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REPORT

Report on the Study to Determine the Suitability of GPS Disciplined Oscillators as Time and Frequency Standards Traceable to the UK National Time Scale UTC (NPL).

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REPORT ON THE STUDY TO DETERMINE THE SUITABILITY OF GPS DISCIPLINED OSCILLATORS AS TIME AND FREQUENCY STANDARDS TRACEABLE TO THE UK NATIONAL TIME SCALE UTC(NPL).

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Approved on behalf of the Managing Director, NPL, by Dr J R Laverty, Centre Manager, Centre for Time Metrology.

Executive Summary

The use of Global Positioning System Disciplined Oscillators (GPSDOs) is one of the principal methods of world-wide high accuracy time and frequency dissemination. However, the GPS is highly complicated, and is under the direct control of the US Military. Questions have been raised, both on the integrity of the GPS signals, and also on the satisfactory operation and typical performance of GPSDOs. So far GPSDOs have not been recognized as standards traceable to the UK national time scale, UTC(NPL).

Due to the widespread use of GPSDOs throughout industry in the UK, the National Physical Laboratory (NPL) has undertaken a study to characterize GPSDOs, with the aim of establishing the suitability of GPSDOs as traceable standards. An account of the study is presented in this report.

A total of 15 GPSDOs have been borrowed from 11 manufacturers for a period of three months. Extended measurements have been made on both the phase of the GPSDOs frequency output and on the One Pulse Per Second (1PPS) timing signals, by making direct comparisons with the national time scale UTC(NPL). Information on both the status of each GPSDO and the GPS have been collected from each unit. Other measurements made in this study include environmental data, the monitoring of the GPS at NPL, and data collected from the United States Naval Observatory on the performance of the GPS. The GPSDOs are found to exhibit wide variations in their performance characteristics, both in the accuracy of the absolute time dissemination, and in their frequency dissemination characteristics, particularly over medium averaging times, eg (τ = 1,000 s). Some unexpected characteristics have been observed, in particular the occurrence of time and frequency transients, with amplitudes of up to several microseconds and durations of several hours. Recommendations are made on the suitability of GPSDOs as traceable standards. The direction of future work is considered.

Acknowledgments

The authors thank: Absolute Time, Datum, Efratom, Hewlett Packard, Motorola, Navstar, Quartzlock, Radiocode Clocks, Rapco Electronics, Tekelek, Trak and Truetime for their participation in this study.

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1.1) Time and frequency dissemination using GPSDOs

The US Global Positioning System (GPS) is principally a navigation system [1], although in the last ten years it has also been used extensively for time and frequency dissemination. Timing signals from the GPS are known to show excellent long term stability, but they also possess considerable short to medium term noise. The development of the GPS Disciplined Oscillator (GPSDO) is an attempt to combine the short term stability of a high quality oscillator, with the long term accuracy obtainable from the GPS.

GPSDOs have several advantages compared with other time and frequency standards. The signals will be constantly steered to UTC(USNO) and so will not require periodic re-calibrations. The devices may be used anywhere in the world, they are widely available, and may not be excessively expensive.

There are many applications for GPSDOs in areas diverse as navigation, broadcasting and the telecommunications industry (here they are used as frequency standards). Currently there is a growing demand for time synchronization [2]. If GPSDOs do become accepted as standards traceable to the UK's national time scale, UTC(NPL), then they are likely to have a much wider application in UK calibration laboratories.

1.2) GPSDO traceability issues

At present, GPSDOs are not accepted as standards traceable to UK national standards of time and frequency. As part of this study NPL has been in close discussion with United Kingdom Accreditation Service (UKAS) to establish how the results from this work may be used to enable industry in the UK to use GPSDOs as traceable standards. In this work, two aspects of the performance of the GPSDOs are of particular interest, these being their accuracy and integrity. Other aspects of GPSDO performance, for example availability and continuity of operation are also examined. The GPSDOs have been initially studied as complete units, however time has also been spent examining their component parts, along with the GPS, from which they derive their disciplining signals. In each case the integrity and accuracy of the system or system component under study was investigated.

1.3) Elements of the GPSDO study

A total of 15 GPSDOs were loaned to NPL for the period January - March 1997 inclusive, by 11 manufacturers. The GPSDO manufactures taking part in this study were Absolute Time, Datum, Efratom, Hewlett Packard, Navstar, Quartzlock, Radiocode Clocks, Rapco Electronics, Tekelek, Trak and Truetime. GPSDOs have several major components. These include a GPS "engine" or receiver, a local oscillator, normally either quartz or rubidium, an algorithm for combining signals from these two components, and a Digital to Analogue Converter (DAC) which is used to apply control voltages to the local oscillator. There are several outputs from a

GPSDO: a standard 5 MHz or 10 MHz frequency output, a One Pulse Per Second (1PPS) output and a RS232 communications port, through which GPSDO status information is transmitted. The GPSDOs contained a variety of GPS "receivers" capable of tracking either six or eight satellites simultaneously. All of the GPSDO are single L1 frequency C/A code devices. Information on the operation of the GPSDOs was downloaded via the RS232 port.

The key measurements made in this study were the comparisons of the time and frequency outputs of the GPSDOs against the UK national time scale UTC(NPL). UTC(NPL) is a particularly stable time scale being based on signals from an active hydrogen maser. A phase comparator was used to study the standard frequency outputs from the GPSDOs, while a One Pulse Per Second (1PPS) logging system was used to compare the GPSDO timing pulsed against UTC(NPL). Cable delays between UTC(NPL) and the 1PPS logging system was measured using a portable HP5071A caesium clock. The local environment was monitored using a temperature and humidity logging system.

The GPS at NPL was monitored continuously using three eight channel GPS receivers. NPL's principal GPS receiver is an Allen Osborne Associates TTR-4P receiver. In addition NPL operated two Motorola VP Oncore receivers. These receivers were particularly valuable, as their performance would be similar to the front end receivers used in the GPSDOs.

NPL's monitoring of the GPS was supplemented by data obtained from the USNO WWW site. This data included records of satellite changes and outages, along with measurements of UTC(USNO) - GPS Time. Because the GPSDOs are ultimately tracking UTC(USNO) it is important to constantly measure the values of UTC(NPL)-UTC(USNO). This is achieved on a routine basis through GPS common-view time transfer, where both NPL and USNO follow the recognized BIPM schedule.

Standard time and frequency analytical techniques have been applied to the data collected in this study, along with more general analytical techniques. Several GPSDO meetings have taken place at NPL. Copies of this report will be forwarded to UKAS to provide information on the GPSDO traceability issue.

This report is structured as follows: in section 2 an overview is given of the GPS. The monitoring of the GPS at NPL is reported along with GPS information obtained from the USNO WWW site. The aim is to examine the accuracy and integrity of the GPS signals received at NPL during the study. In Section 3, the time dissemination characteristics of the GPSDOs are examined, from which recommendations are made on the use of GPSDOs as time standards traceable to UTC(NPL). A similar treatment is provided of GPSDO frequency dissemination in section 4. Section 5 deals with the occurrence of transients on the GPSDO time and frequency outputs. In sections 6 to 8 the components of the GPSDOs are considered individually. In section 6 the performance of the GPSDO free running oscillators are examined. Section 7 deals with correlation effects between GPSDOs, from which conclusions are drawn relating to the GPSDO front end receives and the GPS. In section 8 the GPSDO determination of antenna coordinates is examined, and recommendations made for the determination of the GPSDO coordinates when being installed as traceable standards. A more complete picture of several of the GPSDOs is provided via the case studies developed in section 9. In section 10 an account is given of several tests designed to study the effects of GPSDOs operating under non-ideal conditions. This includes the effects of reducing the number of satellites in the GPS constellation, operating the

GPSDOs using erroneous coordinates, and the study of both the loss of mains power to the GPSDO and the GPS signal itself. These tests will help to determine if GPSDOs would still function as traceable standards if operated under these environments. Conclusions and recommendations are provided in section 11, along with an outline of the proposed future work.

1.4) References

[1] Elliott D Kaplan, *Understanding GPS, Principles and Applications,* Artech House mobile communications series, Artech House, Boston and London, February 1996.

[2] Sover Wong, *How to synchronize telecommunications networks,* To be published in Proceedings 11th European Frequency and Time Forum, Neuchatel, March 1997.

2) The Global Positioning System

2.1) Introduction

In order to examine the performance and reliability of GPSDOs as time and frequency standards, the Global Positioning System needs to be continuously monitored in parallel to check its accuracy and integrity. In this section, a brief description is given of the GPS and how it was monitored throughout the study. Three receivers were used at NPL to check the accuracy, availability, continuity and integrity of the GPS signals. Published lists of outages for each satellite were also obtained and compared to measured data during the study period. The timing accuracies expected from using the GPS are discussed in addition to some of the key factors which influence them.

2.2) Description of the GPS

The GPS consists of a constellation of 24 satellites (including three active spares). The satellites are positioned in six earth-centred orbital planes with four satellites in each plane. Each satellite is located in a 11 hr 58 min orbit. The orbits are nearly circular, which are equally spaced about the equator with a 60° separation, and an inclination to the earth's equatorial plane of 55°.

To use the GPS for a complete time and positioning solution, it is necessary to receive signals simultaneously from four or more GPS satellites. If the coordinates of the receiver are accurately determined, then a user may obtain a separate measure of precise time from each available GPS satellite.

Each satellite is identified by its Satellite Vehicle Number (SVN). In addition to this identity, GPS satellites may also be referred to by a number which corresponds to its transmitted Pseudo-Random Noise code (PRN). It is important to remember that the SVN and PRN numbers are not always identical for each satellite.

The signals transmitted by GPS satellites contain two types of information: navigation data (e.g., satellite ephemerides and satellite health), and ranging codes; which allow the signal propagation times to be determined. These signals are propagated on two separate frequencies referred to as L1 and L2. The L1 frequency is set at 1575.42 MHz and is modulated with two ranging codes known as the Coarse Acquisition code (C/A) and the precise P1 code. The L2 frequency is set at 1227.6 MHz and is modulated with only the precise P2 code. The precise P1 and P2 codes are usually encrypted as the Y1 and Y2 codes and are not available to the civilian user.

The standard physical model of the earth used for GPS applications is the World Geodetic System 1984 (WGS-84). All coordinates supplied are given with respect to this frame of reference. It is well known that coordinates determined in different reference frames (e.g., ED 50, OSGB 36, WGS-84) may not necessarily agree each other due to a number of errors in projection, the datum value, the process of surveying and in their compilation.

In this study, GPSDOs were only capable of receiving the C/A code on the L1 frequency.

UTC(USNO) time dissemination accuracy is within 340 ns (95% confidence) for a single channel C/A code receiver [1].

2.3) Traceability of the GPS timescale

Transmissions from each GPS satellite are referenced to atomic frequency standards on board each satellite. This atomic clock is synchronised to the GPS 'system' time. The GPS 'system' time is effectively a 'paper clock' and is formed from a weighted mean of all the on board GPS atomic frequency standards. This system time is continuously monitored by a network of ground stations and referenced to the time scale at the United States Naval Observatory, UTC(USNO).

2.4) Sources of error affecting GPS time and frequency dissemination

A number of factors can influence the timing signals derived from GPS satellites. Listed below is a brief description of common timing errors. Table 1 at the end of this section, gives a summary of typical error budgets for use of the Standard Positioning Service (SPS) C/A-Code.

i) Selective availability (SA)

This is a time varying signal which is applied to the Coarse Acquisition (C/A) pseudo-ranging code. Its application is controlled by the Department of Defence (DOD) and the Department of Transport (DOT) in the US, with the aim of reducing the instantaneous accuracy of the GPS obtainable when using the SPS. The resultant effect is to both 'dither' the satellite clock and alter the satellite orbital data, causing errors in the measured signal propagation time, i.e., the time it takes to send a signal from a satellite to a GPS receiver. Different levels of dither are applied to the C/A code, these are related to a User Range Accuracy index, URA, found in the navigation message.

ii) Multipath or shadowing

Multipath is caused by reflected signals near the receiver that can either add to the principal signal or be mistaken for the signal that follows the straight line path from the satellite. These effects may be minimised by siting the antenna in a good location away from tall buildings and reflective objects.

iii) Satellite clock

On board each GPS satellite there are several atomic frequency standards that control all the timing operations including the broadcast signal generation. The time difference between the satellite clocks and GPS system time may be as much as 1 ms [2]. The Master Control Station (MCS) determines and transmits clock correction parameters to each satellite for rebroadcast in the navigation message.

iv) Satellite availability and integrity

Since 1993, a minimum of four satellites should be observable at any point on the globe. Depending on the mode of operation of the GPSDO, if the position has already been accurately determined and is fixed in the receiver, then it is possible to obtain timing information from only one satellite. However, if this satellite is broadcasting erroneous signals and it has not been identified as being unhealthy, then large errors will occur in the time and frequency output.

v) Ionosphere delay

The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionised air. The ionosphere is a dispersive medium, and ionosphere delays are frequency dependent. Both measured and modelled ionospheric delay corrections are provided by the TTR-4P receiver at NPL. Modelled ionosphere corrections may be in error by up to 50 %. In figures 1 (a) and (b), typical modelled ionosphere corrections are plotted during the tracks of several GPS satellites. There is a strong correlation with elevation angle. The ionospheric delays at low elevation angles are a factor of three greater at low elevation angles compared to when the satellite is directly overhead. The ionospheric delays vary on a daily basis.

vi) Troposphere delay

The troposphere is the lower part of the earth's atmosphere up to 13 km, and is non dispersive for frequencies up to 15 Hz. Although tropospheric delay changes have not been examined in this study, their effects have been examined previously[3]. Tropospheric delay changes are a function of the tropospheric refractive index which is dependent on the local temperature, pressure and humidity. The refractivity is modelled in terms of a dry and a wet component. The dry part corresponds to dry air and contributes up to 90% of the troposphere delay and can be predicted accurately. The wet component of the troposphere, is dependent on the water content in the air and is more difficult to predict. Delay changes for the wet component are typically 1 ns for signals from satellites directly overhead, increasing to a few nanoseconds for low elevation angle satellites.

vii) Satellite broadcast ephemeris

Inaccurate broadcast ephemeris data will cause errors in the measurement of satellite signal propagation times.

viii) Antenna coordinates

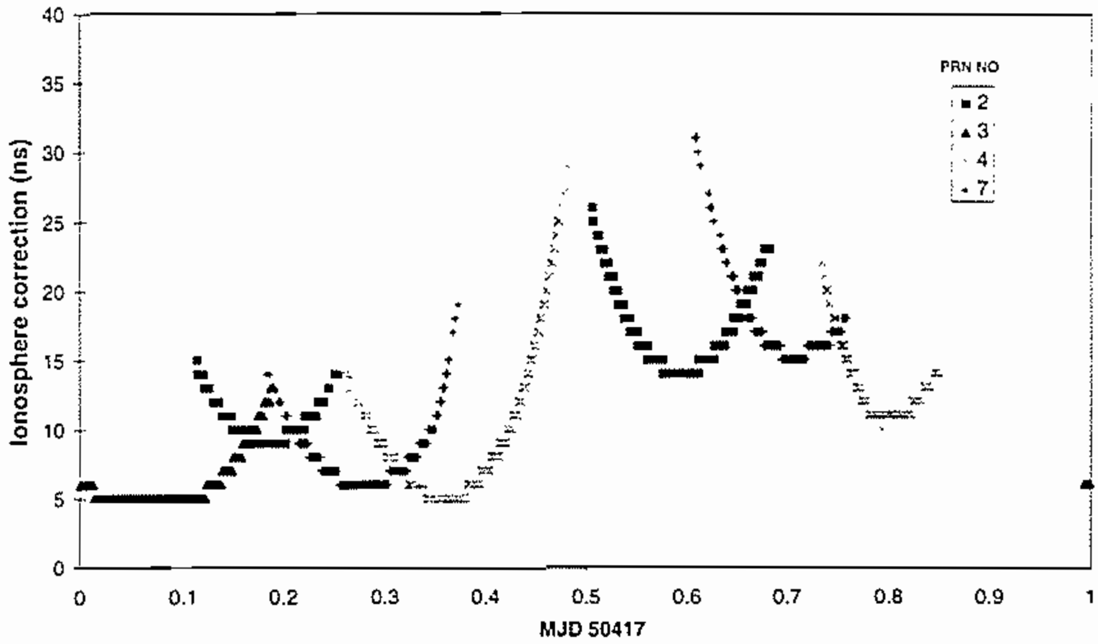
The use of accurate antenna coordinates is important when using GPSDOs. Results from this study have suggested large diurnal variations in both the 1PPS and phase outputs occur if the antenna coordinates are grossly offset e.g., by 100 m.

ix) Instrumentation delays

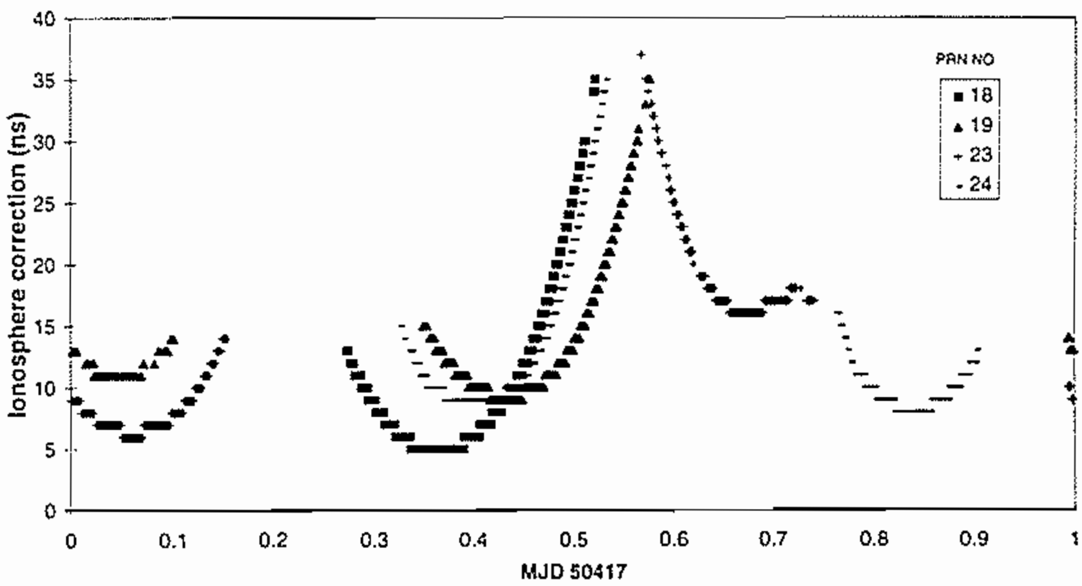
For each GPSDO there will be a number of hardware and software delays which need to be calibrated, e.g., antenna-receiver cable lengths need to be known accurately to allow for any

FIGURE 1 : TTR-4P Modelled Ionosphere correction

(a)



(b)



additional signal propagation delays to be accounted for. The type of cable used also needs to be known. Delays can also arise from the antenna, the down converter, from filters and correlators in the hardware and from the software algorithm used.

x) Satellite health and integrity

The GPS constellation is monitored continuously by a control network. If a problem does occur with one of the satellites it may take between 5 and 45 minutes for this network to identify that there is a problem with a satellite and broadcast that is unhealthy. If there is satellite redundancy in the GPS receiver, then the effect of picking up the broadcast transmissions from an unhealthy satellite may not be a serious problem. There are several ways in which this problem can be overcome e.g., using Receiver Autonomous Integrity Monitoring (RAIM) which is an over determined solution to perform a consistency check on the satellite constellation [4].

Table 1: Summary of estimated C/A-Code Pseudo-range error budget [5].

Segment Source	Error Source	GPS 1σ Error (m) with SA
Space	Satellite clock stability	3.0
	Satellite perturbations	1.0
	Selective availability	32.3
	Other (thermal radiation, etc.)	0.5
Control	Ephemeris prediction error	4.2
	Other (thruster performance, etc.)	0.9
User	Ionosphere delay	5.0
	Troposphere delay	1.5
	Receiver noise type and resolution	1.5
	Multipath	2.5
	Other (interchannel bias, etc.)	0.5
System UERE*	Total root sum square (rss)	33.3

* where UERE is defined as the User Equivalent Range Error.

2.5) Integrity monitoring of GPS at NPL

2.5.1) Introduction

At NPL, three 8-channel GPS receivers were used to monitor the GPS continuously: one Allen Osborne Associates Timing Turbo Rogue receiver (model TTR-4P), and two Motorola VP Oncore receivers (with Z option). The configuration used by all the GPS receivers are shown in figure 2. For an explanation of the local clock and how it is related to UTC(NPL) (see section 3.3). Both Motorola receivers have an identical set up so the layout of only one receiver is shown.

Although the TTR-4P receiver is a dual frequency L1 and L2 (C/A and P) code receiver, it was only set to receive the C/A code since the GPSDOs in the study were only capable of receiving the C/A code. Data from the TTR-4P was recorded every 30 seconds to a computer. A mask angle of 7° was applied. The coordinates of the TTR-4P were determined by allowing the receiver to operate for several days with a medium time constant of a few days on its position algorithm. The receiver was then set with a long position time constant i.e., several years, to effectively operate in a position hold mode.

The Motorola Oncore is an inexpensive high quality GPS receiver which is not used principally for time and frequency applications. A PC was used to record the output from each receiver, and an external counter timer was used to measure the external 1PPS against a 1PPS derived from UTC(NPL). Both the Oncore receivers were set to track the eight highest satellites in the sky. The receivers were also operated from a fixed set of antenna coordinates. These coordinates were determined by operating the receivers in a 3-D position mode for several days and post processing the collected data. The GPS time and status information was recorded every 30 s and is shown in table 2.

Table 2: Data sets recorded from NPL's multi-channel GPS receivers every 30 seconds.

Data set recorded	AOA TTR-4P	Motorola Oncore
Antenna coordinates	yes	yes
No. of satellites tracked	yes	yes
PRN of satellites tracked	yes	yes
Satellite strength	yes	yes
Satellite azimuth	yes	no
Satellite elevation	yes	no
Measured ionosphere correction	yes	no
Modelled ionosphere correction	yes	no
Tropospheric correction	no	no

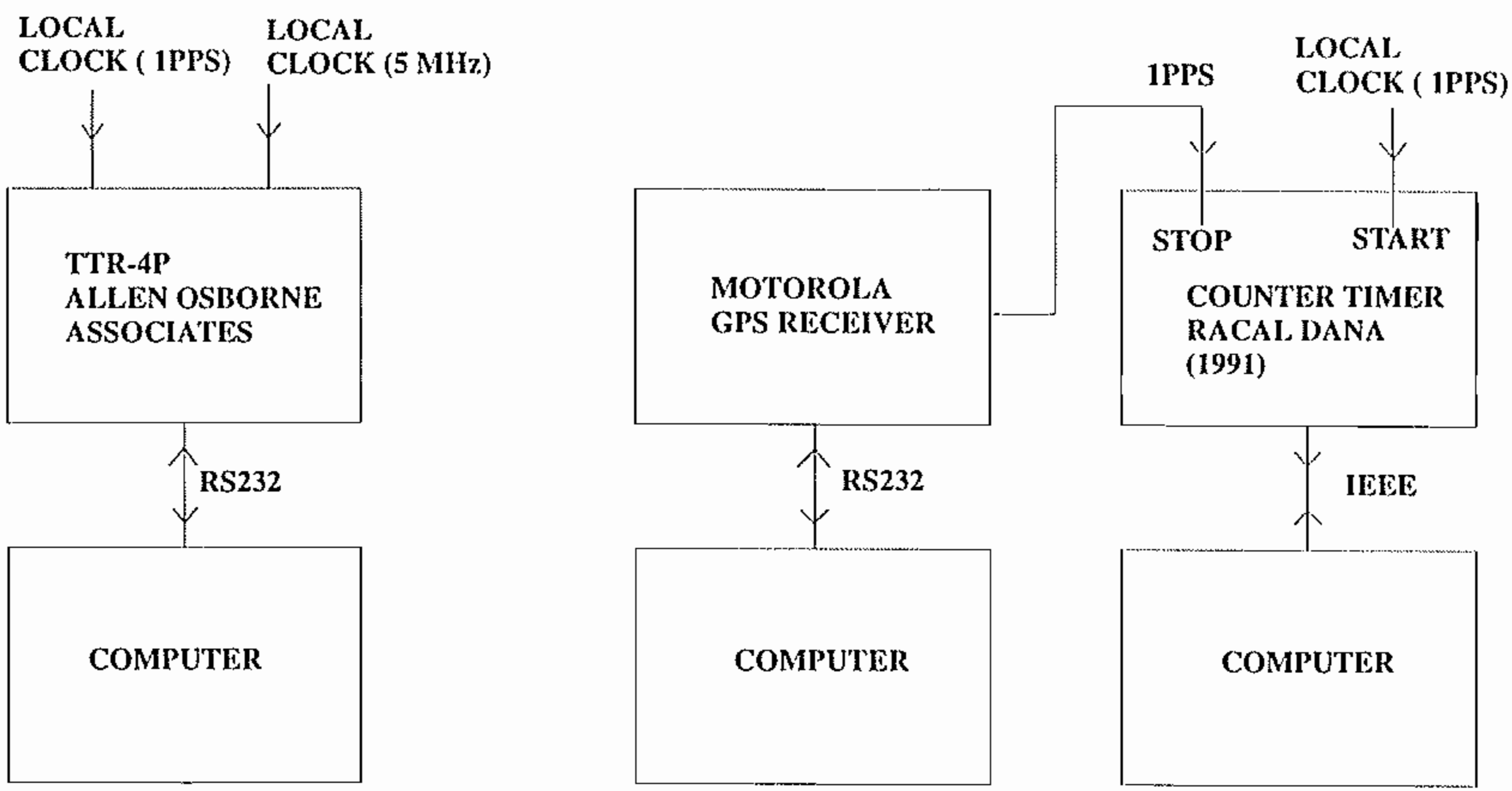


FIGURE 2: Configuration of NPL'S GPS receivers

Data set recorded	AOA TTR-4P	Motorola Oncore
Local clock-UTC(USNO) for each satellite	yes	yes
Satellite health	yes	yes

2.5.2) Availability of GPS satellites

Figure 3 shows the number of GPS satellites visible above the horizon at NPL on four separate days, as viewed by a Motorola Oncore receiver. There was a noticeable variation in the number of satellites visible above the horizon at different times of the day, varying between 7 and 12.

2.5.3) Location of GPS satellites

The location of each GPS satellite is determined from its broadcast almanac. This also gives details on the azimuth and elevation angles of each GPS satellite. The trajectory of all the healthy GPS satellites observed at Teddington is shown in figure 4 on MJD 50459. Several trends were observed, the GPS satellites have maximum orbit latitudes of 55°. This has the effect that there is an absence of satellites when looking directly north from Teddington, especially at high elevation angles. This 'hole' in the GPS constellation will become larger as the latitude of the antenna site increases. This constellation asymmetry should be considered when setting up GPSDO installations. There is a large variation in the maximum elevation angles of the satellites, with some satellites reaching almost directly overhead and others having a maximum elevation angle which is less than 10°.

2.5.4) 1PPS time output

The Motorola Oncore receivers can provide a 1PPS output, and this was compared to the local clock derived from the national time scale. Typical plots of GPS(1PPS)-Local clock for each receiver are shown in figures 5 (a) and (b). There is a peak to peak data spread of typically 200 ns, the long term time transfer characteristics are excellent. As expected from common-view measurements there is a strong correlation between the 1PPS output from the two receivers, and this is examined in more detail in section 7.2.

2.5.5) Pseudo-range correction data

The pseudo-range correction time is the measured time difference between the receiver clock and the satellite clock reading, when the propagation delay is being corrected from the antenna coordinates and the broadcast ephemeris. The effects of satellite and receiver clock offsets and various sources of error e.g., satellite clock error, ephemeris error, SA, relativistic effects, atmospheric effects, etc, all contribute to the corruption of the satellite-to-user pseudo-range measurement. In this study, measurements of pseudo-range corrections were made for each

FIGURE 3 : (ONCORE1) Number of satellites visible, tracked and locked

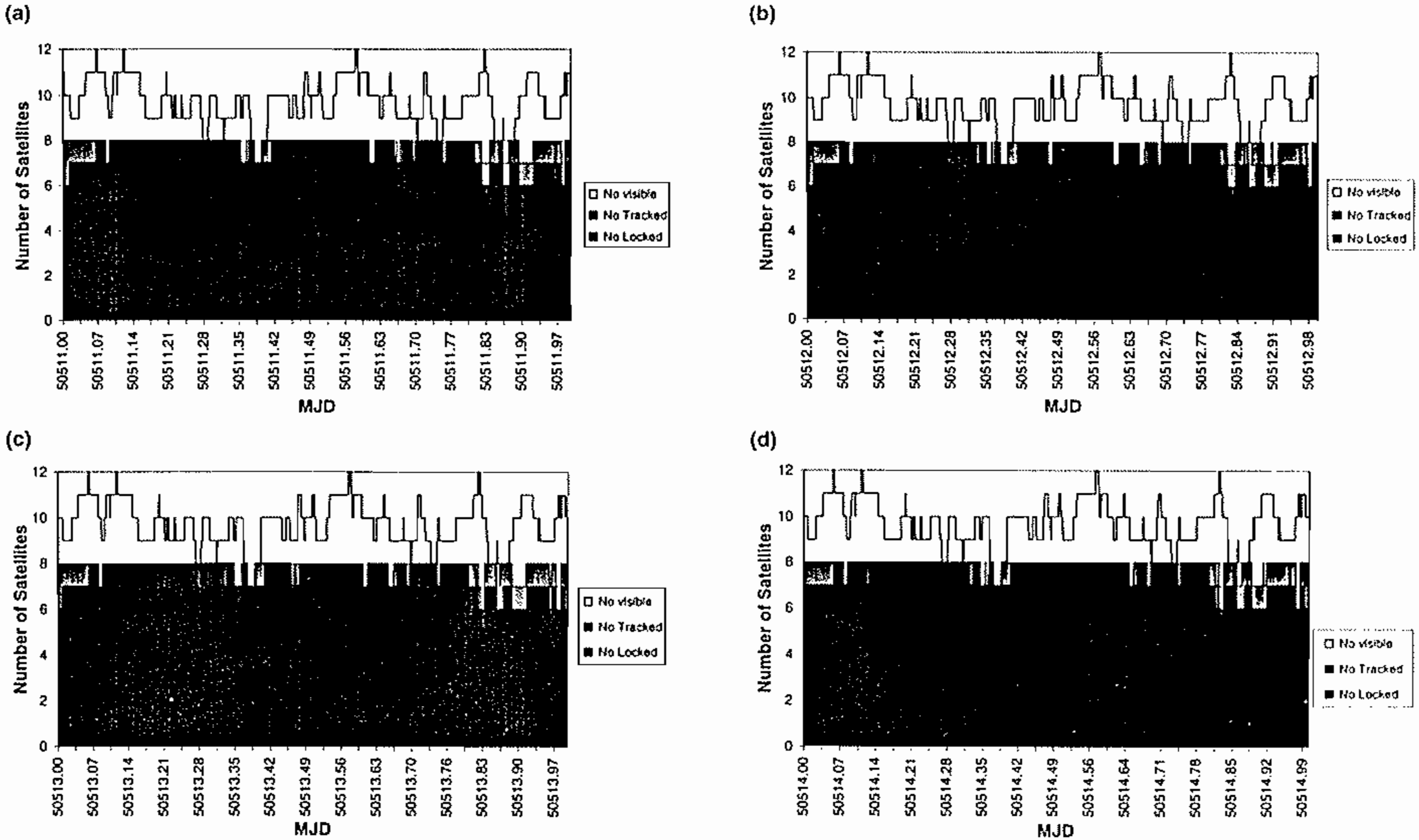


FIGURE 4: Location of healthy GPS satellites on MJD 50459 as viewed from Teddington

