THE JOURNAL OF NAVIGATION (2002), **55**, 463–475.
DOI: 10.1017/S0373463302001960 Printed in the United Kingdom

The Usefulness of GLONASS for Positioning in the Presence of GPS in the Indian Subcontinent

P. Banerjee

(*National Physical laboratory, India*)

Anindya Bose

(*Burdwan University, India*)

and Ashish Dasgupta

(*Calcutta University, India*)

The effort to integrate the use of GPS and GLONASS constellations resulted in the production of a special receiver, which can use both constellations in combination. These receivers may be used in GPS only mode, GLONASS mode and combined (both GPS and GLONASS) mode. Utilising this type of receiver, GPS and GLONASS signals were monitored for one calendar year simultaneously in different places in India to study the status of visibility of satellites and the positioning accuracy. The number of satellites in GLONASS constellation gradually depleted from 16 to 7 during the course of this study. So a 3-D solution was rarely possible using only GLONASS satellites. However, appreciable improvement in PDOP was observed in the combined mode. Before the withdrawal of GPS Selective Availability (SA), significant improvement of position accuracy could be observed in the combined mode. After the removal of GPS-SA, the accuracies of the combined mode and that of GPS-only mode have been found to be of the same order. While this does not apparently reflect any advantage, it indirectly confirms that both the GPS and the GLONASS systems have similar limits of accuracy and also confirms that optimal interoperability of two systems has been achieved. These studies reveal that the combined use of GLONASS and GPS will always be beneficial to a varying degree depending on different applications and circumstances.

KEY WORDS

1. GPS. 2. GLONASS. 3. Integration.

1. INTRODUCTION. The Global Positioning System (GPS) deployed by the US Department of Defence (US DoD) and GLObal Navigation Satellite System (GLONASS) (Langley, 1997) deployed by the Russian Federation offer, independently, precise location and time transfer continuously anywhere in the world and in space itself. The reliability and availability of GPS in Indian subcontinent has been exhaustively studied and presented in a report (SRAGI) (Banerjee and Bose, 1997). The interest in GLONASS stems from the recognition that GPS alone falls short of meeting the requirements of a global sole means, or stand-alone, navigation system.

Similarly, GLONASS alone (even with a complete constellation) cannot meet this requirement. The performance capabilities of GLONASS are substantially similar to those of GPS as claimed by the respective authorities. GPS has achieved and maintained its operation status in full, while the prospects of GLONASS are less clear. The two systems taken together, however, should offer amply redundant measurements to all users, and seem capable of meeting most navigation system requirements. Further attempts have been made to integrate the two constellations.

The recommendations of 85th Meeting of the CIPM specifies the basis for harmonising the two constellations so that GLONASS does not depend on GPS nor GPS on GLONASS, but time and space references in agreement with International standards are followed. These efforts resulted in the availability of few special receivers that may be operated in GPS-only mode, GLONASS-only mode and also in a combined mode of GPS and GLONASS. In view of this circumstance, GPS and GLONASS signals were monitored for one year in different places in India in order to study the utility of GPS and GLONASS in combination for positioning applications. The number of satellites with good signal strength, the geometry of the available satellites and the corresponding achievable accuracy were recorded during this study. This paper attempts to examine the performance capabilities of GLONASS and compare them with those of GPS based on monitored data.

2. EXPERIMENTAL PLAN. Although both GPS and GLONASS work on the same principle, there are technical dissimilarities in their signal characteristics. Receivers that can use both the GPS and GLONASS signals have already come on the market. Three such receivers have been used at three well-scattered sites in India, viz. Bangalore, Kolkata and New Delhi so that observations may be generalised for the entire Indian sub-continent. All of the three receivers were operated in either GPS-only, GLONASS-only or GPS+GLONASS combined mode in a preplanned schedule so that a co-relation of simultaneity could be established. Data was stored in computers in each of the three monitoring stations for future analysis.

In order to make a comprehensive conclusion on the availability of the satellites, it was necessary to have prior knowledge of the status of both the GPS and GLONASS constellations. The GPS constellation was full with 24 satellites or more during the entire period of this study; there were sometimes 29 satellites operational. Out of these, 6 satellites were launched in the year 1990 or earlier.

The first satellite of the GLONASS system was launched in 1982. The full 24-satellite constellation became available for the first time on 18 January 1996. This status, however, was relatively short-lived and the constellation has gradually fallen into decline, as failed satellites have not been replaced. After December 1995, there were no replacements till December 1998 when three new satellites were launched. For replenishment after a gap of two years, three satellites were launched in December 2000 but only one of them has become successfully operational. The status of the constellation during the period of December 1998 to January 2001 (the timescale of this study) is shown in Table 1. Thus, during the timescale of this study, the number of GLONASS satellites operating varied from 16 to 7.

3. AVAILABILITY OF GPS AND GLONASS SATELLITES. Monitoring was carried out independently at three different sites, and the recorded data has been analysed. As the number of satellites in GLONASS constellation varied widely

Table 1. GLONASS Constellation Status.

