J. Ind. Geophys. Union (October 2005)
Vol.9, No.4, pp.255-262

GPS Satellite and Receiver Instrumental Biases Estimation using Linear Adaptive Filter Algorithm

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ABSTRACT

The Category I (CAT I) Precision Approach (PA) requirements can be achieved by augmenting the Global Positioning System (GPS). The space based augmentation system (SBAS) in India is known as GPS And Geo Augmented Navigation (GAGAN). One of the prominent errors in GAGAN that limit the positional accuracy is instrumental biases. Calibration of these biases is particularly important in achieving the CAT I PA landings. In this paper, a new algorithm is proposed to estimate the instrumental biases by modelling the TEC using 4^{th} order polynomial. The algorithm uses values corresponding to a single station for a 12 day period and the results confirm the validity of the algorithm. The experimental results indicate that the estimation precision of the satellite-plus-receiver instrumental bias is of the order of ±0.17nsec. The observed mean bias error is of the order –3.638nsec and –4.71nsec for satellite 1 and 31 respectively. It is found that results are consistent over the period.

INTRODUCTION

Global Positioning System (GPS) is a satellite based positioning system based on radio ranging technique. GPS is designed and operated by DoD, USA. The GPS provides accurate three-dimensional position, velocity and timing information to users any where in the world. However, the accuracy of the standalone GPS system is limited by several errors such as ionospheric error, tropospheric error, clock error, multipath error and ephemeris error etc.,. Because of these errors, GPS navigation signals alone are not adequate to support CAT I PA landings. Therefore, GPS augmentation system is required to provide users with orbit, clock, and ionosphere corrections.

The first space based augmentation system (SBAS) was initiated by USA for providing coverage of Continental United States (CONUS) region. This augmentation system is called Wide Area Augmentation System (WAAS). The European Geo-stationary Navigation Overlay System (EGNOS) is being implemented by the European Space Agency since 1996 for the European countries and the MTSAT Satellite Augmentation System (MSAS) is being implemented by Japan. Canadian WAAS (CWAAS) is also at the advanced stage of its implementation and is expected to be ready by 2006. Countries such as Brazil, Mexico and China are also developing their own SBAS. Like in USA, the Airports Authority of India (AAI) has decided to implement an indigenous satellite based regional GPS augmentation system, known as GPS And Geo Augmented Navigation (GAGAN) as a part of the CNS/ATM requirements of civil aviation in India (Ramalingam 2002a). The GAGAN system for this purpose will be implemented jointly by the Indian Space Research Organization (ISRO) and AAI. The objectives of GAGAN are to provide the navigation performance parameters such as accuracy, integrity, time to alert, continuity and availability to the Global Navigation Satellite System (GNSS) users over the Indian service region (Ramalingam 2002b).

GAGAN architecture consists of i) Indian Reference Stations (INRESs) ii) Indian Mission Control Center (INMCC) iii) Indian Navigation Land Uplink Station (INLUS), iv) The GEO Payload and, v) User GNSS receivers (Fig.1).

