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FREQUENCY AND TIME STABILITY OF GPS AND GLONASS CLOCKS

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SUMMARY

The frequency stability and reliability of the clocks are critical to the success of the GPS and GLONASS programs. We will show some of the similarities and differences between the clocks involved in these two systems. Because both systems plan to be operational in the next few years, the data leading up to this operational stage is of significant interest. On-board clocks and the stability of the master control clocks for these systems are analysed.

We will discuss the attributes of these two systems as time and frequency references. Their relationship to UTC will also be illustrated. More data over a longer period of time was available for the authors from GPS than from GLONASS. Even so it is obvious that both systems have matured. Though the GLONASS system was developed later, its overall clock performance has improved more rapidly. Some of the more recent GLONASS clock performance is at about the same level as that of the GPS clocks.

The analysis has yielded some very interesting contrasts, comparisons and changes in these systems that should be of great interest for time and frequency users, as well as for clock vendors and receiver vendors.

KEY WORDS Satellite navigation and time transfer Atomic satellite clocks Allan variance

INTRODUCTION

The Global Positioning System (GPS) and the GLONASS (U.S.S.R. satellite navigation system) are the first systems to use atomic clocks in the space environment. The reasons for using atomic clocks to assist in forming an accurate navigation solution for a receiver set are obvious. In the error budget for navigational accuracy, the performance of satellite clocks is an important entry. As a direct source of time and frequency from space, the performance of the satellite clocks, again, is an important consideration, as are the methods of controlling the systems.

The purpose of this paper is a cursory study of the performance of these two systems as time and frequency reference sources. We do not have access to all of the data from these systems for their full time of operation but do have significant samples from which it is possible to assess the general performance. For this paper the GLONASS database is that taken by the receivers at the University of Leeds.[1] The database for GPS is that of the National Institute of Standards and Technology (NIST) in Boulder, Colorado.

We will study the time inaccuracy and time instability, and the frequency inaccuracy and frequency instability, of both systems. Contributing to the investigation are the frequency offsets, the frequency drifts, and methods of estimating these states as seen through clock noise, measurement noise, and uncertainties associated with other relevant system parameters.

GPS SATELLITE-CLOCK PERFORMANCE

The timing references used for the analysis of the GPS were UTC as generated by the Bureau International des Poids et Mesures (BIPM), UTC(NIST) and UTC(USNO). UTC is the official international reference scale, and we will use it wherever data permit and values are relevant. The frequency stabilities of all three of these reference time scales are better than a few parts in 10^{14}. In the long term, both UTC(NIST) and UTC(USNO) are kept synchronous within a few microseconds of UTC.

The receivers used for measuring GPS are L1 clear-access timing receivers. The inaccuracies in

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determining the time of a GPS satellite clock are sums of the uncertainties associated with the broadcast estimate of the satellite's position and ionospheric correction for the signal path, the tropospheric delay, multipath perturbations, receiver hardware delays and software perturbations. From experience, the size of these inaccuracies can amount to a few tens of nanoseconds.

A given GPS satellite position with regard to a fixed receiver on the earth remains the same from day to day when measurements are made once per sidereal day. With the data taken in this way the time instabilities from day to day are typically less than 10 ns.

The frequency inaccuracy and the systematic trends in the frequencies of the GPS satellite clocks are determined by an appropriate filtering of the daily time readings. The frequency instabilities are measured in the usual manner using a $\sigma_y(\tau)$ diagram to characterize the time-domain performance.

Figures 1(a) and 1(b) are plots of the time accuracy and the frequency accuracy of the GPS-received signal, with respect to UTC. GPS time is estimated with a Kalman–Bucy filter for each operating satellite clock. The filter determines a correction to be applied for each satellite clock and broadcasts this information. Biases and random variations of the order of a few nanoseconds have been observed between the GPS time as given by the different GPS satellites.[2] The time stability from day to day of a given satellite is typically better than if the measurement is made on different satellites. Figure 2 is a plot of the frequency stability of GPS time over the entire interval shown in Figure 1.

When a weighted set of the GPS satellites is used for time transfer in a common-view mode, day-to-day stabilities less than 1 ns have been achieved.[3] The common-view mode is most commonly used for transfering clock time to the BIPM (pertinent to the UTC generation). Internationally the range of time transfer stabilities from day to day is from 0·8 to about 6 ns when using a weighted set of the GPS satellites.

Under a Department of Defense directive, U.S. military time is to be synchronous with UTC(USNO). Figure 3 is a plot of how well the GPS has achieved that goal. Because of the low Fourier frequency processes present in the data, the standard deviation of the data can be deceptive in meaning. Figure 4(a) is a plot of $\sigma_x(\tau) \equiv \tau \text{mod}\sigma_y(\tau)/\sqrt{3}$ for these data, which provides a way of dealing with these low frequency processes in a statistically valid way. The GPS data word provides a correction to GPS time; this correction provides an estimate of UTC(USNO). Plotted in Figure 4(b) is the time stability of the estimate of UTC(USNO) as obtained from GPS satellite NAVSTAR 10.

Figure 5 is a plot of the frequencies of several of the GPS satellite clocks corresponding to rubidium-gas cell clocks and to caesium-beam clocks. The plots are with respect to the rate of UTC(USNO) which is typically within a few parts in 10^{14} of the rate of UTC.

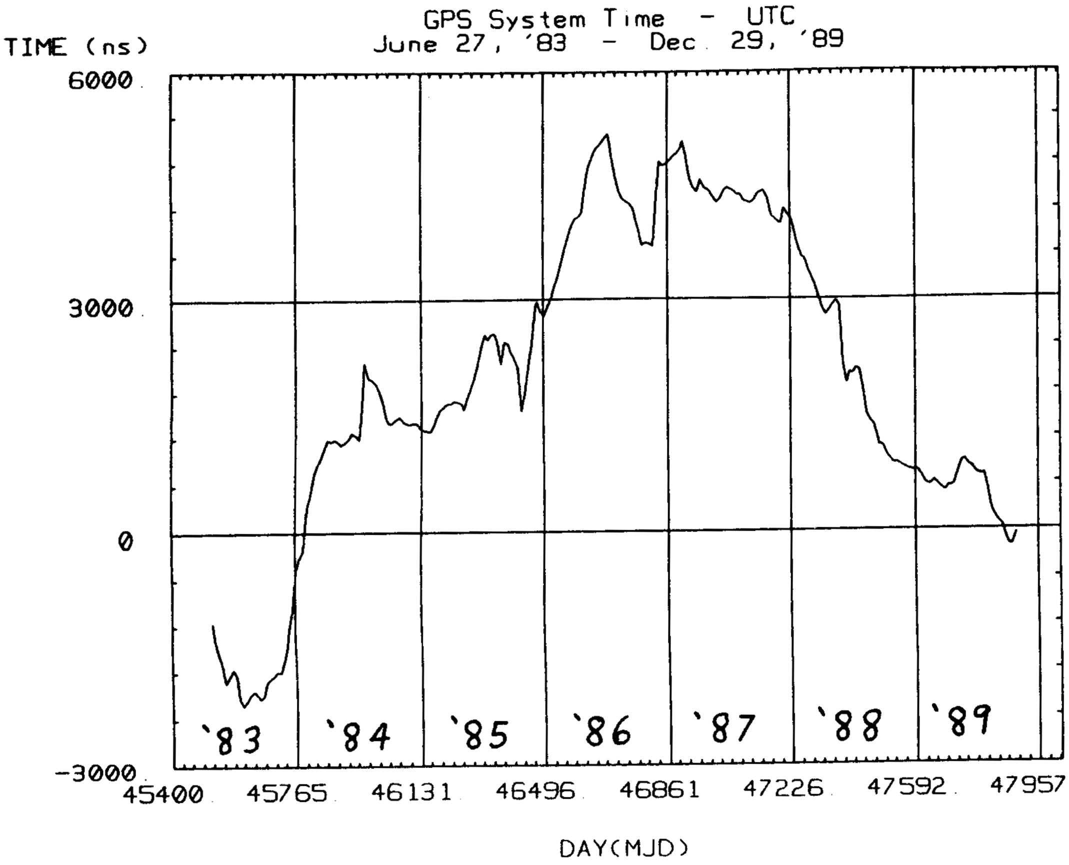
Figure 6 shows plots of the frequency stabilities of samples of the GPS satellite clocks. Each kind of clock seems to have a characteristic kind of 'fingerprint'. In addition, the frequency drifts—as can be observed in Figure 5—are very different between the different kinds of clocks.

