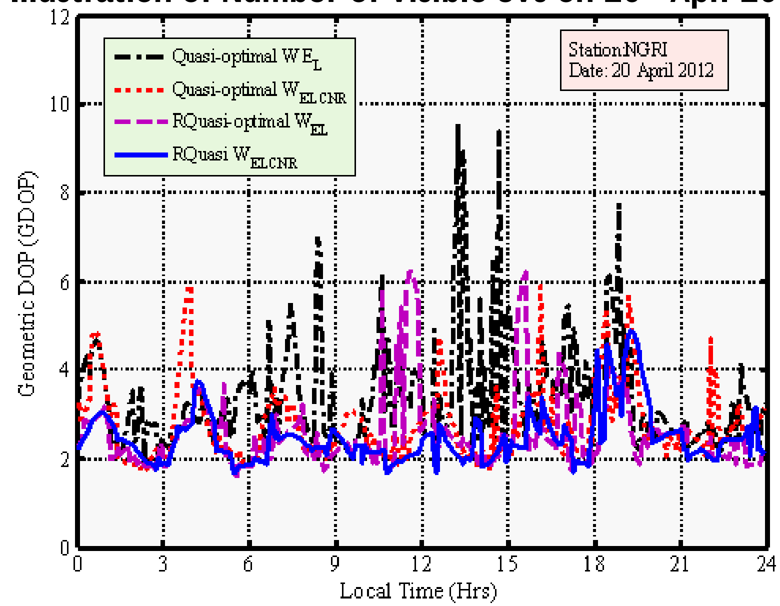


Fig. Variations in GDOP with respect to local time due to weighted Quasi-optimal and Recursive Quasi-optimal for GPS constellation on 20th April 2012

Table Minimum, maximum and mean of GDOP for weighted quasi-optimal and recursive quasi-optimal techniques for GPS constellation (20th April 2012)

GDOP	Weighted Quasi-optimal		Weighted Recursive Quasi-optimal	
	W_{EL}	W_{ELCNR}	W_{EL}	W_{ELCNR}
Minimum	1.89	1.66	1.50	1.68
Maximum	9.48	5.89	6.21	4.87
Mean	3.38	2.78	2.57	2.46

It is observed that at 10.6 Hrs, the GDOP estimation due to recursive quasi-optimal with weight functions W_{EL} and W_{ELCNR} are 5.7 and 2.16 respectively.

And due to quasi-optimal technique with weight functions W_{EL} and W_{ELCNR} are 6.17 and 2.15 respectively.

Comparison of Quasi-optimal & Recursive Quasi-optimal (GPS +GLONASS constellations)

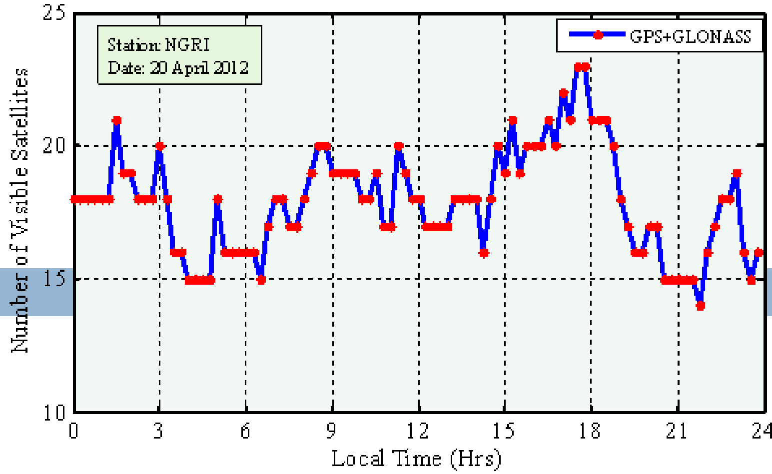


Fig. Number of Visible SVs (GPS+GLONASS) (20th Apr. 2012)