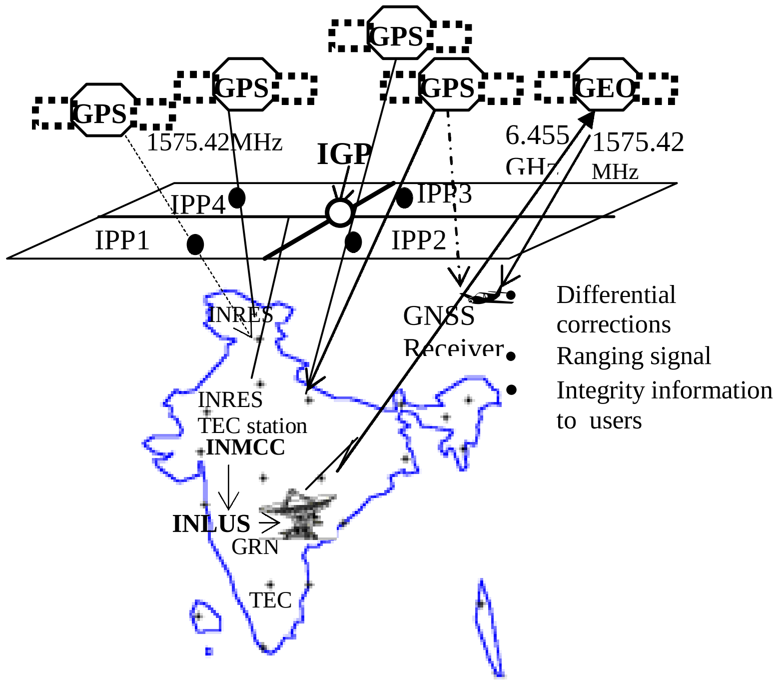

Figure 1. GAGAN architecture

Initial studies on placement of 20 TEC stations for Indian region are carried out by Sarma, Sasibhushana Rao & Venkata Rao (2000). Based on this, 20 TEC stations are placed at surveyed locations over widely separated geographical area in India. The networks of 20 TEC stations and INRESs receive and monitor the GPS signals for estimating the clock, ephemeris and ionospheric error corrections. The INRESs and TEC stations acquire broadcast ephemeris and pseudorange data from all the GPS and GEO satellites in view. Data from these stations are transmitted to the INMMC, where the validity of the signals from each satellite is assessed and corrections are computed. The INMCC consists of a mainframe computer and a host of secondary computers connected to a network of INRES and TEC stations. The INMMC also develop the ephemeris and clock information of the Geostationary Earth Orbiting Satellites (GEOs). All these data are packed into GAGAN message and is sent to the INLUS. The INLUS uplink this message on 6455.2 MHz to the GEOS that broadcast GPS like signals to the GNSS users. INMCC is collocated with the INLUS at Bangalore. One 40kg navigation payload with EIRP of 33.5 dBW is planned in the Indian Ocean Region (IOR) between the orbital location 48^0 to 100°E longitude through GSAT4 to meet the objectives of GAGAN (Kibe 2003).

Ionospheric delay is one of the prominent errors in the GAGAN that limit the positional accuracy. The ionospheric delay corrections are broadcast as vertical delay estimates at specified Ionospheric Grid Points (IGPs) in the predefined global IGP grid to suitably modify single frequency GPS receivers. The predefined global IGP grid consists of 1808 IGPS. For providing the ionospheric error corrections over the GAGAN service region, 60 IGPS are identified (Sarma, Sasibhushana Rao & Venkata Rao 2000). However, the estimation of the IGP delay, which is a function of TEC, is limited by instrumental biases. The instrumental bias is the difference of the propagation paths of L1 and L2 signals and is due to the circuitry in the GPS satellite and receiver hardware. Even though the bias error are of the order of ±10nsec it will become critical in SBAS (Brain, Wilson & Anthony 1999). Calibration of hardware biases is particularly important in augmented GPS systems where vertical accuracy of 4.5m is required for PA landings.

If the differential delay parameters are not calibrated, they propagate into the differential correction through the ionospheric models (Bishop & Mazzella 1995). The differential delays are environmentally dependent and hence time varying. In the case of hardware calibration, it will be difficult for the master station of the GAGAN located at Bangalore, India to continually monitor all the geographically distributed 20 TEC stations. Therefore, software calibration is to be used.