Date	Number of operational satellites
December 1998	14
March 1999	15
June 1999	15
September 1999	11
December 1999	14
March 2000	14
June 2000	14
September 2000	9
December 2000	8
23 January, 2001	7

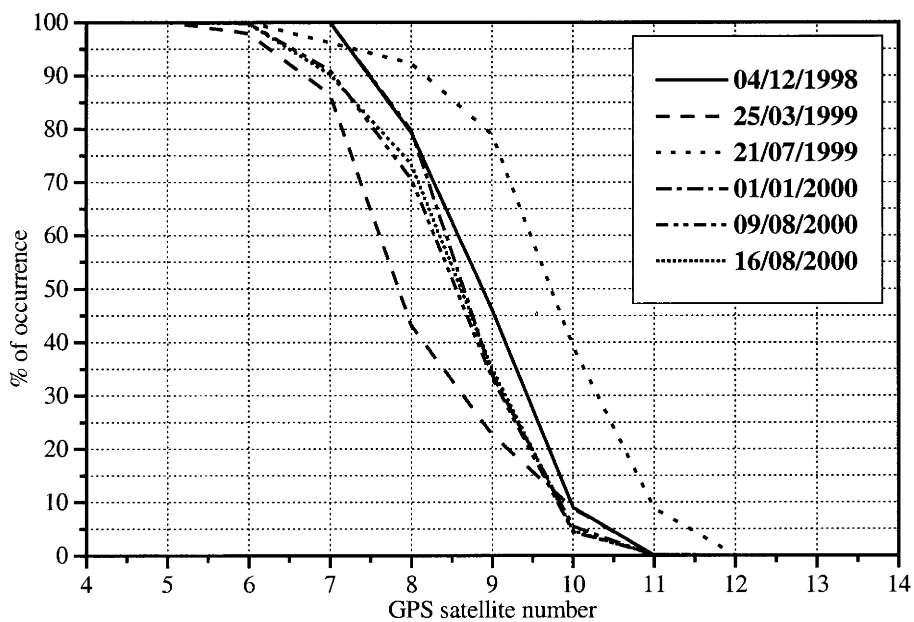

Figure 1. GPS Satellite visibility at New Delhi.

during the period of study (as evident from Table 1), the availability of GLONASS has been referenced to its constellation status. The GPS constellation was full with 24 or more satellites during the entire period of observation. So GPS constellation status may be assumed to be uniform during the period of this study.

When the receiver operates in GPS + GLONASS mode, each sample of observation displays the elevation and azimuth of all GPS and GLONASS satellites being used for finding the position solution. These satellites are counted and the numbers analysed in a very comprehensive manner. The observations do not project any variability of a diurnal or seasonal nature. Also, it was noted that the availability of signals from both the constellations are very similar in nature with insignificant variations over the whole of India.

Some of the observations on GPS availability are shown in Figure 1 for the New Delhi site, and similar results have also been observed for Kolkata and Bangalore. On

https://doi.org/10.1017/S0373463302001960 Published online by Cambridge University Press

average, 95 % of the time, six or more GPS satellites are available anywhere in India. The maximum number of thirteen GPS satellites was available in Kolkata and Bangalore, but New Delhi never received more than twelve satellites.

GLONASS satellites are not meeting their expected operational life and, possibly due to economic and political reasons, scheduled replenishment has not been carried out. So the number of satellites in GLONASS constellation was found to be gradually declining during the course of this study. For different conditions of constellation status, the visibility of GLONASS satellites is shown in Figure 2. For the best status

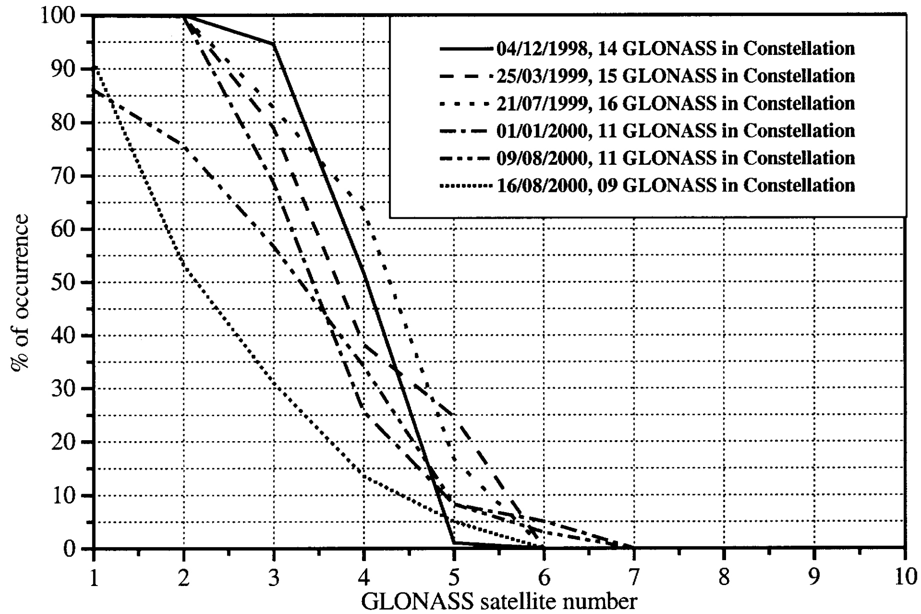

Figure 2. GLONASS satellite visibility at New Delhi.

