IEEE 1990

POSITION LOCATION AND NAVIGATION SYMPOSIUM

CH2811-8

IEEE
PLANS '90
POSITION LOCATION AND NAVIGATION SYMPOSIUM

RECORD

"THE 1990's— A DECADE OF EXCELLENCE IN THE NAVIGATION SCIENCES"

SPONSORED BY

IEEE AES SOCIETY

Additional copies may be ordered from:

IEEE Order Dept.
445 Hoes Lane
Piscataway, NJ 08854

IEEE Catalog No. 90CH2811-8
Library of Congress Catalog Card No. 89-81578

PLANS 1990 Executive Committee

General Chairman
PETER M. SCHULTZ
IBM Federal Systems Division

Vice Chairman
THOMAS E. SANDERS
Naval Air Development Center

Program Chairman
MICHAEL J. HADFIELD
Honeywell Military Avionics
Division

Finance Chairman
MARVIN D. SWENSEN
Communications Division
Ground Systems Group
Hughes Aircraft

Registration Chairman
LARRY ATKINS
Lockheed-California Company

Publicity Chairman
EDWARD DINTER
Bell Aerospace Textron

Exhibits Chairman
CHARLES H. EVANS
Litton Guidance & Control
Systems Division

Publications Chairman
ROBERT BEYER
Naval Air Systems Command

Member-at-Large
THOMAS A STANSELL, JR.
Magnavox

PLANS 1990

"THE 1990's—A DECADE OF EXCELLENCE IN THE NAVIGATION SCIENCES"

Tuesday March 20	Wednesday March 21	Thursday March 22	Friday March 23
TUTORIAL SCHEDULE:	8:30	8:30	8:30
8:30-12:00 PART 1	SESSION 1.1 Space Based Navigation Systems	SESSION 1.3 GPS Applications & Equipment # 1 Civil, Governmental and Commercial	SESSION 1.5 Differential GPS
12:00-1:30 LUNCHEON 1:30-5:00 PART 2	SESSION 2.1 Inertial Sensor Development SESSION 3.1 Radio Navigation Systems	SESSION 2.3 Integrated Navigation and Targeting Systems	SESSION 2.5 GPS/Inertial Navigation SESSION 3.5 Civil Aviation and Marine Navigation/Traffic Control—Part 2
TUTORIAL PROGRAM: 1. "Inertial Technology," Robert G. Brown	SESSION 4.1 Surveying, Mapping, and Digital Electronics Technology	SESSION 3.3 Civil Aviation and Marine Navigation/Traffic Control—Part 1	SESSION 4.5 Terrain Aided Air Vehicle Navigation
2. Land Vehicle Navigation and Information Systems," Robert L. French		SESSION 4.3 Geodesy, Gravity Measurement, and Earth Reference Systems	
3. "GPS Technology," Thomas A. Stansell 4. "Kalman Filtering Technology and Techniques," Dr. Mohinder S. Grewal 5. "The Art and Science of Navigation Integration into Avionics Systems," Dr. James L. Farrell	12:00 LUNCHEON SPEAKER: A. David Klein Litton Guidance and Control Systems Division "Positioning for the Future"	12:00 LUNCHEON SPEAKER: Steve Matousek Jet Propulsion Laboratory "Voyager and Neptune"	12:00 SYMPOSIUM CONCLUDES
	1:30	1:30	
	SESSION 1.2 Positioning, Pointing, and Stabilization of Space Systems	SESSION 1.4 GPS Applications and Equipment #—Military	
	SESSION 2.2 Inertial Systems Development and Applications	SESSION 2.4 Integrated Aircraft Navigation and Flight Control	
	SESSION 3.2 Integrated Communication/Navigation Systems and Standard Avionics	SESSION 3.4 Federal Radio—Navigation Policy Forum	
	SESSION 4.2 Application of Statistical Filtering to Navigation Technology	SESSION 4.4 Land Vehicle Navigation, Positioning, and Information Systems	

General Chairman's Message

Welcome to PLANS '90!

I am confident that this symposium will be of great value to all of us as we develop and manage position location and navigation systems for the future.

We appreciate the sponsorship of the IEEE Aerospace and Electronic Systems Society and I extend my sincere thanks to the Executive Committee for their time and support in planning and arranging the symposium.

I appreciate the efforts of the authors in contributing to our symposium; I am sure that you will find the papers very worthy of your attention.