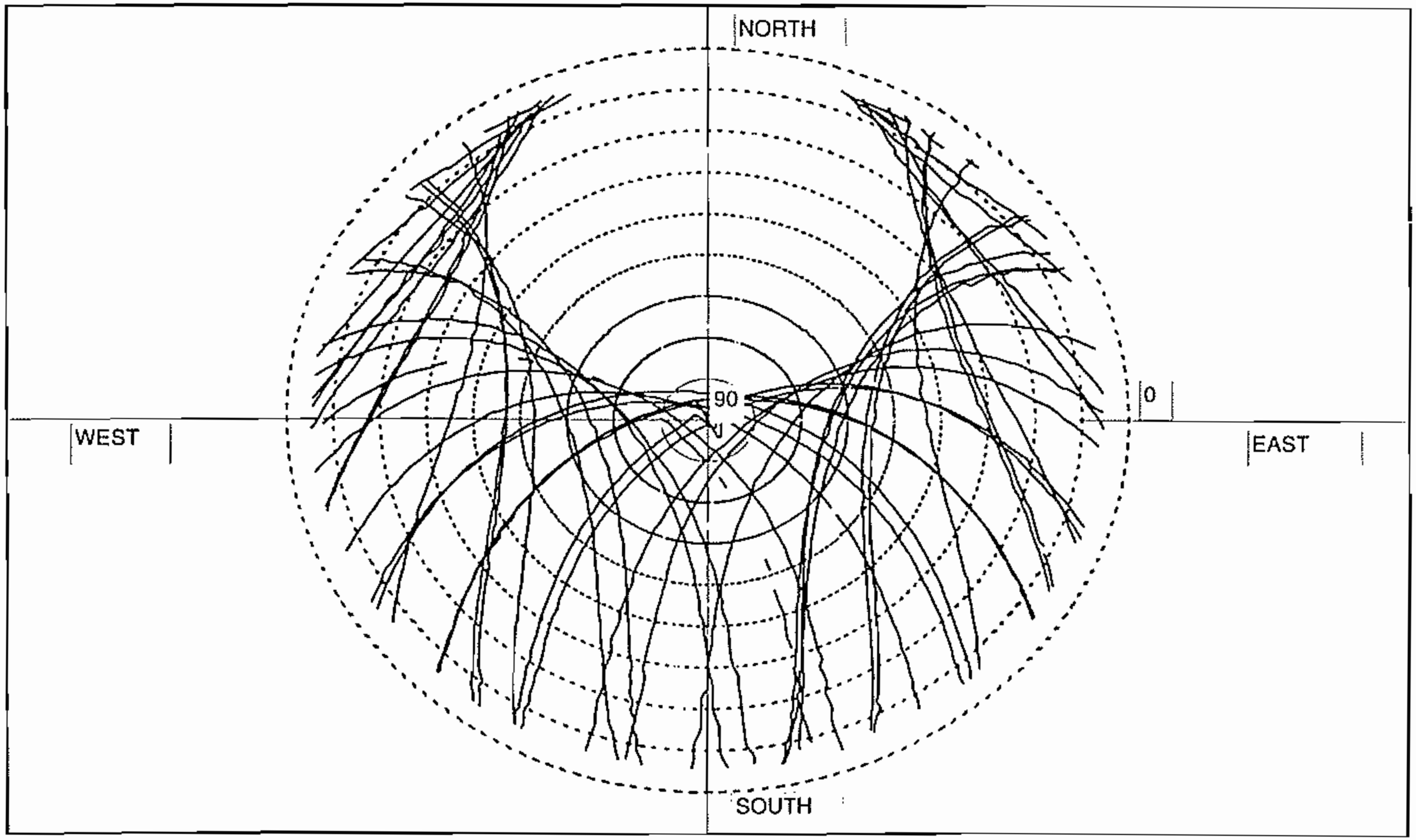
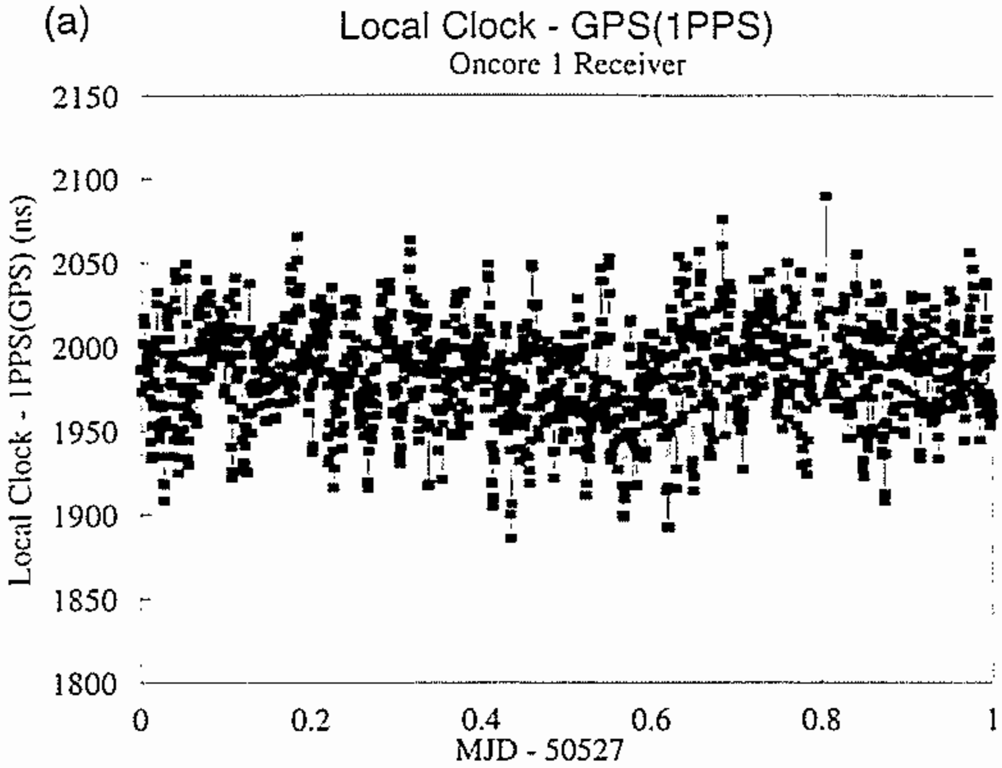
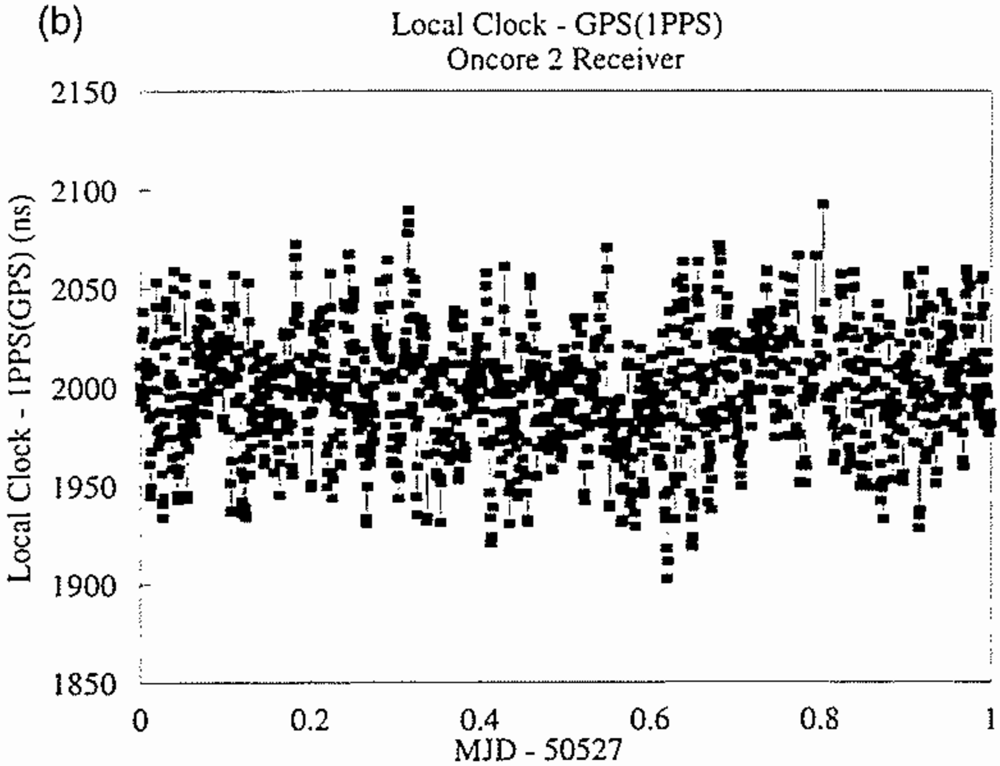


FIGURE 5(a-b)

(a)



(b)



satellite. In figure 6(a), typical values for the pseudo-range corrections plotted in ns of delay are shown. The curves in figure 6(a) are dominated by periodic variations which are arise from the application of Selective Availability. The SA correlates between the different GPS receivers and will dominate the short and medium term performance. SA is present on all the GPS satellites with the exception of PRN 15.

Pseudo-range correction measurements were made on both the Motorola Oncore receivers throughout the study. Pseudo-range corrections for each satellite typically lie within the range of SA (e.g., ± 250 ns), although occasionally these corrections may be larger (e.g., 780 ns). The origins of these large deviations need to be investigated further.

2.5.6) Satellite signal strength

The relative signal strength of all the visible GPS satellites were recorded by all three receivers. The variation of the signal strength of individual satellites during their tracks are shown in figure 6(b). Although the transmitted signal strength is constant for each satellite, the variation in signal strength depicted in this figure is due to the gain of the receiving antenna changing as a function of angle.

2.6) External integrity monitoring of the GPS

2.6.1) Introduction

The United States Naval Observatory (USNO) makes available substantial information on the time and frequency performance of the GPS system. During the period of the study, a log was kept of all the GPS system outages of the individual satellites, in addition to plots of GPS Time-UTC(USNO) using sampled mean data from each satellite.

2.6.2) Availability of the GPS

The number of active GPS satellites remained relatively constant during the study with 25 satellites available for the majority of the time. GPSDO status information was obtained from the USNO World Wide Web site (http://tycho.usno.navy.mil/gps.html), table 3 lists information on the outages of individual satellites for the period 1/1/97 to 31/3/97. There was no permanent loss of satellite signal or new satellites coming on line. It is important that GPSDOs correctly interpret the broadcast health information. RS232 data describing the individual satellites tracked by the GPSDOs has not yet been studied in depth, however it is planned to compare this information with the satellite availability data obtained from USNO.

FIGURE 6(a): Pseudo range correction data (Motorola Oncore 1)

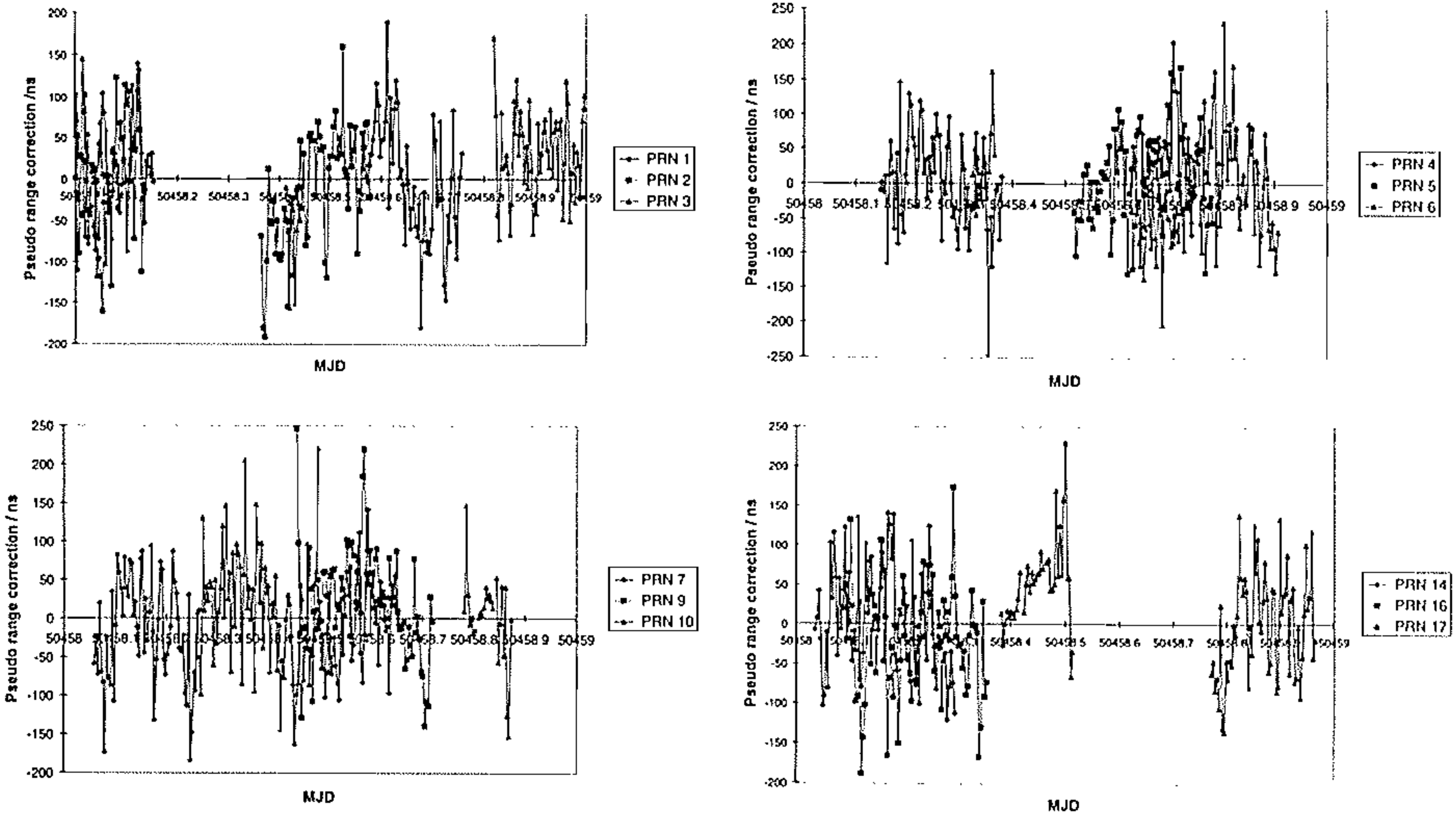


FIGURE 6(a): Pseudo range correction data (Motorola Oncore 1)

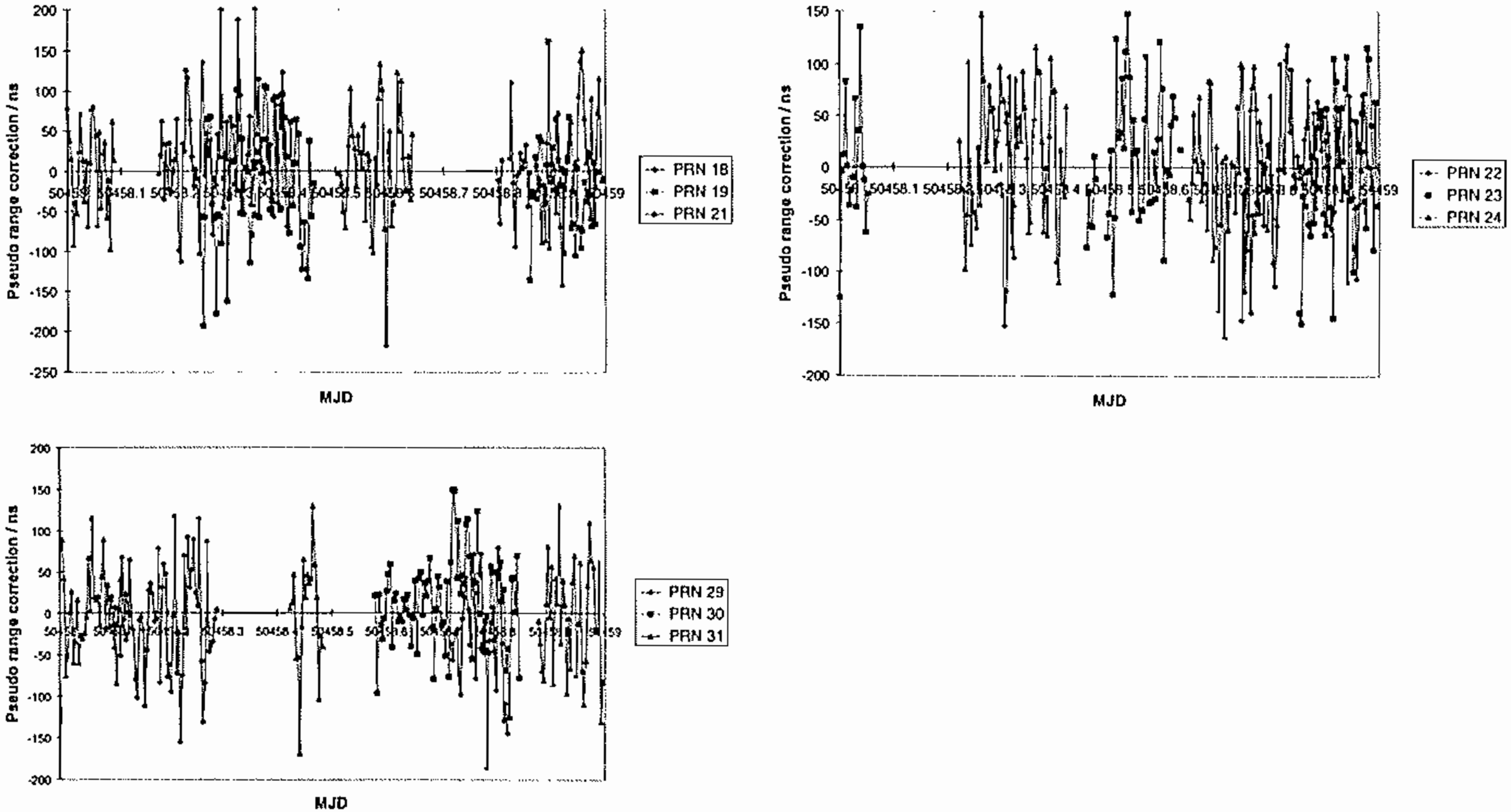


FIGURE 6(b): Relative Signal Strength (Motorola Oncore 1)

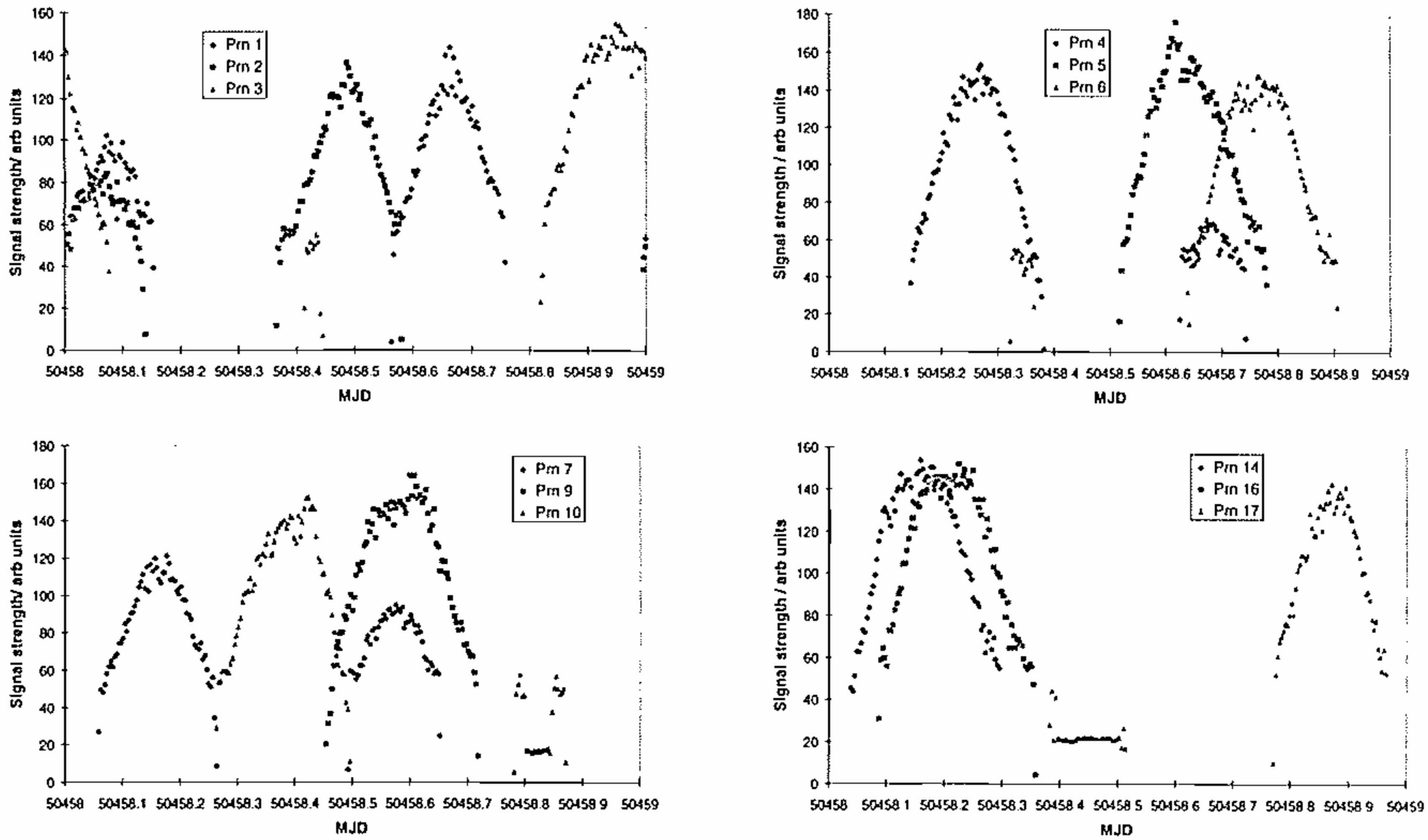


FIGURE 6(b): Relative Signal Srength (Motorola Oncore 1)

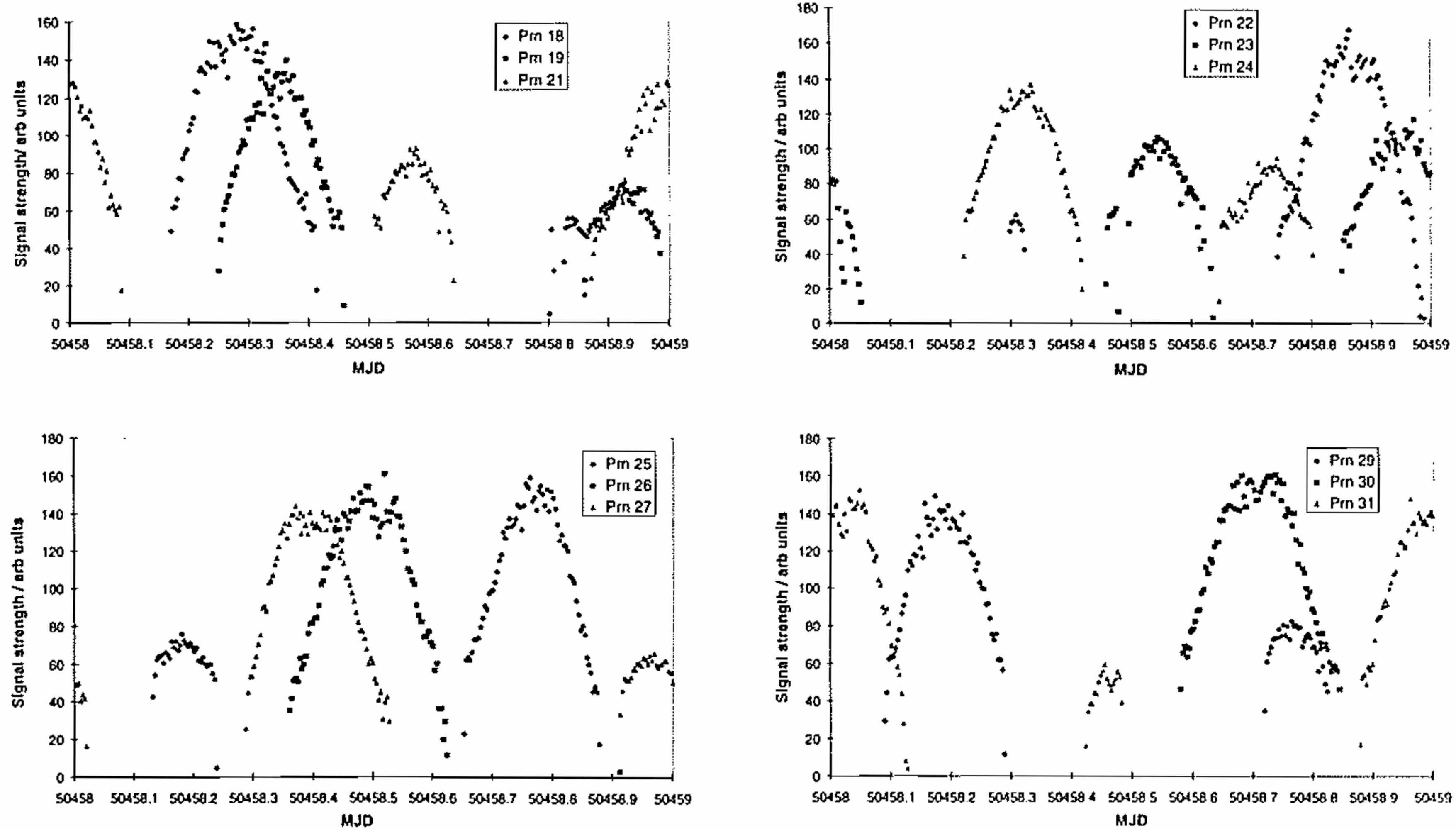


Table 3: Outages occurring in the GPS constellation during the course of the study.

Start MJD:hh:mm	Stop MJD:hh:mm	Duration hh:mm	PRN no.	Operation
50450-16-15	50491-01-25	9-10	16	repositioning
50462-04-40	50462-04-55	0-15	16	-
50483-21-02	50484-03-08	6-06	23	repositioning
50485-19-10	50525-12-55	3-45	23	-
50489-11-19	50489-16-24	5-05	16	maintenance
50490-16-46	50490-23-23	6-37	18	maintenance
50492-15-12	50492-17-50	2-38	10	maintenance
50493-14-01	50493-19-27	5-26	27	repositioning
50506-07-48	50506-08-40	0-52	18	-
50517-23-02	50518-00-30	1-28	24	maintenance
50518-18-17	50519-01-29	7-12	27	-
50520-21-35	50520-22-41	1-06	22	maintenance
50521-21-16	50522-06-36	9-02	17	maintenance
50533-22-00	50534-02-43	4-43	30	repositioning
50538-18-44	50538-23-08	4-24	3	maintenance

In figure 7, examples of UTC(USNO)-GPS time for individual GPS satellites are plotted which have been recorded by USNO during the course of the study. The scatter on all the results are similar except for PRN 15 where SA is absent. During the study period there have been no excessively large outliers, the typical peak-to-peak scatter over the three month period is within 340 ns which is consistent with the GPS specification.

There are several limitations in using the USNO data to monitor the time and frequency transfer characteristics of the GPS. Each datum used in these figures is calculated from a mean value of 12.5 minutes of GPS data (i.e, the repeat time for the broadcast satellite ephemeris), and so rapid changes are not recorded. Also, each satellite is recorded only once or twice a day using a single channel timing GPS receiver. Consequently, these results give only a small sample of the time transfer performance of the GPS. The GPS receivers at USNO only monitor the satellites visible at the USNO site. Although there is a reasonable overlap in visibility between NPL and USNO, many satellites observed at NPL will not be simultaneously observed at USNO reducing the effectiveness of the monitoring.

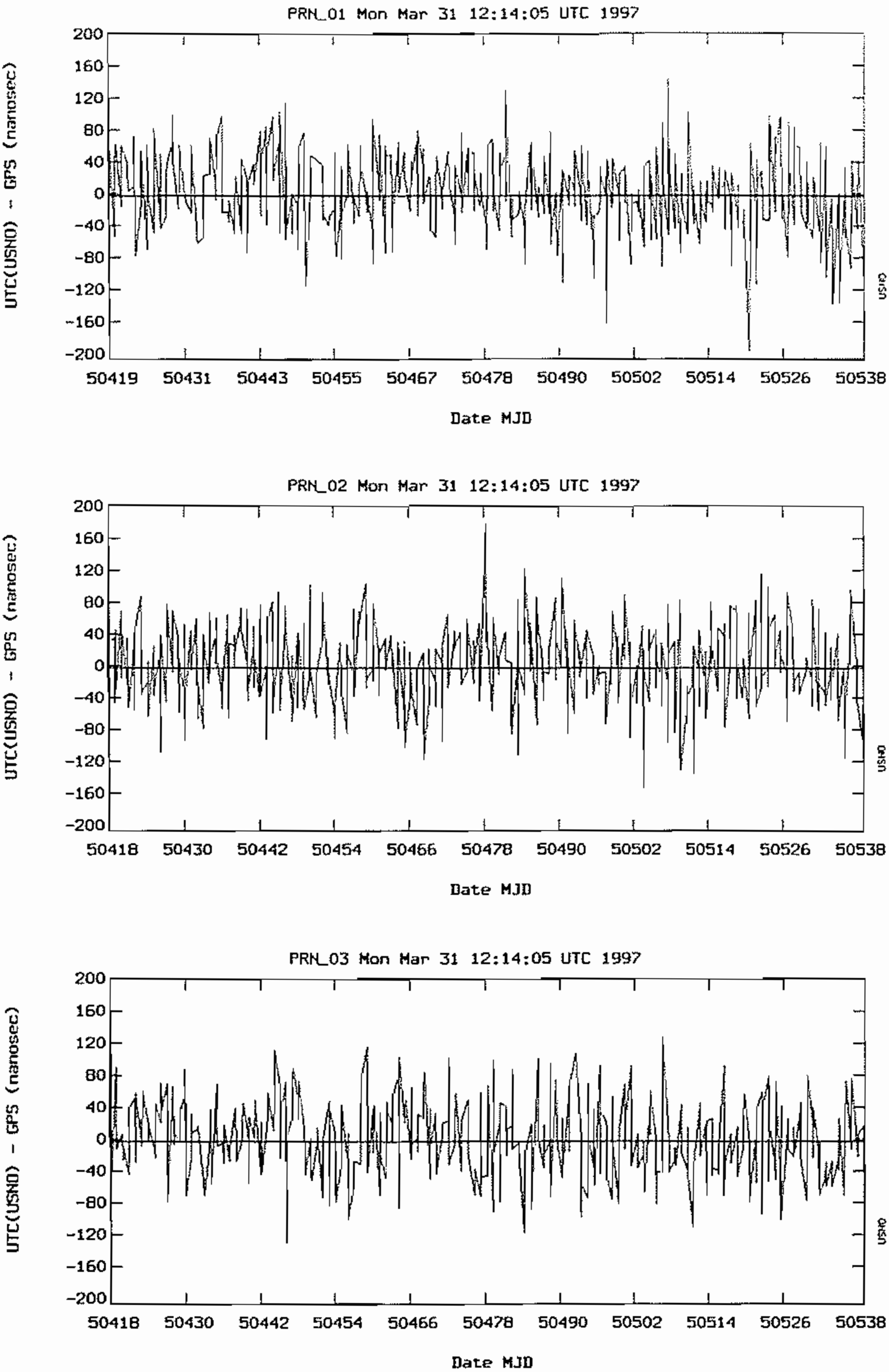
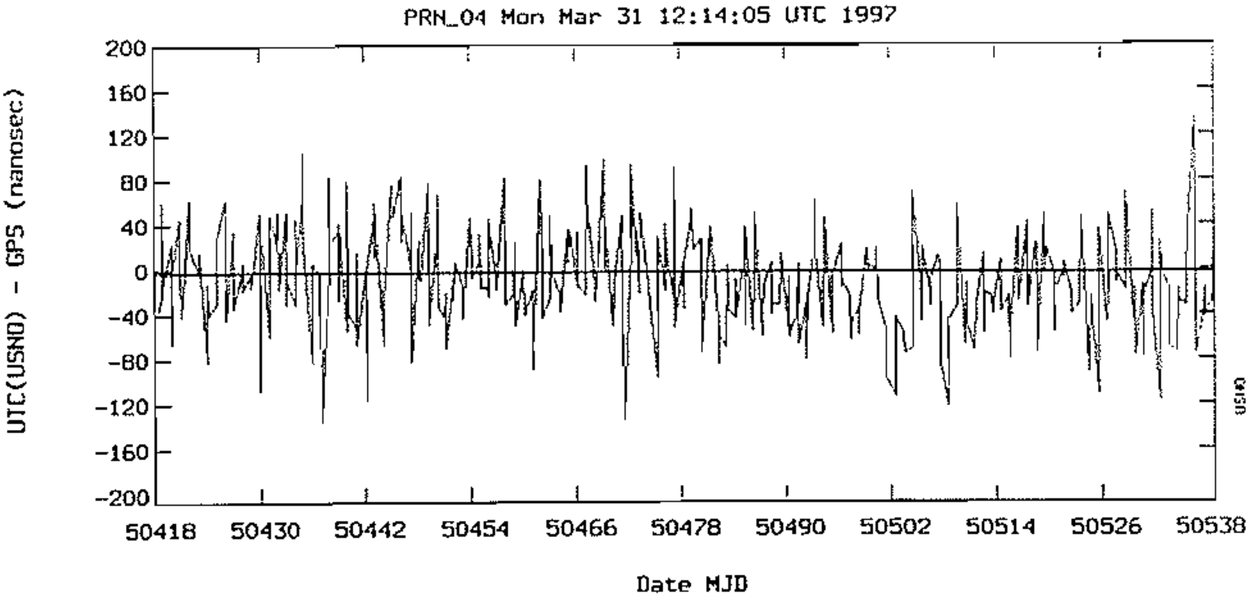
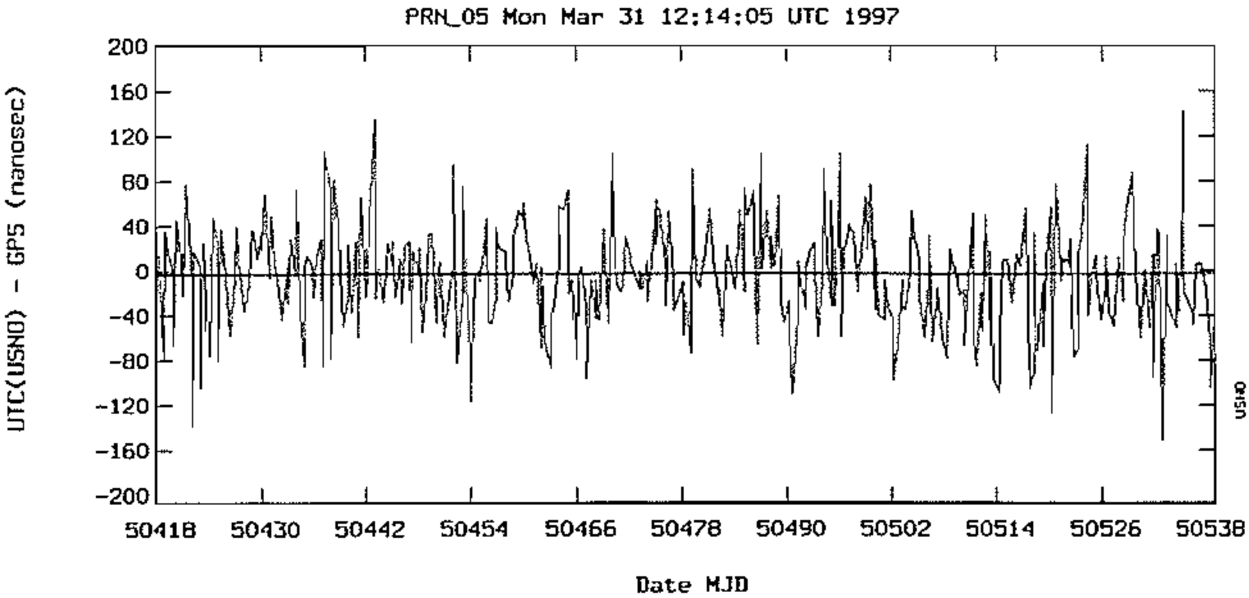


Figure 7: Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.