of sixteen available satellites, 95 % of the time, three or more satellites were available whereas only one or more satellites were available for worst status of seven satellites. The maximum number of available GLONASS satellites varied from eight or nine at Kolkata and Bangalore to seven at New Delhi. The required minimum number of four satellites for a 3-D position solution was visible around 50 % of time when fifteen or sixteen GLONASS satellites were available in the constellation. This pattern came down sharply to nearly 15 % of time with a lesser number of satellites. In other words, the GLONASS constellation was never good enough to ensure that a 3-D solution was always available from GLONASS alone.

4. GEOMETRICAL CONFIGURATION OF AVAILABLE SATELLITES. It was noted that a sufficient number of GPS satellites or GPS + GLONASS satellites were always available at all the monitoring sites to obtain a navigation solution. But to achieve a desired accuracy, it is not only necessary to track a sufficient number of satellites with sufficient signal strength, but it is equally important that the geometrical configuration of the tracked satellites is favourable

(Banerjee *et al.*, 1997). All modern receivers calculate Positional Dilution Of Precision (PDOP) for all combinations of available satellites and select the set of satellites with minimum PDOP for navigation. The variation of PDOP for each day of observation has been studied. The percentage of occurrence of PDOP was determined by just counting the number of samples that corresponds to PDOP values within a particular range.

From the availability study, it was clear that status of the GLONASS constellation prevented use of these satellites alone for navigation applications. So a study was made of the impact on PDOP from the combined presence of GLONASS and GPS satellites. Appreciable improvement in PDOP was observed in the combined mode (e.g. PDOP of 2 in GPS-only mode was improved to 1·6 for combined mode) as shown in Figure 3. Here, numbers of cases of PDOP values falling within very short

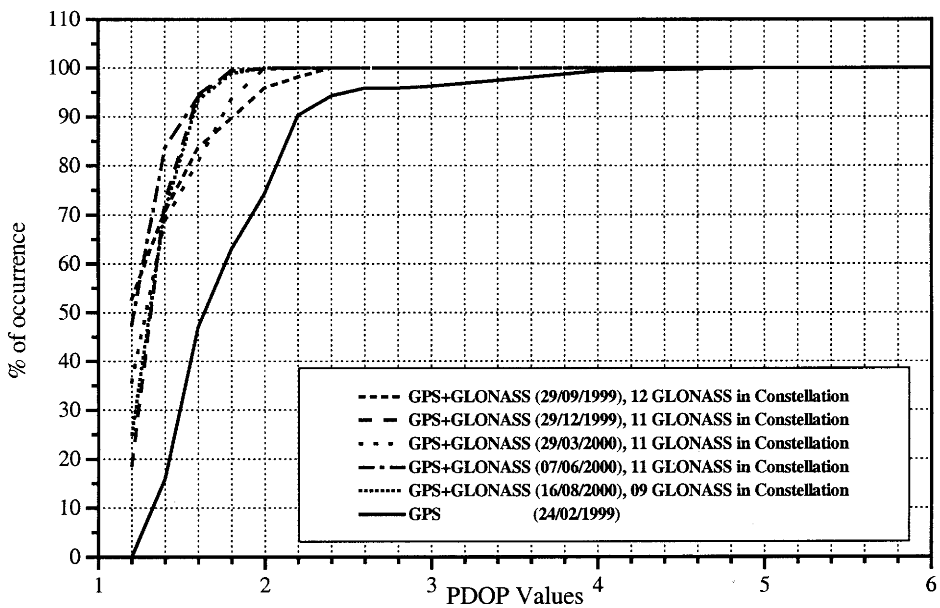

Figure 3. Probability of PDOP distribution, Kolkata.

ranges (e.g. 1 to 1·2, greater than 1·2 to less than or equal to 1·4, greater than 1·4 to less than or equal to 1·6 etc.) were counted, and the percentage of occurrence for a particular class was obtained with respect to the total number of observations.

Figure 3 shows the result of the study for Kolkata; similar results were also obtained for New Delhi and Bangalore. It is also of interest to note that the improvement of PDOP was hardly affected by depletion of GLONASS satellites. This apparently implies that the improvement of PDOP may be optimally achieved by addition of only one or two more suitably placed satellite(s). Furthermore, the addition of satellites with the improvement of the GLONASS constellation status, may not definitely make any further perceptible impact on PDOP. However, it should be noted that the addition of satellites in GLONASS constellation improves the probability of having at least one or two more satellites in favourable position and thereby showing more confidence in improvement of PDOP.