ESTIMATION OF THE SATELLITE AND RECEIVER BIASES

A new algorithm based on Coco et al. (1991) is proposed to estimate the instrumental biases by modelling the TEC using 4th order polynomial. This algorithm is an approximation of the steepest descent algorithm, which uses an instantaneous estimate of the gradient vector of a cost function. In this algorithm, the combined satellite and receiver differential delays are estimated using least-squares method. The vertical TEC at each Ionospheric Pierce Point (IPP) is represented as 4th order polynomial model in this algorithm. The inputs to the algorithm are azimuth, elevation angle of each satellite tracked, slant factor, slant TEC, IPP latitude and longitude. The slant TEC measurement (TEC_{sl}) made on GPS satellite at WRS is the sum of the real slant TEC, satellite differential delay (b_S) and receiver differential delay (b_R). The differential delay can be modeled as the sum of a receiver bias, a satellite transmitter bias, and a constant times the line-of sight ionospheric total electron content (TEC) (Gao & Liu 2002). The following three assumptions are made in implementing this algorithm.

i) The slant and vertical TECs are related by a constant obliquity factor,

ii) Satellite-plus-receiver (SPR) differential delays are assumed to be constant over several hours the TEC, at the IPP is represented by 4th degree polynomial and is represented as follows (Lao-Sheng Lin 2001).

$$TEC_v(\phi_m,\lambda_{cr}) = a_0 + a_1\phi_m + a_2\lambda_{cr} + a_3\phi_m^2 + a_4\lambda_{cr}^2 + a_5\phi_m\lambda_{cr} + a_6\phi_m^3 + a_7\lambda_{cr}^3 + a_8\phi_m^2\lambda_{cr} + a_9\phi_m\lambda_{cr}^2 + a_{10}\phi_m^4 + a_{11}\lambda_{cr}^4 + a_{12}\phi_m^3\lambda_{cr} + a_{13}\phi_m^2\lambda_{cr}^2 + a_{14}\phi_m\lambda_{cr}^3 \quad (1)$$

where $a_0, a_1, \ldots a_{14}$ are the unknown ionosphere model coefficients. ϕ_m and λ_{cr} are the IPP latitude and longitudes in geomagnetic coordinate system.

Modelling of instrumental biases

The biases and the vertical TEC can be modeled as (Ma & Maruyama 2003)

$$S(E)_{ik} \times TEC_{v\,i} + (b_{Si} + b_{Rk}) = TEC_{sl\,ik} \quad (2)$$

where

$TEC_{sl\,ik}$ = measured slant TEC from the receiver k to the satellite i,

E = elevation angle from the receiver j to the tracked satellite i,

$S(E)_{jk}$ = slant factor

TEC_{vi} = vertical TEC at the ionospheric pierce point due to the satellite i.

$b_{Si} + b_{Rk}$ = satellite-plus-receiver (SPR) differential delay

The algorithm is a linear adaptive filtering algorithm, This, in general, consists of two basic processes (Haykin 2003);

i) a filtering process, which involves computing the output of a linear filter in response to an input signal and generating an estimation error by comparing this output with a desired response

ii) an adaptive process, which involves the automatic adjustment of the parameters of the filter in accordance with the estimation error.

The combination of these two processes working together constitutes a feedback loop (Fig.2). The figure shows that a transversal filter, around which the least mean square algorithm is built; this component is responsible for performing the filtering process. The second component is mechanism for performing the adaptive control process on the tap weights of the transversal filter. The detailed structure of the transversal filter (Fig.3) consists of 3 basic elements, namely, a unit delay element, a multiplier and an adder.

The number of delay elements used in the filter determines the finite duration of its impulse response. The role of each multiplier in the filter is to multiply the tap input by a filter coefficient referred to as a tap weight. The combined role of the adders in the filter is to sum the individual multiplier outputs and produce an overall filter output.