I look forward to seeing you at PLANS '90!

Peter M. Schultz
General Chairman, PLANS '90

Table of Contents

Space Based Navigation Systems

Chairperson:
J. McNeff, *Office of the Asst. Secretary of Defense, C³I*

Inertial Sensor Development

Chairperson:
R.G. Brown, *R.G. Brown Associates, Inc.*

Other Radio Navigation System Technologies

Chairperson:
B.J. Uttam, *Synetics*

Surveying, Mapping and Digital Electronics Technology

Chairperson:
N.M. Anderson, *Canadian Hydrographic Service*

Positioning, Pointing and Stabilization of Space Systems

Chairperson:
D.A. Lacer, *The Aerospace Corporation/Naval Postgraduate School*

Inertial Systems Development and Applications

Chairperson:
J.R. Weyrauch, *Honeywell*

Integrated Communication/Navigation Systems and Standard Avionics

Chairperson:
W.R. Fried, *Hughes Aircraft Company*

Application of Statistical Filtering to Navigation Technology

Chairperson:
M.S. Grewal, *California State Univ.-Fullerton*

GPS Applications and Equipment I—Civil, Governmental and Commercial

Integrated Navigation and Targeting Systems

Civil Aviation and Marine Navigation/Traffic Control—Part I

Geodesy, Gravity Measurement and Earth Reference Systems

GPS Applications and Equipment II—Military

Integrated Aircraft Navigation and Flight Control

Land Vehicle Navigation, Positioning and Information Systems

Differential GPS

GPS/Inertial Navigation

Civil Aviation and Marine Navigation/ Traffic Control—Part II

Terrain Aided Air Vehicle Navigation

---

† Manuscript unavailable for publication in *Proceedings*. Contact author or Session Chairman for copy of paper.

CHARACTERISATION OF NAVSTAR GPS & GLONASS ON-BOARD CLOCKS

P Daly & I D Kitching

Department of Electrical and Electronic Engineering
University of Leeds, Leeds LS2 9JT, United Kingdom

Abstract

In the last year, both the Navstar GPS and Glonass satellite navigation systems have experienced a new impetus in the space segment with the US programme recovering from the Shuttle accident and GLONASS steadily increasing the number of operational satellites. The ultimate capability of any navigation or time-transfer system depends heavily on the quality and performance of the controlling frequency source. The paper reports on investigations into navigation satellite on-board clock frequency references and performance. Allan-variance techniques are applied to determine the long-term time-domain behaviour of satellite clocks in an attempt to identify different regions of power-spectral density. Coupled with analysis of relative-frequency drift over a period of many weeks, this behaviour allows the type of satellite on-board standard to be tentatively identified. Comparisons are made with Navstar GPS spacecraft clocks and conclusions drawn.

1. Introduction

Accuracy and repeatability of both GLONASS and NAVSTAR GPS are both ultimately determined by the inherent stability of the on-board clocks. The ability of the MCS to model the departures of satellite clocks from the system time scales, as a function of time, reflects directly in the time dissemination and navigation potential of the systems. The variation in the clock frequency or phase with time determines the refresh rate of the correction parameters in the data message so as to maintain a given level of accuracy. It also characterises how the system will behave during periods of limited data up-loads i.e. determines how gracefully the system will degrade without updating of the data message. The development of compact, low-power and high-stability atomic clocks, which have been proven in the space environment, has enabled what are approaching state-of-the-art precision oscillators to be utilised by space-based navigation systems.

We are concerned here with the stability of the clocks aboard NAVSTAR and GLONASS satellites as well as those used by their respective Master Control Stations (MCS) and associated time scales. Allan variance analysis [1] of clock phase data present in the transmitted data message is performed and the results confirmed by measurements of arrival time of satellite epochs against a local high-performance Caesium clock. Both GLONASS and NAVSTAR GPS satellites are examined and the known nature of the GPS clocks is utilised to provide a basis for formulating a conjecture on the nature of GLONASS on-board standards. Lastly, the analysis is repeated on other NAVSTAR/GLONASS derived data such as that of UTC(USNO) against NAVSTAR and GLONASS system times.