Figure 7(a) is a plot of the time of GPS satellite No. 14's clock with the corrections applied to give an estimate of UTC(USNO). It is obvious where selective availability (SA) is turned on and off. SA is the purposeful degradation of the broadcast signal in order to deny full GPS accuracy to a non-cleared receiver. This degradation is accomplished by modulating the effective output of the satellite clock and/or by degrading the broadcast ephemeris (satellite position information). Figure 7(b) is a frequency stability plot with and without selective availability (SA) present. This plot employs the statistical measure $\text{mod}\sigma_y(\tau)$ to show that the long-term variations, though at a high level, can be characterized as a white phase or time modulation process.[4] With SA on it takes a couple of weeks of averaging before the instabilities of a caesium-beam clock become measurable.

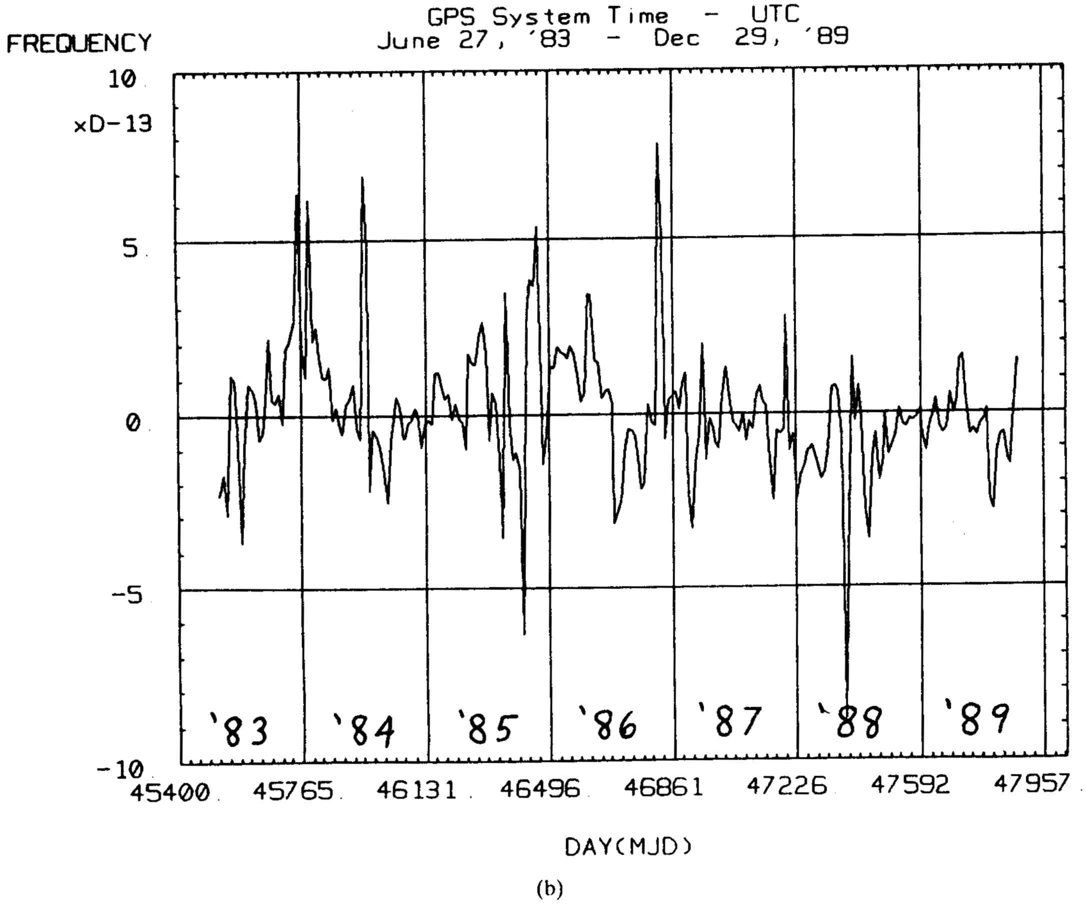
On 25 March 1990, GPS went officially to the SA mode of operation on all of the block 2 satellites (those satellites launched since 1988). The effects of SA are readily apparent. We have been given to understand that as long as the block 1 satellites last, there will be no SA on them. We performed an experimental test of the effects of SA on GPS common-view time transfer via satellite 14. We measured the once per sidereal day time instabilities, $\sigma_x(\tau = 1\text{ d})$ over a three-month period as compared to the block 1 satellites. The results are tabulated in Table I. We conclude from this that little or no ephemeris degradation was present on SVN 14 during this period. In other words, if the SA present on SVN 14 were mostly placed in the modulation of the on-board clock's output, this would probably cancel when the differences are computed in the common-view mode and if the measurements were simultaneous at the two sites involved. The very small time instabilities observed would confirm this hypothesis. The common-view sites chosen were Boulder, Colorado to Washington D.C. and Boulder, Colorado to Paris, France.

GLONASS SATELLITE CLOCK PERFORMANCE

The receivers used for the measurement of GLONASS satellite clocks were developed and built at the University of Leeds, and this work is described elsewhere.[1] The frequency band used by GLONASS is the same, nominally, as that of GPS, and the timing accuracies and stabilities will be limited by the same sets of phenomena as for GPS. As to



(a)



(b)

Figure 1. GPS time and normalized frequency from 1983 onward as measured against the international time and frequency reference, UTC