The physical phenomenon is characterized by the two set of variables $TEC_{sl}(i)$ and $S(E)_{ik}(i)$,. The variable $TEC_{sl}(i)$ is observed at time i in response to the subset of variables $S(E)_{ik}(i)$, $S(E)_{ik}(i-1)$, $S(E)_{ik}(i-2), \ldots S(E)_{ik}(i-+M+1)$, applied as inputs. The $TEC_{sl}(i)$ is a function of the inputs $S(E)_{ik}(i)$, $S(E)_{ik}(i-1)$, $S(E)_{ik}(i-1), \ldots S(E)_{ik}(i-M+1)$. This functional relation ship is modeled as (Haykin, 2003),

$$TEC_{sl}(i) = \sum_{k=0}^{M-1} a_k b_{jk}(S(E)(i-k)) + \Pi(i) \quad (3)$$

$$\Pi(i) = TEC_{sl}(i) - TEC_v(n-1)S(E)(i) \quad (4)$$

$$\bar{TEC}_V(n+1) = \bar{TEC}_V(n) + 2\mu\Pi_n \bar{S(E)}(n) \quad (5)$$

where $a_0, a_{M-1,}$ and b_{jk} are unknown parameters of the model, $\bar{TEC}_V(n+1)$ is the tap weight vector adoption, m is the step size parameter and (Π_i) represents the measurement error.

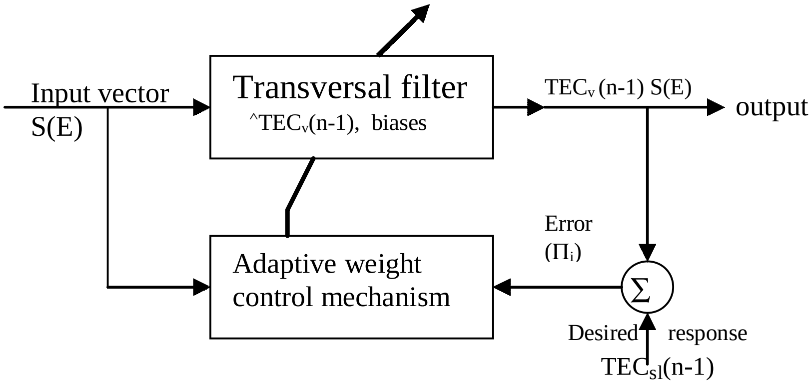

Figure 2. Block diagram of adaptive filter algorithm

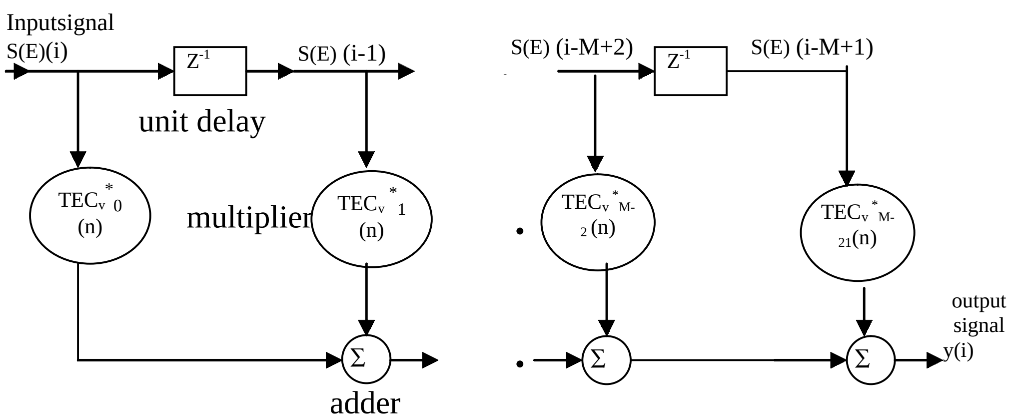

Figure 3. Detailed structure of the transversal filter components

DATA ACQUISITION AND PROCESSING

As a part of GAGAN setup, a Novtel make dual frequency GPS receiver is located at Hyderabad airport(17.431^{0}N, 78.453^{0}E), India. Several days of navigation and observation data in RINEX format were collected and analyzed. The navigation data file consists of 38 parameters. However, in our calculations only 23 parameters are used. Navigation data is available for every two hours. In between data is generated using standard formulae. Observation data file consists of C/A, P1 and P2 pseudoranges and L1 and L2 phases for all the visible satellites. From this information satellite position, elevation and azimuth angle of satellite, IPP local time, IPP latitude, longitude, geomagnetic latitude, geomagnetic longitude, slant factor, ionospheric time delay and slant TEC for all the visible satellites are estimated.