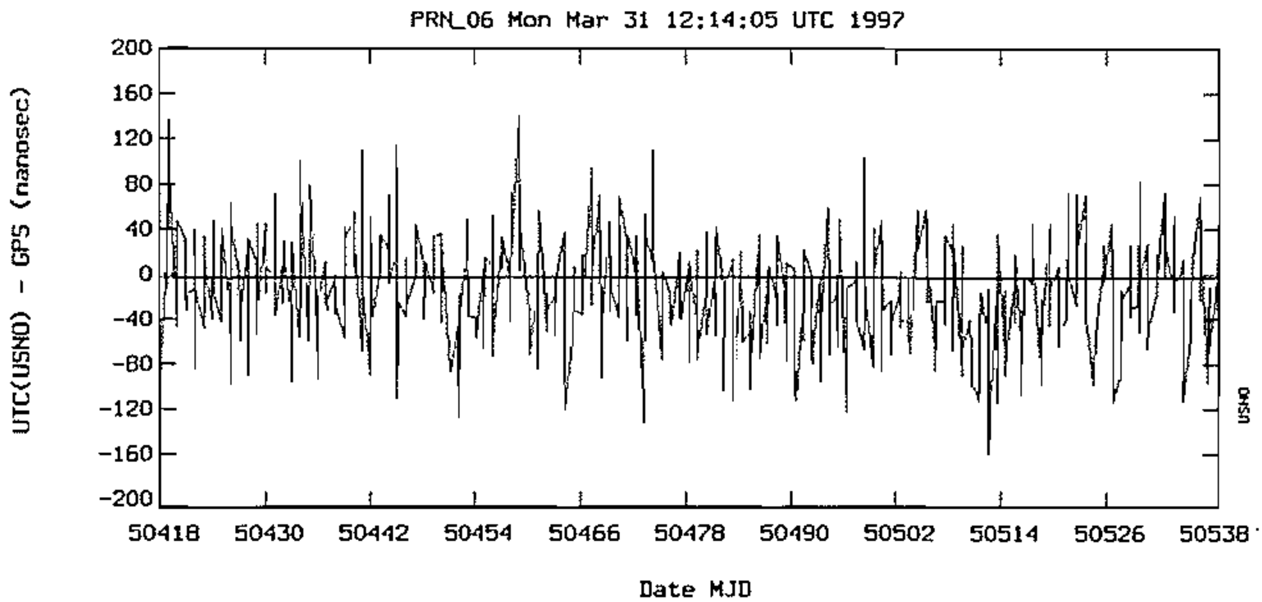
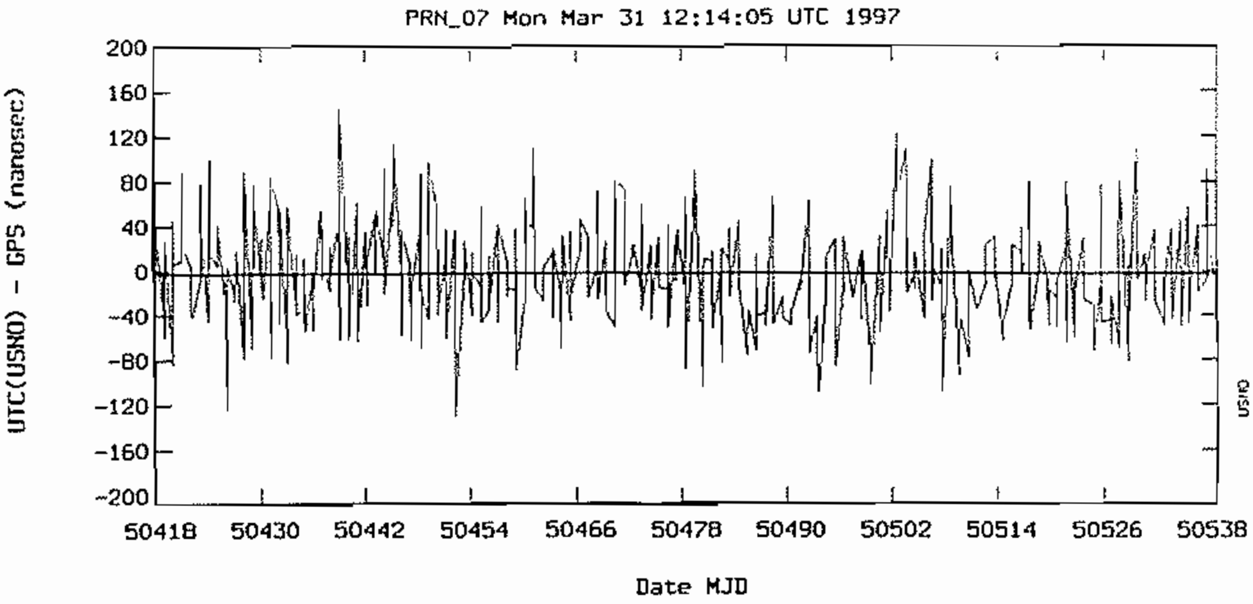
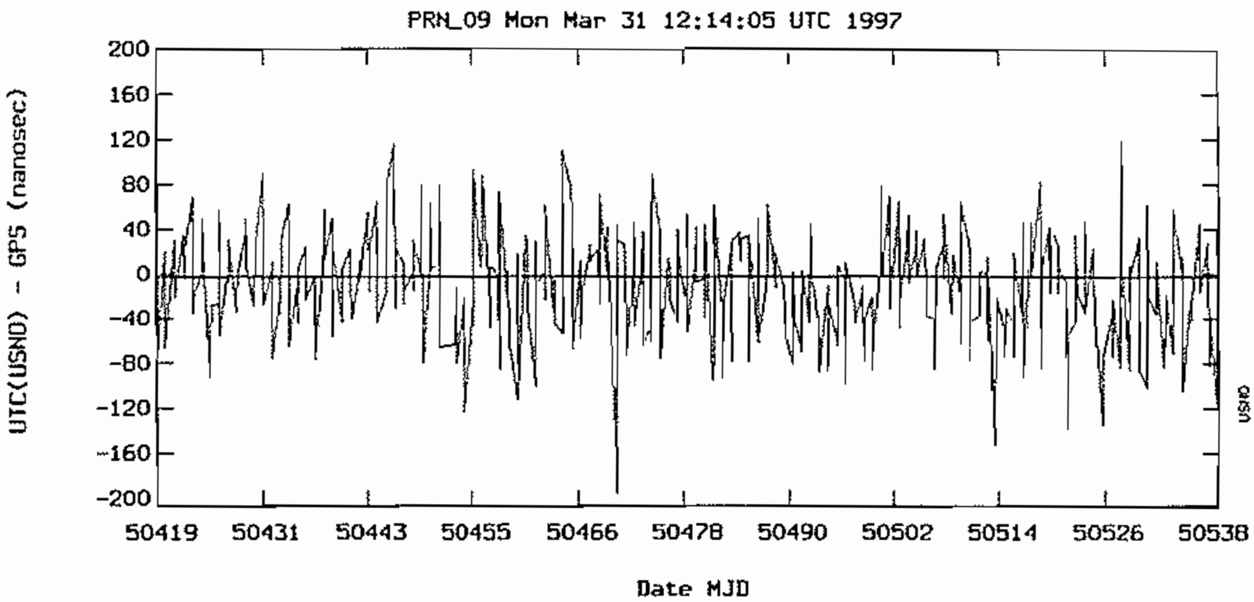


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.





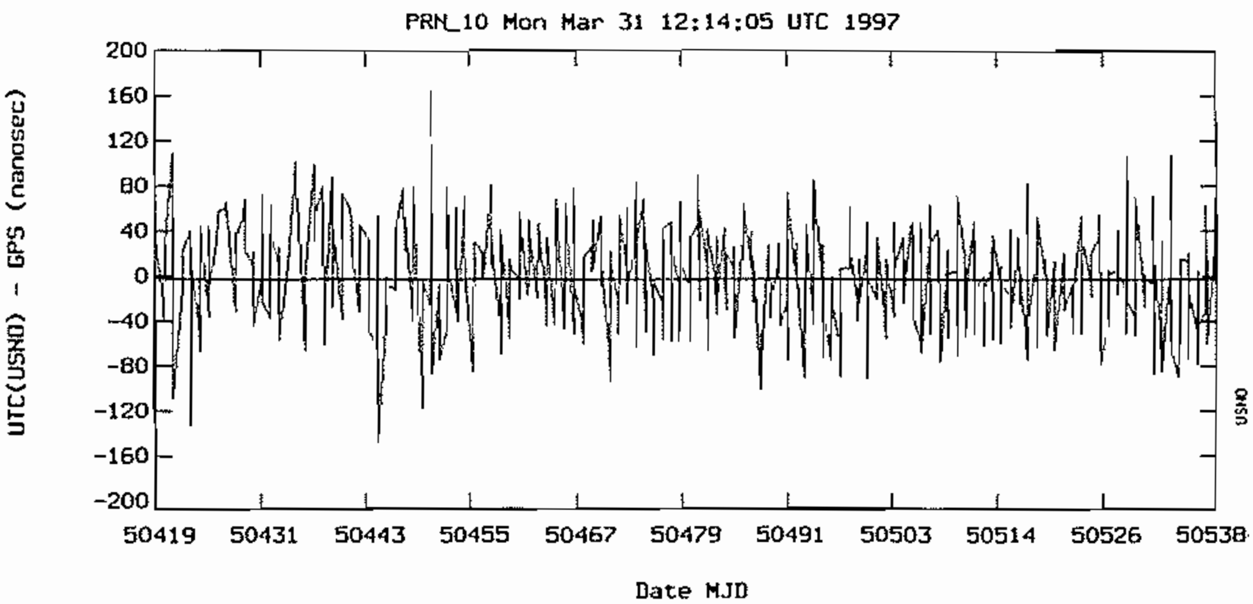


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.

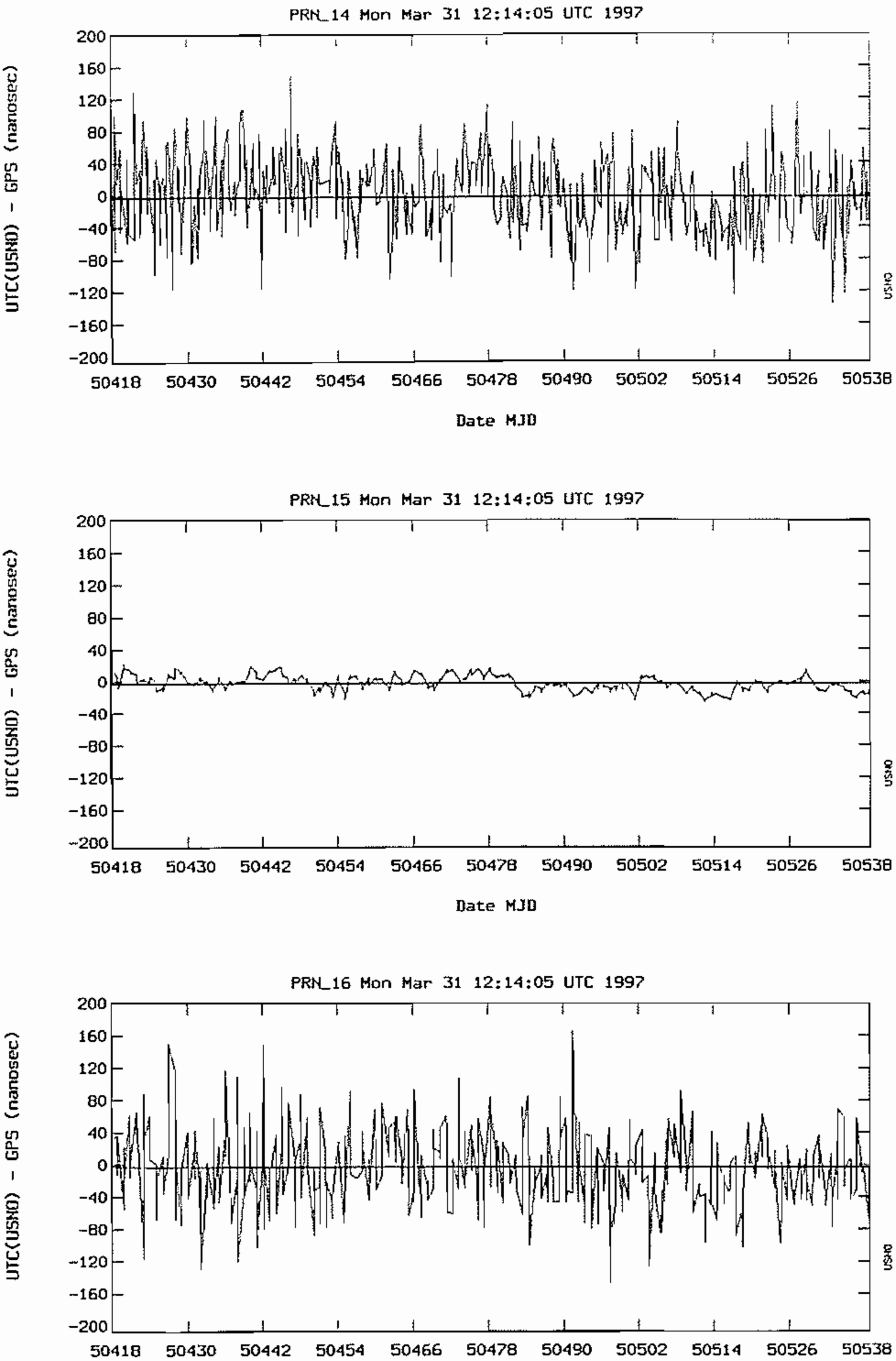
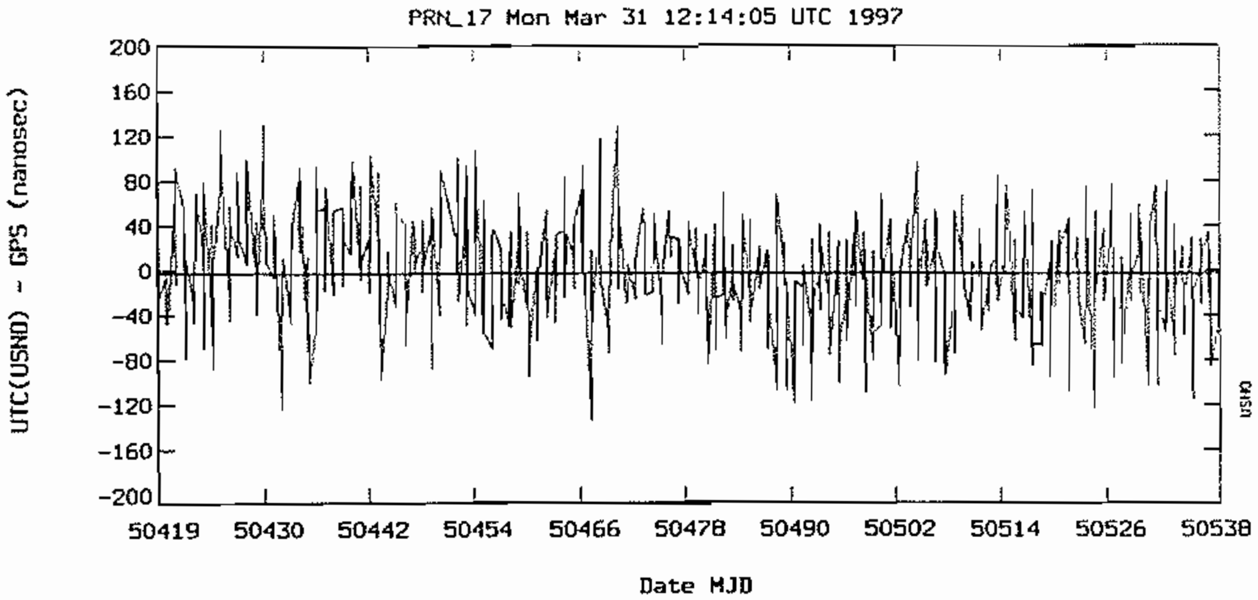
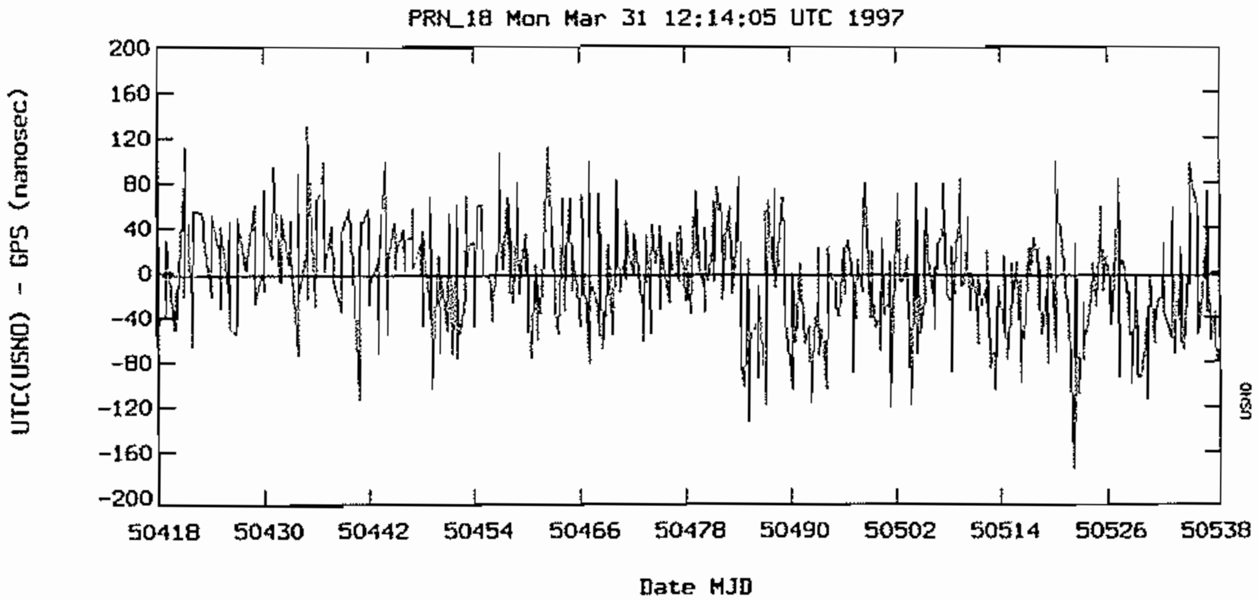


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.





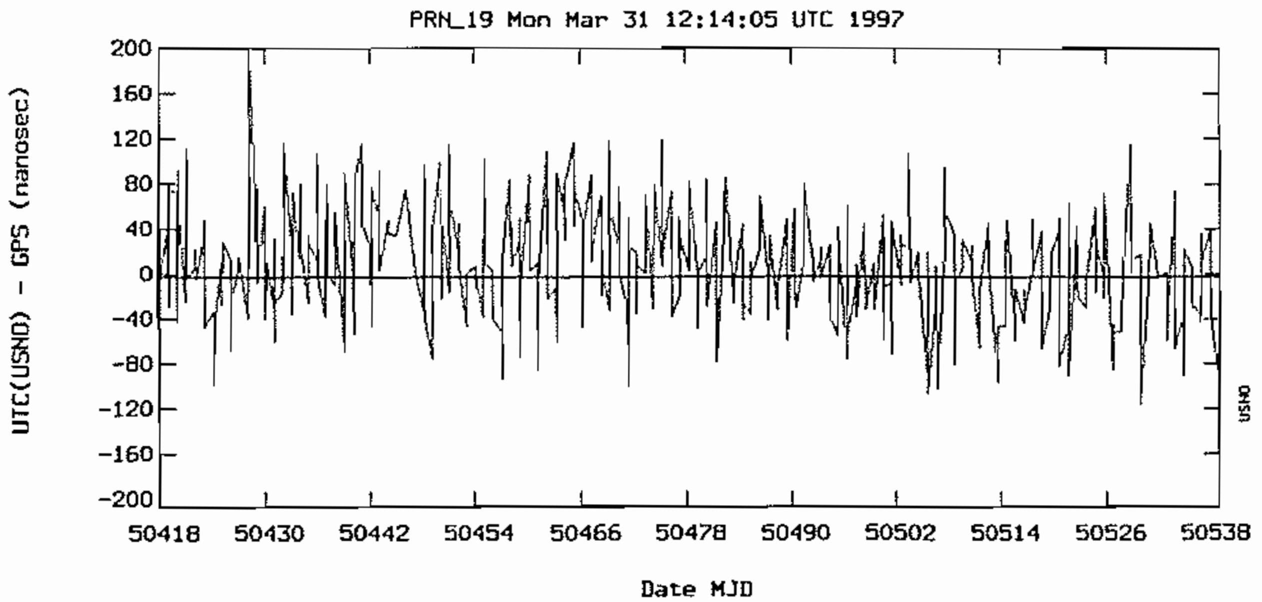
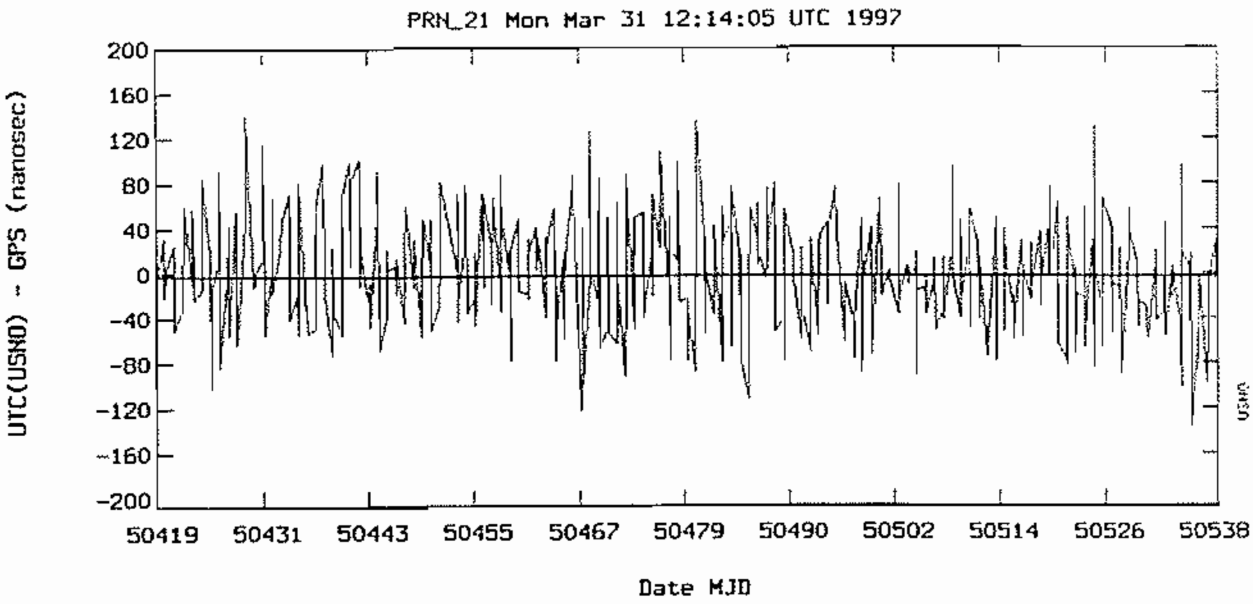
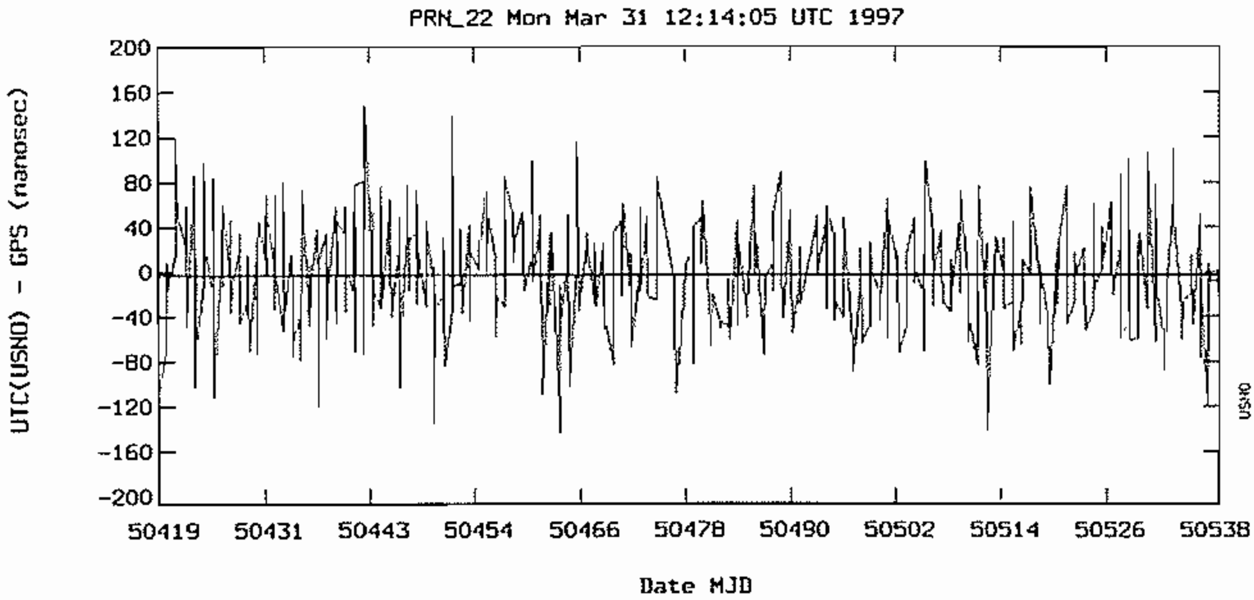


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.





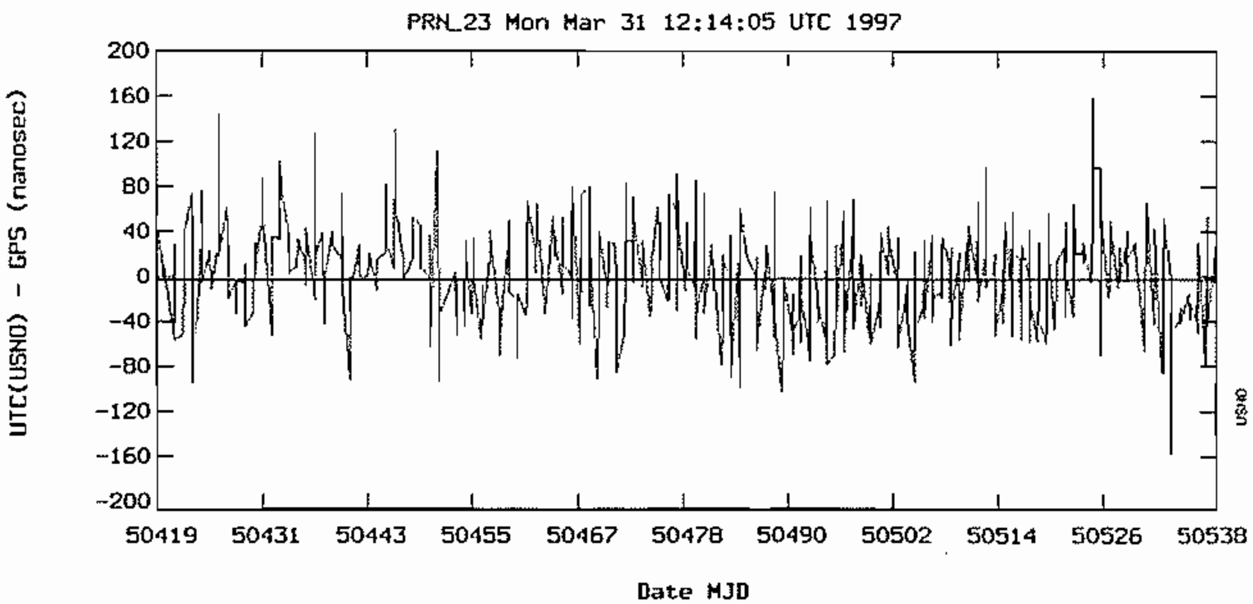
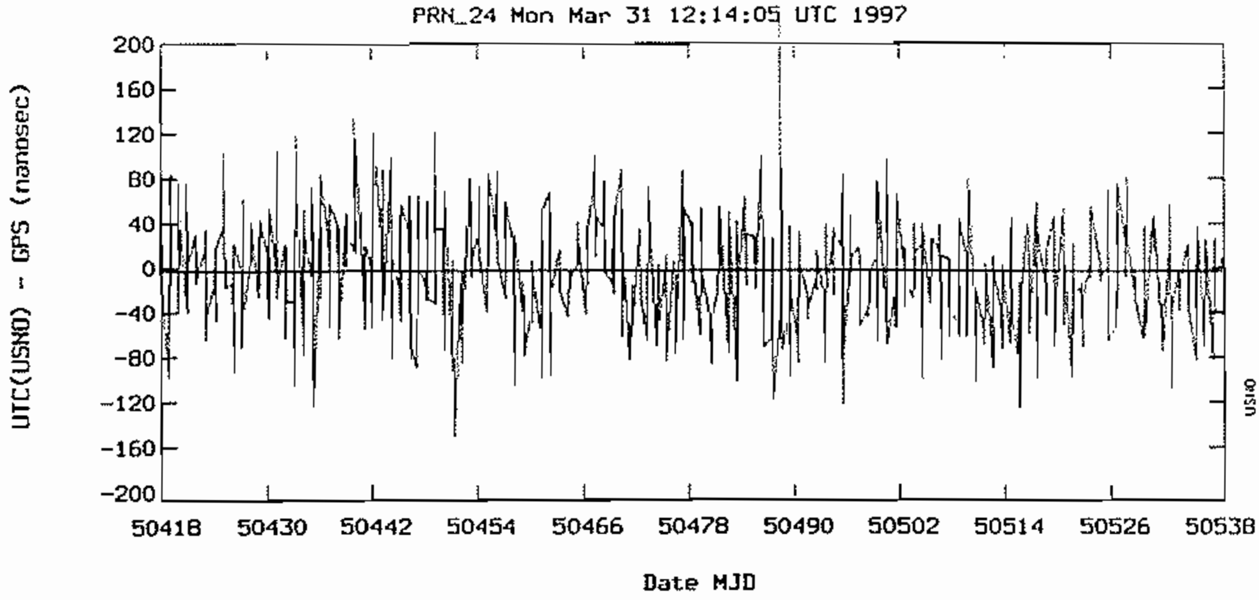
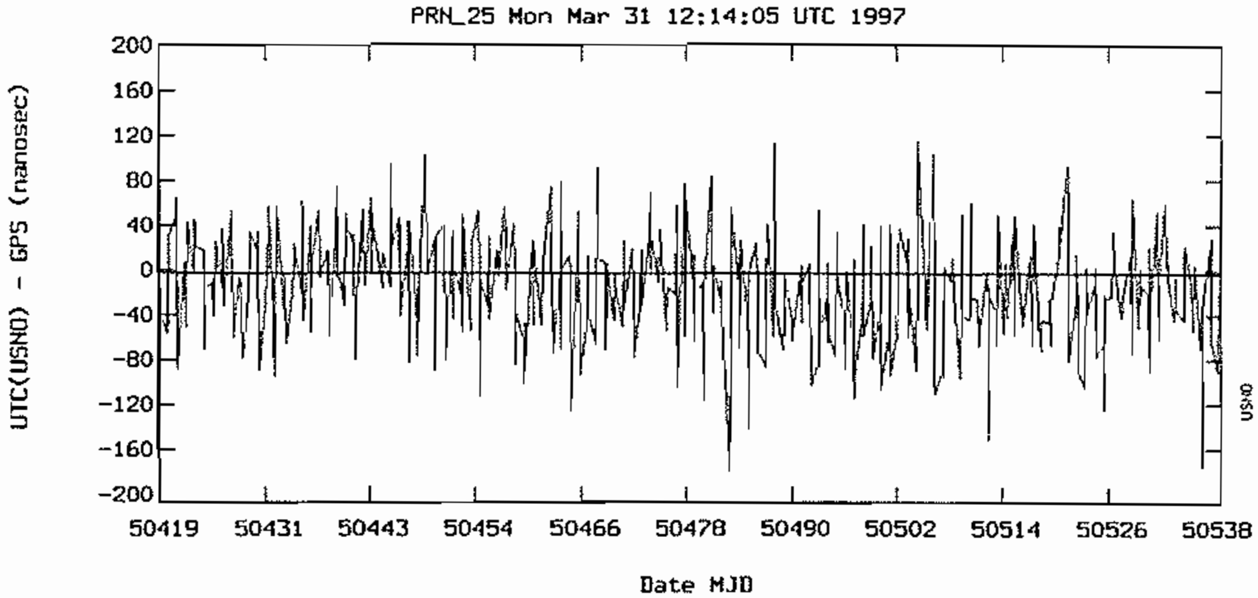


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.