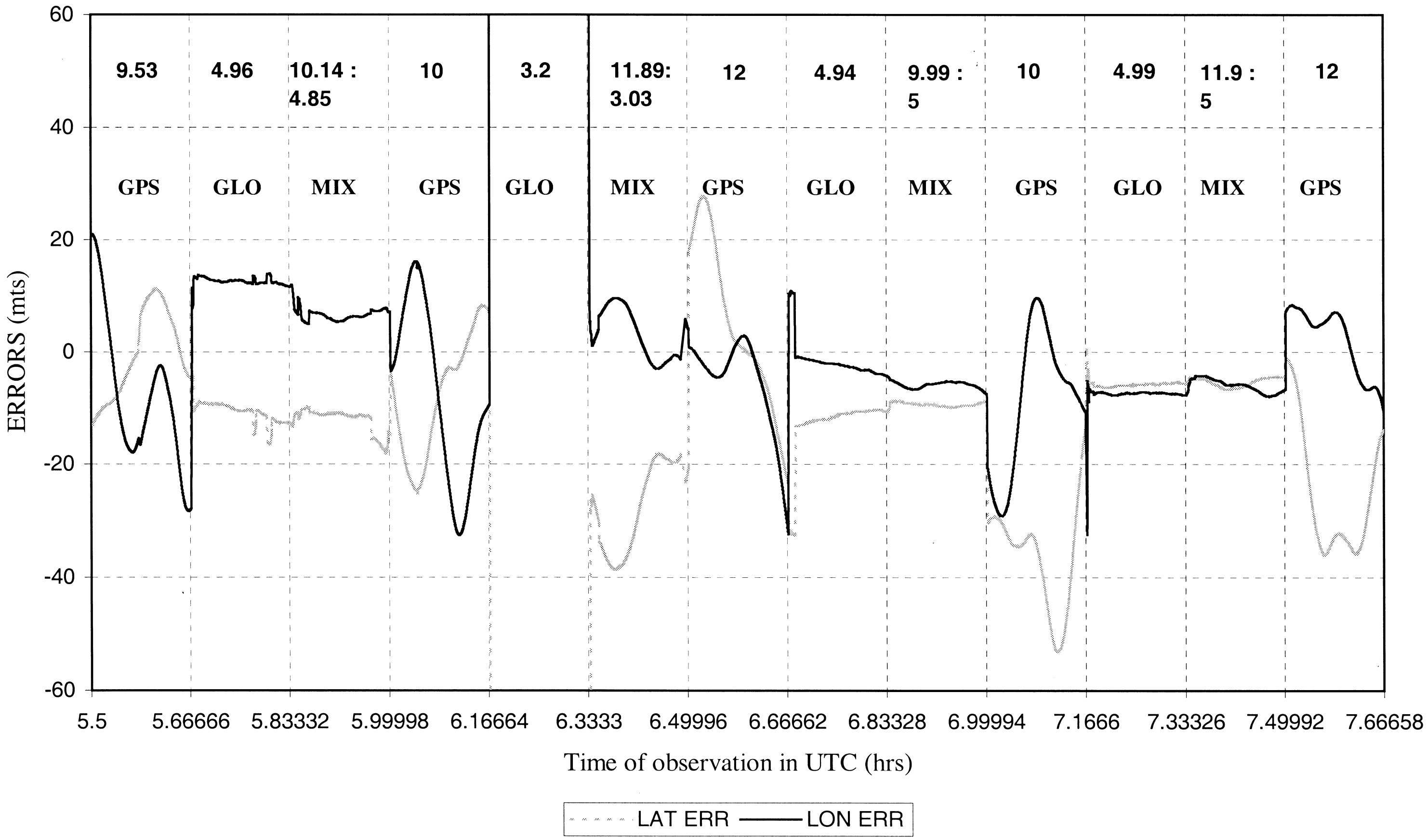

Figure 4. Latitude and Longitude variation at Kolkata in different modes of operation – 17 May, 1999.