RESULTS AND DISCUSSION

Using the data corresponds to 12 days (1st July 2004 to 12 July 2004), the biases are estimated. Using the satellite elevation and azimuth information, for each satellite the IPP latitude and longitude are estimated. A mesh grid with a square grid spacing of 5^0 x 5^0 in latitude and longitude is assumed at an altitude of 350 km above the earth surface. In each 5^0 square grid, the number of IPPs available are determined. The instrumental biases are assumed to be constant over several hours in a particular mesh grid of 5^0 square grid size. The differential delay ($b_S + b_R$) and the 15 coefficients of the polynomial for all the 29 satellites that were visible from 1st July to 12th July 2004 were estimated for a particular 5^{0}square grid (17.431 ± 2.25^0, 78.4530 ± 2.25^0). In this particular grid the IPPs are due to 13 visible SVs (PRNs 1,4,6,8,10,13,15,16,21,24,25,27,31).

Table 1. SPR instrumental biases for the 12 day period for 13 satellites

SV PRN / Date	31	27	25	24	21	16	15	13	10	8	6	4	1
	SPR (nsec)												
July01	-4.16	-3.77	6.12	-3.99	2.2	4.9	6.05	0.59	-6.53	-5.1	2.1	-4.0	5.3
July02	-4.76	-3.93	6.40	-4.3	2.3	5.3	5.93	0.64	-6.90	-4.5	2.3	-3.9	5.7
July03	-3.56	-2.62	7.10	-3.92	4.93	4.49	5.35	-1.16	-6.17	-3.48	0.58	-3.71	-0.03
July04	-5.06	-3.85	6.01	-	2.31	5.97	4.76	-0.91	-6.21	-4.42	0.74	-	1.52
July05	-4.11	-2.96	5.01	-4.38	3.36	4.89	4.20	1.06	-6.43	-3.74	1.61	-4.21	5.73
July06	-3.66	-2.91	6.32	-3.85	1.32	6.05	4.13	0.82	-6.09	-3.66	0.28	-3.62	3.16
July07	-3.53	-2.51	4.52	-2.44	0.53	4.52	3.43	0.36	-5.75	-3.22	0.55	-2.64	4.52
July08	-2.99	-1.81	3.80	-2.78	0.18	5.61	3.17	0.24	-5.97	-2.54	-0.19	-2.59	3.12
July09	-2.70	-1.60	4.22	-3.50	1.70	2.60	3.79	0.90	-6.12	-3.19	0.18	-3.16	3.50
July10	-4.07	-3.07	5.27	-3.67	1.48	4.39	4.09	1.39	-6.23	-3.41	-0.18	-3.21	5.43
July11	-5.24	-3.90	3.18	-	-1.09	4.93	1.53	0.86	-	-4.70	1.76	-	5.24
July12	-3.34	-2.62	6.99	-5.78	-0.83	6.66	4.59	3.16	-8.07	-4.71	-1.71	-5.34	7.95

Table 2. Mean standard deviation ($\overline{\sigma}$) of the mean SPR instrumental biases for 13 GPS satellites for the period 01 July to 12 July 2004.

SV PRN	31	27	25	24	21	16	15	13	10	8	6	4	1
	SPR Value (nsec)												
Mean	-4.71	-2.96	5.41	-3.86	1.53	5.02	4.25	0.66	-6.40	-3.88	0.66	-3.63	-3.63
$\overline{\sigma}$	2.91	0.79	1.27	0.91	1.70	1.04	1.24	1.09	0.62	0.77	1.14	0.81	0.81