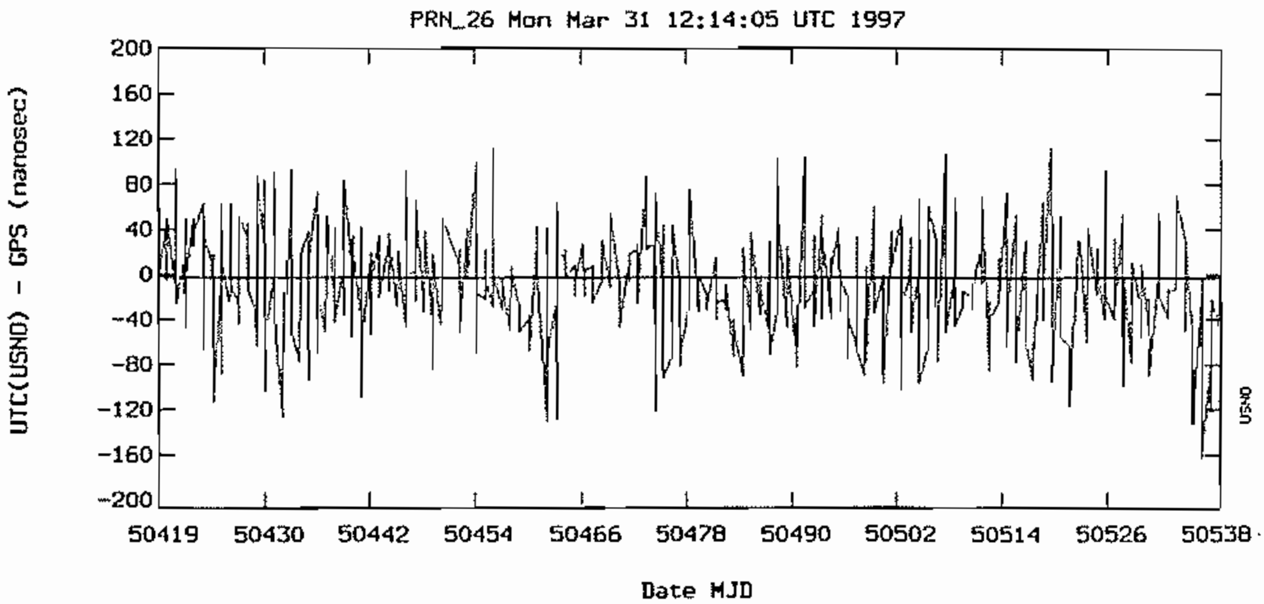


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.

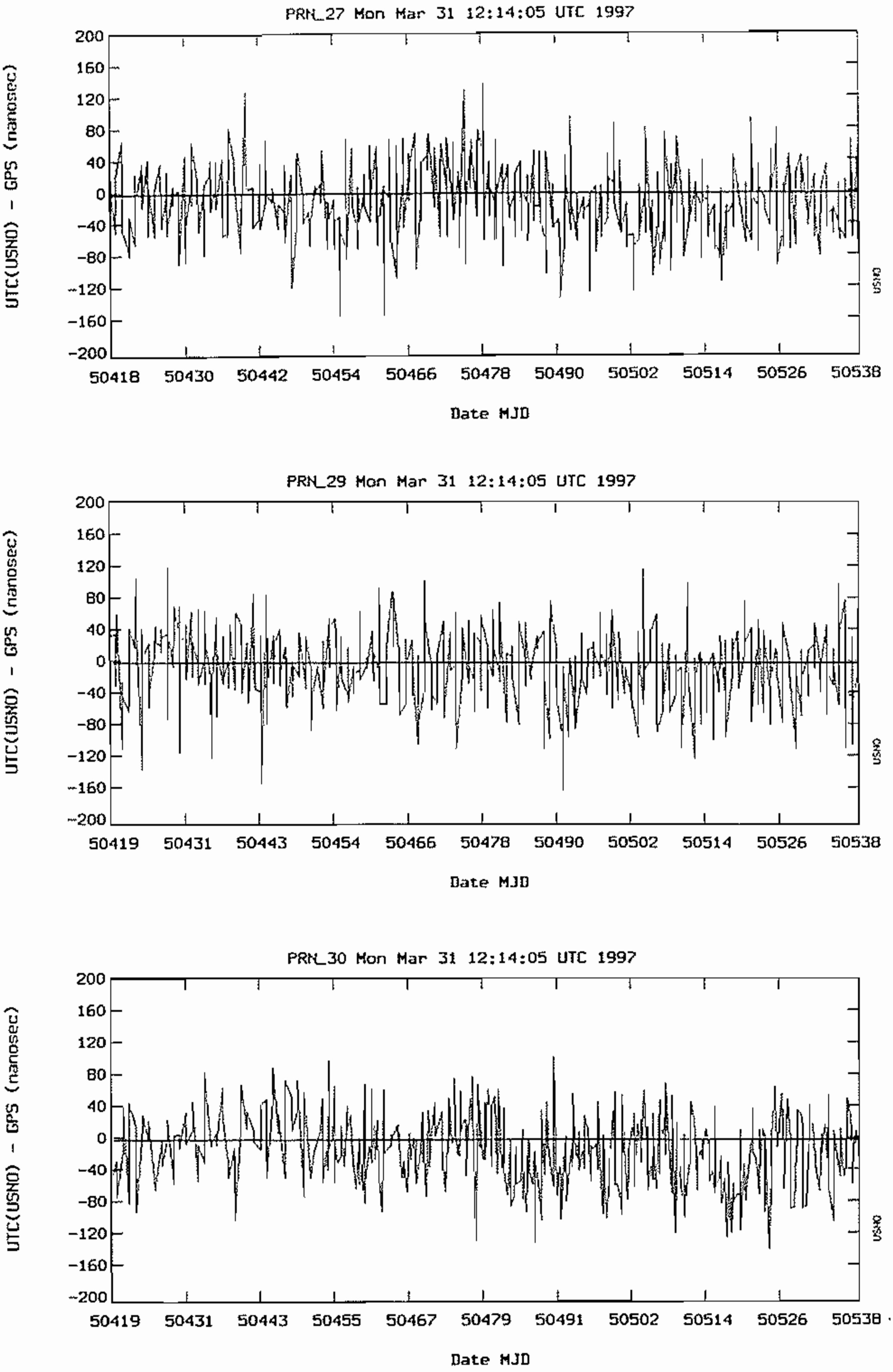


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.

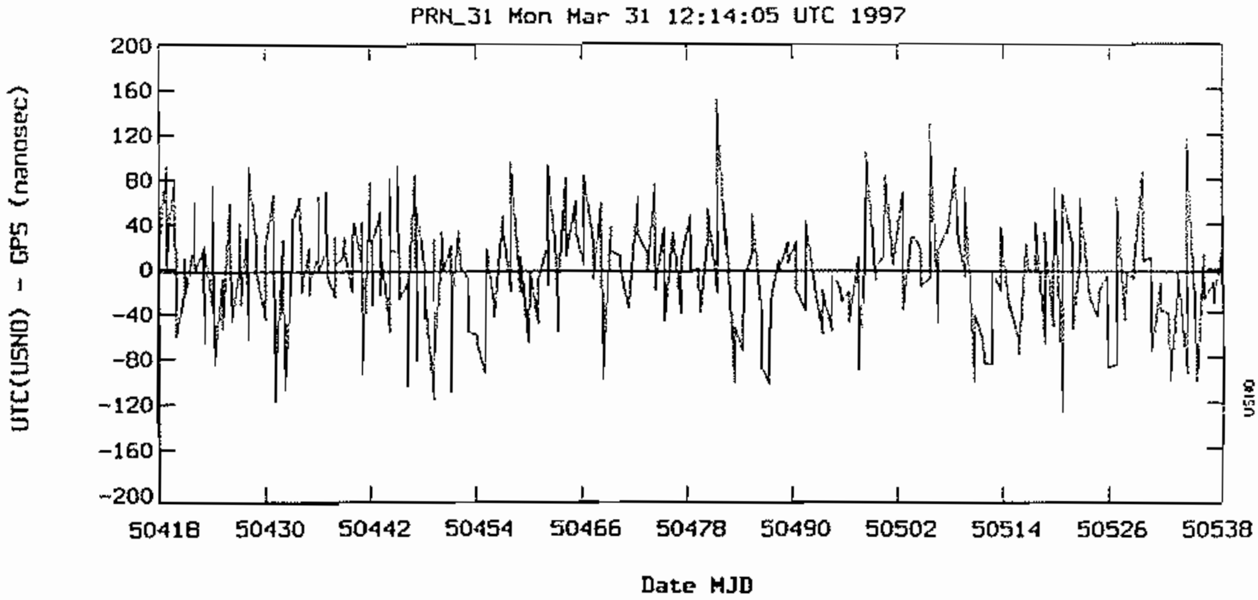


Figure 7 (cont...): Graphs of UTC(USNO) - GPS for individual satellites during the NPL study obtained from USNO.

2.7) Abnormal operation of the GPS

The integrity of the GPS is an important consideration when considering GPSDOs as traceable standards. If a satellite becomes unreliable, it can take the Control Segment up to 45 minutes to identify the problem and remove a bad satellite from the constellation [6]. The application of receiver autonomous integrity monitoring would be a key technique during such periods. Alternately, independent monitoring of the GPS constellation would also serve as an excellent integrity check.

2.8) Conclusions and recommendations

User range errors are dominated by the effects of SA (see table 1, section 2.4), and this is found to ultimately limit the performance of GPSDOs. The effects due to multipath remain to be investigated.

The GPS constellation was monitored continuously during the three month course of the study and no irregularities that might impact on the performance of the GPSDOs were detected. Such a result is encouraging for the use of GPSDOs as time and frequency standards. However, if GPSDOs are to be incorporated into the national measurement system in a robust way, it is appropriate that the GPS signals be monitored by an independent reference. Hence we recommend that NPL should monitor the GPS relative to UTC(NPL), and publish any irregularities with the GPS constellation to the UK time and frequency measurement community.

NPL should also publish measured values of UTC(NPL)-UTC(USNO) as the GPS system time refers to the UTC(USNO) timescale.

NPL should from further studies of GPSDOs produce an error budget on User Range Errors to provide quantitative guidelines on the level of traceability that can be achieved. It is appropriate that such guidelines should consider how site specific factors (e.g., multipath) might impact on the uncertainty assessment.

2.9) References

[1] Department of Defence/Department of Transportation, *1994 Federal Radionavigation Plan*, Springfield, VA, National Technical Information Service, May 1995.

[2] Spilker, J. Jr., *GPS Signal Structure and Performance Characteristics*, GPS Papers in Navigation, Vol. 1. Institute of Navigation, 1980.

[3] Kirchner, D., Lentz, C., *Tropospheric Corrections to GPS Measurements Using Locally Measured Meterological Parameters Compared with General Tropospheric Corrections*, Proc. 25th PTTI, p 231-248, 1994.

[4] Leva, J.L., de Haag, U.M., and Van Dyke, J., *Performance of Standalone GPS*, in Understanding GPS Principles and Applications, ed Kaplan, E.D., Artech House Publishers, 1996, chapter 7, pp 306.

[5] Leva, J.L., de Haag, U.M., and Van Dyke, J., *Performance of Standalone GPS*, in Understanding GPS Principles and Applications, ed Kaplan, E.D., Artech House Publishers, 1996, chapter 7, pp 316.

[6] Geier, G.J., King, T.M., Kennedy, H.L., *Prediction of the Time Accuracy and Integrity of GPS Timing*, Proceed. Of the 1995 IEEE International Frequency Control Symposium, 1995, IEEE, New York, p 266-274.

3) Time Dissemination

3.1) Introduction

There is considerable interest in using GPSDOs to disseminate absolute time (UTC). UK manufacturers of high accuracy time dissemination equipment have identified an immediate need for precise time dissemination within the UK. Traceability issues for time and for frequency will be considered in section 4. For traceability to UK standards of time and frequency, UTC(NPL), it is important to establish both the accuracy and integrity of the GPSDOs . Other GPSDO performance characteristics, for example the availability and continuity of the 1PPS outputs are also considered.

3.2) Measurements made over an extended period

During this study, regular continuous operation of the GPSDOs was monitored for a period of six weeks, between MJD 50465 and MJD 50506. In some examples, the period of measurement was significantly shorter either due to the measurement time being used to perform other tests; the late arrival of some GPSDOs; and/or the failure of some GPSDO instrumentation. The GPSDOs were left for 24 hours after set-up so as to determine their own co-ordinates before any data was included in the final data set. The GPSDOs were operated in their default mode, except where explicitly directed by either the manufacturer or supplier. All of the elements of the GPSDO study outlined in section 1.3 have been operational during this period. The data obtained from these extended measurements forms the backbone of this study and are used to generate most of the time and frequency statistics used in this report, for example the Root Allan Variance σ_y, MODσ_y, and σ_x.

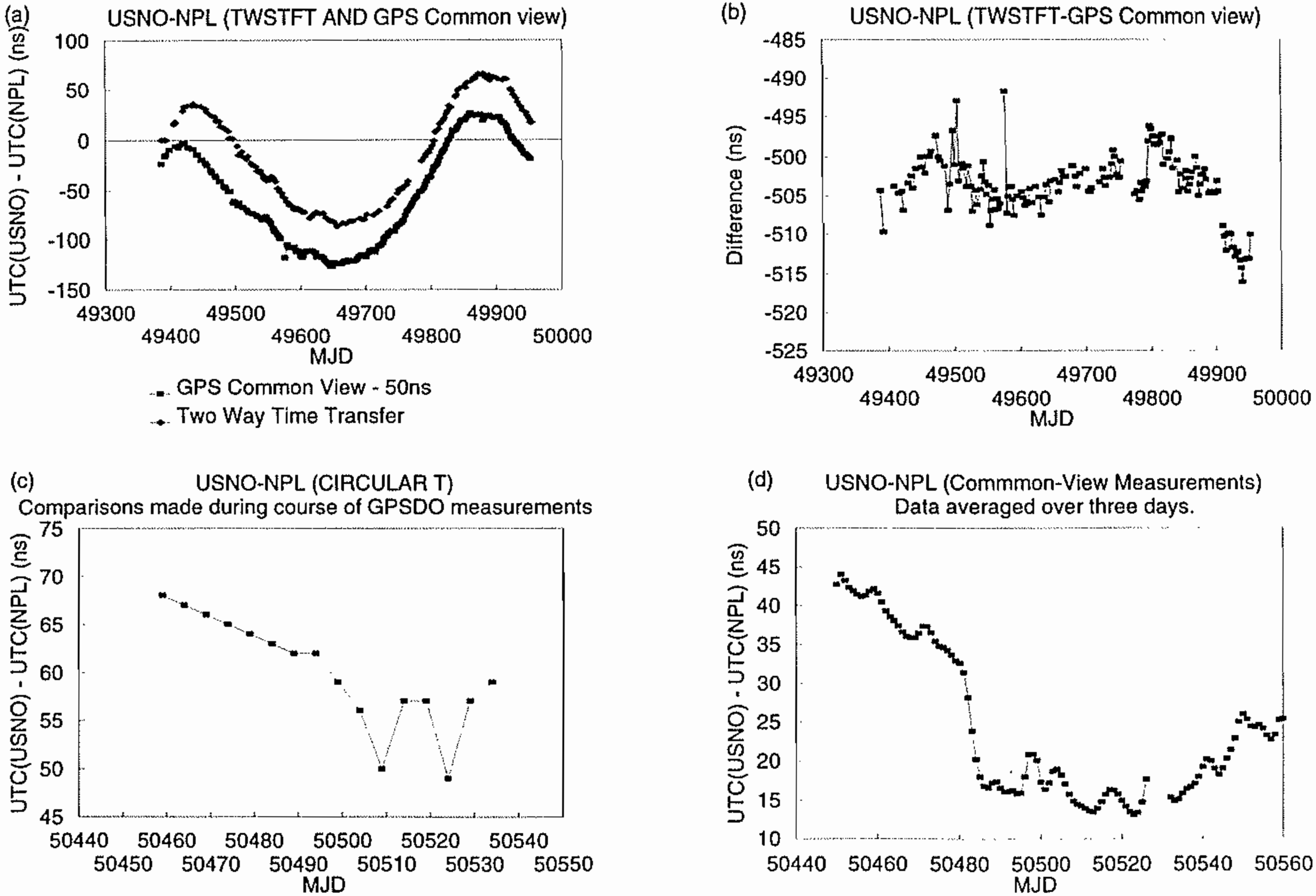
3.3) NPL's time scale UTC(NPL)

NPL possesses one of the worlds most stable time scales based on two active Sigma Tau hydrogen masers, (model MHM 2010), two high performance and one standard caesium clocks (model HP 5071A). This time scale is an excellent reference against which to compare the timing outputs of the GPSDOs. The stability of UTC(NPL) is typically ±4 ns over a 5 day averaging time. This normally enables it to be maintained typically to within ±100 ns of UTC. UTC(NPL) is at present derived directly from one of the hydrogen masers.

3.4) International time transfer

The time and frequency signals transmitted by the GPS are ultimately referenced to the time scale of the United States Naval Observatory, UTC(USNO). The accurate comparison of the two time scales UTC(NPL) and UTC(USNO) therefore forms an important part of this study. Regular satellite time transfer are performed between NPL and USNO. The routine method is through the use of common-view of GPS signals [1]. A curve of the NPL-USNO time transfers made during the course of the GPSDO signals are shown in figure 8d. Each point is constructed from the mean of three days data. Figure 8c shows the results of post processing this data by BIPM, to form part of the

FIGURE 8 (a-d) USNO-NPL TIME TRANSFER



BIPM "Circular T" intercomparisons. Discrepancies in the absolute values are due to the calibration factors added by BIPM to the GPS receiver delays. The sharp change in the raw common-view measurements on MJD 50482 (figure 8d) is likely to be due to instrumentation changes at USNO, as this has been corrected in the data used by BIPM (figure 8c). Variations of UTC(NPL) - UTC(USNO) are small during the period of continuous GPSDO measurements. A typical maximum variation of 11 ns is observed on the Circular T measurements. However, these small variations may be significant when examining the most stable of GPSDOs.

Two-Way Satellite Time and Frequency Transfer (TWSTFT)[2] has been used to compare the clocks at NPL and USNO. The TWSTFT method provides an independent, yet more precise method of comparing the two time scales. Examples of time transfers using the two methods are shown in figure 8(a) and (b). The absolute delays of the TWSTFT instrumentation are un-calibrated. In June 1996, (MJD50249-50251), NPL and USNO compared their national time scales by performing a flying atomic clock experiment [3]. A portable calibrated GPS receiver has been loaned to NPL by BIPM in order to calibrate the absolute values of the GPS common-view time transfers. This calibrating GPS receiver has spent substantial time calibrating the common-view GPS receivers at USNO. From these measurements it is estimated that the difference UTC(USNO) -UTC(NPL) may be determined with an accuracy better than ±10 nanoseconds. The absolute time transfers quoted in this report will be revised in the light of this calibration. Changes in the values of UTC(USNO) -UTC(NPL) may be determined with an uncertainty of a few nanoseconds. This uncertainty has been determined by comparing the independent TWSTFT and GPS common-view time transfer methods over the (USNO -NPL) link [4] (figure 8(a) and (b)). It is important to be able to compare the GPSDO 1PPS output GPSDO(1PPS) against UTC(USNO), the timescale to which it is ultimately locked. The mean values of UTC(USNO) -UTC(NPL) may be added to the UTC(NPL)-GPSDO(1PPS) values so as to relate GPSDO(1PPS) to UTC(USNO). In this study GPSDOs have been directly compared against UTC(NPL) when performing time and frequency transfer statistics for example σ_y, MODσ_y and σ_x. However correction factors for UTC(NPL) -UTC(USNO) have been applied when calculating the absolute time dissemination.

3.5) Portable clock measurements

NPL possesses several commercial high performance HP5071A caesium clocks. One of these may be used with a battery back-up unit to perform portable atomic clock time and frequency calibrations. This method is extremely useful for determining the internal delays within NPL's time and frequency hardware systems. The portable clock has been used to calibrate the delays between UTC(NPL) and various points within the GPSDO logging system. The GPSDO 1PPS measurement system is shown in Figure 9. The calibration of absolute delays is described in Appendix A. It is estimated that internal time transfers performed using a portable caesium clock will have an uncertainty better than ±1 ns. The internal delays between UTC(NPL) and the GPSDO measurement hardware may also be determined by directly measuring cable and loop delays. These two methods agree to within ±1 ns.

3.6) One Pulse Per Second (1PPS) data logging system

The GPSDO 1PPS logging system is shown in figure 9. The core of the system consists of four Racal Dana 1991 Universal Counter Timers, each with a 1 ns timing resolution. Each counter

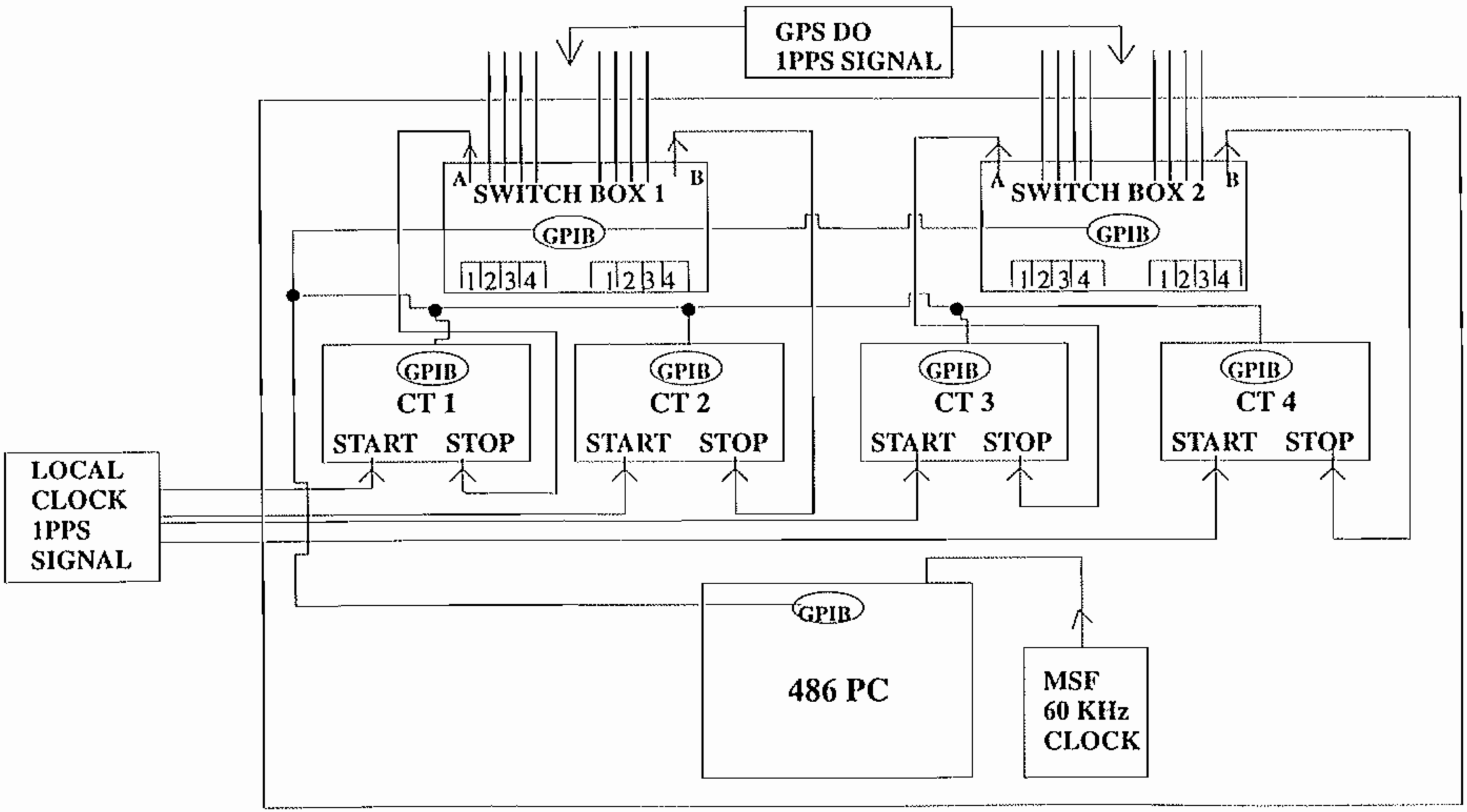


FIGURE 9: Experimental arrangement for the 1PPS logging system

timer was externally referenced using a signal derived from UTC(NPL). It is estimated that the counter timer measurement uncertainties are typically ±1 ns. Four, 4-way switch boxes were used to switch between the 16 available 1PPS input channels. The switch boxes are normally switched every minute to produce a measurement cycle of one minute on, three minutes off for each unit. Unfortunately, this measurement system is not useful for calculating values of σ_x, MODσ_y and σ_y for averaging times (τ) between 30 seconds and 4 minutes. A second 1PPS logging system was therefore set up so that the 1PPS from each GPSDO may be recorded continuously.

Since the GPSDOs are located in a different building to the one which generates the national time scale, the 1PPS signal used for the GPSDO data logging has to be generated locally. The arrangement is shown in Figure 10. The main problem in generating stable signals in a distant building, is due to delay changes in the cables linking the two buildings. These delays may be measured by looping a 5 MHz signal between the two buildings and measuring the phase delays occurring in the loop. Assuming that the two cables used in the measurements have the same temperature coefficient, the delay change through a single cable may be determined. Results are shown in Figure 11. The cable delay instabilities are very small, a daily peak to peak variation of 250 ps (one way) being observed. The "local clock" used in this GPSDO work possesses medium and long term time and frequency stabilities almost identical to the hydrogen maser.

The local clock was offset from UTC(NPL) by approximately 2,000 ns. This large offset ensured that the 1PPS originating from the GPSDO always reached the counter timer *after* the pulse from the local clock. Time transfer statistics from the measurements are shown in table 4. Figure 12 displays plots of Local Clock-GPS(1PPS) determined from the GPSDO 1PPS measurements.

3.7) Results

Rows 1 and 2 of table 4 display the duration of the measurement (inclusive), and the total number of days of continuous measurements. Curves of (Local clock - GPS(1PPS)) are shown in figure 12 using both individual counter timer readings sampled once per hour and the mean of each hours reading. Rows 3 to 11 provide statistics on the scatter on the (Local clock - GPS(1PPS)) measurements. Where the GPSDOs show good medium term stability, e.g., those using an internal rubidium oscillator, including GPSDOs (C),(D),(N),(H) and (J), the standard deviations obtained from a data set of single reading and a data set of hourly means are very similar, as will the resulting plots in figure 12. Where less stable quartz oscillators are used, e.g., GPSDOs (A),(B),(E),(F) and (I), both the curves and standard deviations are significantly different.

Five of the GPSDO measurements displayed transients with amplitudes greater than 100 ns. Examples are shown in figure 21(a-l). These transients are discussed in more detail in section 5.

When the GPSDO is susceptible to the occasional transient, the peak-to-peak data spread may be uncharacteristically large when compared to the standard deviation. Several calculations of standard deviation are included. Because the standard deviation is not completely independent of the data averaging time (τ), the averaging time has been stated. The data spread varies dramatically between the different GPSDOs, e.g., from 52 ns to 3,400 ns, almost two orders of magnitude. The standard deviations of the individual values varies less, between 10 ns and 155 ns, this however is still very significant. This variation illustrates the importance of examining the performance of GPSDO rather than accepting an uncertainty budget based on theoretical considerations alone.

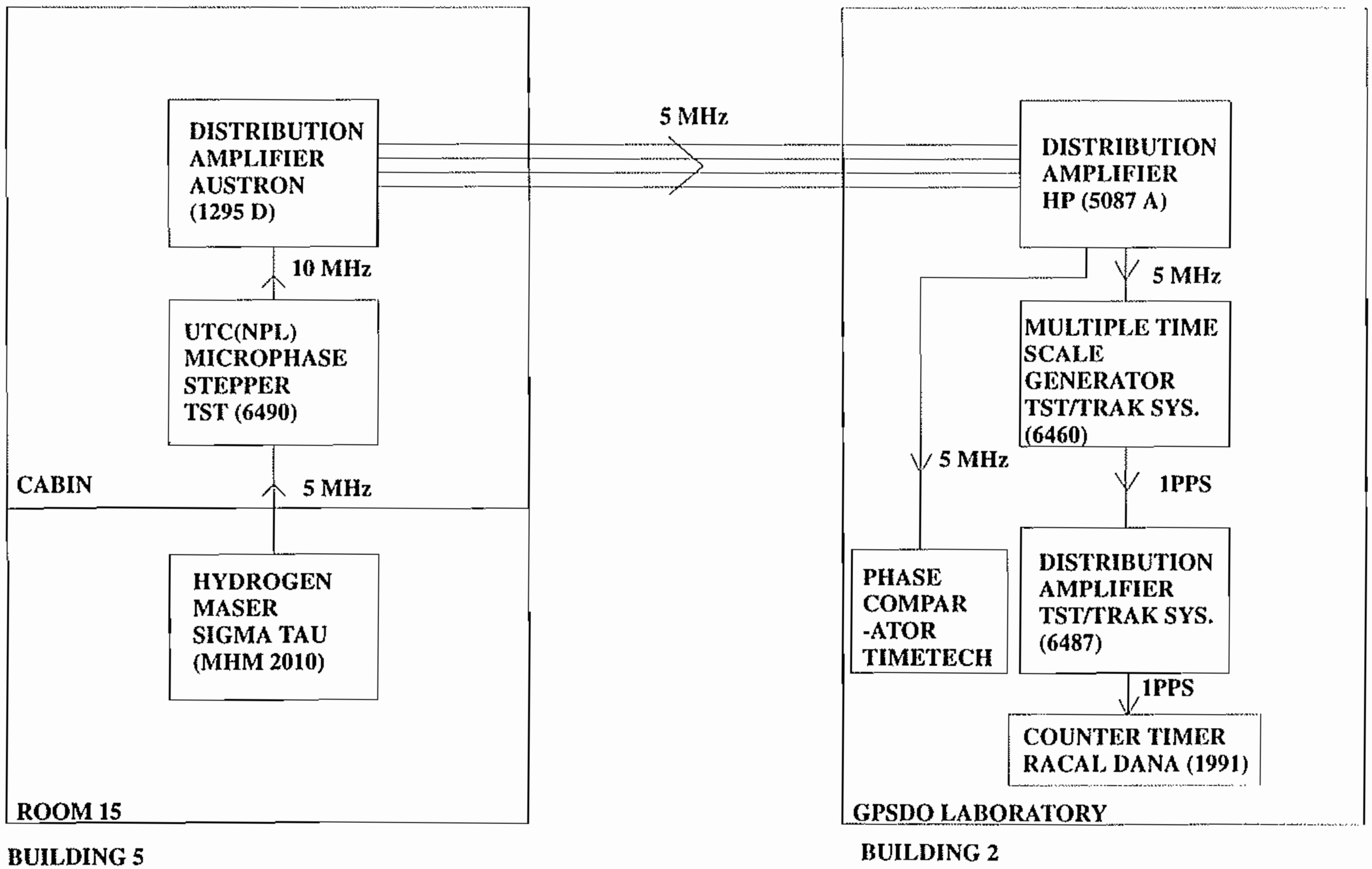


FIGURE 10: Local Clock to UTC(NPL)

Table 4a: GPSDO Time dissemination values and statistics measured during the study.

GPSDO	A	B	C	D	E
Period of extended measurements (MJD)	50466 - 50495	50479 - 50495	50479 - 50495	50466 - 50506	50466 - 50495
No of days	30	17	17	41	30
Mean ((Local Clock(NPL) - GPS 1PPS) (ns)	1,893	2,662	2,000	4,032	2,115
Max((Local Clock (NPL) - GPS 1PPS (ns)	2,060	2,780	2,025	4,170	2,180
Min ((Local Clock(NPL) - GPS 1PPS) (ns)	1,680	2,550	1,973	3,940	2,060
Data spread (ns)	380	230	52	230	120
Step > 100 ns	No	No	No	No	No
Transients > 100 ns	No	No	No	No	No
Standard Deviation (ns) (Individual readings) (1PPS)	45.1	31.6	9.9	34.4	18
Standard Deviation (ns) (Hourly mean) (1PPS)	21.2	11.2	9.9	34.2	11.4
Standard Deviation (ns) (Typical 24 Hr Readings) (minute means) (1PPS)(ns)	36.2	28.7	8.5	7.2	17.5
Antenna / cable delay external correction (ns)	0	15	0	74	162
UTC(NPL) - GPSDO(1PPS) (ns)	-90	672	27	1,983	-28
Mean UTC(USNO) - UTC(NPL) (Circular T) (ns)	65	64	64	62	62
UTC(USNO) - GPSDO(1PPS) (ns)	-25	736	91	2,045	34
Oscillator Type	Quartz	Quartz	Rb	Rb	Quartz

Table 4b: GPSDO Time dissemination values and statistics measured during the study.