2. Clock data transmitted by navigation satellites

Following early success in developing an understanding of the rf structure of GLONASS satellites [2], it later proved possible to derive and interpret the GLONASS data message [3] which contains information on the satellites position and timing information. Both Navstar GPS and GLONASS satellites transmit clock data to ground observers so as to allow space vehicle clocks to be referred to (i) system time and then (ii) to UTC. Individual space vehicle clock offsets for Navstar GPS are given in terms of instantaneous phase, frequency and rate of change of frequency. These parameters are valid for a specified epoch allowing phase to be computed at any time in a specified period. Data for Navstar GPS is usually valid for several hours whereas GLONASS clock data is updated every half-hour obviating the need to transmit the third offset (rate of change of frequency). The estimation of clock offsets for a specified period is not independent of the satellite position ephemeris; the data transmitted from a given satellite will be a best-fit to a model based on measurement data probably obtained once or at most twice a day. In other words, the data will be an estimate based on Kalman filtering over periods of many hours.

A fixed ground station is only able to receive data from a global navigation satellite for less than about 8 hours per day divided between two passes. For Navstar GPS with ground-track repeat every sidereal day, these two passes are the same every day but the situation is rather different with GLONASS whose repeat period is 8 days. Over 8 days the duration of a GLONASS pass varies cyclically; at the start of a cycle the two passes may be roughly of equal duration (~3.5 hours) and 4 days

CH2811-8/90/0000/0001 $1.00 © 1990 IEEE

later there is one long pass (~5 hours) and one short pass (~1 hour).

In view of the factors mentioned above:- (i) the clock data subject to filtering with a time constant of the order of at least half a day and (ii) the spread in the observation period of the ground observer, it was decided to use available data on phase and frequency during any one day to produce an estimate of phase and frequency valid for the whole day. In this way the phase and frequency data used in computing Allan variances (see later) would be based on a unit time of one day (both Navstar GPS and GLONASS). This approach would appear to be justified since long-term differences in the behaviour between various atomic clocks are apparent from Allan variance plots based on data taken at 1-day intervals.

In addition, care must be taken in analysing raw clock data to detect and where possible to remove the effects of ground-commanded phase and/or frequency resets. It can safely be assumed that either a single phase or a frequency reset can be removed unequivocally. It is safer to ignore data where several resets follow one another within a time scale short compared to the integration period. A combination of both phase and frequency reset in the data can be taken as a strong but not conclusive indication that a complete change of on-board standard has taken place.

3. Characterisation of Stability

The frequency stability of precision oscillators has been studied for many years and indeed a Special Issue on Frequency Stability of the IEEE Proceedings was produced in February 1966. It was not until May 1971 that an attempt was made [4] to standardise the definitions used in frequency stability analysis. A number of techniques still exist for characterising oscillator behaviour but the technique used subsequently is that of Allan Variance analysis [5], [6] and [1] which has been widely accepted as the standard technique when discussing oscillator frequency deviations.

3.1. Random Fluctuations

For the random noise processes generally found in precision oscillators the frequency deviations can be characterised by power law spectra [7]

$$S_y(f) \sim f^{\alpha} \qquad (1)$$

where f is the Fourier frequency.

α takes on the values of +2, +1, 0, -1 and -2 for the five noise processes that are commonly encountered.

In descending order of α the five noise process have been named and attributed to the following physical effects :-

1) White PM ($\alpha = +2$)

2) Flicker PM ($\alpha = +1$)

3) White FM ($\alpha = 0$)

4) Flicker FM ($\alpha = -1$)

5) Random walk FM ($\alpha = -2$)

Although the previous discussion relates to the analysis of stability in the frequency domain it is more common for oscillator measurements to made and analysed in the time domain. It is thus desirable to have a time domain characterisation of phase fluctuations. The standard which is recommended by the IEEE and is almost exclusively used by analysts of clock stability, is that of Allan variance.

3.2. Allan Variance

Consider a set of discrete time deviations taken from the measurement of the difference between two clocks where the i'th deviation is given by x_i and the separation between measurements is τ_o. The average fractional frequency over the ith measurement interval is then given by,

$$\bar{y}_i^{\tau_o} = \frac{x_{i+1} - x_i}{\tau_o} \qquad (2)$$

For a complete set of discrete phase fluctuations a corresponding set of frequency values can be calculated. The classical standard deviation of the frequency fluctuations can be calculated but it has been shown [8] that for certain of the noise processes of interest the standard deviation is divergent with increasing data length. Therefore the IEEE recommendation for clock stability in the time domain is that of Allan variance (or two-sample variance as it is also known). The Allan variance is given by

$$\sigma_y^2(\tau) = \frac{1}{2} < (\Delta\bar{y}^{\tau})^2 > \qquad (3)$$

where $\Delta\bar{y}^{\tau}$ is the difference in adjacent fractional frequency measurements, each over the interval τ, and < > means an infinite average or the expectation value. It has also been verified that this quantity is convergent for increasing data length. Therefore, we have

$$\sigma_y^2(\tau_o) = \frac{1}{2\tau_o^2} < (x_{i+2} - 2x_{i+1} + x_i)^2 > \qquad (4)$$