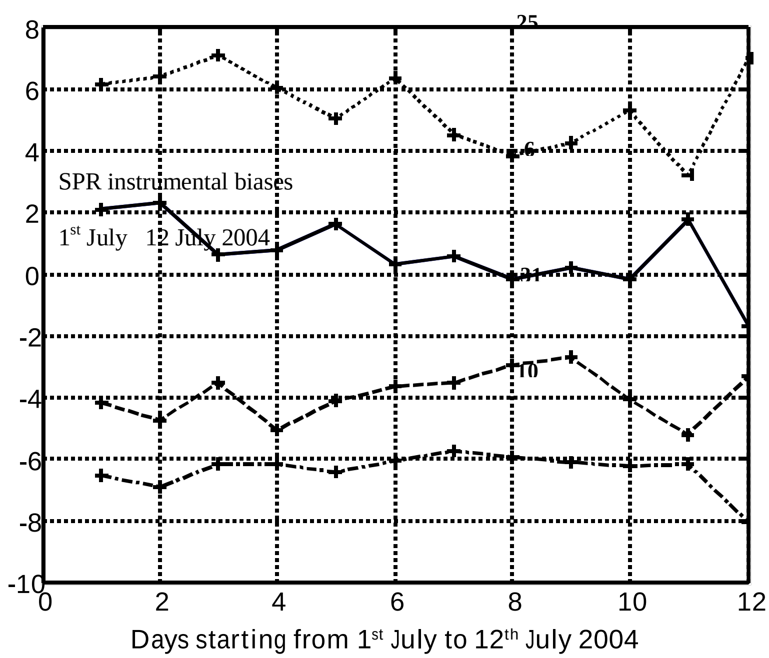

Figure 4 SPR instrumental biases for the 12 day period for 4 satellites at Hyderabad(17.431°N, 78.453°E)

The mean SPR differential delay for 13 satellites over the 12 day period is computed and are presented in Table 1. The standard deviation (σ) of the mean SPR differential delay for the 12 day period was computed for each satellite and the mean standard deviation ($\overline{\sigma}$) for 13 satellites are presented in Table 2. Figure 4 shows the SPR instrumental biases for the SV PRN 31, 25, 10 and 6. The biases observed are positive values (2 to 7 nsec.) for SVs 6 and 31 and negative values (-3 to –8 nsec.) for SVs 10 and 31. Figure 5 shows the $\overline{\sigma}$ of the mean SPR instrumental biases for 13 GPS satellites. Maximum $\overline{\sigma}$ is observed for the SV 31 and minimum $\overline{\sigma}$ is observed for SV 10.

The standard deviation values indicate the day to day variability of the SPR differential delay estimates. Figure 6 compares the TEC estimation for a SV PRN 1 and 31 (12 July 2004) after modelling of instrumental biases. The bias error estimated is –3.638 nsec and –4.71 nsec for satellites 1 and 31 respectively. From the results, it is found that the SPR differential delays of 13 satellites are varying from -6.4060 to 5.4117 nsec. The results indicate that day to day variation of SPR differential delay is small and it is less than 1nsec. The average value of the σ of the SPR differential delay estimate is 1.17 nsec, which represents an error estimate of the SPR differential delays.