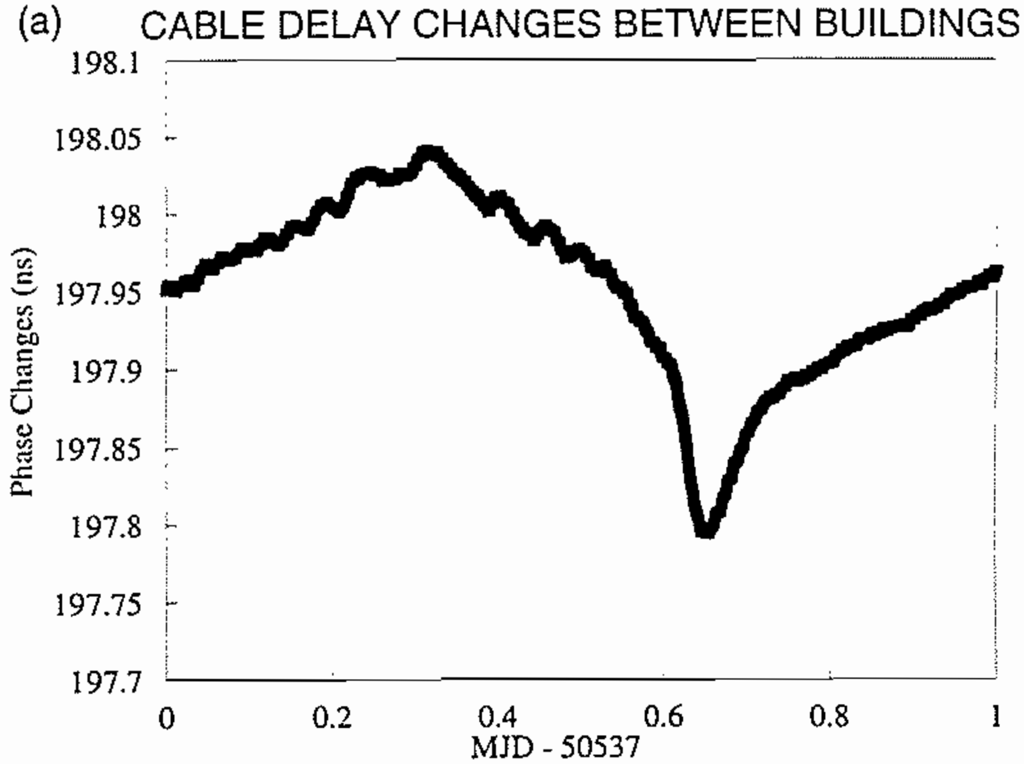
GPSDO	F	G	H	I	J
Period of extended measurements (MJD)	50466 - 50506	50477 - 50506	50485 - 50506	50466 - 50495	50487 - 50495
No of days	41	30	22	30	9
Mean ((Local Clock(NPL) - GPS 1PPS) (ns)	2,216	1,890	1,920	1,691	1,690
Max ((Local Clock (NPL) - GPS 1PPS (ns)	3,800	2,120	2,035	1,800	1,755
Min ((Local Clock(NPL) - GPS 1PPS) (ns)	400	1,630	1,890	1,560	1,625
Data spread (ns)	3,400	230	145	240	130
Step > 100 ns	No	No	No	No	No
Transients > 100 ns	Yes	Yes	Yes	No	No
Standard Deviation (ns) (Individual readings) (1PPS)	121.7	22.9	31.2	34	22
Standard Deviation (ns) (Hourly mean) (1PPS)	46.9	20.9	31.4	25.2	20.8
Standard Deviation (ns) (Typical 24 Hr Readings) (minute means) (1PPS)(ns)	20	16.9	2.4	32.9	7.2
Antenna / cable delay external correction (ns)	0	132.2	107.5	64.7	64.7
UTC(NPL) - GPSDO(1PPS) (ns)	224	-224	-163	-366	-350
Mean UTC(USNO) - UTC(NPL) (Circular T) (ns)	62	59	58	65	62
UTC(USNO) - GPSDO(1PPS) (ns)	286	-165	-105	-301	-288
Oscillator Type	Quartz	Quartz	Rb	Quartz	Rb

Table 4c: GPSDO Time dissemination values and statistics measured during the study.

GPSDO	K	L	M	N	O
Period of extended measurements (MJD)	50466 - 50506	50477 - 50506	50477 - 50481	50466 - 50495	50479 - 50495
No of days	41	30	5	30	17
Mean ((Local Clock(NPL) - GPS 1PPS) (ns)	2,489	2,143	1,979	1,986	2,107
Max ((Local Clock (NPL) - GPS 1PPS (ns)	2,950	2,500	2,400	2,018	2,300
Min ((Local Clock(NPL) - GPS 1PPS) (ns)	2,000	1,700	1,600	1,953	1,850
Data spread (ns)	950	870	800	65	450
Step > 100 ns	No	No	No	No	No
Transients > 100 ns	No	Yes	No	No	Yes
Standard Deviation (ns) (Individual readings) (1PPS)	97.7	51.9	155	9.9	14.7
Standard Deviation (ns) (Hourly mean) (1PPS)	67.5	40.0	117	9.5	11.7
Standard Deviation (ns) (Typical 24 Hr Readings) (minute means) (1PPS)(ns)	107.1	43	163	10.1	14.2
Antenna / cable delay external correction (ns)	120	150	65	50	60
UTC(NPL) - GPSDO(1PPS) (ns)	332	-47	-61	-40	56
Mean UTC(USNO) - UTC(NPL) (Circular T) (ns)	65	59	64	62	64
UTC(USNO) - GPSDO(1PPS) (ns)	397	12	3	22	120
Oscillator Type	Quartz	Quartz	Quartz	Rb	Quartz

FIGURE 11(a-b)

(a)



(b)

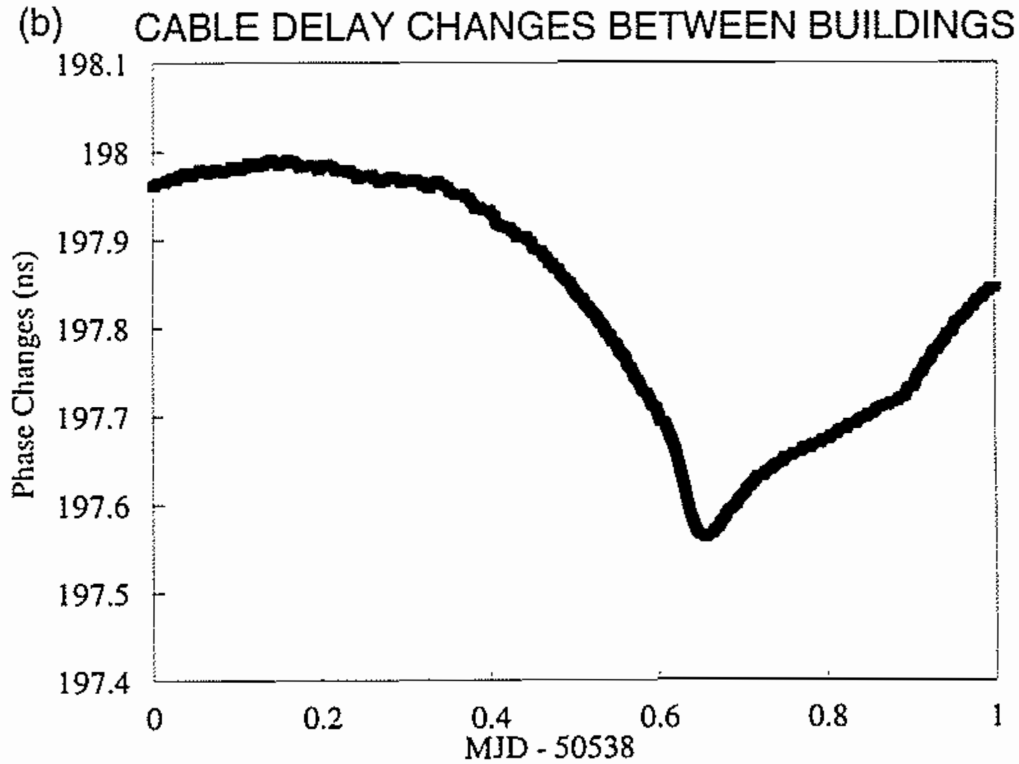


FIGURE 12 (a-d) LOCAL CLOCK - GPSDO(1PPS) CALCULATED FROM AN EXTENDED RUN OF 1PPS MEASUREMENTS

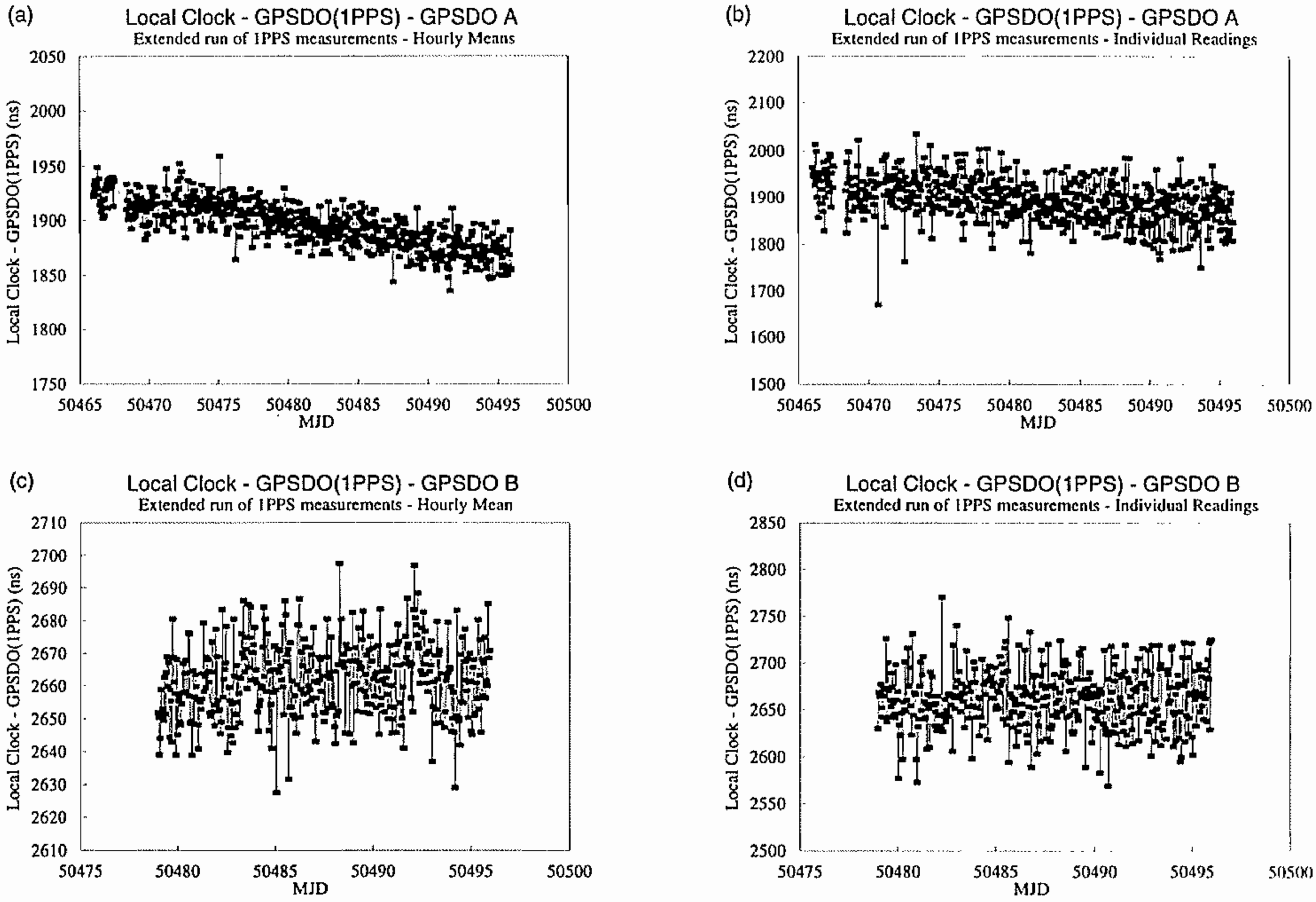
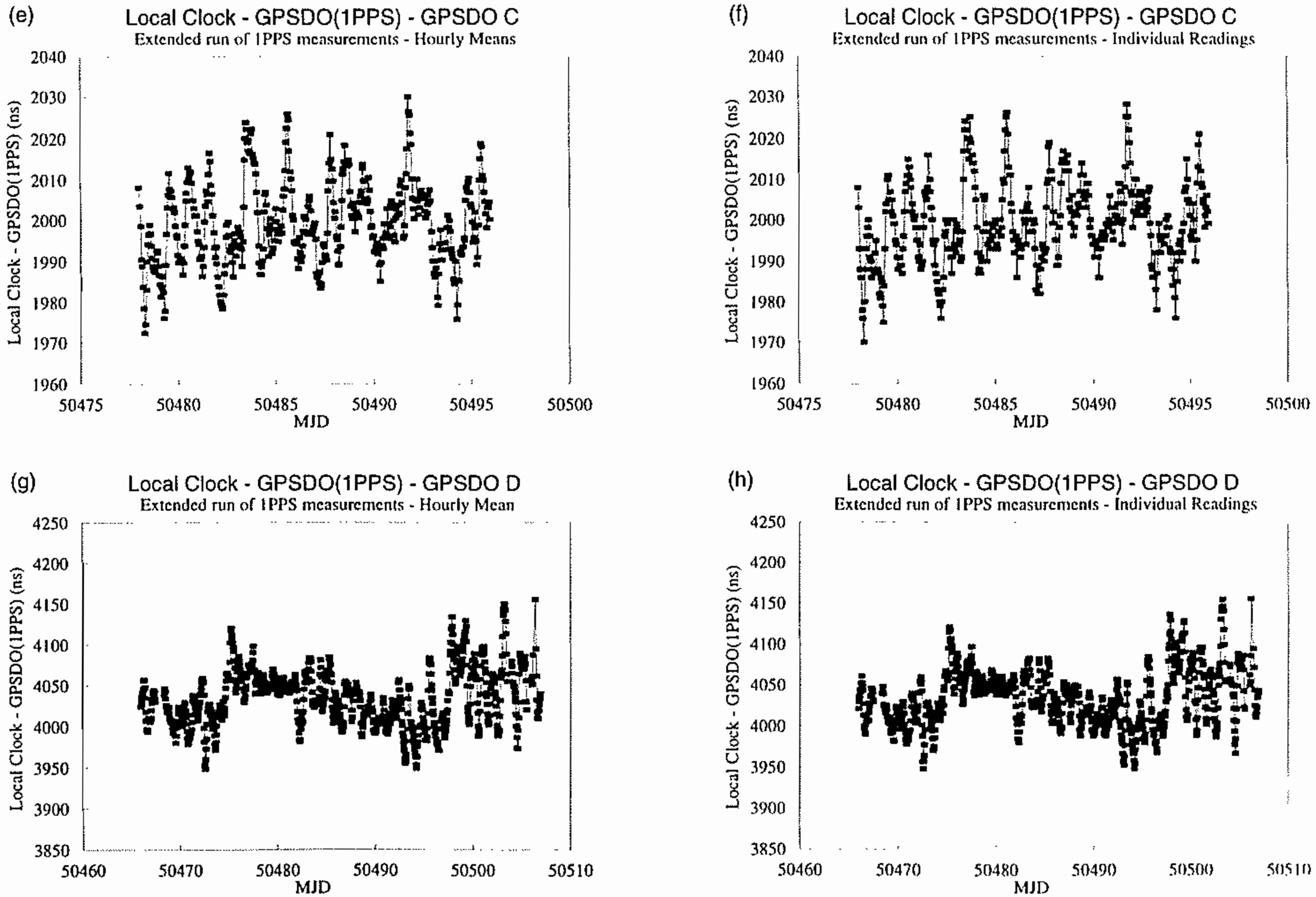


FIGURE 12 (e-h)



(e)
Local Clock - GPSDO(1PPS) - GPSDO C
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2040
2030
2020
2010
2000
1990
1980
1970
1960
50475
50480
50485
50490
50495
50500
MJD
(f)
Local Clock - GPSDO(1PPS) - GPSDO C
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2040
2030
2020
2010
2000
1990
1980
1970
1960
50475
50480
50485
50490
50495
50500
MJD
(g)
Local Clock - GPSDO(1PPS) - GPSDO D
Extended run of 1PPS measurements - Hourly Mean
Local Clock - GPSDO(1PPS) (ns)
4250
4200
4150
4100
4050
4000
3950
3900
3850
50460
50470
50480
50490
50500
50510
MJD
(h)
Local Clock - GPSDO(1PPS) - GPSDO D
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
4250
4200
4150
4100
4050
4000
3950
3900
3850
50460
50470
50480
50490
50500
50510
MJD

FIGURE 12 (i-l)

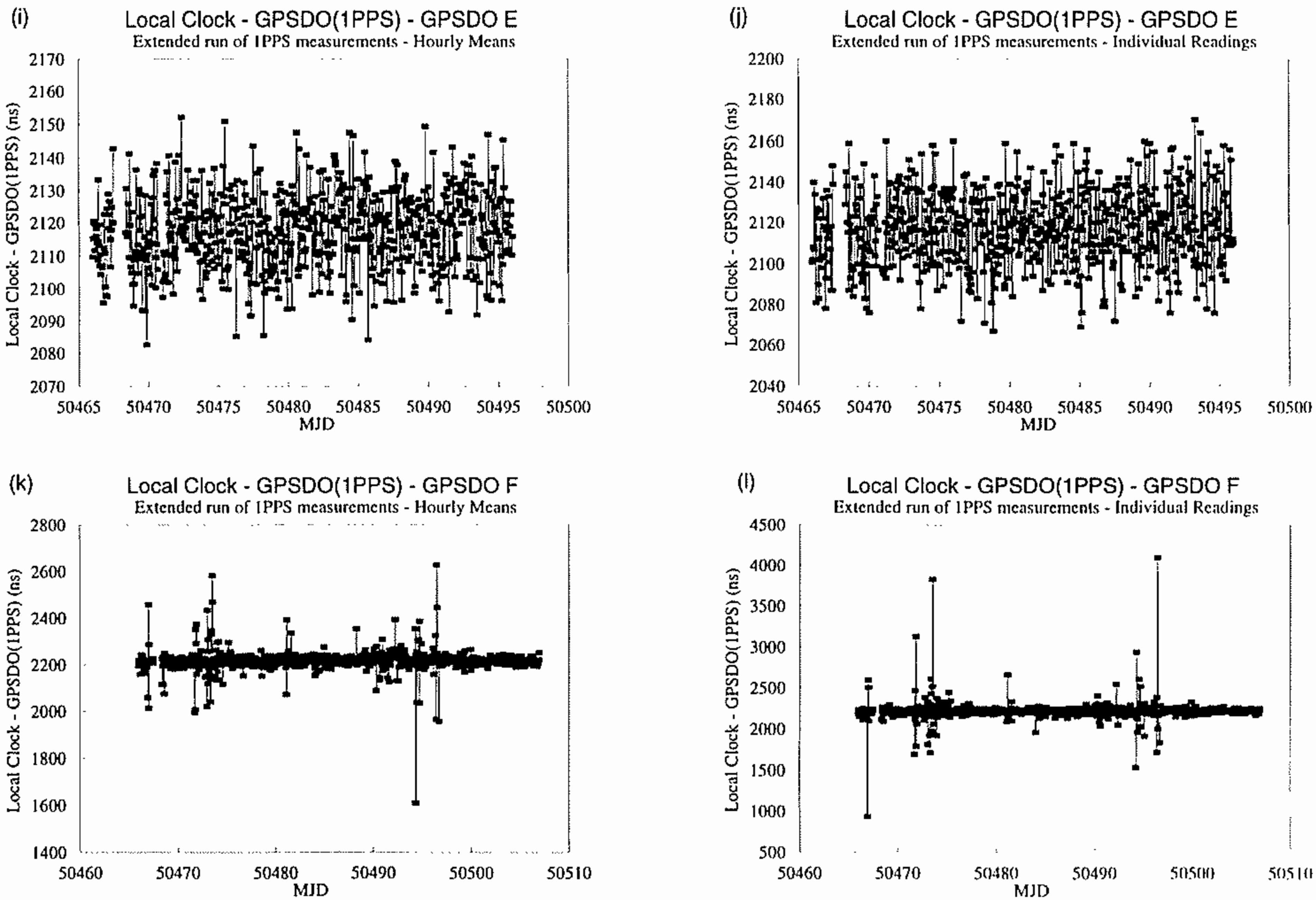

(i)
Local Clock - GPSDO(1PPS) - GPSDO E
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2170
2160
2150
2140
2130
2120
2110
2100
2090
2080
2070
50465
50470
50475
50480
50485
50490
50495
50500
MJD
(j)
Local Clock - GPSDO(1PPS) - GPSDO E
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2200
2180
2160
2140
2120
2100
2080
2060
2040
50465
50470
50475
50480
50485
50490
50495
50500
MJD
(k)
Local Clock - GPSDO(1PPS) - GPSDO F
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2800
2600
2400
2200
2000
1800
1600
1400
50460
50470
50480
50490
50500
50510
MJD
(l)
Local Clock - GPSDO(1PPS) - GPSDO F
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
4500
4000
3500
3000
2500
2000
1500
1000
500
50460
50470
50480
50490
50500
50510
MJD

FIGURE 12 (m-p)

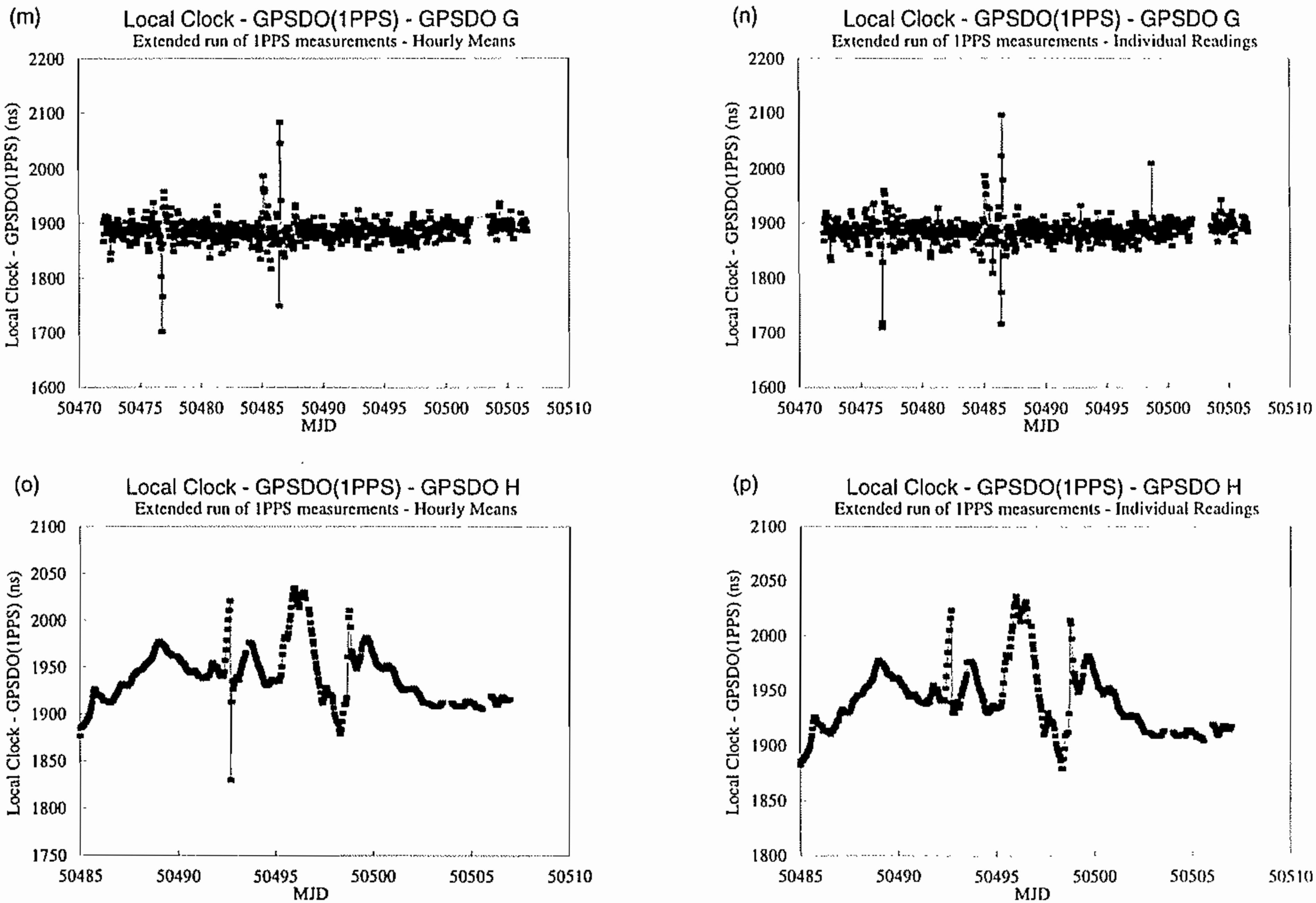
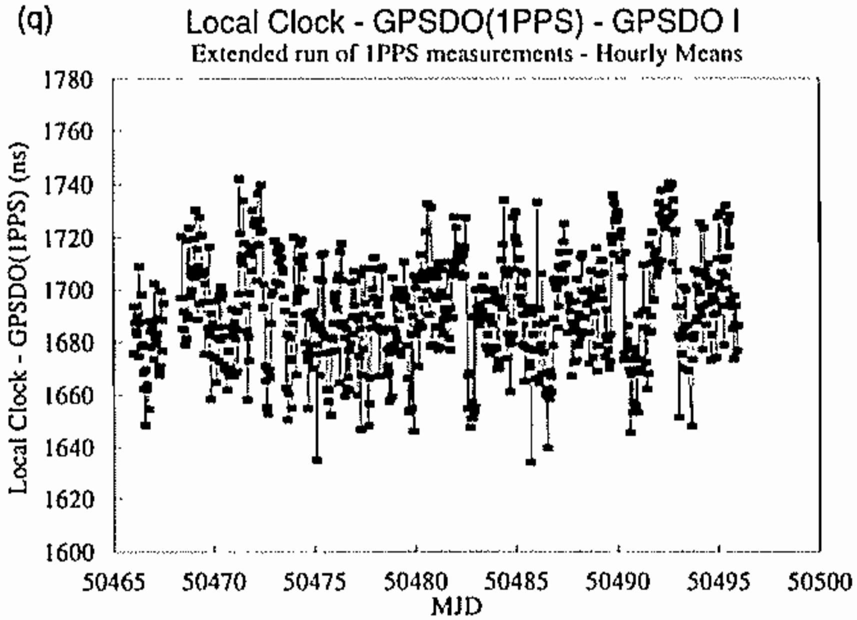
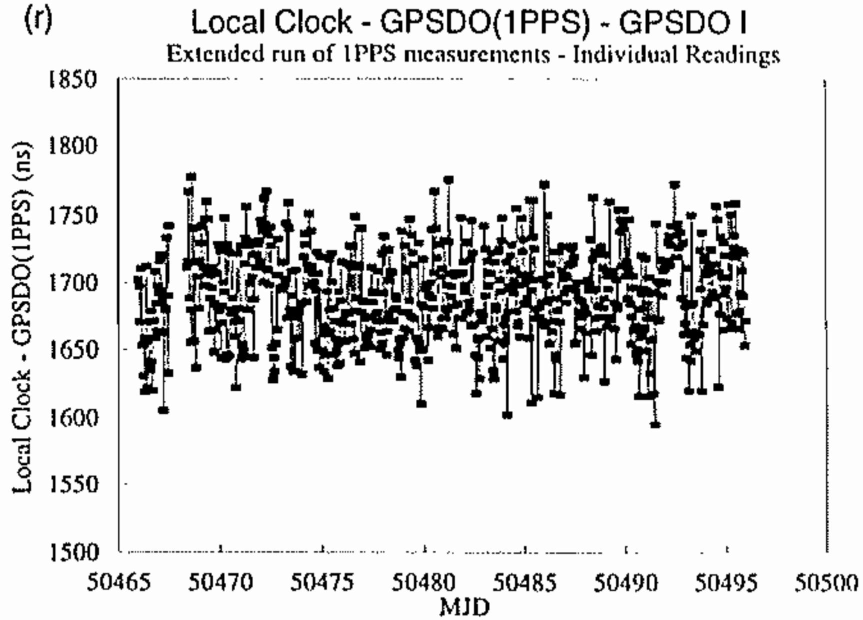

(m)
Local Clock - GPSDO(1PPS) - GPSDO G
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2200
2100
2000
1900
1800
1700
1600
50470 50475 50480 50485 50490 50495 50500 50505 50510
MJD
(n)
Local Clock - GPSDO(1PPS) - GPSDO G
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2200
2100
2000
1900
1800
1700
1600
50470 50475 50480 50485 50490 50495 50500 50505 50510
MJD
(o)
Local Clock - GPSDO(1PPS) - GPSDO H
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2100
2050
2000
1950
1900
1850
1800
1750
50485 50490 50495 50500 50505 50510
MJD
(p)
Local Clock - GPSDO(1PPS) - GPSDO H
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2100
2050
2000
1950
1900
1850
1800
50485 50490 50495 50500 50505 50510
MJD

FIGURE 12 (q-t)

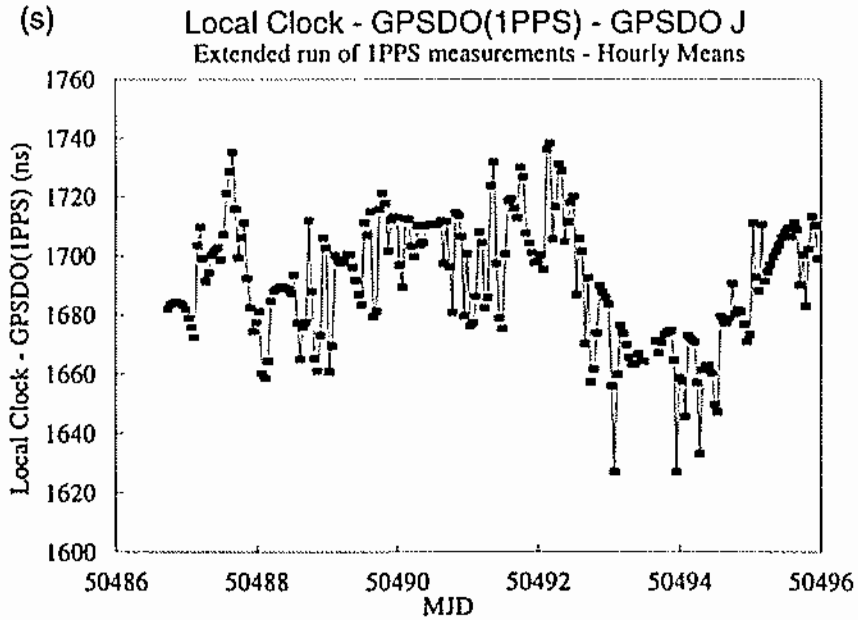
(q)



(r)



(s)



(t)

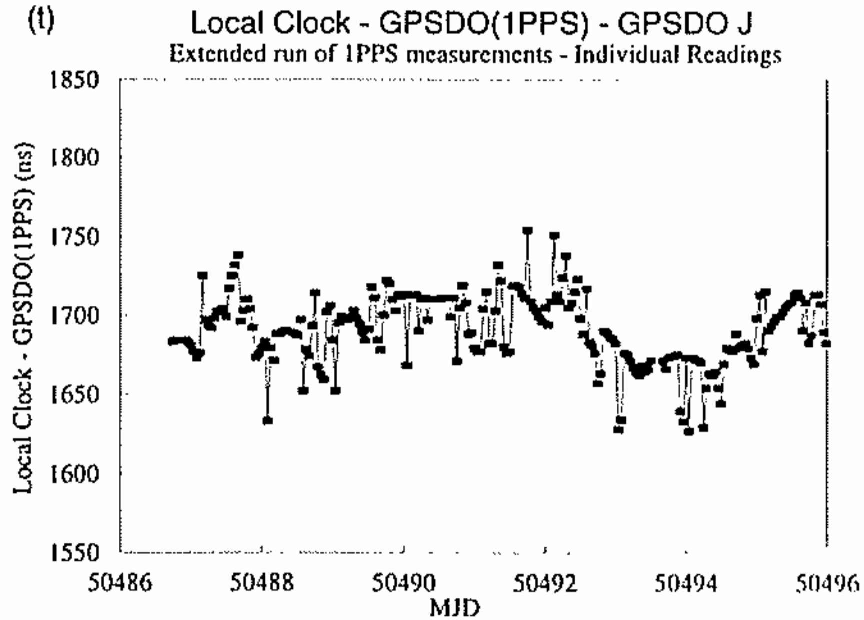
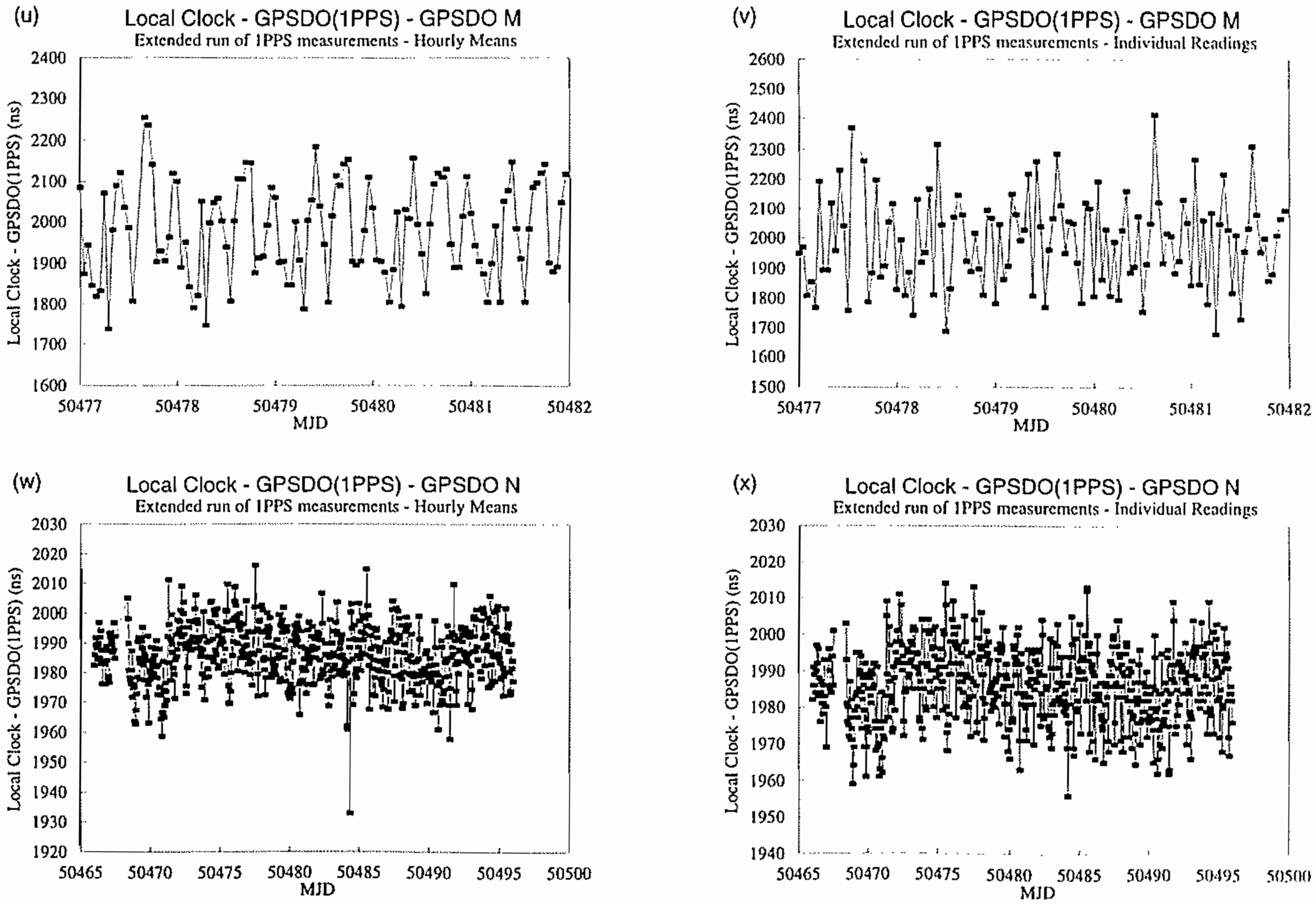