For a data set of N adjacent phase differences, M average frequencies can be calculated where N = M + 1. For any data set of N samples, independent Allan variances can be calculated without any overlap in the phase intervals being used to calculate each individual Allan variance. It is clear that the possibility exists to use overlapping data values although they will not all be independent. Nonetheless this overlapping estimate makes a maximum use of the data and goes closest to approaching the expectation value. Therefore with an interval of τ_o, from a data set of N samples, N - 2 values of Allan variance can be calculated. This can be expressed as a summation by,

$$\sigma_y^2(\tau_o) \approx \frac{1}{2\tau_o^2(N-2)} \sum_{i=1}^{N-2} (x_{i+2} - 2x_{i+1} + x_i)^2 \qquad (5)$$

With the set of adjacent phase samples separated by τ_o, it is very easy to calculate Allan variances for intervals greater then τ_o by setting the chosen interval equal to $\tau = n\tau_o$ where n is an integer. In this case N - 2n Allan variances can be calculated from the data set and equation 5.11 can be rewritten as

$$\sigma_y^2(\tau) \approx \frac{1}{2\tau^2(N-2n)} \sum_{i=1}^{N-2n} (x_{i+2n} - 2x_{i+n} + x_i)^2 \qquad (6)$$

This is the general equation for the overlapping estimate of the two sample or Allan variance.

For the noise processes of interest the following power law applies:-

$$\sigma_y^2(\tau) \sim \tau^{\mu} \qquad (7)$$

The quantity μ takes on the values of -2, -2, -1, 0 and +1 for the five common noise processes described earlier. It is common practice when analysing Allan variances to plot $\log(\sigma_y(\tau))$ against $\log(\tau)$ which gives gradients of $\frac{1}{2}\mu$ for the different noise processes. In the very short-term, plots display White PM characteristics. As the integration time, τ, increases, the noise level decreases to a floor (white FM) and may then increase should the random-walk regime be reached. Figure 1 shows Allan variance profiles for a range of precision oscillators.

4. Frequency stability/drift

The frequency stability of the clocks on-board the NAVSTAR and GLONASS satellites are now analysed. Data will first be presented from GPS because the type of standard on-board the satellites is already known and so the obtained results may be used as a guide when analysing GLONASS. The stability of the GPS clocks in terms of Allan variance analysis has of course already taken place by a number of institutions interested in such work. Two such examples indicating what can be expected from GPS are [9] and [10]. Both found that the GPS Rubidium clocks are well modelled by white FM in the short-term and by random walk FM in the long-term whereas the Caesium clocks are modelled by white FM in the short-term and flicker FM in the long-term.

The timing information in the data message can be used in two ways. Firstly the variation of the frequency offsets of the clocks from the system time can be examined as the change in this parameter is obviously a measure of the stability of the clocks with respect to the system clock. Secondly the phase offsets of the satellite clock to the system clock can be used to calculate Allan variance profiles. It is quite possible that the analysis of the data message will provided the greatest accuracies when determining the stability profiles as the data does not suffer from the errors that occur when performing time transfer with the receiver, although the phase data is be biased by the phase estimation process used by the NAVSTAR/GLONASS MCS.

4.1. NAVSTAR Clock Frequency Offsets

The frequency offsets for the GPS satellites using Rubidium (PRN03, 06 and 09) and Caesium (PRN11, 12 and 13) standards are shown for an eight month interval in Figure 2. It is already evident that the Caesium clocks are much more stable than the Rubidium clocks. The Rubidium with the largest frequency drift is aboard PRN03 which does not have temperature compensation. NAVSTAR PRN08, which carries a crystal clock, has not been included in this data since its clock has frequency offsets and drifts typically two orders greater than the other clocks.