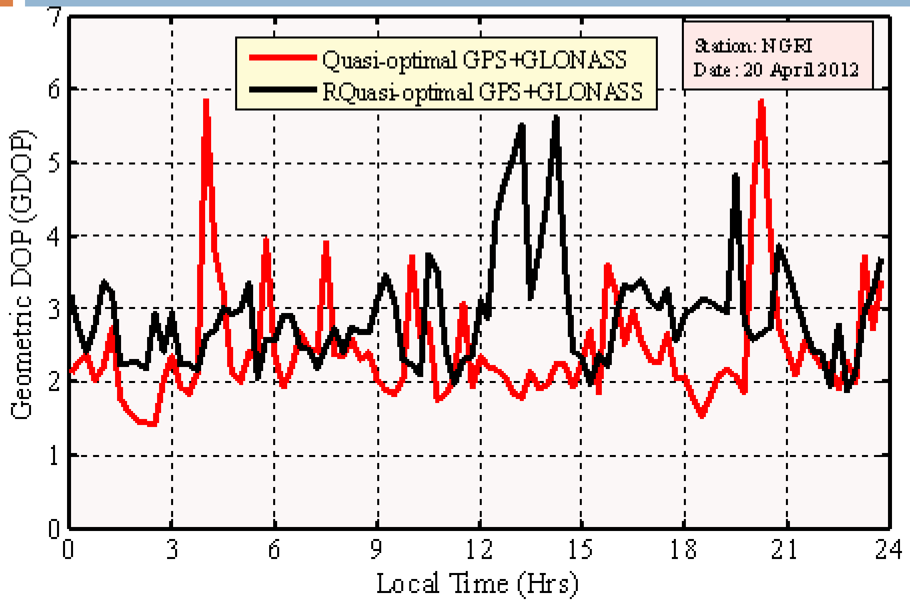


Fig. Variations in GDOP due to combined GPS and GLONASS (20th April 2012)

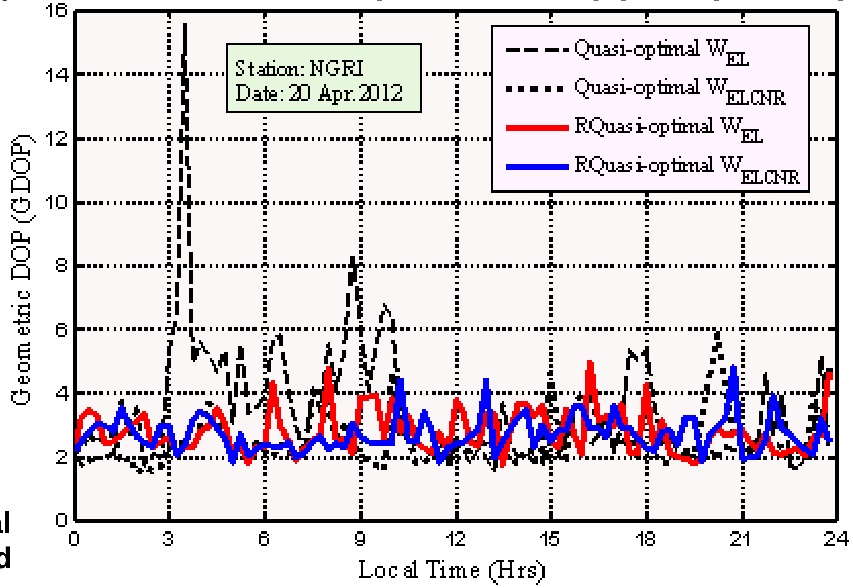


Fig. Variations in GDOP with respect to local time due to weighted Quasi-optimal and Recursive Quasi-optimal techniques for combined GPS and GLONASS.