FIGURE 12 (u-x)



(u)
Local Clock - GPSDO(1PPS) - GPSDO M
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2400
2300
2200
2100
2000
1900
1800
1700
1600
50477
50478
50479
50480
50481
50482
MJD
(v)
Local Clock - GPSDO(1PPS) - GPSDO M
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2600
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
50477
50478
50479
50480
50481
50482
MJD
(w)
Local Clock - GPSDO(1PPS) - GPSDO N
Extended run of 1PPS measurements - Hourly Means
Local Clock - GPSDO(1PPS) (ns)
2030
2020
2010
2000
1990
1980
1970
1960
1950
1940
1930
1920
50465
50470
50475
50480
50485
50490
50495
50500
MJD
(x)
Local Clock - GPSDO(1PPS) - GPSDO N
Extended run of 1PPS measurements - Individual Readings
Local Clock - GPSDO(1PPS) (ns)
2030
2020
2010
2000
1990
1980
1970
1960
1950
1940
50465
50470
50475
50480
50485
50490
50495
50500
MJD

FIGURE 12 (y-b1)

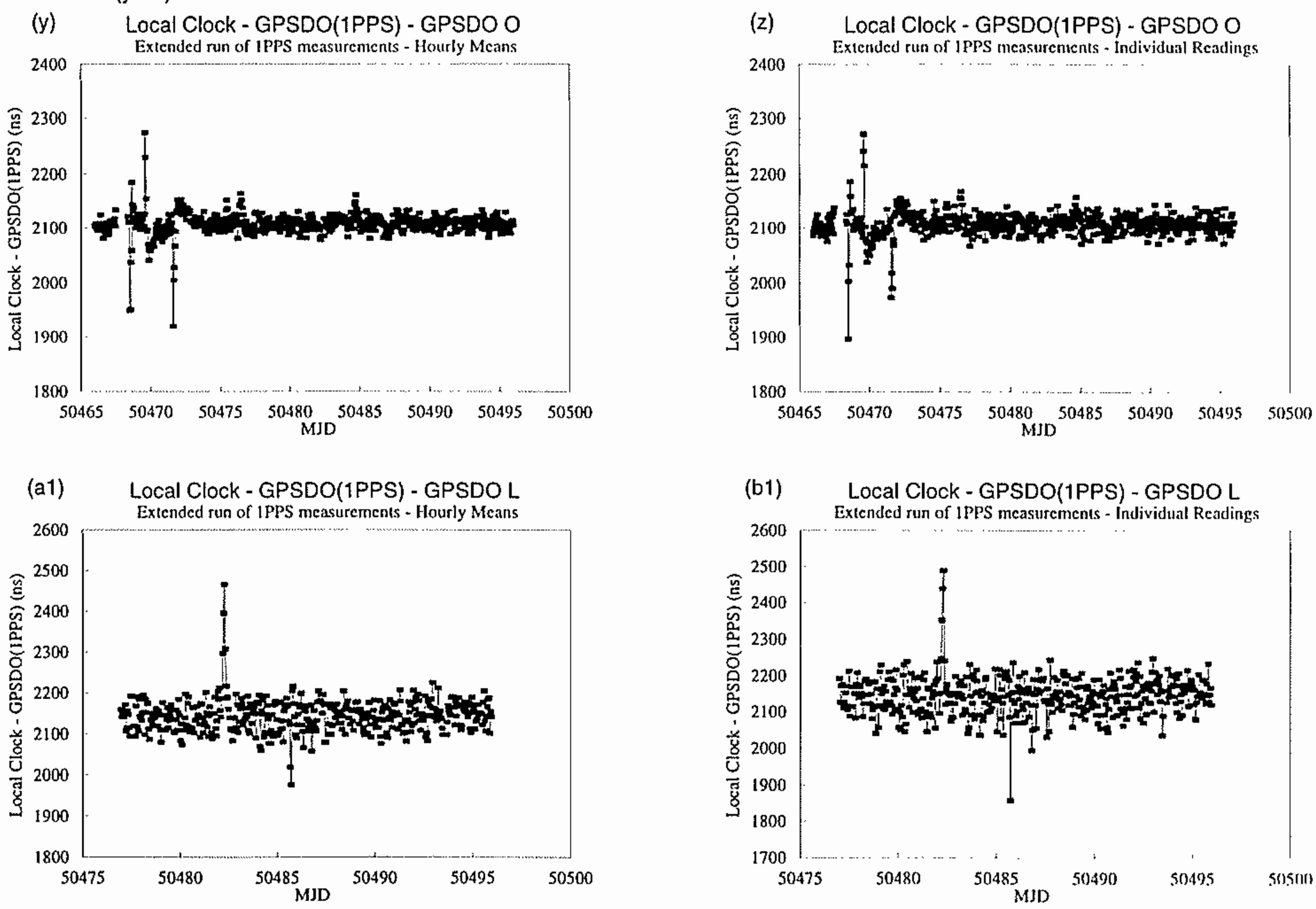
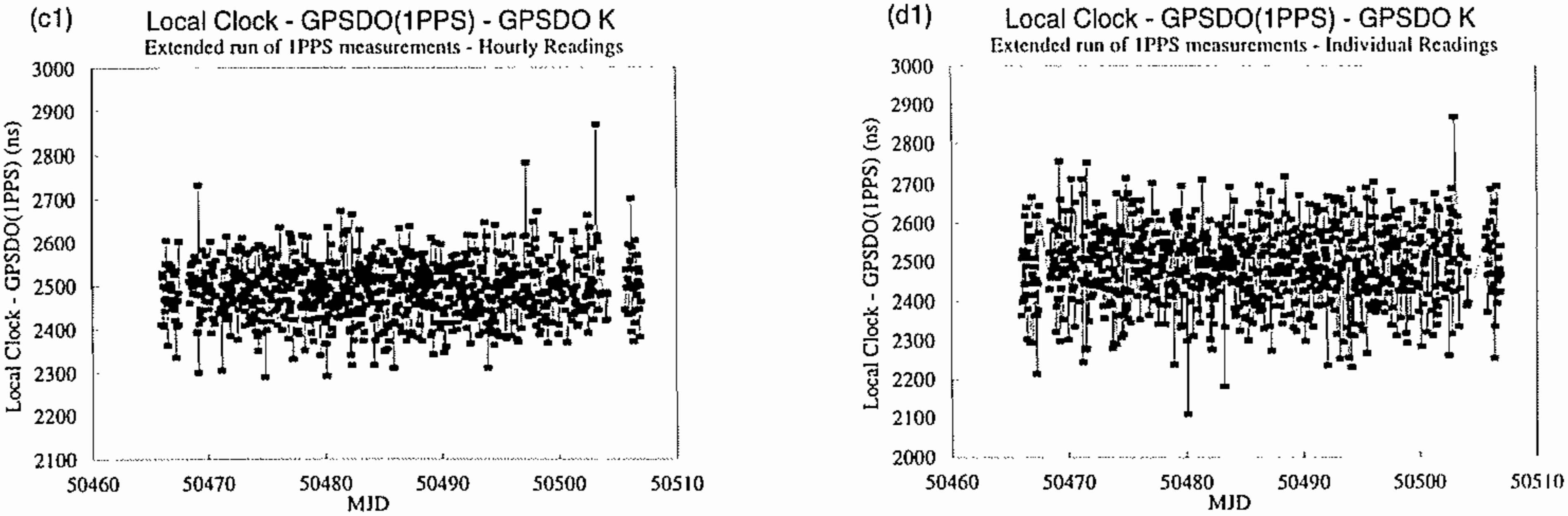


FIGURE 12(c1-d1)



There were no large delay steps observed during the course of the study, however delay steps were observed in NPL's previous GPSDO study [5]. The presence of any delay steps would have severe consequences for the use of GPSDOs as traceable standards. GPSDO (A) shows a slow drift in the value of UTC(NPL) - GPS(1PPS) of -0.3ns/day. This may be caused by the aging of the internal GPSDO components.

The absolute value of UTC(NPL) - GPSDO(1PPS) has been determined for each GPSDO (Appendix A). These values were obtained by adding the (UTC(NPL)-Local Clock) measurements to the (Local Clock - GPSDO(1PPS)) measurements and then subtracting the antennae/cable delay corrections. The GPSDOs were operated without entering values for antenna corrections. These corrections have been determined as described by the GPSDO manufacturers and are included in table 4.

The mean values of UTC(USNO) - GPSDO(1PPS) were found to vary considerably between the different GPSDO units, ranging from 3 ns to over 2,000 ns. For many of the GPSDOs, the mean values for the UTC(USNO) - GPSDO(1PPS) offset is much greater than the standard deviation, due to the presence of significant biases. The most likely cause of the biases is due to the un-calibrated delays within each GPSDO, or errors in the manufacturers delay calculations. Other possible causes include inaccurate antenna coordinates and errors in the cable delay determinations.

3.8) Comparison with the 1PPS signals from the Motorola Oncore receivers

The 1PPS output from NPL's Motorola Oncore receivers was logged in a similar manner to the GPSDO 1PPS data. The data was post processed using identical methods. Figure 5 shows the variations of the Motorola 1PPS over a period of 24 hours presented in a similar way to the GPSDO 1PPS outputs. The two Motorola Oncore receivers are identical models. However, there are transients in the 1PPS output of Motorola 1 that did not occur for Motorola 2, see figure 21(m) and (n). These are discussed in section 5. The Motorola Oncore receivers are relatively inexpensive costing a maximum of £600. The 1PPS output from this receiver is considerably better in performance than the outputs of several of the GPSDOs, both in absolute time transfer and stability. It is surprising that several of the GPSDOs, for example (F) and (M), do not offer an improved 1PPS output stability when compared against inexpensive GPS receivers. It is unlikely that by using a GPS signal to discipline a local oscillator would be expected to improve the mean value of UTC(USNO) - GPS(1PPS) and hence absolute time transfer, as the total instrumentation signal delay is likely to be increased. Many of the 1PPS outputs from the better GPSDOs for example (C) and (N), are significantly more stable than the 1PPS output from the Motorola receivers. This does demonstrate the beneficial effects of using a high quality local oscillator in a GPSDO.

3.9) Conclusions

There is a very wide range in the time transfer performance of the GPSDOs with the time dissemination errors varying between 3 ns to over 2,000 ns. The largest absolute time transfer error (> 1,000 ns) was however associated with a fault in the manufacture of that particular model of GPSDO. The time dissemination errors were not strongly dependent on the type of local oscillator used. The biases in the absolute time dissemination may be significantly larger than the accompanying data scatter. Rubidium based GPSDOs displayed significantly less short term variations. The data scatter is dependent on both the local oscillator type and on the disciplining algorithms. Time dissemination drifts and transients have been observed on some of the GPSDOs. These may seriously reduce the accuracy of the GPSDO time dissemination. These time dissemination anomalies did not correlate between different GPSDOs. The use of two GPSDOs at a single operating site would therefore isolate these effects.

3.10) Recommendations

Where low level time dissemination traceability is required from the GPSDOs (uncertainties > 1 μs) then examples of the individual models of GPSDOs tested against a primary time scale, so as to ensure the accuracy and integrity of the complete batch.

Where traceability to UTC(NPL) for absolute time is required at a higher level of accuracy (uncertainty < 1 μs) then it is recommended that the individual GPSDOs should have their internal delays calibrated against a primary time scale. It is recommended that two GPSDOs be observed at a single location, so as to check against delay steps transients and drifts.

3.11) References

[1] W Lewandowski and C Thomas, *GPS Time Transfer*, Proceedings of the IEEE, vol. 79 no. 7, pp 991-1,000, July 1991.

[2] D Kirchner, *Two-Way Time Transfer via Communications satellites*, Proceedings of the IEEE, vol. 79 no. 7, pp 983-990, July 1991.

[3] J A Davis and J McA Steele, *A Caesium Flying Clock Experiment between NPL and USNO*, Proceedings 11th European Frequency and Time Forum, Neuchatel, March 1997.

[4] J A Davis et al, *Comparison of Two-Way Satellite Time and Frequency Transfer and GPS Common-View Time Transfer during the Intelsat field trials*, Proceedings of the 10th European Frequency and Time Forum, Brighton, pp 382-387, March 1996.

[5] R Jefferies, *NPL Study of GPS Disciplined Oscillators*, Report circulated to participants, September 1995.

4) Frequency Dissemination

4.1) Introduction

The majority of users of GPSDOs are still primarily interested in their frequency dissemination characteristics. Traditionally the time transfer community has characterised oscillators in term of their fractional frequency stability, σ_y at a given averaging time, τ. However for a disciplined oscillator the frequency offset from its true value may be as important. Both frequency offset and frequency stability are examined in this report. The traceability issues for frequency dissemination using GPSDOs are similar to those for time dissemination, as both the accuracy and integrity of the GPSDO standard frequency output needs to be carefully examined.

4.2) Phase comparison system

NPL has used a 16 channel phase comparator (TimeTech model P/Comp 16-001/96) in order to compare the standard frequency outputs of the GPSDOs against UTC(NPL). Eight channels operate at 10 MHz and the remaining 8 channels at 5 MHz. The 5/10 MHz signals from all the GPSDOs were simultaneously compared against a 5 MHz signal originating from UTC(NPL). A schematic diagram of the phase comparison arrangement is shown in figure 13. Local time is provided by a MSF linked DOS clock. The phase comparator does not itself have access to GPS time. Tests were performed on the phase comparator over a period of 24 hr, this may detect the effects of for example daily temperature cycling. To test the ultimate limitations of the phase comparison system a 5/10 MHz reference signal originating from UTC(NPL) was supplied to both the reference and each input channel of the phase comparator. A distribution amplifier was first used to split this signal before it entered the comparator. The variation of phase angle converted to ns of delay, is shown for a typical channel of the phase comparator for two successive days in figure 14(a) and (b). The changes, typically 60 ps peak to peak, are very small when compared with the phase changes observed within the GPSDOs. The results show that the phase stability of NPL's phase comparator was well in excess of that required for this study.

4.3) Frequency transfer statistics

A variety of statistical methods / tools have been used to analyse the frequency transfer performance of the GPSDOs under test. Much of the analysis in this report makes use of the Allan Variance and similar functions (ie σ_x, σ_y and MODσ_y as detailed below), which is standard practice in the Time and Frequency community. However where appropriate, more standard statistics, for example mean and standard deviations have been used.

4.4) Determination of frequency stability

Consider a data set of N evenly spaced points $x_1..x_N$ spaced an interval τ apart. The fractional frequency stability has been determined using σ_y^2 the Allan variance, where [1]:

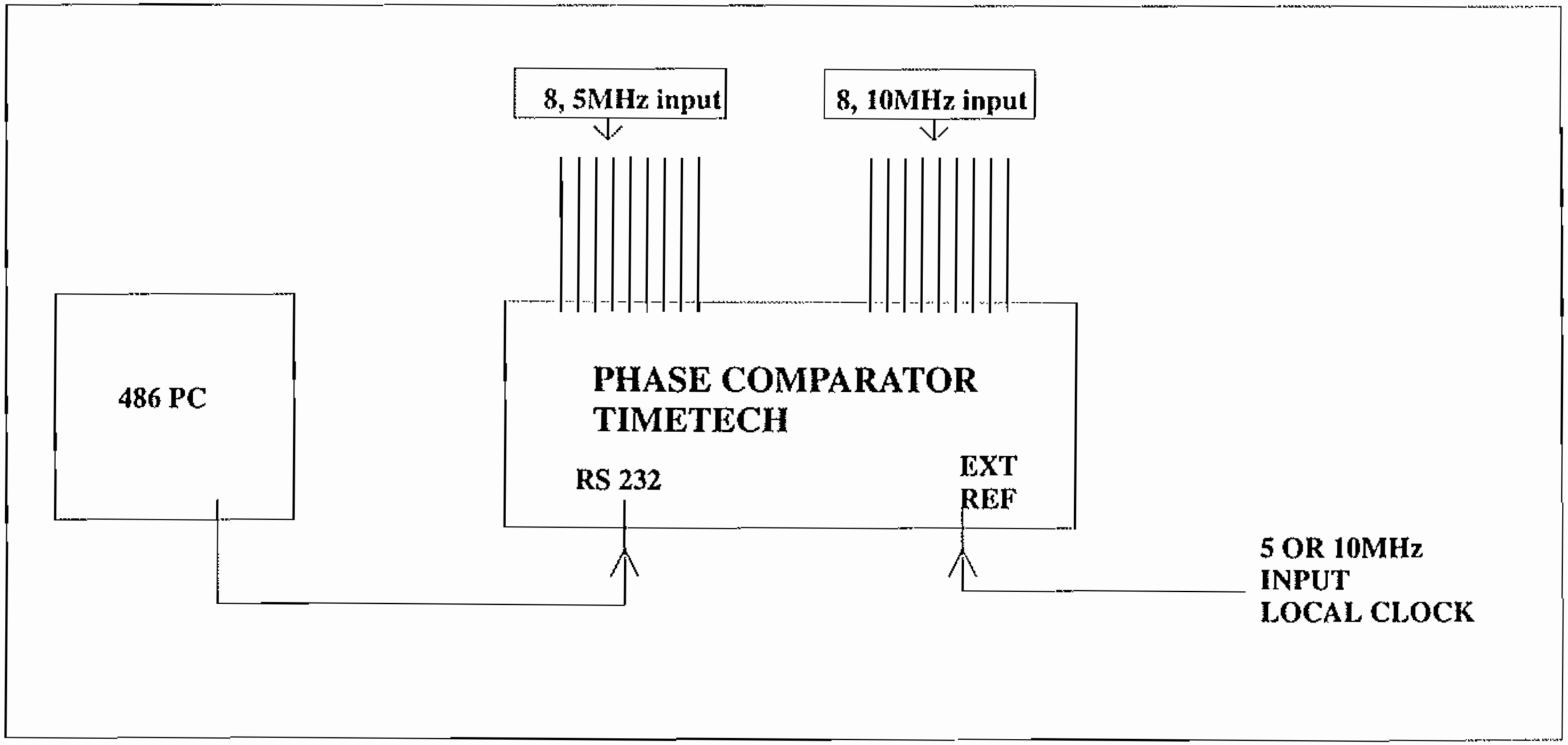
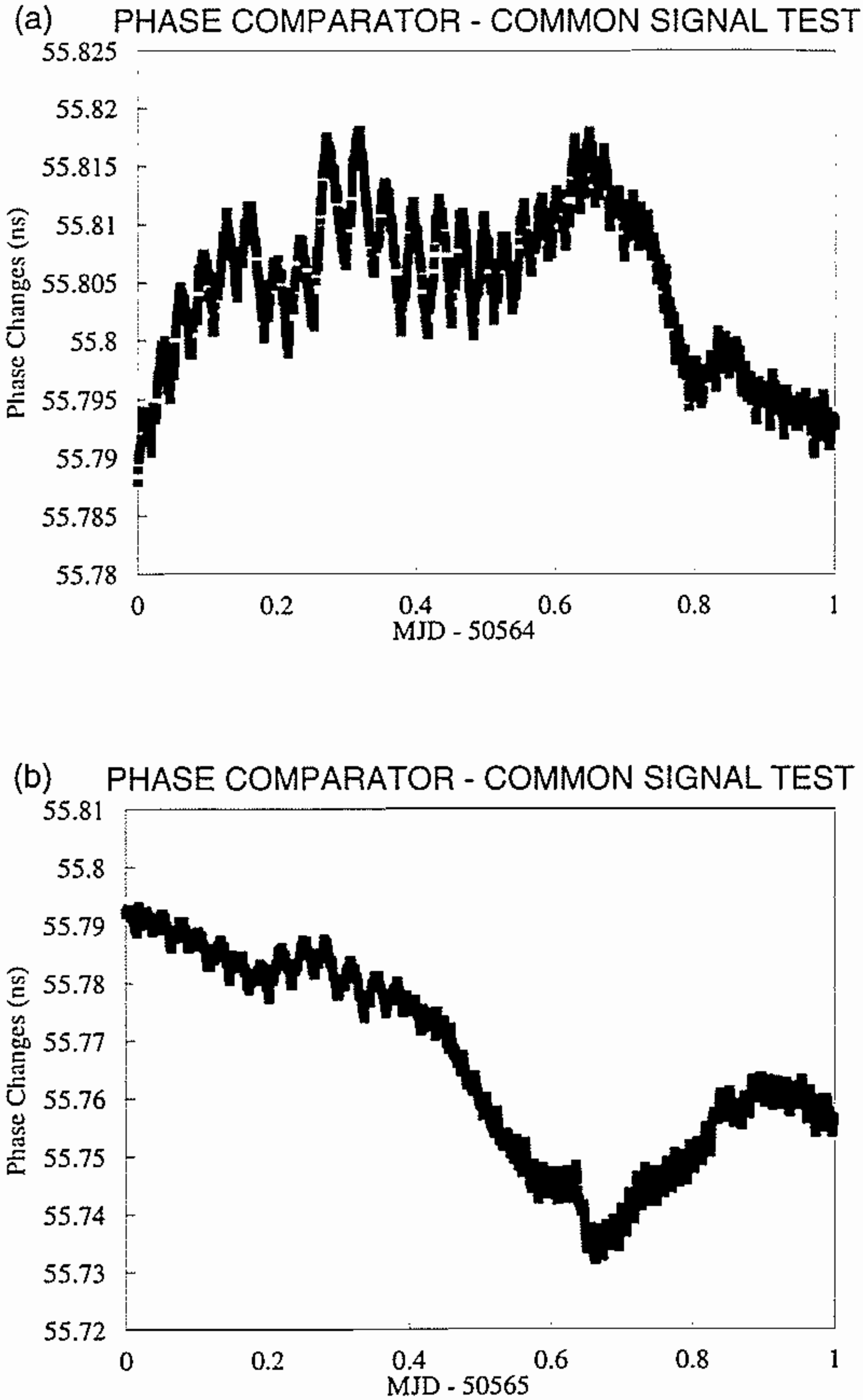


FIGURE 13: Experimental arrangement for logging phase difference

FIGURE 14(a-b)



(a)
PHASE COMPARATOR - COMMON SIGNAL TEST
55.825
55.82
55.815
55.81
55.805
55.8
55.795
55.79
55.785
55.78
Phase Changes (ns)
0
0.2
0.4
0.6
0.8
1
MJD - 50564
(b)
PHASE COMPARATOR - COMMON SIGNAL TEST
55.81
55.8
55.79
55.78
55.77
55.76
55.75
55.74
55.73
55.72
Phase Changes (ns)
0
0.2
0.4
0.6
0.8
1
MJD - 50565

$$\sigma_y^2(\tau)=\frac{1}{2(N-2)\tau^2}\sum(x_{i+2}-2x_{i+1}+x_i)^2$$

A modified Allan variance, has also been calculated where:

$$MOD\sigma_y^2(\tau)=\frac{1}{2(N-2)\tau^2}\langle\frac{1}{N}[\sum(x_{i+2}-2x_{i+1}+x_i)^2]\rangle$$

where $\langle\ \rangle$ represents an infinite time average [1].

Consider a set of data points, with minimum spacing τ_0 and averaging time $\tau= n\tau_0$. $MOD\sigma_y^2(\tau)$ may then be determined by averaging the n adjacent x values, and then calculating $\sigma_y^2(\tau)$ with the resulting averages.

σ_x is defined as:

$$\sigma_x=MOD\sigma_y(\tau)[\frac{(\tau)}{3^{0.5}}]$$

σ_x is a measure of the measurement precision in the time domain. Where white noise is prominent and $\tau=\tau_0$ then σ_x is equal to the standard deviation. σ_x is now being used to characterise GPSDOs for telecom applications [2].

4.5) Determination of frequency offsets

The frequency offset of the GPSDO oscillator is key in determining the performance of the GPSDOs. Two measures have been calculated here, the RMS fractional frequency offset and the RMS mean fractional frequency offset. These two quantities are defined below in a way analogous to σ_y and $MOD\sigma_y$.

$$(FractionalFrequencyOffset)^2=\frac{1}{(N-1)\tau^2}\sum(x_{i+1}-x_i)^2$$

$$(MeanFractionalFrequencyOffset)^2 = \frac{1}{\tau^2}\langle\frac{1}{N}\sum(x_{i+1}-x_i)^2\rangle$$

Where ⟨ ⟩ again represents an infinite time average. The RMS mean fractional frequency offset may be determined in an analogous way to $MOD\sigma_y$. Determination of the fractional frequency offset differs from σ_y in that the first difference rather than second difference of the phase / 1PPS data is being calculated.

4.6) Noise Characteristics

The standard analytical methods have been applied where plots are made of $Log_{10}(\sigma_y)$ and similar functions against $Log_{10}(\tau)$. The type of noise dominating a particular time and frequency standard at a given averaging time may be determined by examining graphs of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ and $Log_{10}(MOD\sigma_y)$ against $Log_{10}(\tau)$. White phase noise will result in the two graphs having gradients of -1 and -3/2 respectively. Flicker phase noise will result in the two graphs both having gradients of -1. Hence $MOD\sigma_y$ may be used to distinguish between noise types that cannot be distinguished using only σ_y. The gradients of graphs of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ and $Log_{10}(MOD\sigma_y)$ against $Log_{10}(\tau)$ produced by common noise types are shown in table 5 [1].

Table 5: Gradient of graphs of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ and $Log_{10}(MOD\sigma_y)$ against $Log_{10}(\tau)$ produced by common noise types.

Noise Type	Gradient of graph of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$	Gradient of graph of $Log_{10}MOD(\sigma_y)$ against $Log_{10}(\tau)$
White phase noise	-1	-3/2
Flicker phase noise	-1	-1
White frequency noise	-1/2	-1/2
Flicker frequency	0	0
Random walk frequency	1/2	1/2

4.7) Characteristics of the 5/10 MHz standard frequency outputs

A spectrum analyser was used to examine the signal strength, the side-bands and the harmonics present on the GPSDO signals. This was primarily done to meet the input specifications of the phase comparator. Figure 15 shows the presence of harmonics at multiples of the reference frequency. Results show that in several examples, strong harmonics are present for example on GPSDOs (E) and (K) suggesting that the sinusoidal 5/10 MHz signals are in some examples significantly distorted. There was however no evidence that the use of a non-sinusoidal standard frequency output degraded the performance of the phase comparison system. In figure 16, plots

FIGURE 15 (a-d) 5 MHZ AND 10 MHZ REFERENCE SIGNAL HARMONICS

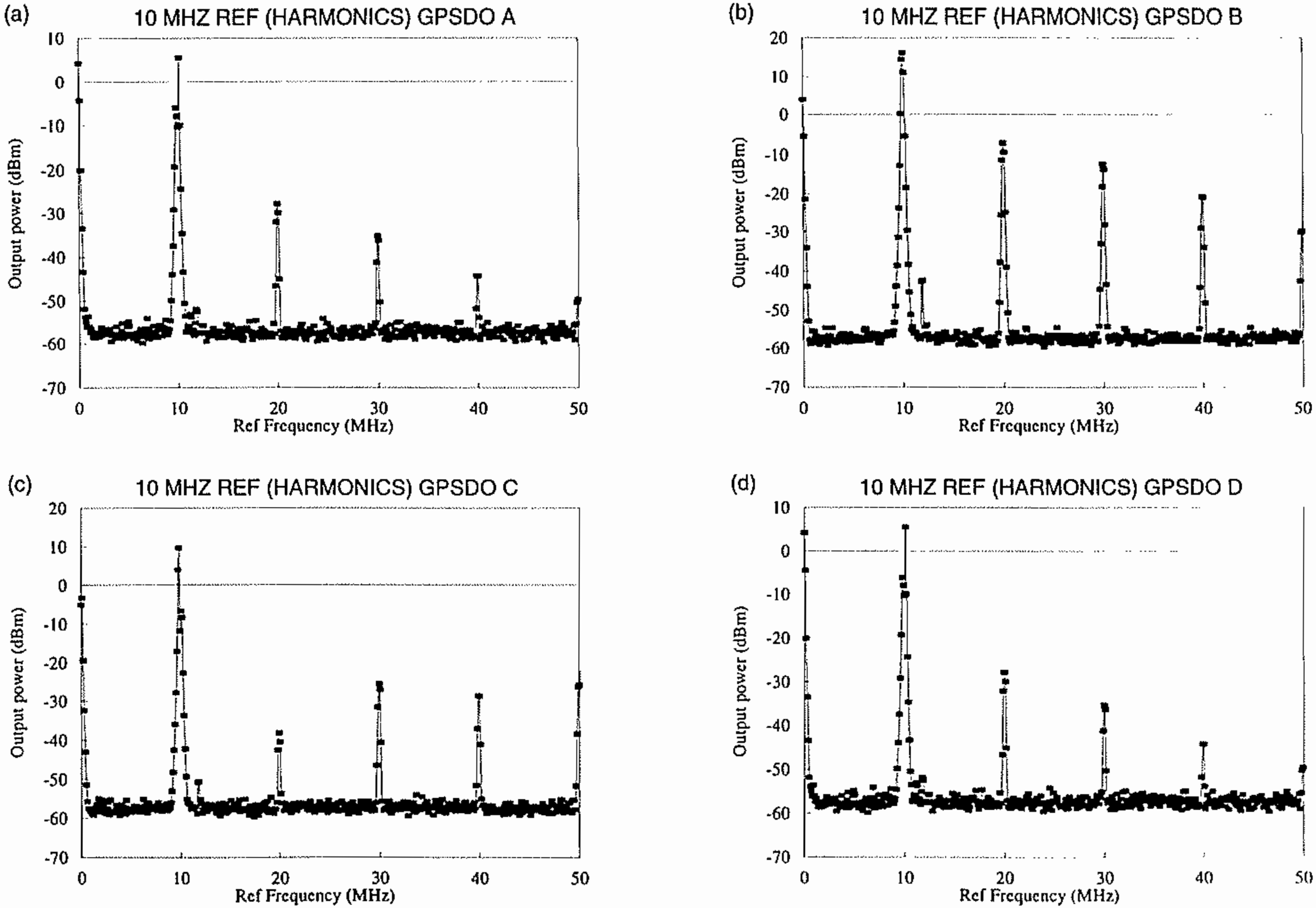
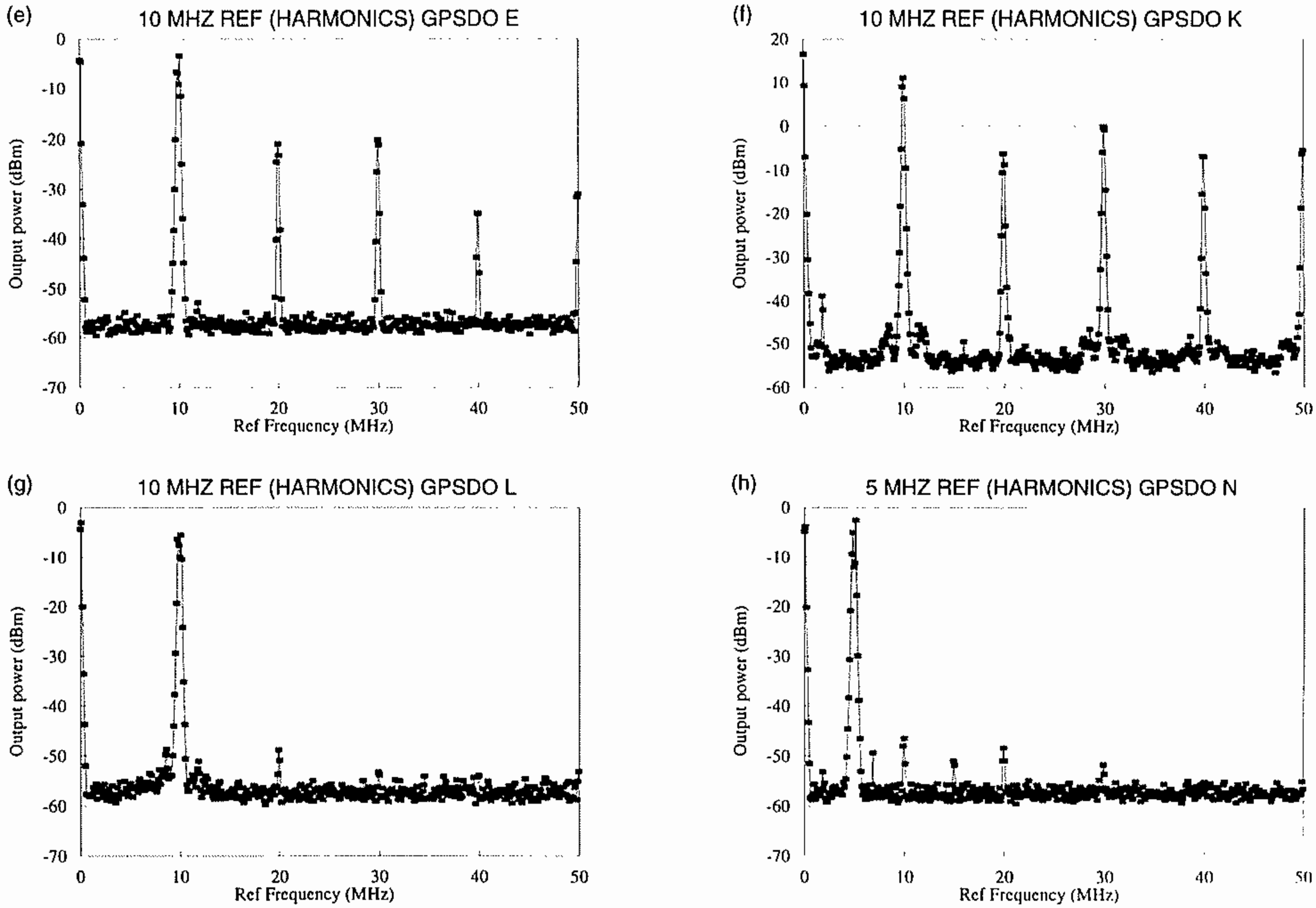