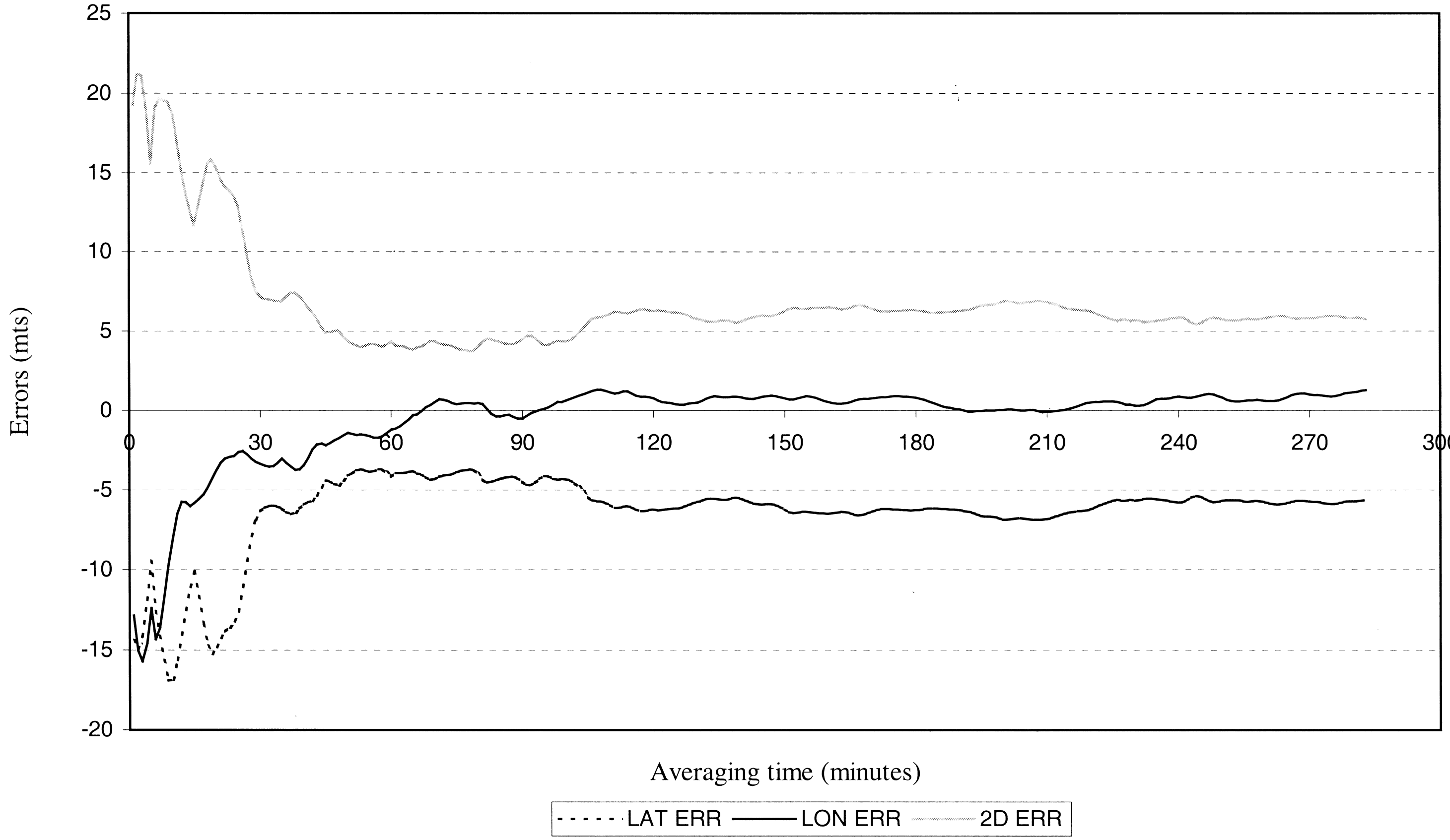

Figure 5. Effect of averaging in GPS-only mode, Kolkata – 24 May, 1999.

5. POSITION ACCURACY. To study position accuracy, the precise co-ordinates of the antenna sites must be known. The coordinates of all three monitoring sites were known a-priori fairly accurately. With the help of these pre-determined position coordinates, the instantaneous error in the latitude, longitude and height may be found out. The 3-dimensional position error was calculated using the following relation.

$$error_{3d} = \sqrt{\Delta h^2 + (1852.\Delta Ln.cos(Lt))^2 + (1852.\Delta Lt)^2},$$

where:

Lt = Nominal value of latitude,

Δh = Departure of the observed height from the known height in metres,

ΔLn = Departure of the observed longitude (in minute of arc) from the known longitude, and

ΔLt = Departure of the observed latitude (in minute of arc) from the known latitude.

The above formulation assumes that 1 minute of arc of the earth curvature is equivalent to 1852 metres.

Since May 2, 2000, GPS Selective Availability (SA) has been withdrawn. Observations taken before May 2, 2000 were studied in a perspective that assumes the presence of SA and afterwards, the analysis of observations had to be reviewed with the newly developed situation. Thus the study of position accuracy has been divided into two groups in the following subsections.

5.1. *Position accuracy in presence of SA*. SA was implemented in GPS Block II satellites and had been effective since April 1990 intermittently at various levels of accuracy. According to US DoD, the introduction of SA would provide a horizontal accuracy within 100 metres and vertical accuracy within 159 metres for standard positioning service (SPS) with C/A code. The time output accuracy would deteriorate to 350 nanoseconds. One of the primary objectives of this study was to observe the optimal use of the GLONASS constellation in combination with GPS to reduce the effect of SA in position accuracy.

In one special campaign, the receivers were made to operate in three different modes (GPS-only, GLONASS-only and mixed or GPS+GLONASS mode respectively) for 10 minutes each sequentially, and the operation was repeated for a few hours. In each slot, the position solutions corresponding to each sample of observation were recorded. The data thus observed was analysed to obtain instantaneous errors in latitude and longitude. These errors in latitude and longitude are shown in Figure 4 for different modes of operation. Numbers at the top of each column indicate the average number of satellites that participated in the observation. In the mixed mode, the first number corresponds to the number of GPS satellites and second number is the number of GLONASS satellites.