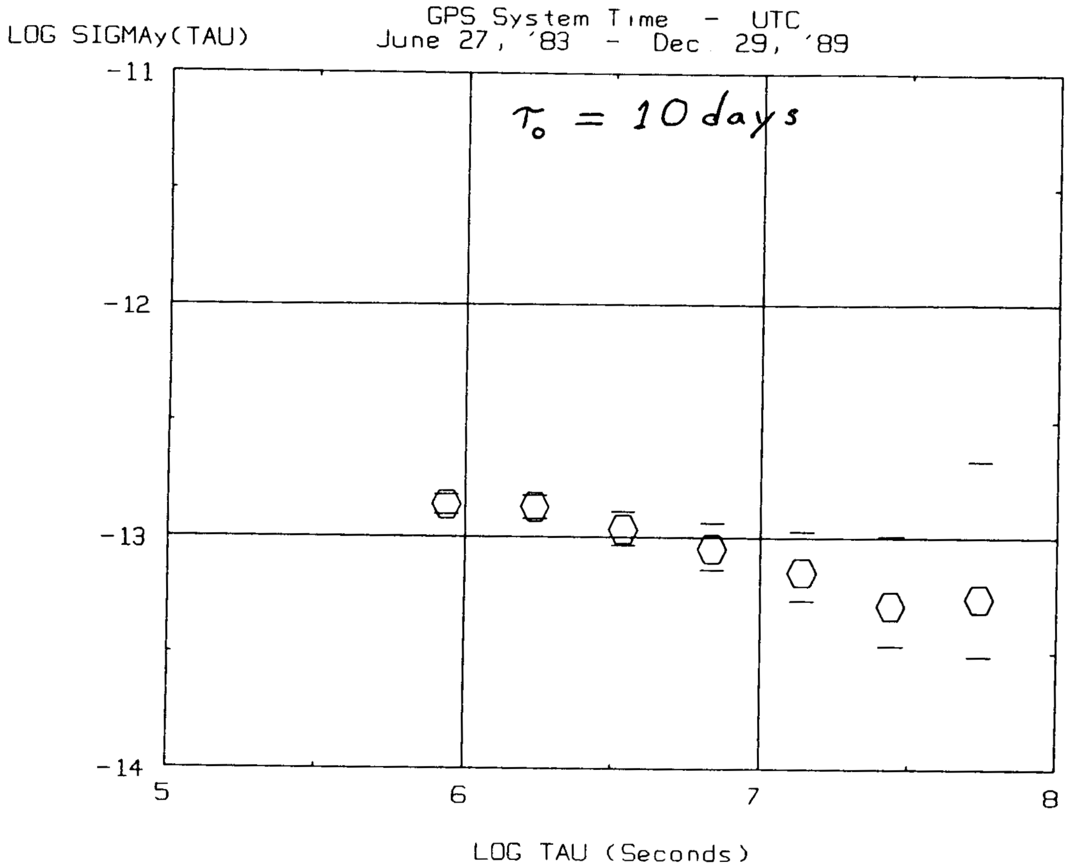


Figure 2. A plot of the fractional frequency stability, $\sigma_y(\tau)$, of the data shown in Figure 1—the stability of GPS with UTC as the reference

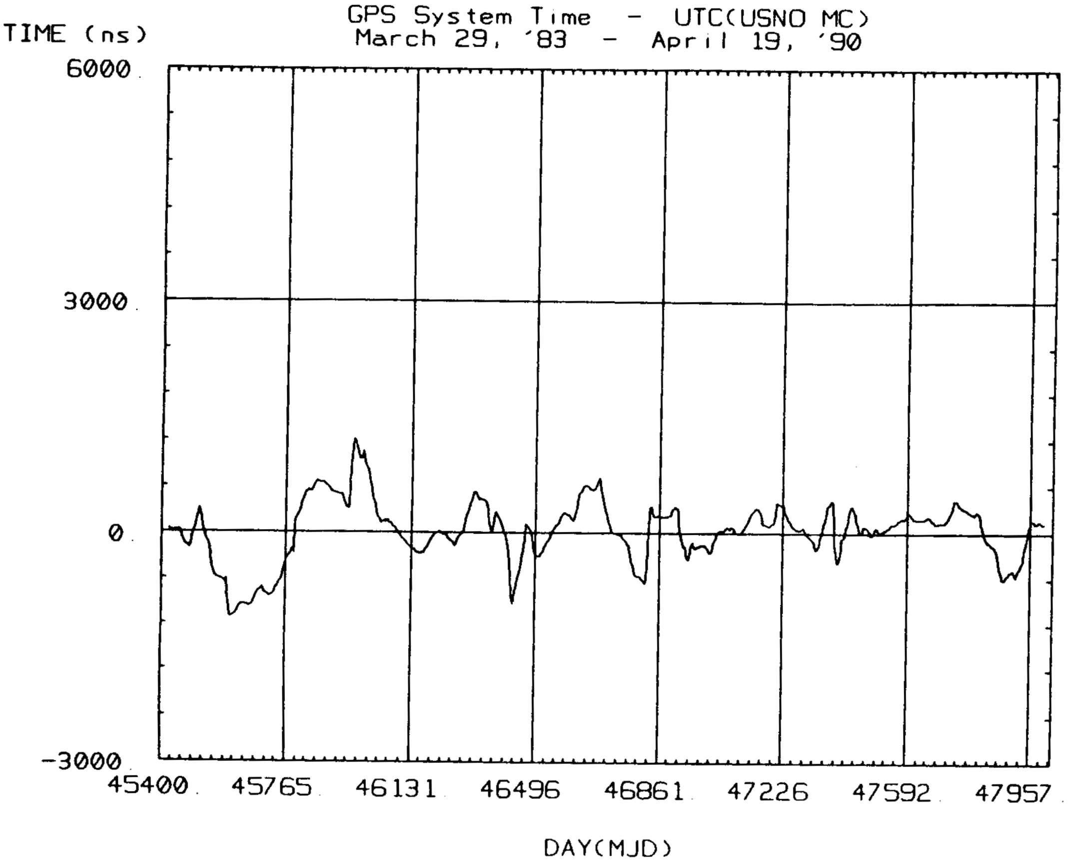
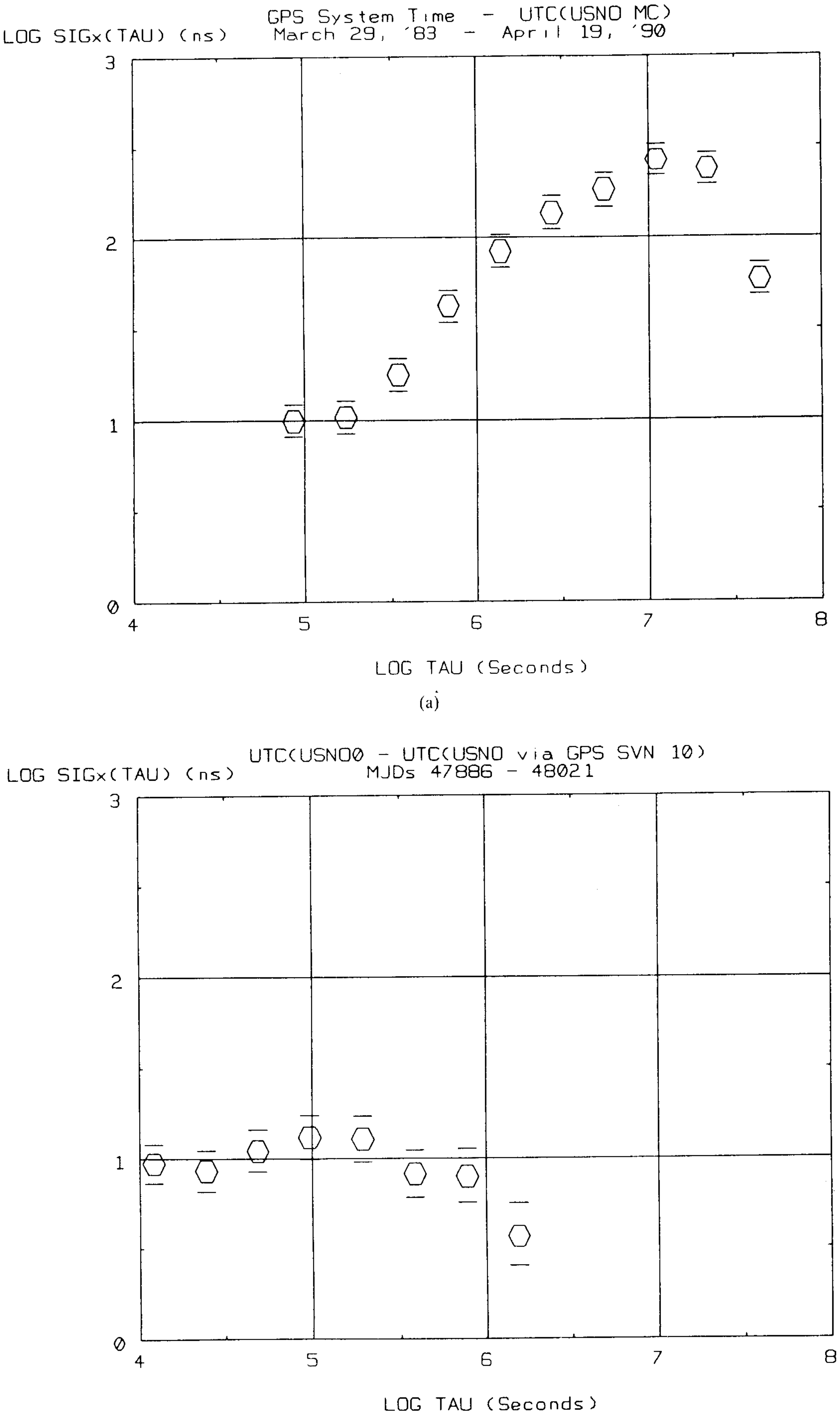