4.2. GLONASS Clock Frequency Offsets

The frequency offsets of the GLONASS clocks as contained in the data message are shown in Figures 3a and 3b and are valid for the same period as the data in Figure 2. First noting that the data resolution in frequency offset is 1 ps/s which accounts for the small jumps seen on the plots, GLONASS 37, 38, 40 and 42 show least drift over the observation period. There appears to be some commonality between satellites that were launched at the same time i.e. GL34, 35 and 36 (launch 12) show somewhat more variation in frequency offset than GL37, 38 and 39 (launch 13) or GL40 (launch 14) or GL42 (launch 15). It is likely that the quality of the clocks would improve with time as technical advances are made. GL41 appears to be the only satellite to experience a frequency reset over the data interval. During July 1989 the satellite stopped transmitting for ten days - before and after this interlude, the frequency drift was quite different. The large change observed could represent a switching of the on-board clock. It is known that GPS satellites carry 4 atomic clocks in case of clock failure, and doubtless GLONASS satellites carry at least one spare.

5. Phase stability

5.1. NAVSTAR Clock Phase Stability

Using the clock phase offset information from the data message Allan variance profiles have been constructed for the all NAVSTAR Block I satellites. Data is shown in Figure 4 for four NAVSTAR satellites:- PRN03 (Rubidium with poor temperature control - Fig.4a), PRN08 (Xtal oscillator - Fig.4b), PRN09 (typical Rubidium - Fig.4c) and PRN12 (typical Caesium - Fig.4d). The systematic phase change was removed using a quadratic least-squares fit. The 90% confidence limits are also included on the profiles and have been calculated for flicker FM noise. Data has been collected for sample times up to $\tau = 64$ days. During the interval for which data was collected some of the clocks experienced phase resets. Careful analysis was performed on both sides of the reset to determine if any change in frequency had accompanied the phase reset. If no frequency adjustment occurred then the phase reset was removed from the data to increase the maximum sample time. The size of the removed jump was calculated by extrapolating the phase data forward and backward about the reset to calculate the mean change. The best estimate will be obtained when phase data has been collected immediately adjacent to the reset. If a change in frequency offset occurred then data was selected which gave the longest uninterrupted data interval. Stability profiles were also constructed from data on either side of the frequency adjustment to confirm that the obtained profiles indicate a common clock i.e. a change in the satellite clock was very unlikely.

The following points can be made from the Allan variance profiles. The crystal clock on PRN08 exhibits random walk FM from $\tau = 1$ day, the first point, and so could be exhibiting the same noise process for even shorter sample times. White FM, flicker FM and random walk FM can be seen on the profiles for PRN09. The flicker floor occurs at approximately 2 parts in 10 exp 13 for $\sigma_y(\tau)$ with random walk FM occurring from sample times between 1 and 4 days. The Rb on PRN03 with no temperature control shows the worst stability with random walk FM occurring between 1 and 2 days. The Caesium clock on PRN12 exhibits white FM out to 8 days and then shows flicker FM at 6 parts in 10 exp 14 for $\sigma_y(\tau)$ out to the full 64 days. No random walk is evident up to the maximum sample time. In general, stability profiles of the Rubidium and Caesium clocks begin to diverge after 4 days with a clear distinction showing random walk behaviour visible after 8 days. The quartz clock on PRN08 is approximately two orders of magnitude poorer than the other clocks on the stability profile.

5.2. GLONASS Clock Phase Stability

Allan variance stability profiles constructed from GLONASS data message phase offsets are shown in Figure 5. The profiles cover launches from 1986 to 1989 with maximum sample times between 16 and 64 days dependent upon available data. As in the previous section, least-squares quadratic fits have been performed on the data to determine frequency offsets and drifts. Where possible, phase resets have been removed from the data to increase the maximum sample time and to reduce the confidence limits. One satellite from each of the years 1986-1989 is chosen for the purposes of illustration:- GL23 (1986- 71B, Fig.5a), GL28 (1987- 79A, Fig.5b), GL35 (1988- 43B, Fig.5c) and GL42 (1989- 39A, Fig.5d).