Table Minimum, maximum and mean of GDOP for weighted quasi-optimal and recursive quasi-optimal techniques for dual constellation (GPS and GLONASS)

GDOP	Weighted Quasi-optimal		Weighted Recursive Quasi-optimal	
	W_{EL}	W_{ELCNR}	W_{EL}	W_{ELCNR}
Minimum	1.57	1.46	1.75	1.81
Maximum	15.5	5.83	4.92	4.75
Mean	3.37	2.56	2.78	2.69

Conclusions

- The recursive quasi optimal technique maximum GDOP observed for GPS constellation on a typical day (30th March 2012) is 28.31. When W_{ELCNR} is used in conjunction with the technique the maximum GDOP noticed is 4.51.
- Significant improvement in DOP is also noticed due to W_{ELCNR} in case of combined GPS and GLONASS.
- The maximum GDOP value observed on 20th April 2012 due to recursive quasi-optimal technique is 5.60 and with weight functions W_{ELCNR} the maximum GDOP is 4.75.
- Significant improvement is achieved when W_{ELCNR} is used as the weight function with recursive quasi-optimal technique.

Thank you

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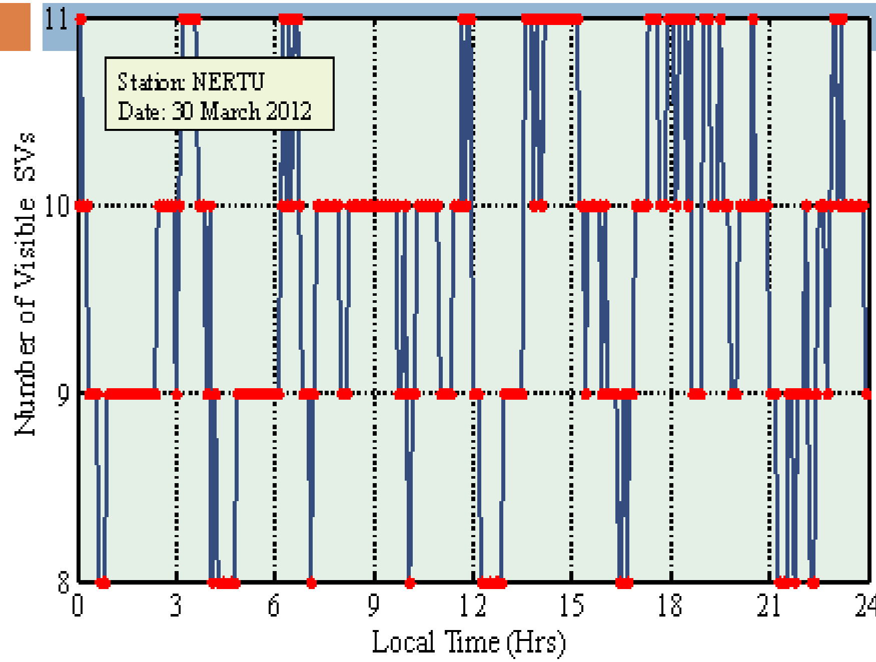
DOP components

- Various DOP components are
- **Horizontal DOP (HDOP)** is the effect of satellite geometry on the horizontal component of the positioning accuracy.
- **Vertical DOP (VDOP)** represents the satellite geometry effect on the vertical component of the positioning accuracy
- **Position DOP (PDOP)** represents the satellite geometry effect of both the horizontal and vertical components of the positioning accuracy.
- **Time DOP (TDOP)** represents the effect of satellite geometry on time.
- **Geometric DOP (GDOP)** represents the combined effect of HDOP, VDOP and TDOP.

Results and Discussions

Comparison of GDOP for Combinations method -(nc4, nc5, nc6, nc7)