In GPS-only mode, the wide fluctuation in error is quite significant, reflecting the effect of SA. In GLONASS-only and mixed modes, the diminishing effect of SA has been obviated by smooth variation of the errors. One may argue that due to total absence of SA in GLONASS, the GLONASS-only mode would exhibit best performance; however, because of the insufficient number of GLONASS satellites, the

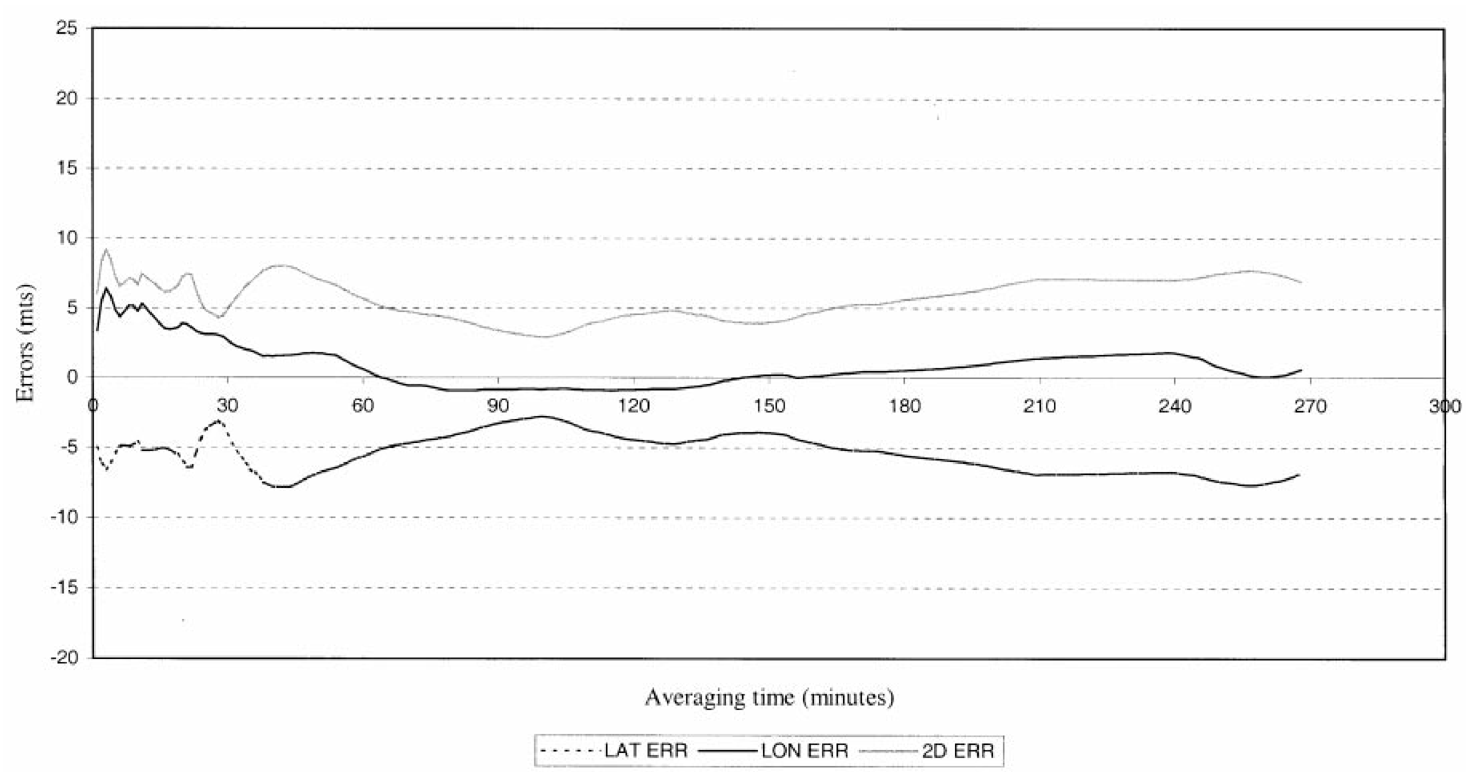

Figure 6. Effect of averaging in GPS + GLONASS mode, Kolkata – 24 May, 1999.

optimum configuration of satellite geometry was not possible leading to higher PDOP in GLONASS-only mode. But in combined mode, a good number of GPS satellites supplemented by fewer GLONASS satellites allowed the selection of satellites with better PDOP. Contribution of more GLONASS satellites might have helped more efficient countering of the telling effect of SA.

The effect of SA may to some extent be lessened through averaging over time. Data was recorded every second. The instantaneous position error was further analysed by averaging over different spans of time (e.g. averaging for 1 minute's data, 2 minute's data and so on). These analyses were compared for different modes of operation. It was observed that in GPS-only mode, error in the time-averaged position data reduces with the increase of averaging. It can be seen in Figure 5 that up to the averaging time of 25 to 30 minutes, improvement in error became optimum. No obvious improvement of position error could be seen with further increase of averaging time. A similar exercise was done with data recorded in the GPS +GLONASS mode. It is interesting to note in Figure 6 that hardly any improvement in positioning error could be observed by averaging. There is hardly any change in the pattern of position error with the increase of averaging time in this mode. This indicates that the effect of SA had been reduced sufficiently in each sample of observation in GPS+GLONASS mode of operation. So an averaging process would not improve the accuracy significantly.