On GL 23, white FM is evident out to between $\tau = 2$ and 8 days and then flicker FM occurs at between 1.5 and 2 parts in 10 exp 13. The behaviour of GL28 is rather similar with an improvement in flicker FM noise floor. This is comparable to the Rubidium flicker floor performance on GPS PRN09 - the difference being that GL28 shows no signs of random walk even at 32 days. GL35 reaches the flicker FM floor already at 4 days and this is followed by random walk behaviour out to 32 days. This could perhaps be the profile of a moderate Rubidium clock or possibly a relatively poor Caesium clock. The most recent launch (1-6-89) was of GL42 and GL43. GL43 has had a variety of health problems and so insufficient data has been collected to merit an analysis of the clock. However, GL42 has been the best clock yet observed in the GLONASS satellites. White FM is present out to a sample time of 16 days, followed by flicker FM out to 32 days with $\sigma_y(\tau)$ equal to 5 parts in 10 exp 14. This is the performance one would expect of an excellent Caesium clock and compares favourably with that of NAVSTAR PRN 12. Table 1 summaries the level of the flicker floor (1/f) for all the satellites, in launch order, together with the GPS satellites for comparison. An indication of the type of on-board clock is also included. In the case of GLONASS the clock type is an estimate based on an examination of all available data including the stability profiles; the estimate must be treated as a conjecture in the absence of confirming evidence.

SV	Launch Date	1/f Floor $\times 10^{13}$	Clock
GL23	16-09-86	2.5	Rb
GL24	16-09-86	2.7	Rb
GL28	16-09-87	1.0	Rb
GL29	16-09-87	5.7	Rb
GL30	16-09-87	11.2	Rb
GL34	21-05-88	4.1	Rb
GL35	21-05-88	3.6	Rb
GL36	21-05-88	1.4	Cs/Rb
GL37	16-09-88	0.6	Cs
GL38	16-09-88	0.6	Cs
GL39	16-09-88	3.1	Rb
GL40	10-02-89	4.8	Rb
GL41	10-02-89	3.3	Rb
GL42	01-06-89	0.5	Cs
PRN06	06-10-78	1.6	Rb
PRN08	10-12-78	140.1	QTZ
PRN09	28-04-80	1.4	Rb
PRN11	14-07-83	0.7	Cs
PRN13	13-06-84	0.7	Cs
PRN12	08-09-84	0.7	Cs
PRN03	09-10-85	1.4	Rb

GLONASS and NAVSTAR Clock Flicker Floor

Table 1

5.3. Measured stability of on-board clocks

Over a period of two months, measurements of epoch arrival time against a locally-generated epoch were made in an attempt to confirm in gross terms the analysis of data just discussed. Phase measurements were made of the satellite clocks against a free running Caesium standard (HP 5061A, option 4). To fit a measurement schedule in with the other routine measurements of the receiver three NAVSTAR and three GLONASS satellites were chosen for the measurement campaign. Measurements were made for one hour per satellite, each day, for GPS, with the schedule incremented forward four minutes each day. To simplify the process the same four minute increment was used for GLONASS but owing to the eight day ground track repeat of GLONASS the satellites are visible for only three days out of every eight. The precision of each days phase measurements is considered to be between 5 and 10 ns. The measurement period is too short to provide more than an general indication of flicker floor levels reached by each satellite. To this extent the measured results confirm those derived from the data message.

5.4. Stability of UTC(USNO) - GPS Time

Figure 6 shows the Allan variance stability profiles of the NAVSTAR clock offset A_0, that is the offset of GPS time from UTC(USNO). It is known that GPS time is maintained within 1 μs of UTC(USNO) and consequently a certain amount of steering of GPS time towards UTC(USNO) occurs. Nonetheless the stability profiles will still give an indication of restrictions in the departure of GPS time as well as the contribution of the UTC(USNO) clock to the profile. As can be seen, white/flicker PM occurs out to 8 days and then flicker FM out to the full 64 days. If the GPS system clock were continually slaved to the USNO clock the long-term behaviour would be expected to mimic that of the USNO clock although the actual behaviour can only be accounted for if one knows the algorithms and techniques used to control the GPS/UTC(USNO) time difference. It is thus unclear as to whether the flicker floor of Figure 6 represents that of the GPS MCS clock or that of the USNO time scale. The former is considered more likely.