Figure 3. A plot of GPS time against UTC(USNO MC). Over the last few years it has stayed within its ± 1 μs goal. UTC(USNO) and UTC(USNO MC) are the same



(a)

(b)

Figure 4. A plot of the time stability ($\sigma_x(\tau)=\tau\mathrm{mod}\sigma_y(\tau)/\sqrt{3}$) of GPS time and of GPS time with the UTC(USNO MC) corrections with respect to UTC(USNO MC)

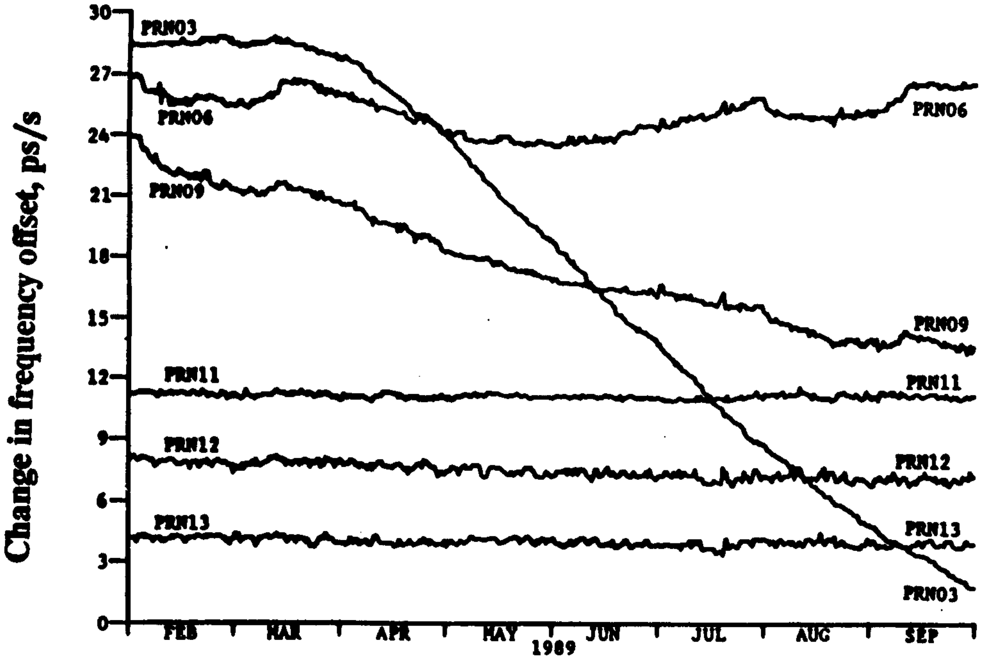


Figure 5. A plot of the normalized frequency offset in parts in 10^{12} with an arbitrary offset subtracted from each GPS satellite clock's frequency for plotting convenience