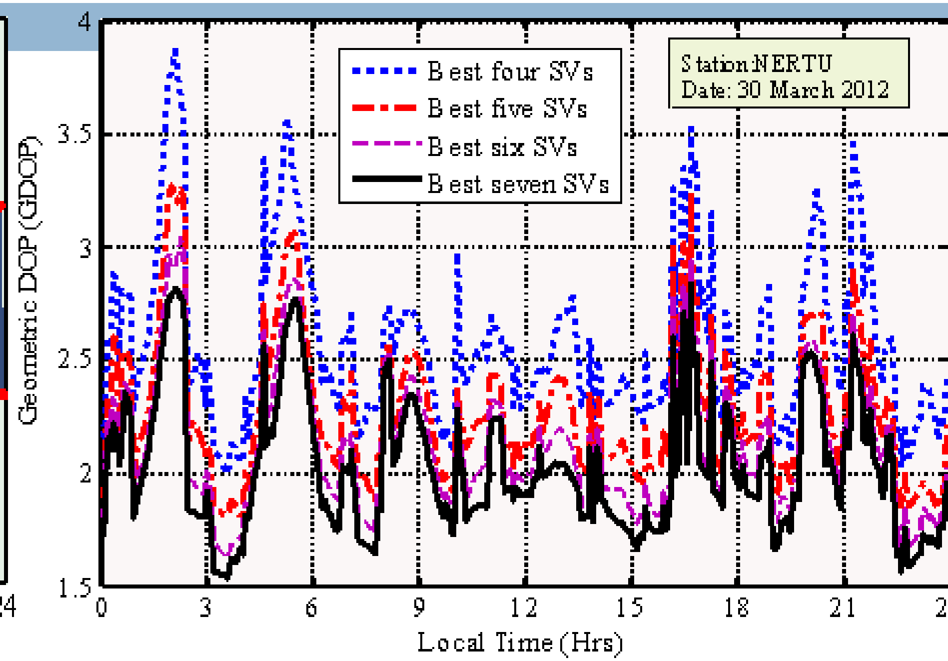


Fig. Variations in GDOP for Best four, five, six and seven SVs

Fig. Number of Visible SVs with respect to local time

Table Comparison of GDOP for Best 'four', 'five', 'six' and 'seven' SVs

S.No.	Combinations Method (Date: 30th March 2012)	Minimum	Maximum	Mean	Standard deviation
1.	Best four SVs	1.99	3.87	2.57	0.37
2.	Best five SVs	1.81	3.27	2.27	0.32
3.	Best six SVs	1.62	3.04	2.20	1.62
4.	Best seven SVs	1.53	2.83	2.11	0.30

Comparison of Quasi-optimal & Recursive Quasi-optimal (GPS constellation)