5.5. Stability of UTC(USNO) - GLONASS System Time

The measured offset of UTC(USNO) - GLONASS system time refers to the period 2-3-89 to 25-9-89. The USNO reference is derived from the NAVSTAR satellite with highest elevation and the Glonass data is based on a satellite ensemble average. The Allan variance derived from this data is presented in

Figure 7 and shows white/flicker PM out to the full 64 days. The modified Allan variance which distinguishes between white/flicker PM shows only flicker PM over the whole profile. There is no hint of a flicker floor or random walk and one is forced to conclude that the GLONASS system time clock is likely to be a high-performance Caesium or passive Hydrogen Maser clock. The flicker PM is more indicative of a steering in frequency than in phase as there is obviously no apparent constraint on the offset of GLONASS system time from UTC(SU) or UTC(USNO). Compared to the UTC(USNO) against GPS time data, the UTC(USNO) against GLONASS system time profile shows no sign of having reached a flicker floor at 64 days and exceeds the stability of the GPS time / UTC(USNO) offset. Since UTC(USNO) is common to both measurements, it may therefore be concluded that the flicker floor of Figure 6 is a result of the GPS MCS clock rather than UTC(USNO) and that the GLONASS MCS clock shows better long-term stability than its GPS counterpart.

Finally it has been possible to demonstrate [11] that GLONASS system time has been directly related to UTC(SU) via the transmitted parameter τ_c since December 1988. This means that the important step of relating UTC(USNO) to UTC(SU) via global satellite time transfer has been achieved.

6. Conclusion

The stability of the satellite clocks of both NAVSTAR and GLONASS have been analysed. The known nature of the GPS clocks has shown that the different types of clock aboard the satellites (crystal, Rubidium and Caesium) can be distinguished given a sufficient sample time. The same approach has been applied to the GLONASS satellites and a comparison of the results obtained from GPS has enabled a conjecture on the type of clocks used by the GLONASS satellites. The analysis has involved a comparison of satellites launched during the period 1986-1989 although data for the early period is sketchy. It would seem however that GLONASS has used clocks of the quality of Rubidium atomic oscillators since 1986 at least and that there has been a steady increase in quality and performance of on-board standards with time. Some current satellites perform well enough in terms of frequency drift, Flicker FM noise floor and long-term stability to compare favourably with the Caesium beam standards carried on Navstar GPS satellites launched in 1983-84.

Additional time scales have also been analysed such as that of GPS and GLONASS time against UTC(USNO) and also the GLONASS data parameter τ_c which since December 1988 has related GLONASS system time to UTC(SU).

7. Acknowledgement

The authors wish to express their appreciation to the National Physical Laboratory, UK for the loan of a high-performance Caesium beam standard.

REFERENCES

[1] D W Allan :
"Time and frequency (time-domain) characterisation, estimation and prediction of precision clocks and oscillators", IEEE Trans., Vol. UFFC-34, No.6, Nov.87.

[2] S A Dale, P Daly :
"Recent observations on the Soviet Union's Glonass Navigation Satellites", IEEE PLANS' 86 (Position Location & Navigation Symposium), Las Vegas, 4-8 November, 1986, pp 20-25

[3] S A Dale, I D Kitching and P Daly
"Position-fixing using the USSR's Glonass C/A code", IEEE PLANS'88, Orlando, 28 Nov - 2 Dec, 1988, pp.13-20

[4] J A Barnes et al :
"Characterisation of frequency stability", IEEE Trans., Vol. IM-20, No.2, May 1971.

[5] D W Allan :
"Accuracy of international time and frequency comparisons via GPS satellites in common view", IEEE Trans., Vol. IM-34, No.2, June 1985

[6] D A Howe et al :
"Properties of signal sources and measurement methods", Proc. 35th AFCS, Monmouth, NJ, May 1981.

[7] D W Allan :
"Statistics of atomic frequency standards", Proc IEEE, Vol.54, No.2, Feb 1966.

[8] J A Barnes :
"Atomic timekeeping and the statistics of precision signal generators", Proc IEEE, Vol.54, No.2, Feb 1966.

[9] T B McCaskill & J A Buisson :
"On-orbit frequency stability of Navstar GPS clocks and the importance of frequency stability to precise positioning", First Int. Symp. on Precise Positioning with GPS, Rockville, MD, Apr.15-19, 1985

[10] D W Allan & T K Peppler :
"Ensemble time and frequency stability of GPS satellite clocks", Time & Frequency Division, NBS, Boulder, Co

[11] P Daly & I D Kitching :
"Progress in transferring time using GLONASS satellites", 21st PTTI meeting, Redondo Beach, Nov 28-30, 1989.