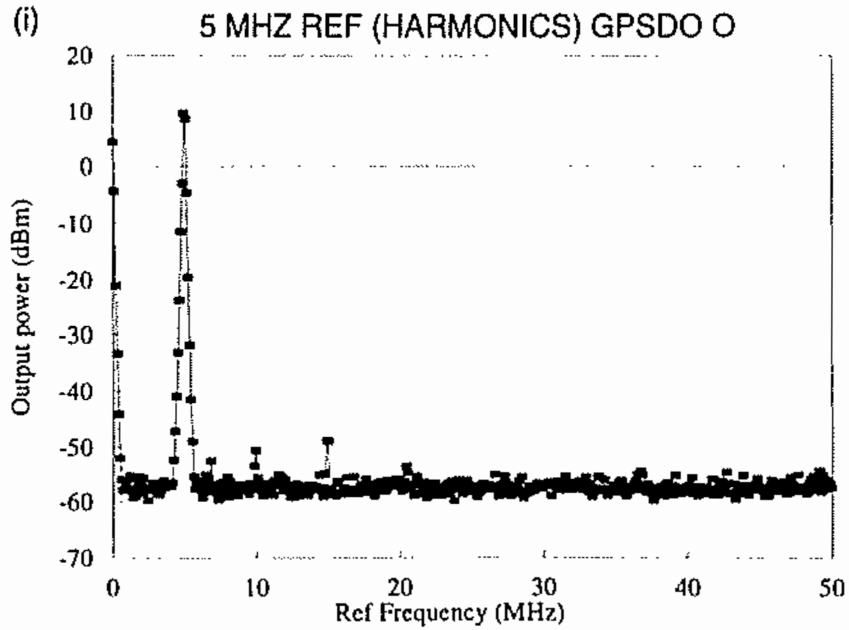
FIGURE 15 (e-h)



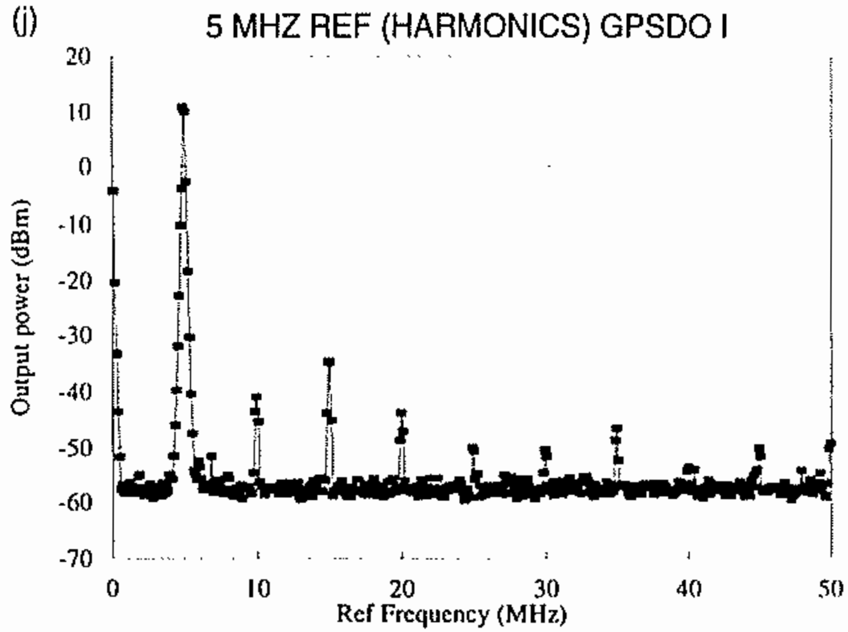
(e)
10 MHZ REF (HARMONICS) GPSDO E
Output power (dBm)
0
-10
-20
-30
-40
-50
-60
-70
0
10
20
30
40
50
Ref Frequency (MHz)
(f)
10 MHZ REF (HARMONICS) GPSDO K
Output power (dBm)
20
10
0
-10
-20
-30
-40
-50
-60
0
10
20
30
40
50
Ref Frequency (MHz)
(g)
10 MHZ REF (HARMONICS) GPSDO L
Output power (dBm)
0
-10
-20
-30
-40
-50
-60
-70
0
10
20
30
40
50
Ref Frequency (MHz)
(h)
5 MHZ REF (HARMONICS) GPSDO N
Output power (dBm)
0
-10
-20
-30
-40
-50
-60
-70
0
10
20
30
40
50
Ref Frequency (MHz)

FIGURE 15 (i-l)

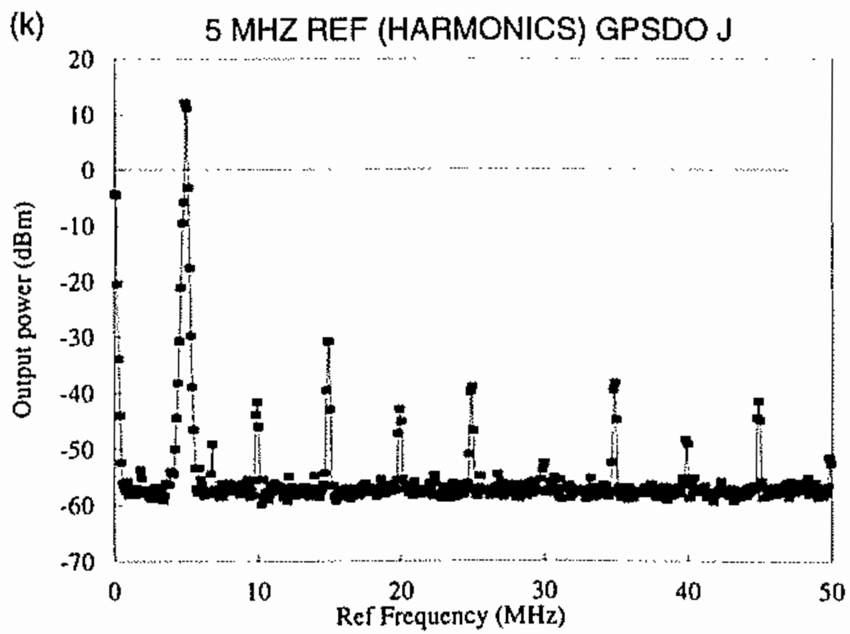
(i)



(j)



(k)



(l)

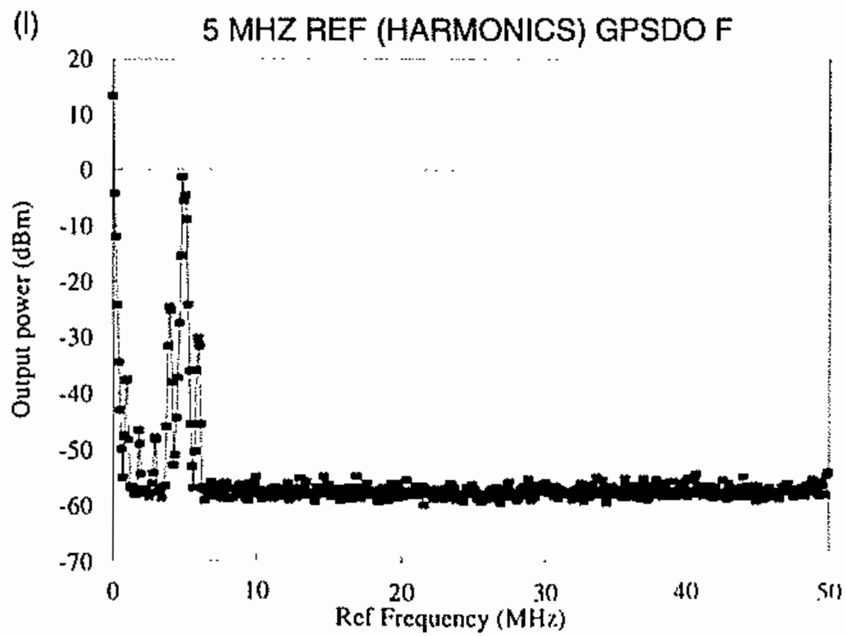


FIGURE 16 (a-d)

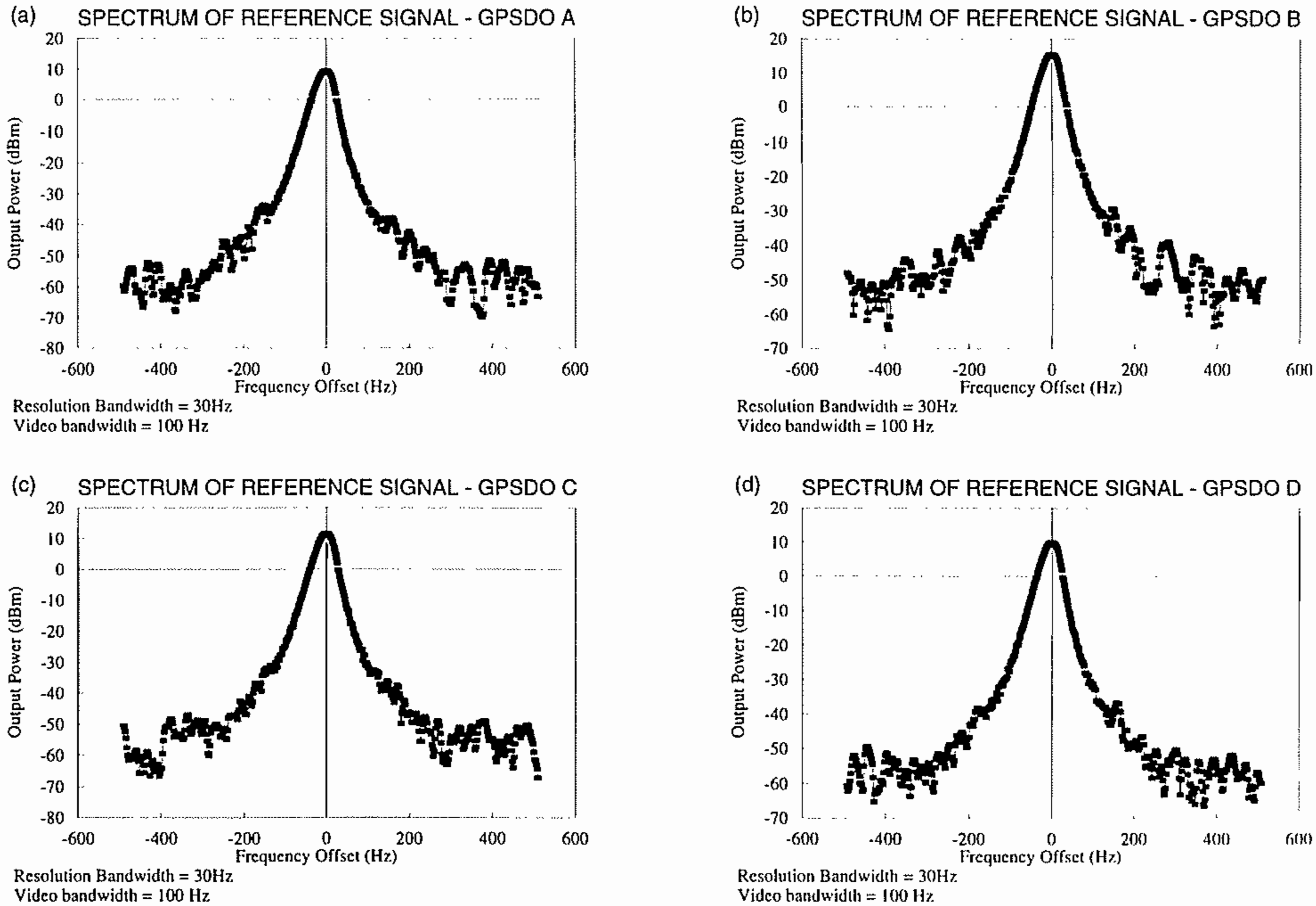

(a)
SPECTRUM OF REFERENCE SIGNAL - GPSDO A
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(b)
SPECTRUM OF REFERENCE SIGNAL - GPSDO B
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(c)
SPECTRUM OF REFERENCE SIGNAL - GPSDO C
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(d)
SPECTRUM OF REFERENCE SIGNAL - GPSDO D
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

FIGURE 16 (e-h)

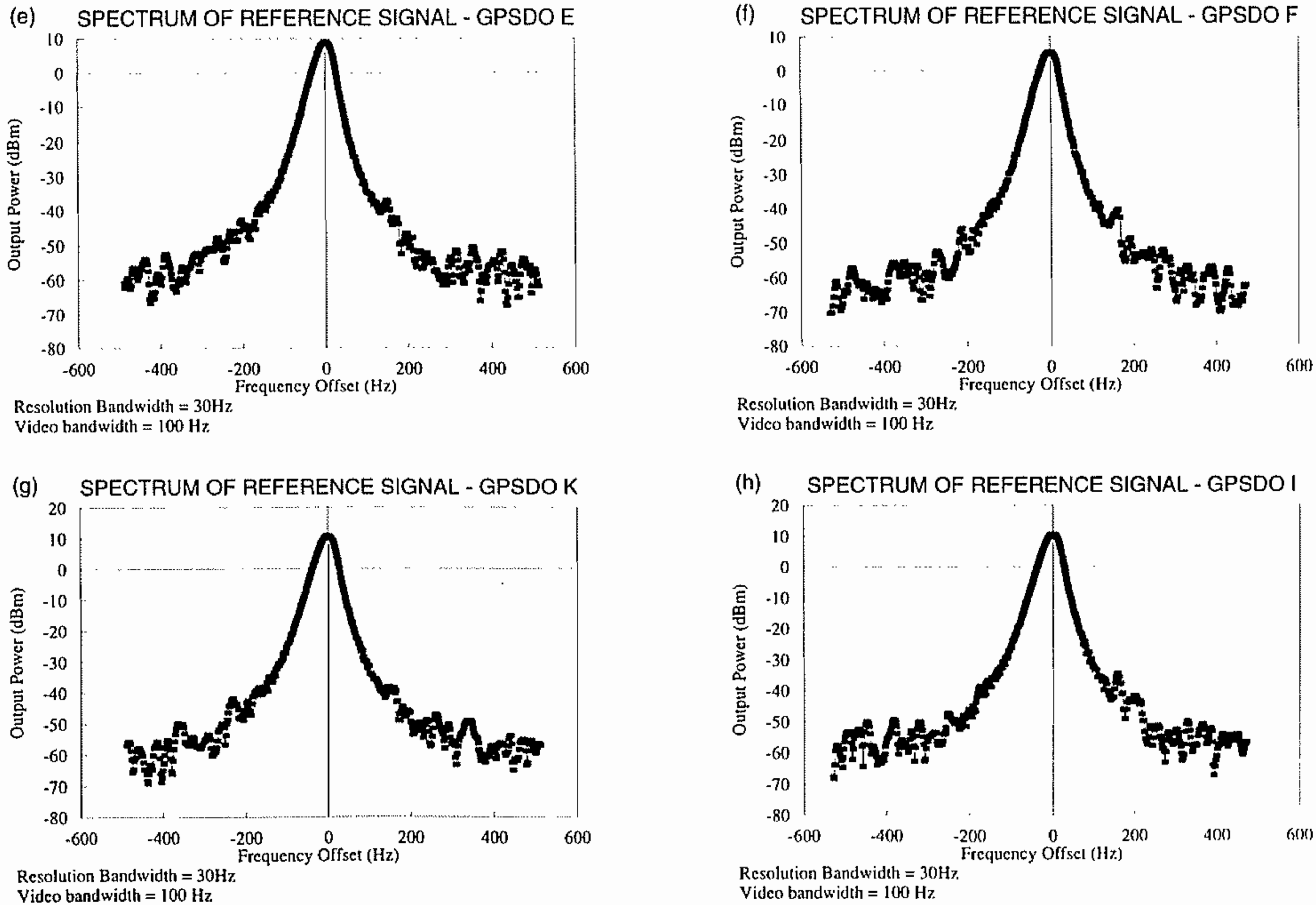
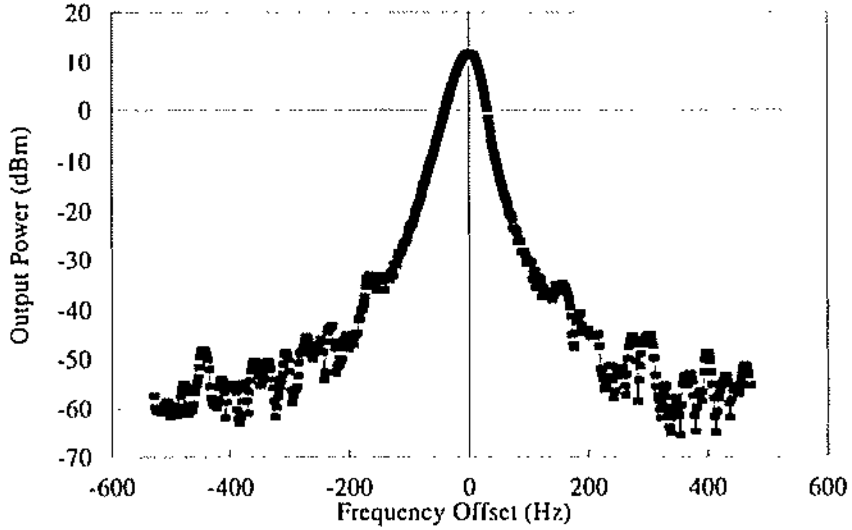

(e)
SPECTRUM OF REFERENCE SIGNAL - GPSDO E
Output Power (dBm)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-600
-400
-200
0
200
400
600
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(f)
SPECTRUM OF REFERENCE SIGNAL - GPSDO F
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(g)
SPECTRUM OF REFERENCE SIGNAL - GPSDO K
Output Power (dBm)
20
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz
(h)
SPECTRUM OF REFERENCE SIGNAL - GPSDO I
Output Power (dBm)
Frequency Offset (Hz)
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

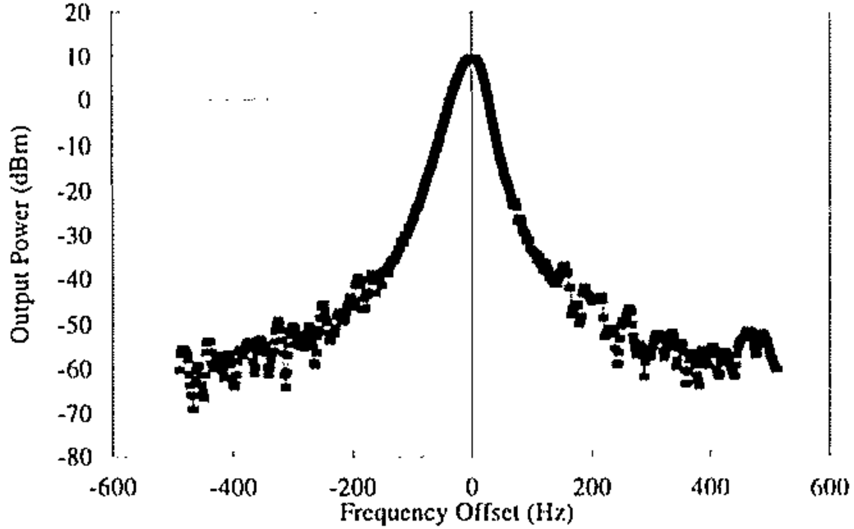
FIGURE 16 (i-l)

(i) SPECTRUM OF REFERENCE SIGNAL - GPSDO J



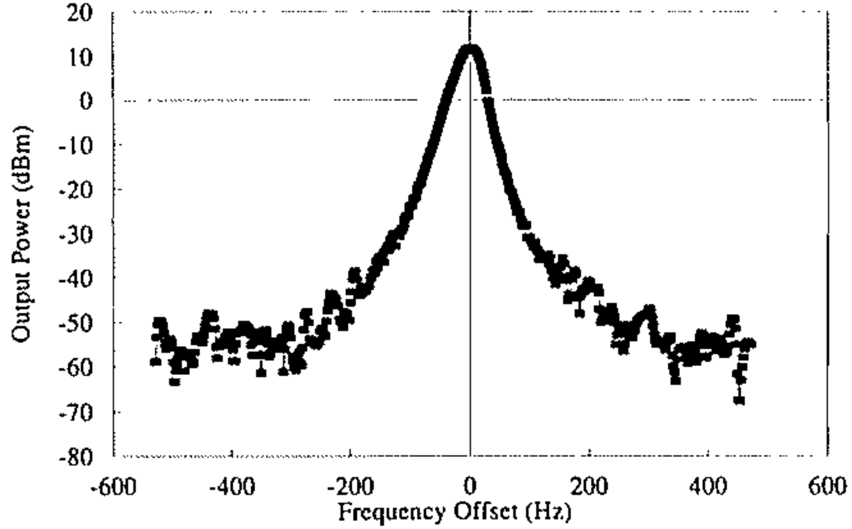
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

(j) SPECTRUM OF REFERENCE SIGNAL - GPSDO L



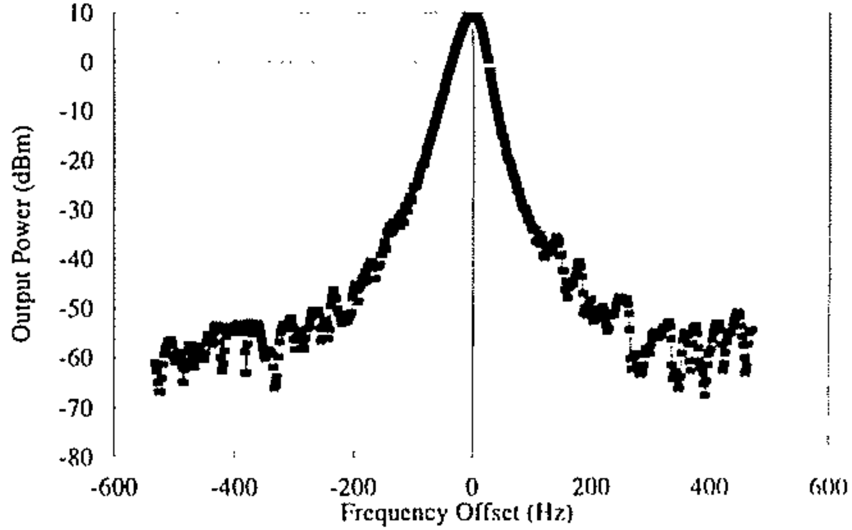
Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

(k) SPECTRUM OF REFERENCE SIGNAL - GPSDO N



Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

(l) SPECTRUM OF REFERENCE SIGNAL - GPSDO O



Resolution Bandwidth = 30Hz
Video bandwidth = 100 Hz

of the close in side-band noise present on the GPSDO reference signals are presented. The similar nature of some of these plots suggests that the results may possibly be limited by the performance of the spectrum analyser.

4.8) Phase measurements made over an extended period

Comparisons of the phase of the GPSDO standard frequency outputs against UTC(NPL) are shown in figure 17, with measurements taken over an extended period of up to 40 days. Standard deviations are calculated for the phase scatter, where phase changes have been converted into ns of delay. Results are shown in table 6. Examples of single day phase and 1PPS measurements recorded on the same day are shown in figure 18. There is a direct correlation between the phase and the 1PPS outputs from most GPSDOs, hence for the majority of the GPSDOs, the values of the standard deviations obtained from phase measurements in table 6 are very similar to standard deviations obtained from the 1PPS measurements given in table 4.

4.9) GPSDO frequency offsets and stabilities

Useful information may be obtained from both the 1PPS and phase data by the application of the statistics described in section 4.4. The use of these statistic enable the performance of the GPSDOs to be compared over a very wide range of averaging times.

Time and frequency statistics have been applied to both the 1PPS and phase data obtained from the extended operation of the GPSDOs. Plots of $Log_{10}(\sigma_y)$, $Log_{10}(\sigma_x)$, $Log_{10}(MOD\sigma_y)$, Log_{10} (fractional frequency offset) and Log_{10}(mean fractional frequency offset), are made against $Log_{10}(\tau)$. These are shown in figures 19 and 20 with data taken from the 1PPS and phase measurements respectively, for averaging times between 1 s and 100,000 s. In many cases there is a direct correlation between the 1PPS signal and the phase of the reference signal. However there are several GPSDOs (A), (I), (J) and (L) where the 1PPS signals and the phase of the GPSDOs do not correlate. These GPSDOs decouple their 1PPS and frequency outputs. The aim is presumably to minimise the bias and possibly standard deviation of the 1PPS output, while minimising the frequency offset and possibly frequency instabilities of the standard frequency outputs. Typical results for averaging time of 1,000 s are shown in table 7. An averaging time of 1,000 s was chosen because this is when the variations between the performance of the GPSDOs show the greatest variation.

Although in most cases, there was a direct correlation between the 1PPS and phase of the of the GPSDOs, the values of σ_y, $MOD\sigma_y$, σ_x, fractional frequency offset, and mean fractional frequency offset from these two data sets did not always agree. For short averaging times ($\tau <$ 100 s) the noise associated with the 1 PPS data was significantly higher than the noise present on the phase comparator readings. This resulted in significantly different stability curves. This difference was due in part to the "quantization noise" introduced by the use of 1 ns resolution counter timers. For longer averaging times the data set used for both the 1PPS and phase outputs may also be significantly different, with different, start times, stop times and outages. The phase data was recorded every second while the 1PPS data was only recorded for one minute in every four. The sampling of the data sets when calculating results for shorter averaging times was also significantly different.

FIGURE 17 (a-d) PHASE VARIATIONS CALCULATED FROM AN EXTENDED RUN OF DATA

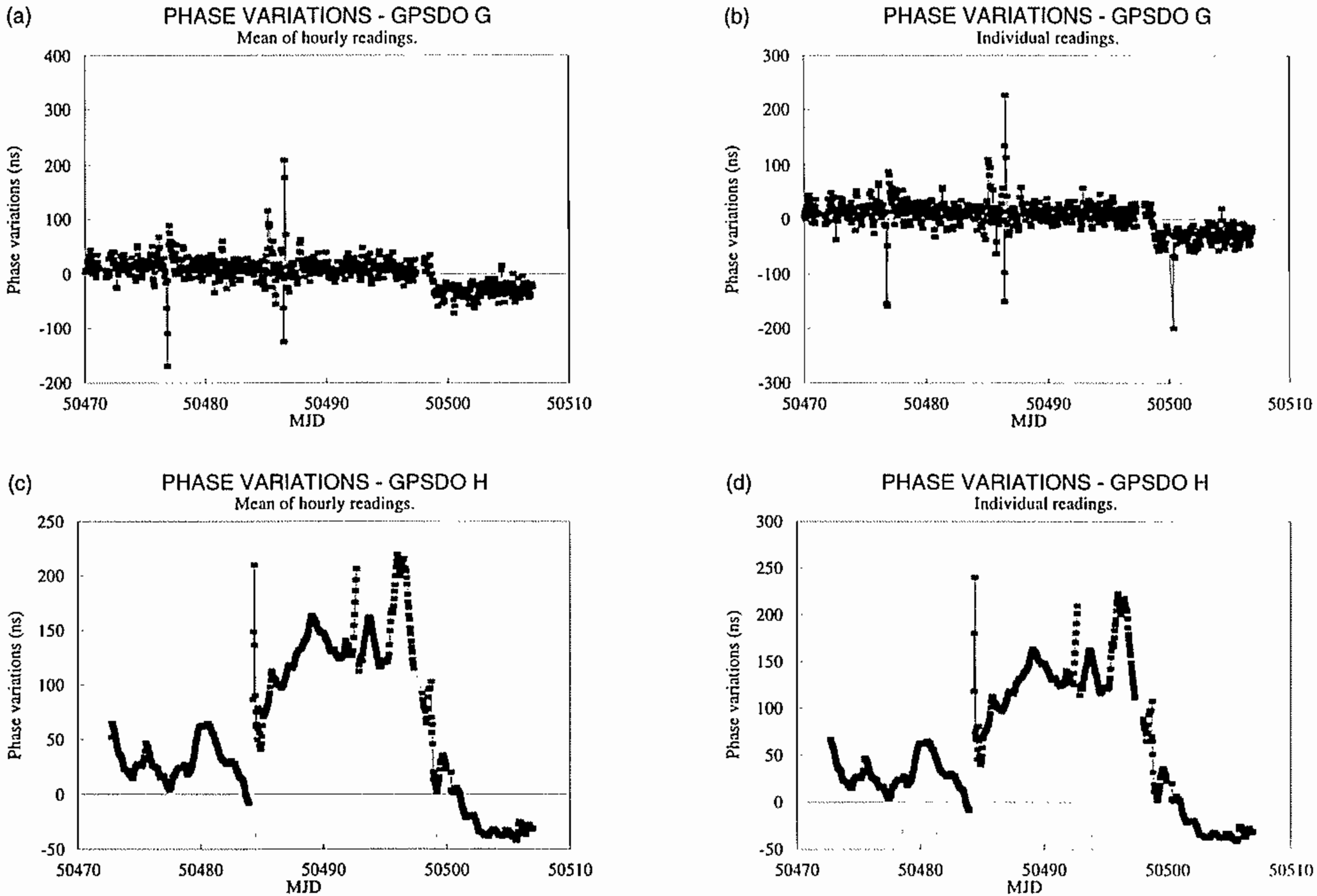
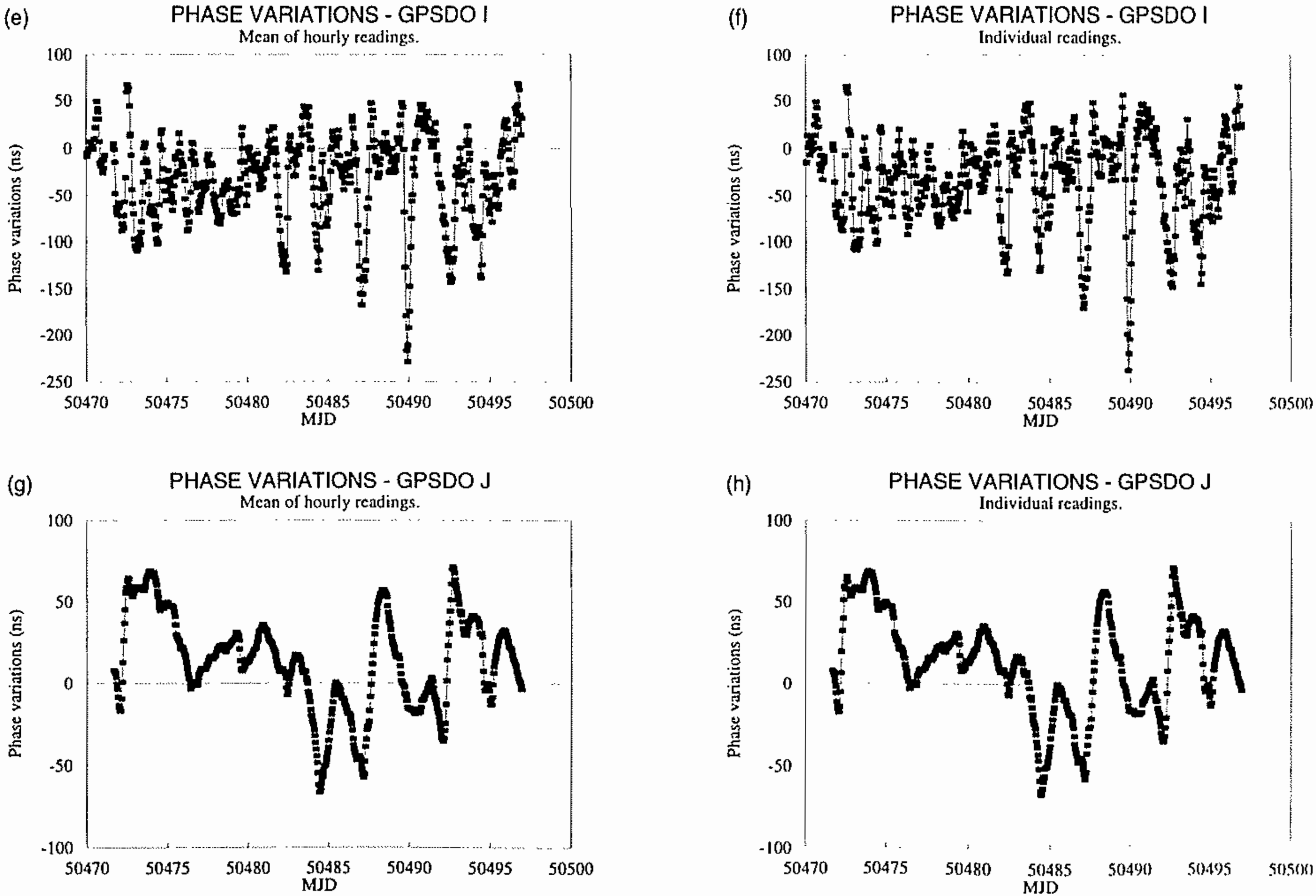