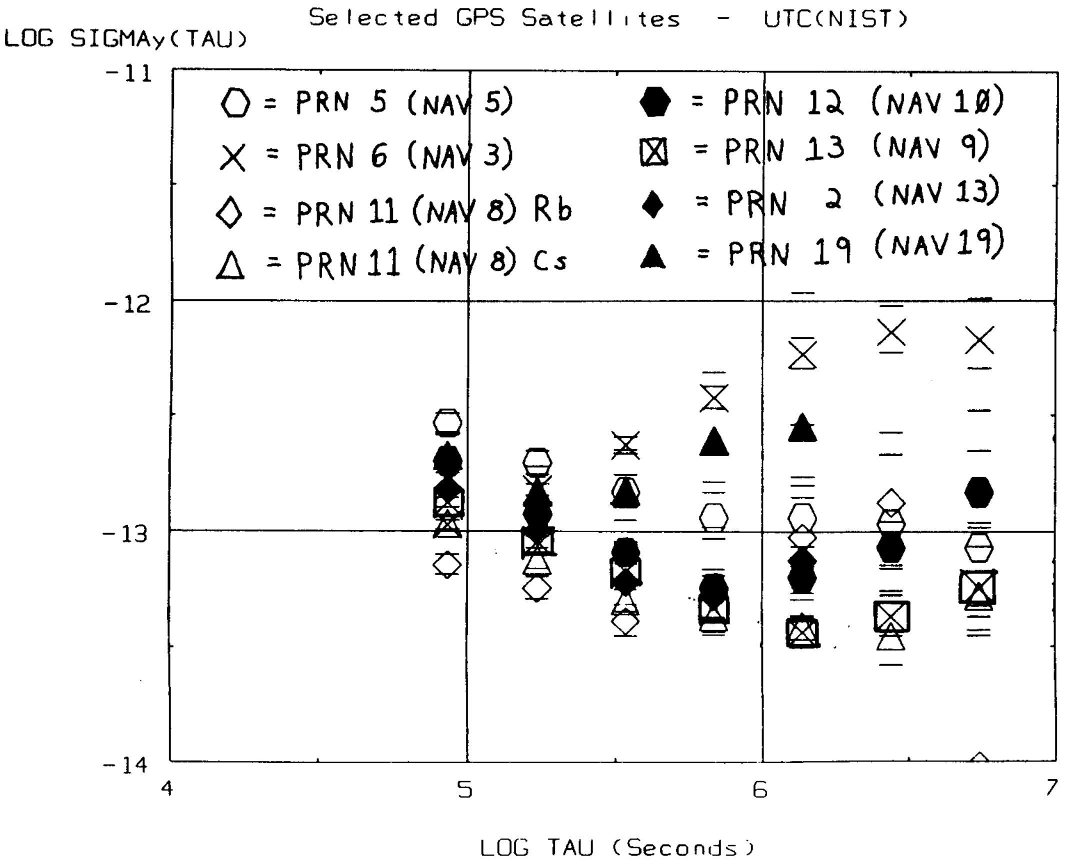
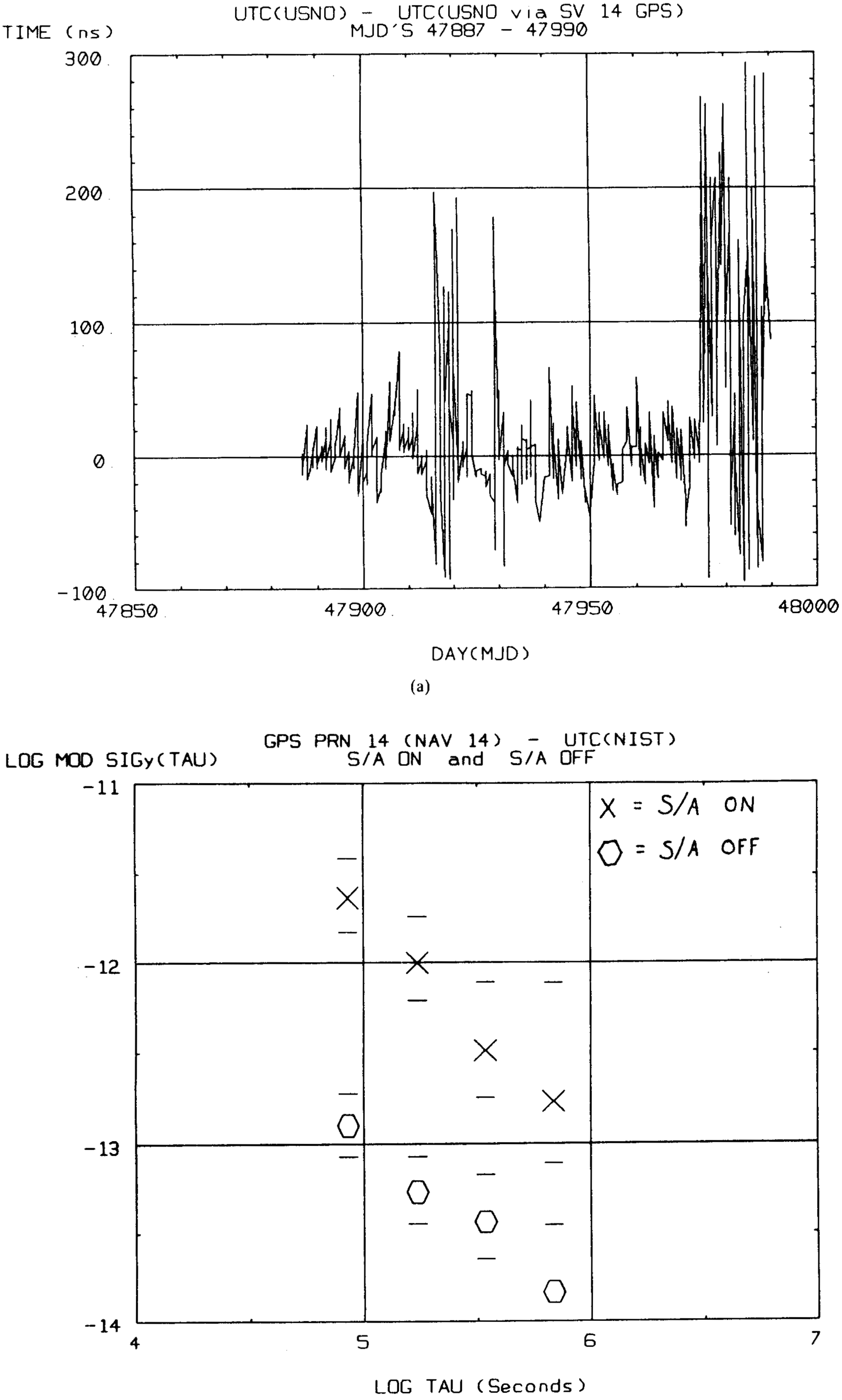


Figure 6. A plot of the fractional frequency stability, $\sigma_y(\tau)$, of most of the GPS satellite clocks with respect to UTC(NIST)

differences, because the GLONASS orbits are slightly lower the geometry does not repeat from day to day but repeats every eight days.

For many of the measurements reported herein, it has been convenient to use the a_0 term as broadcast. This term is the time difference GLONASS system time minus GLONASS satellite clock time. Like GPS, GLONASS transmits correction terms which allow the user to obtain Moscow time, and Moscow time in turn is kept synchronous with



(a)

(b)

Figure 7. A plot of the time (a) and the fractional frequency stability, $\sigma_y(\tau)$, (b) of GPS vehicle No. 14 showing the effects of selective availability (SA) as it is turned off during certain periods and on during others

Table I. Comparison of measurement noises: 1 January 1990–31 March 1990

SVN	Measurement noise (ns)	Per cent valid
UTC(OP)-UTC(NIST)		
12	7·9	99
8	6·7	95
10	12·5	99
9	2·1	99
14	10·6	43
UTC(USNO MC)-UTC(NIST)		
12	7·3	96
3	4·7	96
6	3·5	93
8	2·1	94
10	8·1	96
9	3·0	96
14	2·1	97

UTC(SU). SU is official Standard Time for the USSR as kept by VNIIFTRI—their standards laboratory 40 km north of Moscow. VNIIFTRI is the nominal equivalent of the NIST in the U.S. Over the last four years UTC(SU) has moved from a time difference with respect to UTC of about 30 μs to now about 10 μs.

Figure 8 is a plot of GLONASS system time versus UTC(USNO).We chose to analyse the quiet segment during the March–June 1989, period to see how good the performance (in terms of frequency stability) might be. Figure 9 is a mod$\sigma_y(\tau)$ plot for this period. The reference clock at the USNO is a synthesized output from a hydrogen maser. We understand that the reference for the GLONASS control facility is also a hydrogen maser. The one-day instability is too large for the clocks involved. Also, the slope of the data plotted in Figure 9 can indicate the type of noise, and in this case it is nominally well modelled by flicker noise phase modulation (PM). Neither the amplitude nor the type indicates clock noise. Instead, the observations could be explained by short-term receiver instabilities or clock estimation noise. In the latter case, the source is likely to be GLONASS, because the estimation noise for GPS has been traditionally lower than this for typical time transfer receivers.

Figures 10(a) and 10(b) are plots of the frequencies from several of the GLONASS satellite clocks. These data are derived from the GLONASS system estimate of the time of the clock with respect to GLONASS system time. There are periods where there appear to be long-term correlated frequency drifts between the satellite clocks. If the system clock were drifting, that would explain some of these segments. Or if the satellite clocks had correlated production dependencies which could effect the frequency drift, such a performance might be observed.