The status of position error was also analysed by grouping the errors in certain ranges. For a certain period of observation, say for one complete day, the number of samples found with a two-dimensional error of 5 metres or less, then 10 metres or less and so on, was calculated, and these numbers were normalised against the total number of samples. These calculations help in indicating the probability of the error being within the respective range. The analysis is given in Tables 2(a) and 2(b). It may be noted that the probability of a 2-D error being within 5 metres or 10 metres is much higher in mixed (GPS+GLONASS) mode than that in GPS only mode. On one

Table 2(a). Distribution of 2-dimensional position error at the Kolkata observation site.

Date	Mode	Data No	% of 2-dimensional position error values below						% above 40 m
			5 metres	10 metres	15 metres	20 metres	30 metres	40 metres	
17/5/99	MIX	15130	9·74	42·28	70·32	87·42	97·44	100·00	0·00
	GPS	17052	6·73	23·09	46·92	62·83	85·80	97·24	2·76
	GLO	11143	8·04	25·83	39·82	48·52	66·62	76·07	23·92
19/5/99	MIX	14902	8·78	32·27	59·73	77·16	97·75	99·91	0·01
	GPS	17732	9·14	29·97	51·16	68·30	88·03	96·63	3·37
	GLO	12236	4·05	26·03	57·45	67·11	90·14	93·94	6·06
20/5/99	MIX	13768	14·96	66·82	84·22	92·64	98·37	99·82	0·18
	GPS	16565	4·52	19·14	36·03	56·66	85·39	98·73	1·27
	GLO	13319	4·63	47·02	61·83	68·41	83·22	88·00	11·99
21/5/99	MIX	11146	22·38	48·46	77·21	91·96	100·00	100·00	0·00
	GPS	13112	5·42	21·48	44·93	62·48	85·66	95·26	4·74
	GLO	8759	14·00	42·39	83·78	85·02	92·12	92·33	7·67
24/5/99	MIX	16087	17·49	53·48	71·57	84·96	95·73	97·88	2·12
	GPS	17005	7·76	27·21	48·64	69·92	90·97	98·08	1·92
	GLO	14235	30·51	53·17	58·68	71·83	78·04	84·33	15·67

Table 2(b). Distribution of 2-dimensional position error at the New Delhi observation site.

Date	Mode	Data No	% of 2-dimensional position error values below the range of 5 metres	10 metres	15 metres	20 metres	30 metres	40 metres	% above 40 m
21/5/99	MIX	49666	77·32	90·62	95·46	99·39	99·80	99·99	0·01
	GPS	6819	10·76	54·91	75·10	80·45	90·89	97·61	2·39
	GLO	3762	0·00	32·80	47·87	48·38	98·62	100·00	0·00
04/6/99	MIX	8772	14·31	51·58	73·39	84·95	96·43	100·00	0·00
	GPS	6685	9·81	36·28	57·40	70·67	92·55	96·59	3·41
07/6/99	MIX	5568	4·24	93·07	99·23	99·34	99·59	99·83	0·16
	GPS	6071	1·10	24·43	44·61	77·83	96·99	98·17	1·83
09/6/99	MIX	11451	22·21	50·50	90·50	98·72	99·85	99·99	0·01
	GPS	8790	7·43	41·57	75·52	85·28	96·76	99·77	0·23

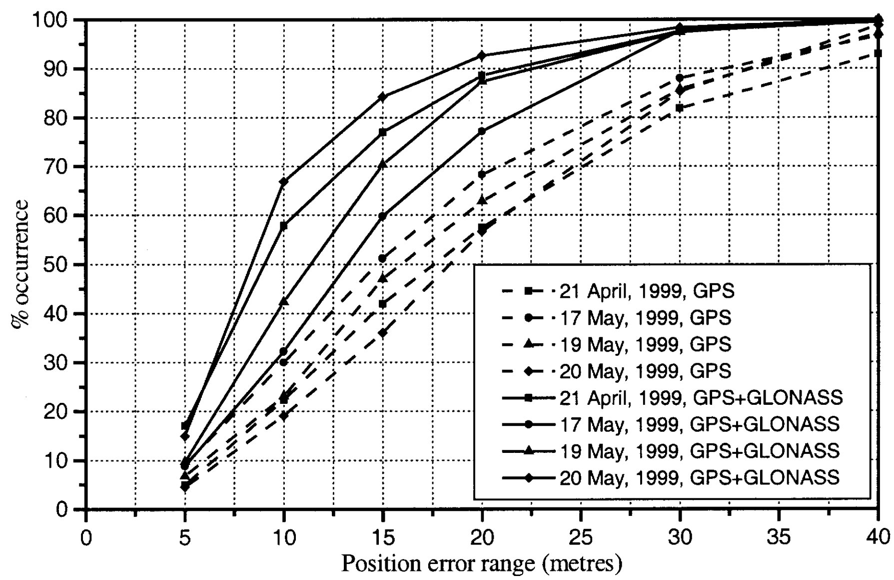

Figure 7. 2-D position error distribution at Kolkata in presence of SA.

particular day, the probability of position error remaining within 5 metres or less was as high as 77 % in mixed mode, whereas it was only 10 % in GPS-only mode. These observations are illustrated in Figure 7. It is clear that, more than 90 % of time, the position error remains within 10 metres in mixed mode but, in GPS-only mode, the position error goes as high as 30 metres.