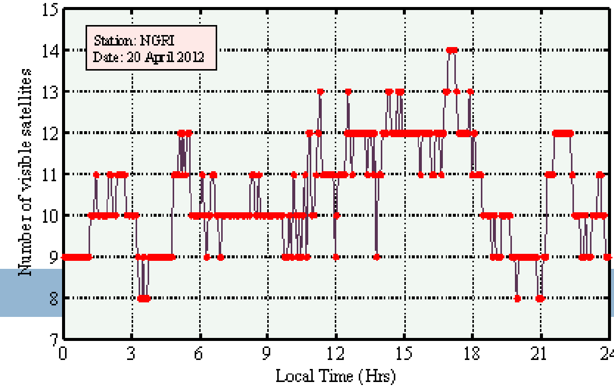


Fig. Illustration of Number of Visible SVs on 20th Apr. 2012

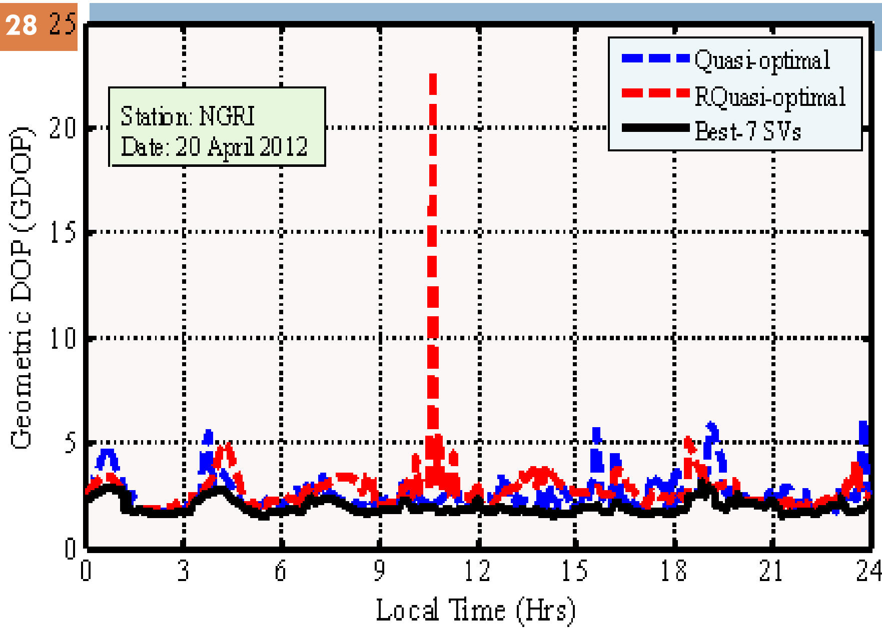


Fig. Variations in GDOP with respect to local time due to (a) Best-7 SVs (b) Quasi-optimal and (c) Recursive Quasi-optimal for GPS constellation on 20 Apr.2012

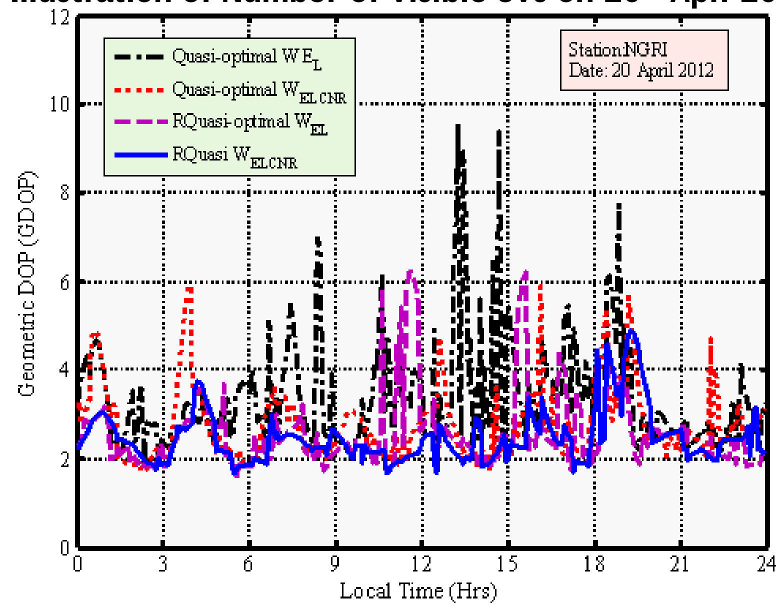


Fig. Variations in GDOP with respect to local time due to weighted Quasi-optimal and Recursive Quasi-optimal for GPS constellation on 20th April 2012

Table Minimum, maximum and mean of GDOP for weighted quasi-optimal and recursive quasi-optimal techniques for GPS constellation (20th April 2012)

GDOP	Weighted Quasi-optimal		Weighted Recursive Quasi-optimal	
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Comparison of Quasi-optimal & Recursive Quasi-optimal (GPS +GLONASS constellations)