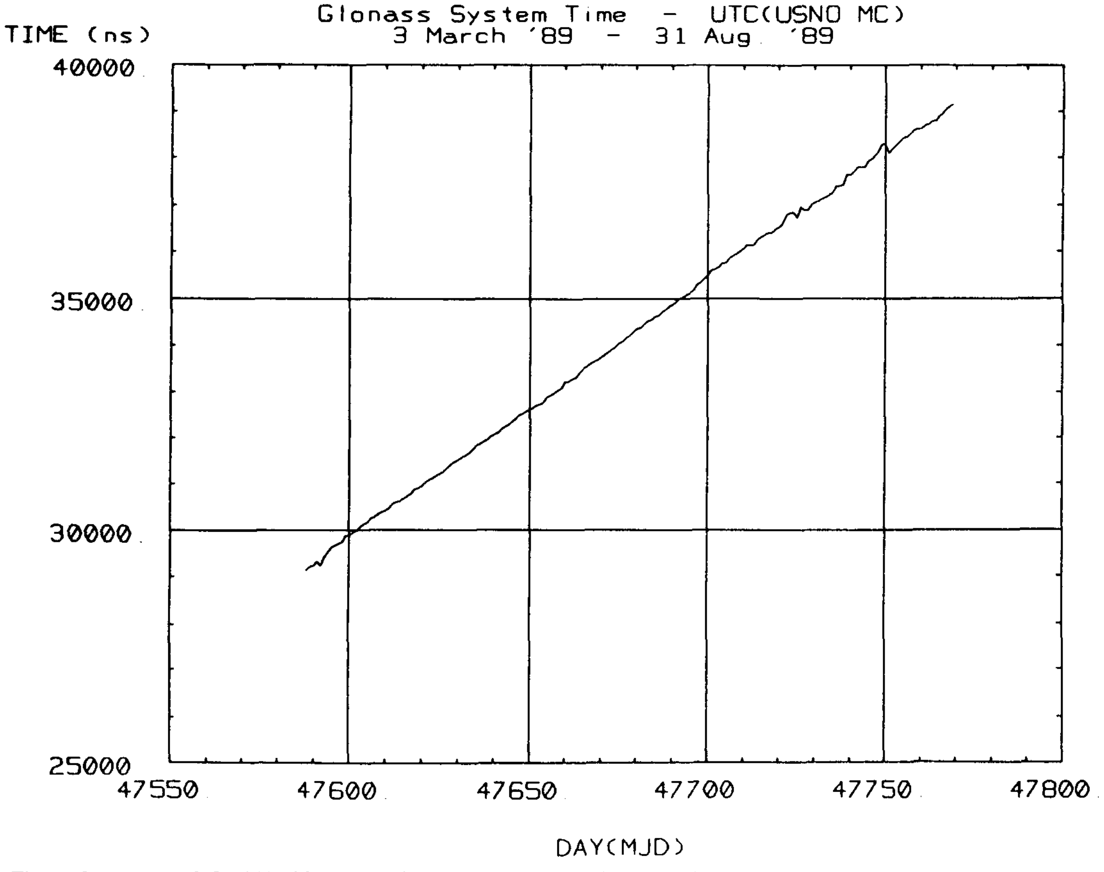


Figure 8. A plot of GLONASS system time as measured against UTC(USNO MC). These data were measured at Leeds deriving an estimate of UTC(USNO MC) with a GPS receiver

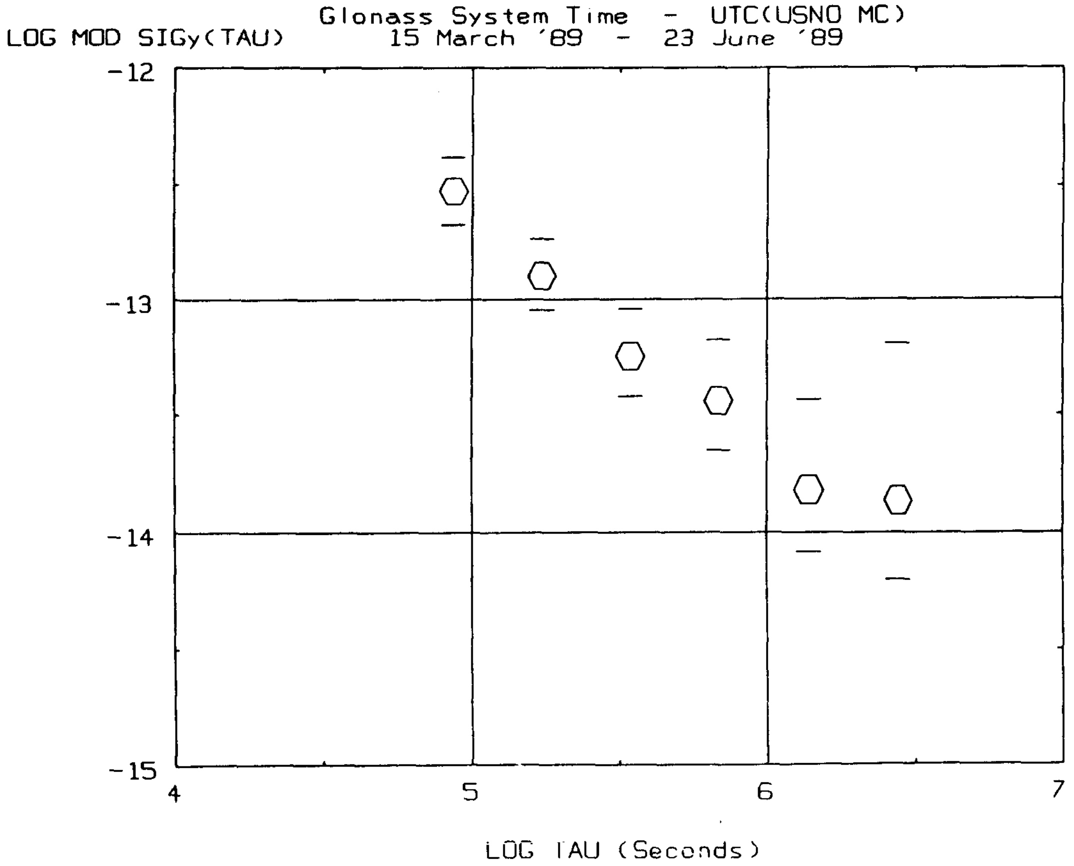


Figure 9. A plot of the fractional frequency stability mod$\sigma(\tau)$, of the smoothest part of the data plotted in Figure 8. The τ^{-1} behaviour is modelled by flicker noise PM. This is not characteristic of the clocks involved

Figure 11 shows $\sigma_y(\tau)$ plots for several of the GLONASS satellite clocks. We observe a significant improvement in performance with time. Whereas the GPS data, outside of measurement noise, are direct measurements of the satellite clocks with respect to UTC(NBS/NIST), these GLONASS satellite clock data are estimates of the clocks' time with respect to GLONASS system time. The improvement observed with time for sample times, τ, of a few days could be due to an improvement in the estimates or an improvement in the clocks. If performance in this region of sample times is due to the estimate, it is likely that the slope on the $\sigma_y(\tau)$ plot would be steeper than $\tau^{-1/2}$.

The longer-term stabilities shown are undoubtedly due to the clocks involved—the clocks being either the references (probably a hydrogen maser clock) or the satellite clocks. The long-term frequency drifts measured are fairly characteristic of caesium-beam frequency standards.

COMPARISONS OF GPS AND GLONASS CLOCK PERFORMANCE

The databases, as they were available to us for this paper, do not allow a direct and fair comparison, since different reference standards and different measurement systems were used. If the reader takes into account the conditions stated in the previous sections, the following comparisons yield some interesting perspectives.

By way of review, the reference for the GPS data was UTC(NBS/NIST). This reference has a one-day stability of about $1{\cdot}5 \times 10^{-14}$ and a flicker floor of less than 10^{-14} and a frequency drift of about 3×10^{-16}/d or less. Flicker floor means the best stability achieved in a $\sigma_y(\tau)$ plot. For the GPS and GLONASS satellite clocks the τ values for the flicker floor were a few weeks. UTC(USNO) has comparable performance to UTC(NBS/NIST). Other than the data shown in Figures 8 and 9, we have no other direct comparisons of the GLONASS system time to any other UTC time scale.

The frequency accuracies of UTC(NBS/NIST) and UTC(USNO) are a few parts in 10^{14}. The frequency offset of GLONASS system time is about 6×10^{-13} for the period shown. Figure 12 is a plot of the time accuracy of the various systems. UTC(SU) is official USSR time as determined by their primary standards laboratory VNIIFTRI near Moscow. What is plotted for UTC(SU) is obtained from Loran-C measurements as published by the BIPM.