5.2. *Position accuracy in absence of SA.* When SA was discontinued on May 2, 2000, the accuracy of GPS was expected to improve considerably, and the study of position error was reviewed to consider this altogether different perspective. A sharp improvement in accuracy with scatter reducing from 90 metres to 18 metres was reported. This considerable improvement in position accuracy for GPS-only mode was anticipated. In view of this, it was very important to compare the performance

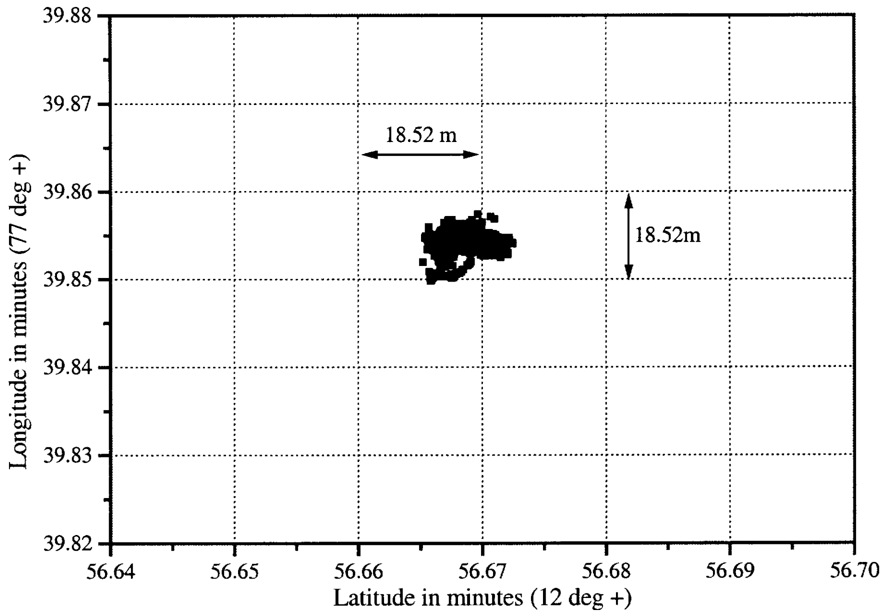

Figure 8. 2-D position solution in absence of SA, GPS+GLONASS mode, Bangalore – 30 May, 2000.

of GPS-only mode without SA and the GPS+GLONASS mode. To achieve this objective, the receivers were operated for 10 minutes in GPS-only mode and next 10 minutes in the mixed mode. Figure 8 illustrates the observed horizontal positions showing the performance of GPS+GLONASS mode. Accuracy was found to be almost equal in this combined mode to that of the GPS-only mode. This implies that, even in absence of SA, the accuracy of GLONASS is comparable with that of GPS.

6. CONCLUDING REMARKS. To derive optimum benefit from both the GPS and GLONASS constellations, efforts have been made to harmonize the timescales and to correlate the two time and coordinate reference frames of these two Global Navigation Satellite Systems. Receivers that use both GPS and GLONASS in a combination have emerged as a result of these efforts.

This study amply demonstrates that the errors imposed by GPS-SA may be effectively compensated when the receiver is operated in GPS+GLONASS mode. This observation not only proves that the GLONASS has better accuracy capability than that of GPS with SA by showing the improvement in accuracy in combined mode but also that the coordination of two systems could be successfully achieved.

After the removal of SA, the accuracy of the combined mode and that of GPS-only mode were found to be comparable. This indirectly confirms that both GPS and GLONASS systems have similar accuracy limits, and that interoperability of the two systems has been to a great extent achieved. The slight decrease in accuracy in the combined mode may be attributed to minor imperfections in the conversion matrix from PZ-90 to WGS-84.

The study has shown that there are significant benefits in using GPS and GLONASS in combination particularly for strategic applications as the later system, having separate frequencies for each satellite, is less prone to jamming. The use of GLONASS with GPS will always accrue benefits to a varying degree depending on different applications and circumstances.

REFERENCES

Banerjee, P. and Bose, A. (1997). *Study on the Reliability and Availability of GPS signals in India* (*SRAGI*). National Physical Laboratory, New Delhi, India, March 1997.

Banerjee, P., Bose, A. and Mathur, B. S. (1997). A study on GPS PDOP and its impact on position error. *Indian J. Radio and Space Physics*, Vol 26, April 1997, pp. 107–111.

Langley, R. B. (1997). GLONASS: Review and Update. *Innovation*, *GPS World*, July 1997, pp. 46–55.