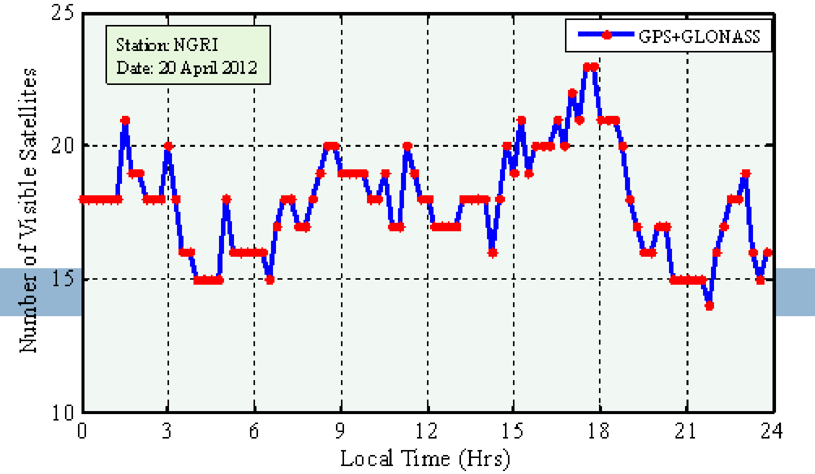

Fig. Number of Visible SVs (GPS+GLONASS) (20th Apr. 2012)

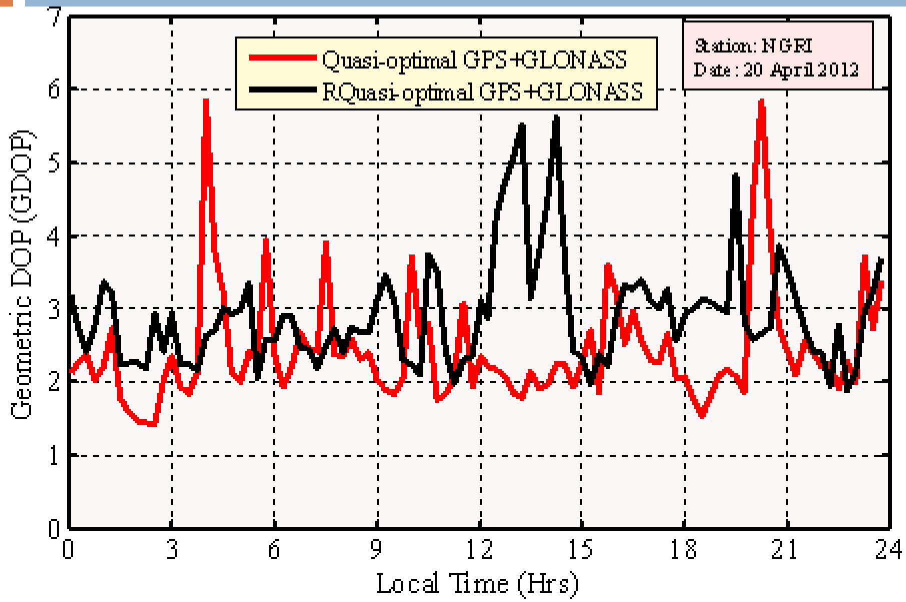

Fig. Variations in GDOP due to combined GPS and GLONASS (20th April 2012)

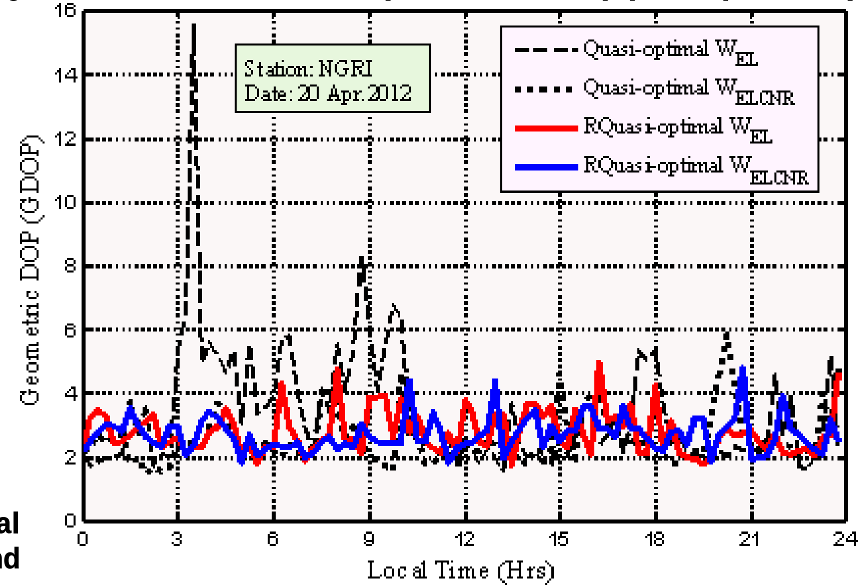

Fig. Variations in GDOP with respect to local time due to weighted Quasi-optimal and Recursive Quasi-optimal techniques for combined GPS and GLONASS.