If the random deviations of the frequency of a

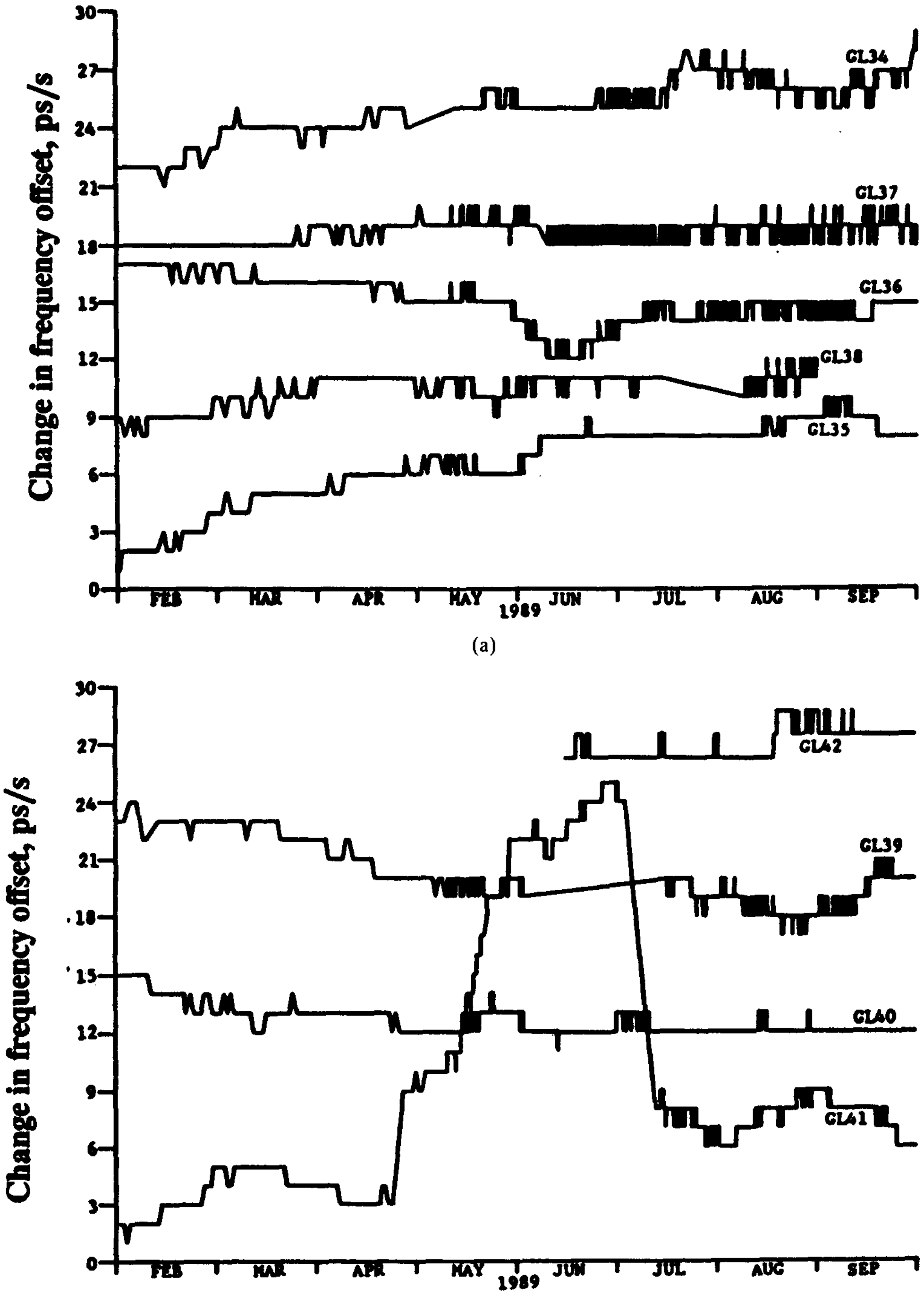


Figure 10. A plot of the normalized frequencies in parts in 10^{12} of most of the GLONASS satellite clocks

clock have a white spectrum, then a linear regression to the frequency is the optimum estimate for the frequency drift. If the random deviations are random walk (if they have an f^{-2} spectrum), then the mean finite second difference is the optimum estimator for the frequency drift. Since in practice we may have combinations of these processes, special algorithms for drift estimation may be necessary.[4]

Table II gives a comparison of the one day stabilities, the flicker floors and the frequency drifts for the GPS and GLONASS clocks. Please note again that these are not direct comparisons because of the different reference standards and measurement systems. The flicker floors and frequency drifts should be fairly representative numbers. Notice the dramatic improvement in the performance of the GLONASS clocks from the earlier to the more recent satellites.

CONCLUSIONS

Our procedure for determining the performance of both GPS and GLONASS on-board clocks is identical—we examine the time series of daily phase

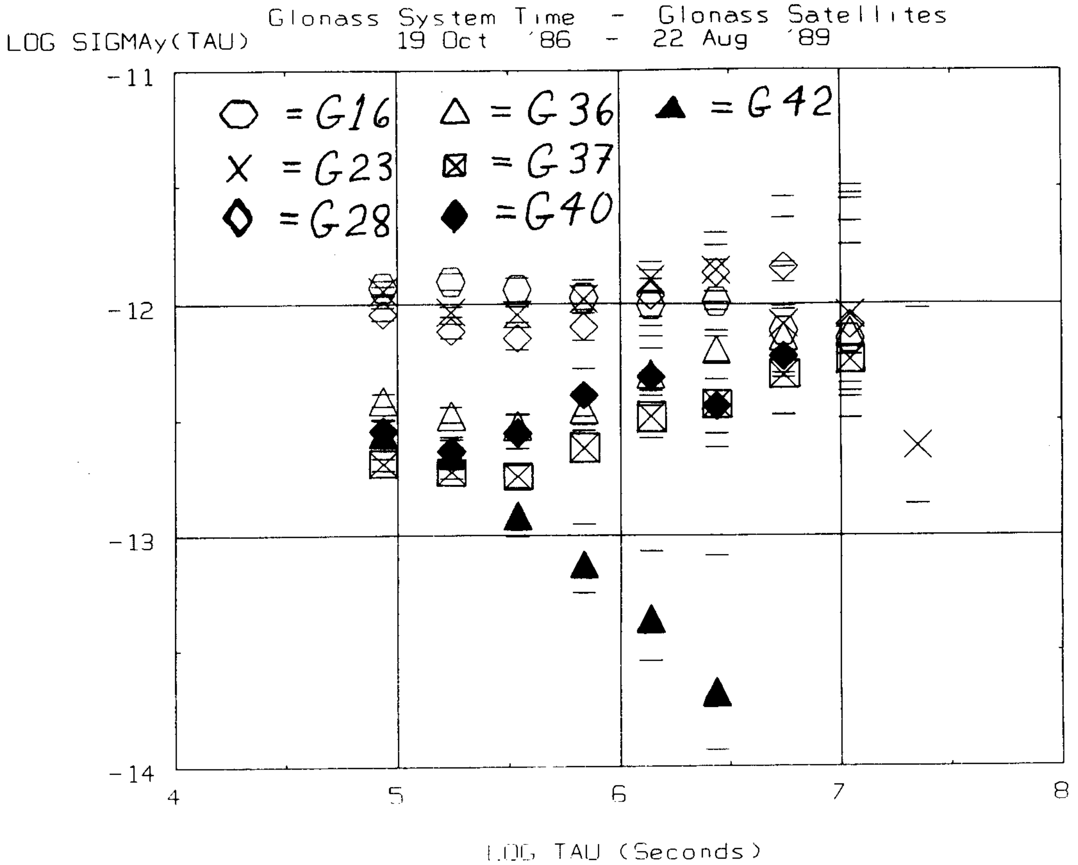


Figure 11. A plot of the fractional frequency stability, $\sigma_y(\tau)$, of several of the GLONASS satellite clocks