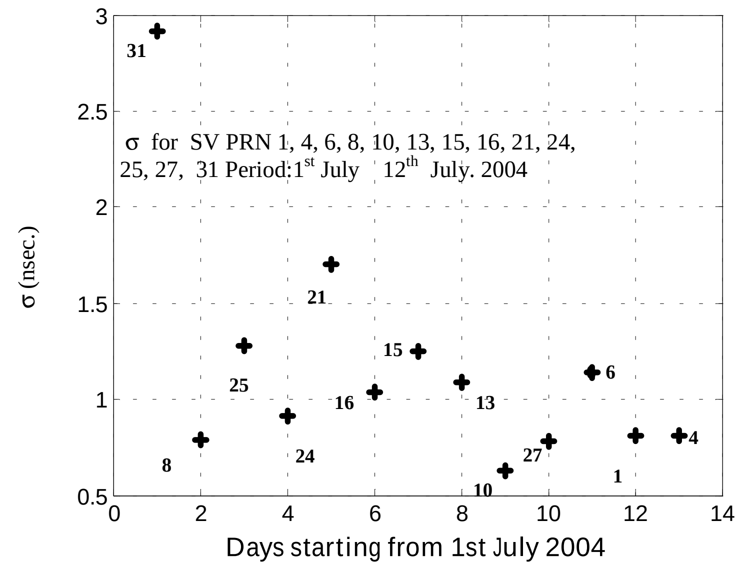

Figure 5. $\overline{\sigma}$ instrumental biases for 13 GPS satellites for the 12-day period (1st July to 12th July 2004)

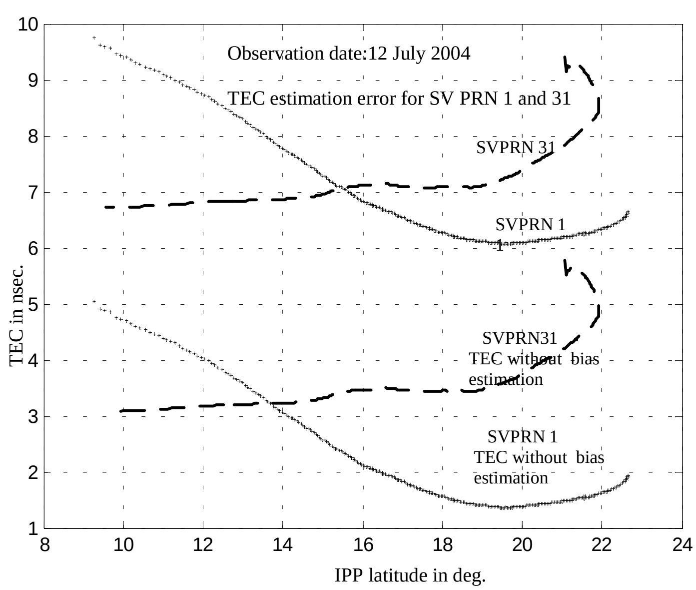

Figure 6 Comparison of TEC estimation after modeling of instrumental biases at Hyderabad (17.431^0N, 78.453^0E)

CONCLUSIONS

A new algorithm is proposed to estimate the instrumental biases by modelling the ionospheric TEC using 4th order polynomial. This algorithm is an approximation of the steepest descent algorithm, which uses an instantaneous estimate of the gradient vector of a cost function. The estimate of the gradient is based on sample values of the tap-input vector and an error signal. The algorithm iterates over each coefficient in the filter, moving it in the direction of the approximated gradient. The algorithm can be used to calibrate the dual frequency GPS receivers for precise TEC measurement even when the receiver internal hardware calibration is not available. The experimental results from the 12 day period indicate that the estimation precision of the satellite and receiver differential delay is of the order of ±0.17nsec. It is found that the error in the TEC estimation for the SV PRN 1 and 31 are –3.638nsec and –4.71nsec respectively. It is also found that the results are consistent over the period and the method is accurate and faster for real time applications like GAGAN.

ACKNOWLEDGEMENTS

Thanks are due to Dr. B.M Reddy, Emeritus Scientist, NGRI, Hyderabad for giving valuable suggestions and constant encouragement during the preparation of the paper. Part of this work is submitted for URSI International Conference to be held in October 23-29, 2005 at New Delhi.

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(Accepted 2005 August 22. Received 2005 August 11; in original form 2005 April 26)

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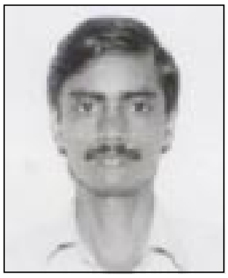

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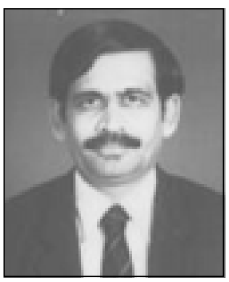

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