Table Minimum, maximum and mean of GDOP for weighted quasi-optimal and recursive quasi-optimal techniques for dual constellation (GPS and GLONASS)

GDOP	Weighted Quasi-optimal		Weighted Recursive Quasi-optimal	
	W_{EL}	W_{ELCNR}	W_{EL}	W_{ELCNR}
Minimum	1.57	1.46	1.75	1.81
Maximum	15.5	5.83	4.92	4.75
Mean	3.37	2.56	2.78	2.69

Computations required for combinations method (nc4, nc5, nc6 and nc7)

- Total number of multiplications required for an iteration in the computation of GDOP

$$= (1/3)p^3 + p^2 + (n^2 - (1/3))p$$

- Total number of additions required for an iteration in the computation of GDOP

$$= (1/3)p^3 + 0.5p^2 + (n^2 + n(5/6))p$$

Where n is the total number of visible satellites and
p is the number of satellites in a subset

UERE

- The effect of all the error sources on pseudorange measurement can be combined, and this combined error is referred to as the UERE. It is the root sum square of all the error components, all expressed in units of length (Grewal et al, 2001).
- $\sigma_{UERE} = \sqrt{\sigma^2_{x_1} + \sigma^2_{x_2} + \sigma^2_{x_3} + \cdots\cdots + \sigma^2_{x_n}}$ (16)
- Where, $\sigma^2_{x_1}, \sigma^2_{x_2}, \sigma^2_{x_3}, \cdots\cdots \sigma^2_{x_n}$ contributes to various sources of errors.

Ionization at 350 kms

- There is enough EUV rays from sun available at 350 km.
- There are enough neutral particles (atomic oxygen).
- X-rays produce ionization in the range of 75-90 km.
- Due to solar radiation (EUV) – when strike the gas molecule, they split – ionize and electron is set free.
- Though layer is named due to existence of ions. The free electrons effect the radiowaves.

Dual frequency GPS Receiver

- Dual frequency GPS receivers are not popular:
  1. The cost is high.
  2. Mounting of wide band antenna

RNP Parameters for Precision Approach

Table Satellite navigation performance requirements (ICAO, 2000)

Operation	Accuracy (95%)	Integrity (1-Risk)	Alert Limit	Time-to-Alert	Continuity (1-Risk)	Availability
Oceanic	12.4 nm	$1-10^{-7}$/hr	12.4 nm	2 min	$1-10^{-5}$/hr	0.9 to 0.99999
En route	2.0 nm	$1-10^{-7}$/hr	2.0 nm	1 min	$1-10^{-5}$/hr	0.9 to 0.99999
Terminal	0.4 nm	$1-10^{-7}$/hr	1.0 nm	30 sec	$1-10^{-5}$/hr	0.9 to 0.99999
NPA	20 m	$1-10^{-7}$/hr	0.3 nm	10 sec	$1-10^{-5}$/hr	0.9 to 0.99999
APVI	20 m (H) 20m (V)	$1-2\times10^{-7}$/ Approach	0.3 nm (H) 50 m (V)	10 sec	$1-8\times10^{-6}$/ 15sec	0.9 to 0.99999
APVII	16 m (H) 8 m (V)	$1-2\times10^{-7}$/ Approach	40 m (H) 20 m (V)	6 sec	$1-8\times10^{-6}$/ 15sec	0.9 to 0.99999
CAT.I	16 m (H) 4.0-6.0m (V)	$1-2\times10^{-7}$/ Approach	40 m (H) 10-15 m (V)	6 sec	$1-8\times10^{-6}$/ 15sec	0.9 to 0.99999
CAT.II	6.9 m (H) 2.0 m (V)	$1-10^{-9}$/ 15sec	17.3 m (H) 5.3 m (V)	1 sec	$1-4\times10^{-6}$/ 15sec	0.9 to 0.99999
CAT.III	6.2 m (H) 2.0 m (V)	$1-10^{-9}$/ 15sec	15.5 m (H) 5.3 m (V)	1 sec	$1-2\times10^{-6}$/ 30Sec (H) $1-2\times10^{-6}$/ 15Sec (V)	0.9 to 0.99999