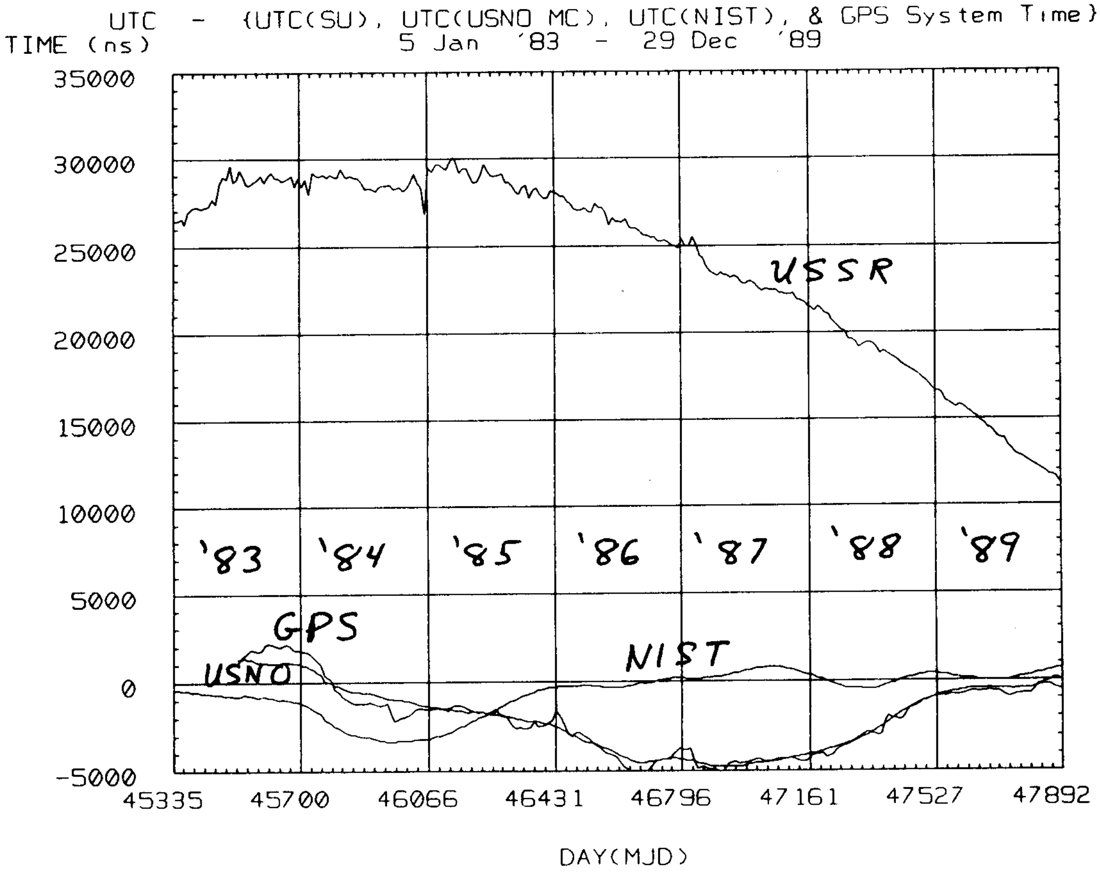


Figure 12. A plot of the principal reference time scales of the U.S.S.R. and the U.S.A. that were available to the authors over the last six years with respect to UTC. All of them appear to be improving in performance with time

Table II

PRN/NAV	1-day stability $\times 10^{14}$	Flicker floor $\times 10^{14}$	Drift/ day $\times 10^{15}$
GPS Satellite			
5/5	29·4	11·6	1·6
6/3 (Rb)	12·3	50·0	−6·0
11/8 (Rb)	6·5	2·8	−168·0
11/8 (Cs)	8·8	3·5	−0·8
12/10	11·1	3·5	−0·8
13/9	13·9	4·0	−0·3
2/13	15·0	5·5	−4·2
14/14	12·5	< 3	−0·5
16/16 (Rb)	26·4	12·5	−330·0
19/19	21·2	15·1	22·0
Glonass Satellite			
G16	119·0	100·0	−8·1
G23	114·0	89·0	−1·8
G28	91·1	78·0	−4·1
G36	38.9	31·0	−4·7
G37	20·4	18·0	−6·1
G40	28·7	24·0	+14·1
G42	28·0	< 4	−0·2

and frequency offsets transmitted by the spacecraft themselves. In the case of ground-based system references, our GLONASS reference is a 1 pps reference itself locked to within 100 ns of UTC(USNO). As far as on-board clocks are concerned, our analysis can be compared with the known performance of individual GPS clocks. In the case of GLONASS it is not known *a priori* what types of clocks are carried and in this sense our analysis of GPS can be seen as a kind of precalibration.

The time-series analysis which results in $\sigma_y(\tau)$ versus τ plots shows the individual characteristics of each satellite clock. Rubidium and caesium clocks are carried by the different GPS satellites. It also leads us to discuss the performance and types of on-board standards carried by GLONASS. In general tems, the time-series analysis shows a consistently higher performance for GPS clocks over GLONASS clocks. This statement is taken to refer to satellites active during a period of several years. However, while the GPS clock performance has been consistently high, the GLONASS clocks started from a mediocre performance and have improved steadily with time so that some of the recently launched GLONASS clocks are comparable to GPS clocks. This conclusion is reinforced by the data presented in Table II.

GPS satellite clocks and their more recent GLONASS counterpart clocks meet specification for global navigation satellites and are capable of transferring time with day-to-day time stabilities of 10 ns or better and long-term frequency stabilities of a few parts in 10^{14}.

Our analysis of measurements of GLONASS system time versus UTC(USNO) give evidence in the short term (1 day) of estimation or receiver errors not properly understood. In the long term (>8 days) we see clear evidence of the high-quality of both reference clocks. The UTC(USNO) reference is known to be a hydrogen maser and it seems more than likely, based on the evidence presented, that the GLONASS system clock is also a hydrogen maser at least during certain periods of time.

REFERENCES

1. S. A. Dale, I. D. Kitching and P. Daly, 'Position-fixing using the USSR's GLONASS C/A code', *IEEE Plans '88*, Las Vegas, 1988, pp. 13–20.
2. D. W. Allan and Lin Ping Ping, 'Estimating the GPS ephemeris plus propagation errors and their effect on time and frequency transfer', submitted to the *41st Annual Symposium on Frequency Control*, 1987.
3. M. A. Weiss and D. W.Allan, 'An NBS calibration procedure for providing time and frequency at a remote site by weighting and smoothing of GPS common view data', *IEEE Trans. Instrum. & Meas.*, **IM-36**, 572–578 (1987).
4. D. W. Allan, 'Time and frequency (time-domain) characterization, estimation, and prediction of precision clocks and oscillators', *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control*, **UFFC-34**, 647–654 (1987).