LAAS Scenario - Architecture & Ionospheric Threat

- The figure below shows a typical LAAS scenario with ionospheric wave front and the table with typical values of threat space parameters.

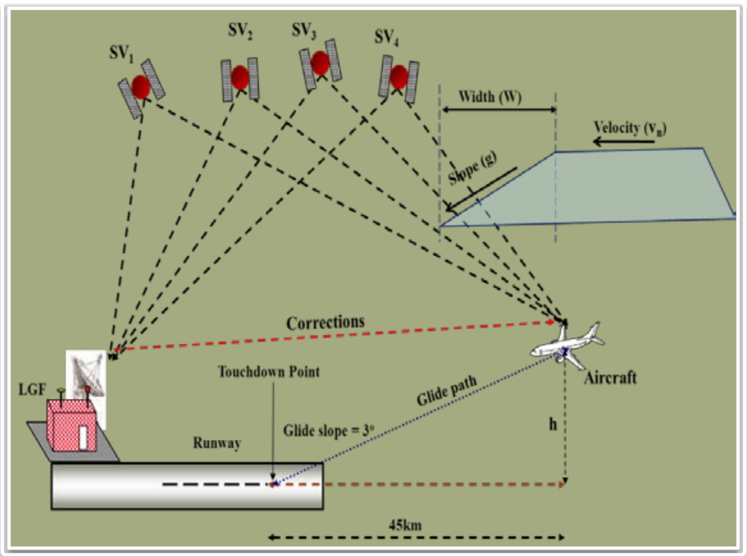

Fig. Illustration of typical LAAS scenario with wave front and Threat space parameters

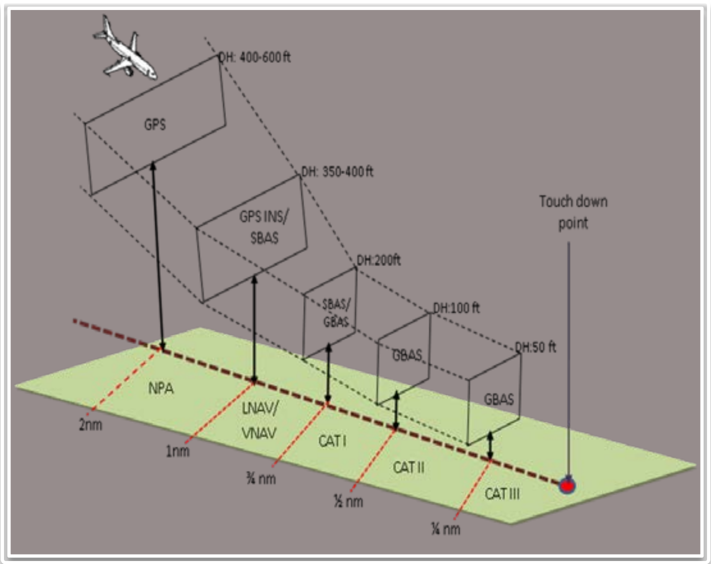

Fig. NPA and PA

Table. Typical range of ionospheric threat space parameters

S.No.	Parameters	Typical Range
1.	Spatial gradient	4 – 450 mm/km
2.	Velocity of ionospheric wave front (V_{iono})	0 – 750 m/s
3,	Width of ionospheric wave front (W_{iono})	3 – 250 km