FIGURE 17 (e-h)



(e)
PHASE VARIATIONS - GPSDO I
Mean of hourly readings.
Phase variations (ns)
100
50
0
-50
-100
-150
-200
-250
50470
50475
50480
50485
50490
50495
50500
MJD
(f)
PHASE VARIATIONS - GPSDO I
Individual readings.
Phase variations (ns)
100
50
0
-50
-100
-150
-200
-250
50470
50475
50480
50485
50490
50495
50500
MJD
(g)
PHASE VARIATIONS - GPSDO J
Mean of hourly readings.
Phase variations (ns)
100
50
0
-50
-100
50470
50475
50480
50485
50490
50495
50500
MJD
(h)
PHASE VARIATIONS - GPSDO J
Individual readings.
Phase variations (ns)
100
50
0
-50
-100
50470
50475
50480
50485
50490
50495
50500
MJD

FIGURE 17 (i-l)

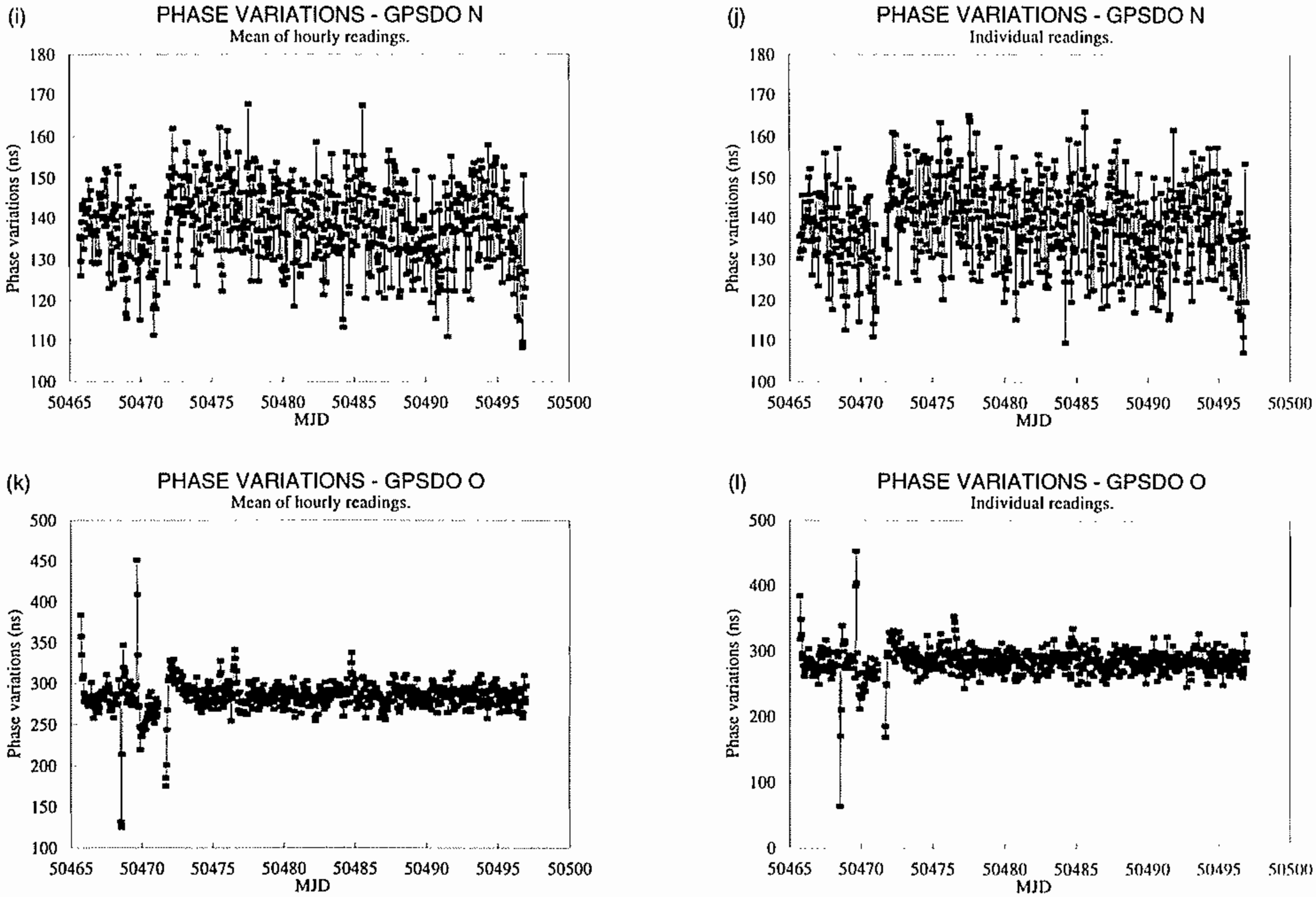
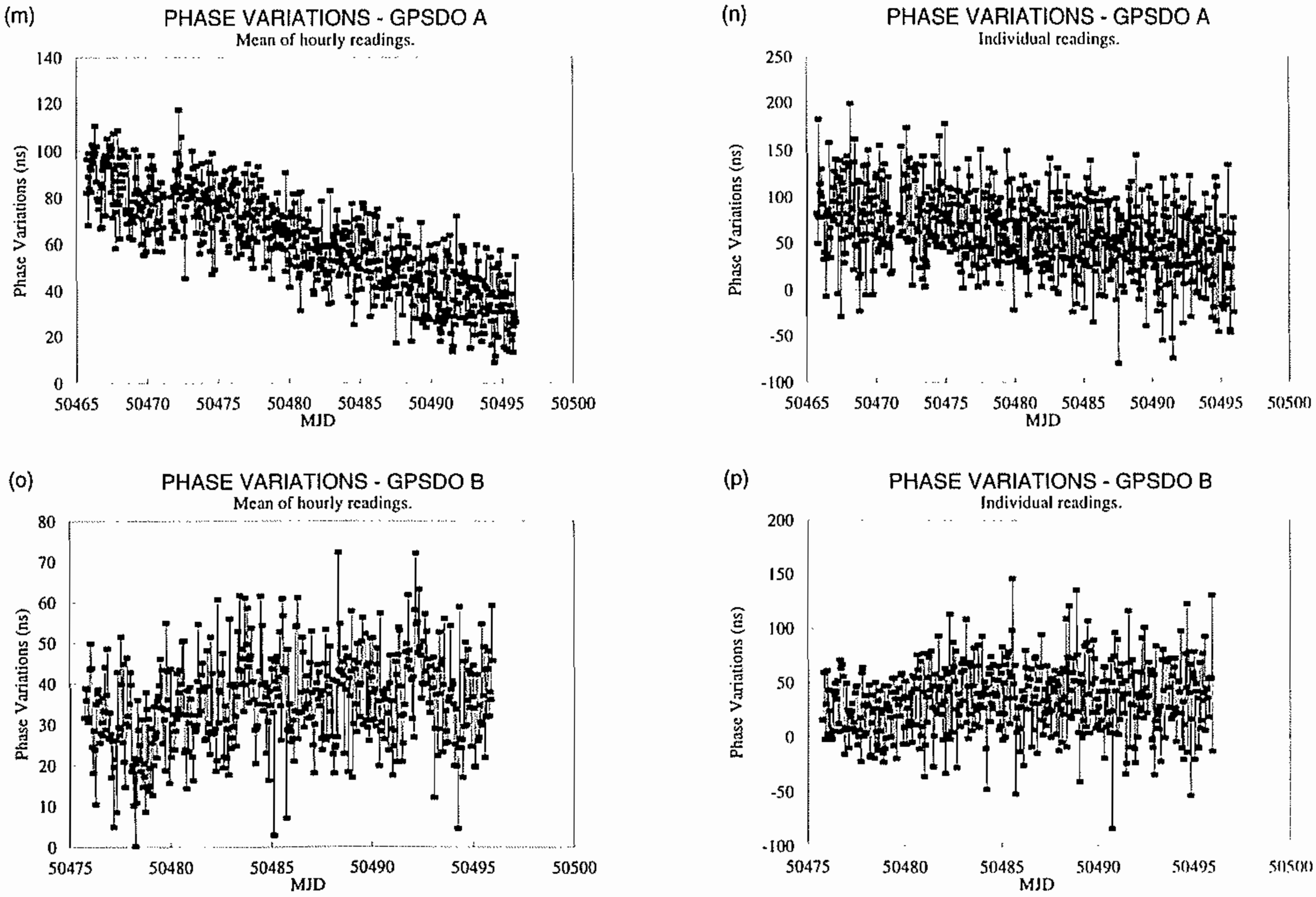

(i)
PHASE VARIATIONS - GPSDO N
Mean of hourly readings.
Phase variations (ns)
180
170
160
150
140
130
120
110
100
50465 50470 50475 50480 50485 50490 50495 50500
MJD
(j)
PHASE VARIATIONS - GPSDO N
Individual readings.
Phase variations (ns)
180
170
160
150
140
130
120
110
100
50465 50470 50475 50480 50485 50490 50495 50500
MJD
(k)
PHASE VARIATIONS - GPSDO O
Mean of hourly readings.
Phase variations (ns)
500
450
400
350
300
250
200
150
100
50465 50470 50475 50480 50485 50490 50495 50500
MJD
(l)
PHASE VARIATIONS - GPSDO O
Individual readings.
Phase variations (ns)
500
400
300
200
100
0
50465 50470 50475 50480 50485 50490 50495 50500
MJD

FIGURE 17 (m-p)



(m)
PHASE VARIATIONS - GPSDO A
Mean of hourly readings.
Phase Variations (ns)
140
120
100
80
60
40
20
0
50465
50470
50475
50480
50485
50490
50495
50500
MJD
(n)
PHASE VARIATIONS - GPSDO A
Individual readings.
Phase Variations (ns)
250
200
150
100
50
0
-50
-100
50465
50470
50475
50480
50485
50490
50495
50500
MJD
(o)
PHASE VARIATIONS - GPSDO B
Mean of hourly readings.
Phase Variations (ns)
80
70
60
50
40
30
20
10
0
50475
50480
50485
50490
50495
50500
MJD
(p)
PHASE VARIATIONS - GPSDO B
Individual readings.
Phase Variations (ns)
200
150
100
50
0
-50
-100
50475
50480
50485
50490
50495
50500
MJD

FIGURE 17 (q-t)

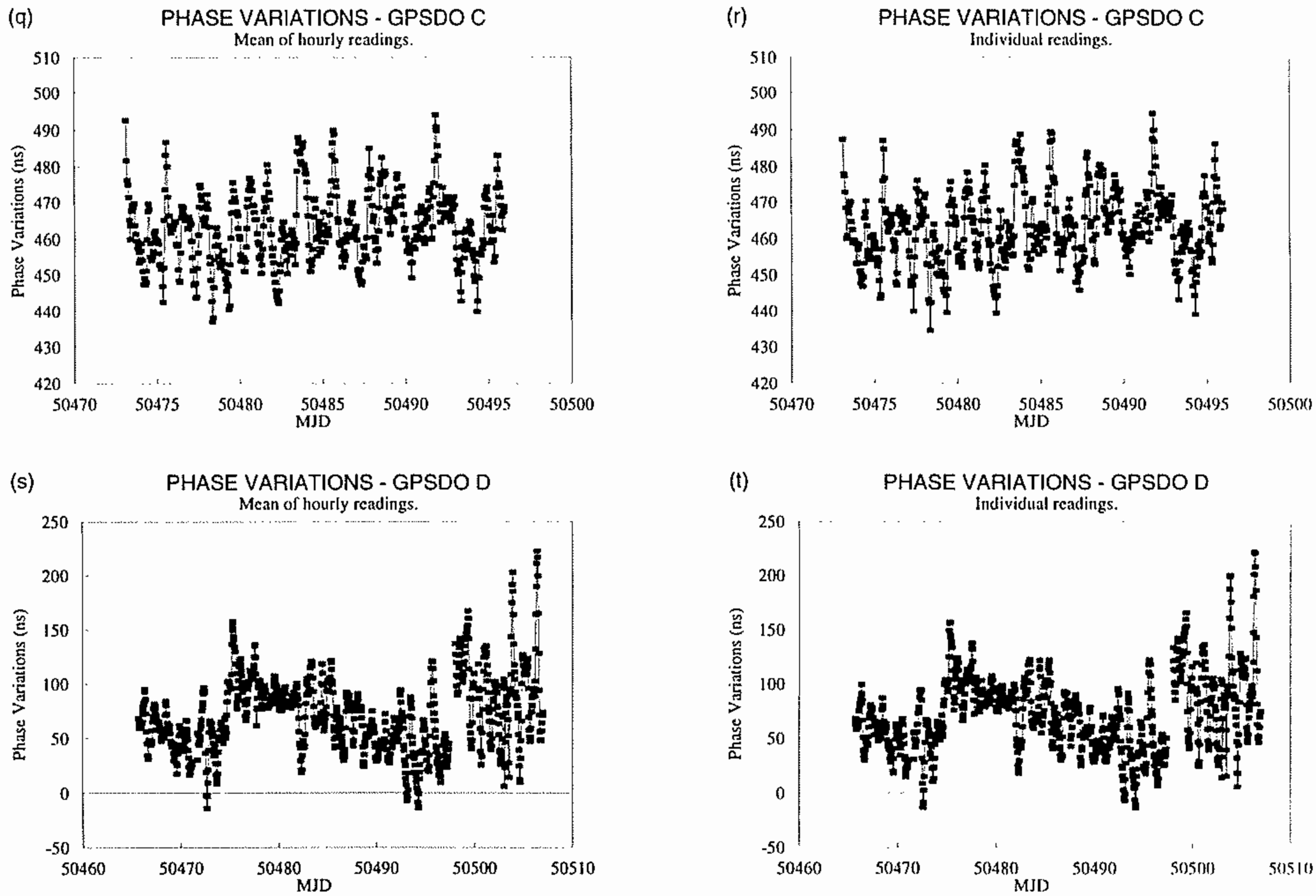
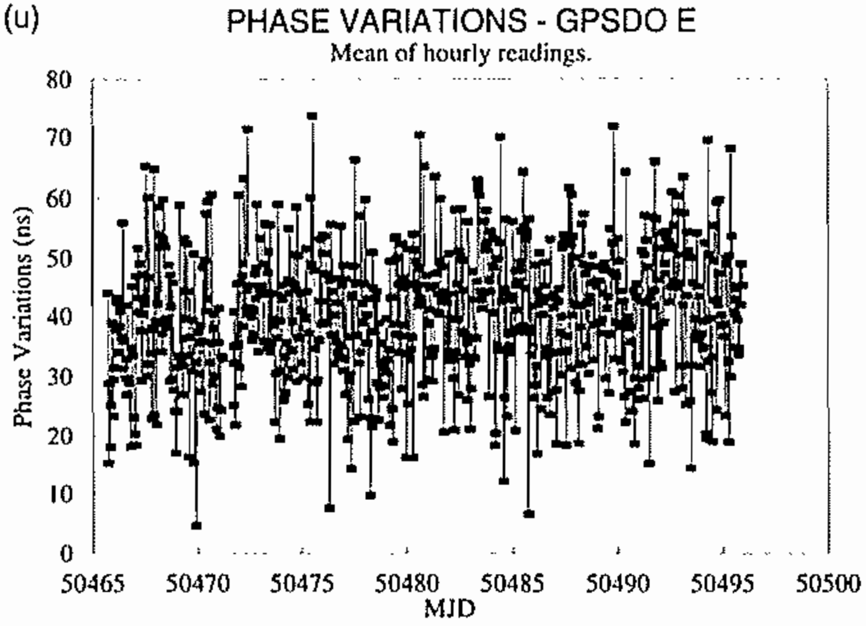

(q)
PHASE VARIATIONS - GPSDO C
Mean of hourly readings.
Phase Variations (ns)
510
500
490
480
470
460
450
440
430
420
50470
50475
50480
50485
50490
50495
50500
MJD
(r)
PHASE VARIATIONS - GPSDO C
Individual readings.
Phase Variations (ns)
510
500
490
480
470
460
450
440
430
420
50470
50475
50480
50485
50490
50495
50500
MJD
(s)
PHASE VARIATIONS - GPSDO D
Mean of hourly readings.
Phase Variations (ns)
250
200
150
100
50
0
-50
50460
50470
50480
50490
50500
50510
MJD
(t)
PHASE VARIATIONS - GPSDO D
Individual readings.
Phase Variations (ns)
250
200
150
100
50
0
-50
50460
50470
50480
50490
50500
50510
MJD

FIGURE 17 (u-v)

(u)



(v)

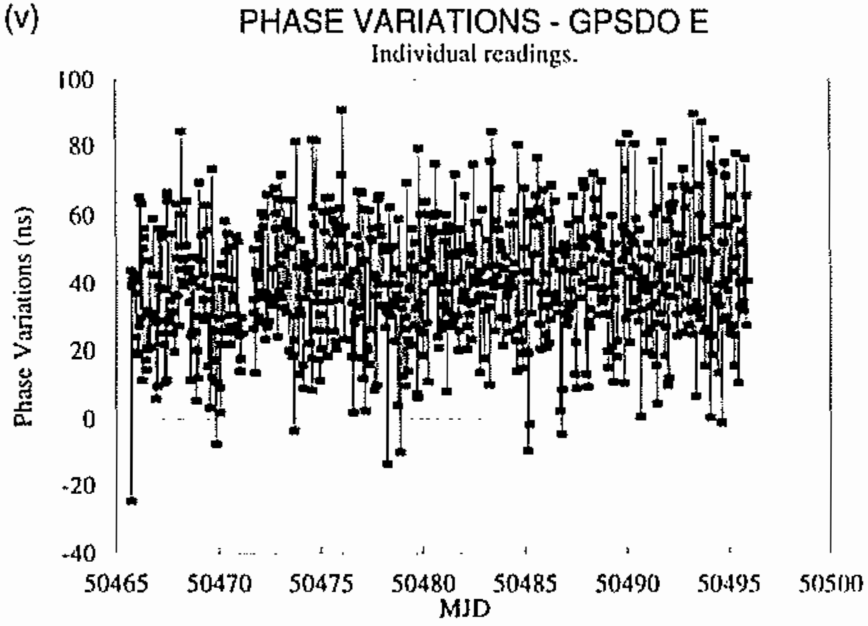


Table 6a: Standard Deviation values and statistics calculated from the phase data.

GPSDO	A	B	C	D	E
Period of extended measurements (MJD)	50466 - 50495	50479 - 50495	50479 - 50495	50466 - 50506	50466 - 50495
No of days	30	17	17	41	30
Data spread	380	230	52	230	120
Step > 100ns	No	No	No	No	No
Transients > 100 ns	No	No	No	No	No
Standard Deviation (ns) (Individual readings) (Phase)	41.4	32.2	9.9	34.3	18.2
Standard Deviation (ns) (Hourly mean) (Phase).	21.1	11.6	9.9	34.3	11.3
Standard Deviation (ns) (Typical 24hr readings) (minute means) (Phase)	54.0	27.9	8.6	7.2	17.6
Oscillator Type	Quartz	Quartz	Rb	Rb	Quartz

Table 6b: Standard Deviation values and statistics calculated from the phase data

GPSDO	F	G	H	I	J
Period of extended measurements (MJD)	50466 - 50506	50477 - 50497	50473 - 50506	50466 - 50495	50487 - 50495
No of days	41	21	34	30	9
Data spread	3,400	1,630	1,890		
Step > 100ns	No	No	No	No	No
Transients > 100 ns	Yes	Yes	Yes	No	No
Standard Deviation (ns) (Individual readings) (Phase)	-	22.9	68.2	45.1	29.0
Standard Deviation (ns) (Hourly mean) (Phase).	-	25.6	68.0	44.7	29.0
Standard Deviation (ns) (Typical 24hr readings) (minute means) (Phase)	-	23.2	2.6	13.9	7.7
Oscillator Type	Quartz	Quartz	Rb	Quartz	Rb

Table 6c: Standard Deviation values and statistics calculated from the phase data.

GPSDO	K	L	M	N	O
Period of extended measurements (MJD)	50466 - 50506	50477 - 50506	50477 - 50481	50466 - 50495	50479 - 50495
No of days	41	30	5	30	30
Data spread	950	870	1,200	65	450
Step > 100ns	No	No	No	No	No
Transients > 100 ns	No	Yes	No	No	Yes
Standard Deviation (ns) (Individual readings) (Phase)	302	-	183	9.8	14.6
Standard Deviation (ns) (Hourly mean) (Phase).	295	-	156	9.2	11.5
Standard Deviation (ns) (Typical 24hr readings) (minute means) (Phase)	107	372	164	10.5	14.3
Oscillator Type	Quartz	Quartz	Quartz	Rb	Quartz

Table 7a : Frequency and time transfer stability characteristics of GPSDOs at τ = 1,000s averaging time calculated from 1PPS data

GPSDO	Phase/1PPS Correlation	σ_y	MOD σ_y	σ_x	Mean Fractional Frequency Offset
A	No	6.0×10^{-11}	3.0×10^{-11}	2.0×10^{-8}	2.5×10^{-11}
B	Yes	4.5×10^{-11}	2.5×10^{-11}	1.5×10^{-8}	1.7×10^{-11}
C	Yes	2.0×10^{-12}	1.4×10^{-12}	9.0×10^{-10}	2.0×10^{-12}
D	Yes	3.3×10^{-12}	1.7×10^{-12}	1.0×10^{-9}	3.4×10^{-12}
E	Yes	2.3×10^{-11}	1.7×10^{-11}	1.1×10^{-8}	1.6×10^{-11}
F	-	2.6×10^{-11}	2.3×10^{-11}	1.3×10^{-8}	2.4×10^{-11}
G	Yes	4.2×10^{-12}	3.8×10^{-12}	2.6×10^{-9}	6.0×10^{-12}
H	Yes	1.0×10^{-12}	5.7×10^{-13}	3.6×10^{-10}	1.3×10^{-12}
I	No	4.5×10^{-11}	3.0×10^{-11}	1.9×10^{-8}	2.5×10^{-11}
J	No	4.7×10^{-12}	3.9×10^{-12}	2.7×10^{-9}	6.3×10^{-12}
K	Yes	7.5×10^{-11}	6.3×10^{-11}	4.0×10^{-8}	7.0×10^{-11}
L	No	5.5×10^{-11}	3.6×10^{-11}	2.3×10^{-8}	5.0×10^{-11}
M	Yes	2.0×10^{-10}	1.6×10^{-10}	9.5×10^{-8}	1.4×10^{-10}
N	Yes	3.2×10^{-12}	2.5×10^{-12}	1.5×10^{-9}	3.0×10^{-12}
O	Yes	9.7×10^{-12}	8.1×10^{-12}	5.5×10^{-9}	9.1×10^{-12}

Table 7b : Frequency and time transfer stability characteristics of GPSDOs at τ = 1,000s averaging time calculated from phase data

GPSDO	Phase/1PPS Correlation	σ_y	MOD σ_y	σ_x	Mean Fractional Frequency Offset
A	No	$6.5x10^{-11}$	$3.0x10^{-11}$	$1.9x10^{-8}$	$3.0x10^{-11}$
B	Yes	$5.0x10^{-11}$	$3.0x10^{-11}$	$1.7x10^{-8}$	$2.5x10^{-11}$
C	Yes	$1.8x10^{-12}$	$1.4x10^{-12}$	$8.0x10^{-10}$	$2.0x10^{-12}$
D	Yes	$2.3x10^{-12}$	$1.8x10^{-12}$	$1.1x10^{-9}$	$2.8x10^{-12}$
E	Yes	$2.4x10^{-11}$	$1.8x10^{-11}$	$1.1x10^{-8}$	$1.7x10^{-11}$
F	-	-	-	-	-
G	Yes	$6.2x10^{-12}$	$5.3x10^{-12}$	$3.4x10^{-9}$	$1.0x10^{-11}$
H	Yes	$5.0x10^{-13}$	$3.5x10^{-13}$	$2.1x10^{-10}$	$6.3x10^{-13}$
I	No	$6.2x10^{-12}$	$4.8x10^{-12}$	$2.8x10^{-9}$	$6.6x10^{-12}$
J	No	$2.8x10^{-13}$	$2.4x10^{-13}$	$1.5x10^{-10}$	$9.2x10^{-13}$
K	Yes	$7.5x10^{-11}$	$6.4x10^{-11}$	$4.0x10^{-8}$	$7.5x10^{-11}$
L	No	-	-	-	-
M	Yes	-	-	-	-
N	Yes	$2.2x10^{-12}$	$2.0x10^{-12}$	$1.3x10^{-9}$	$3.6x10^{-12}$
O	Yes	$1.0x10^{-11}$	$8.8x10^{-12}$	$5.5x10^{-9}$	$1.0x10^{-11}$

FIGURE 18 (a-d) LOCAL CLOCK - GPSDO(1PPS), 24 HOURS OF DATA

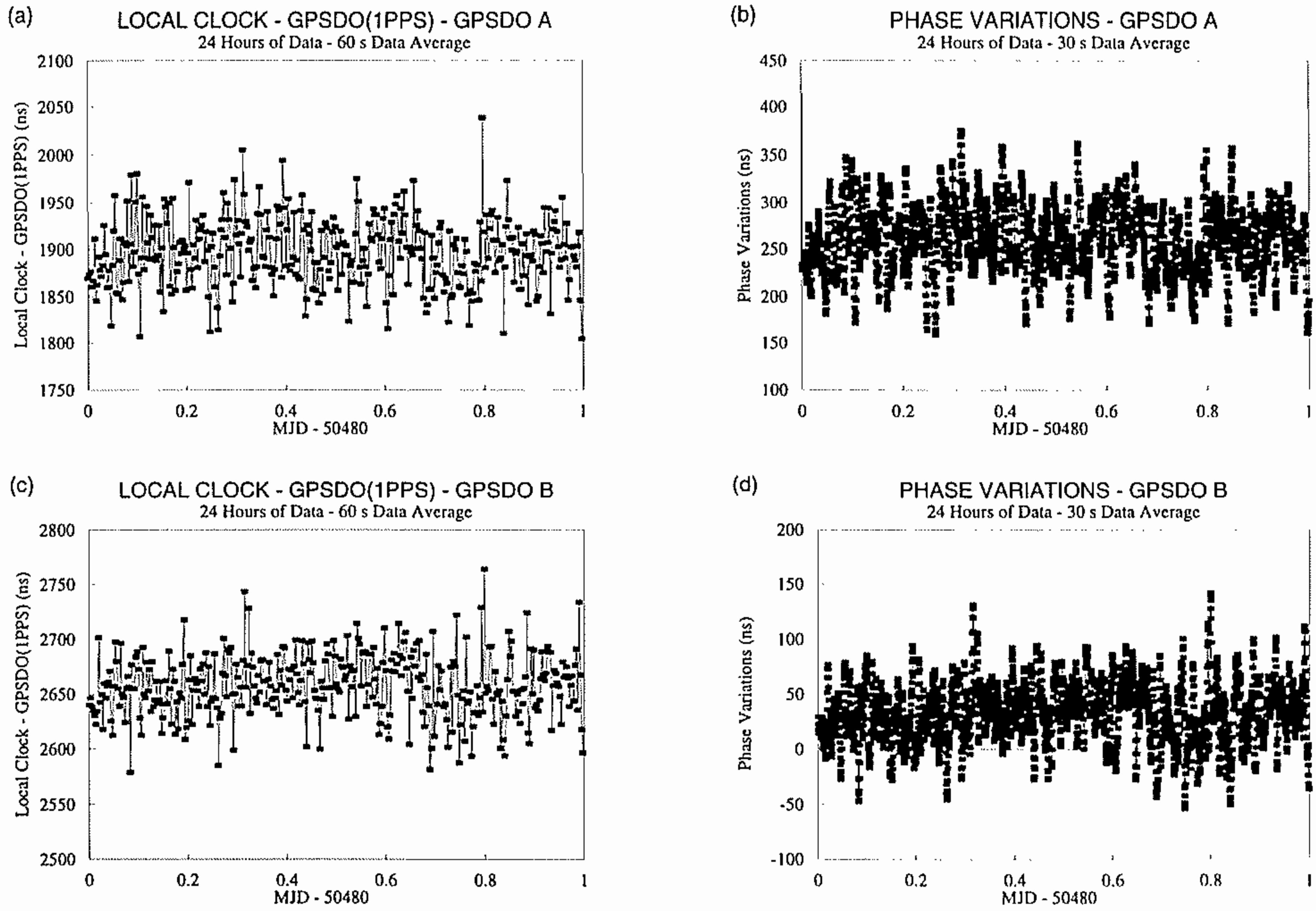


FIGURE 18 (e-h)

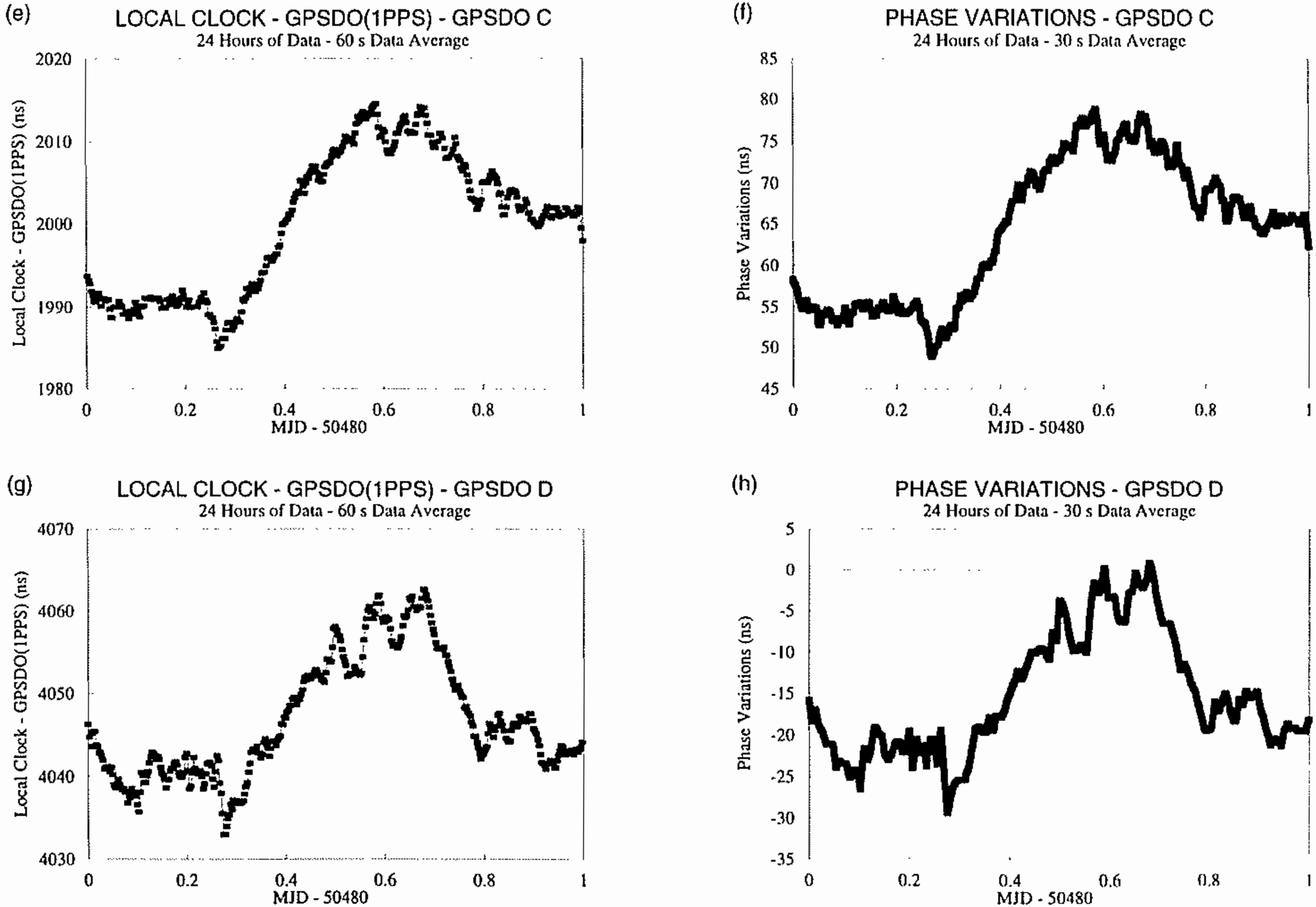
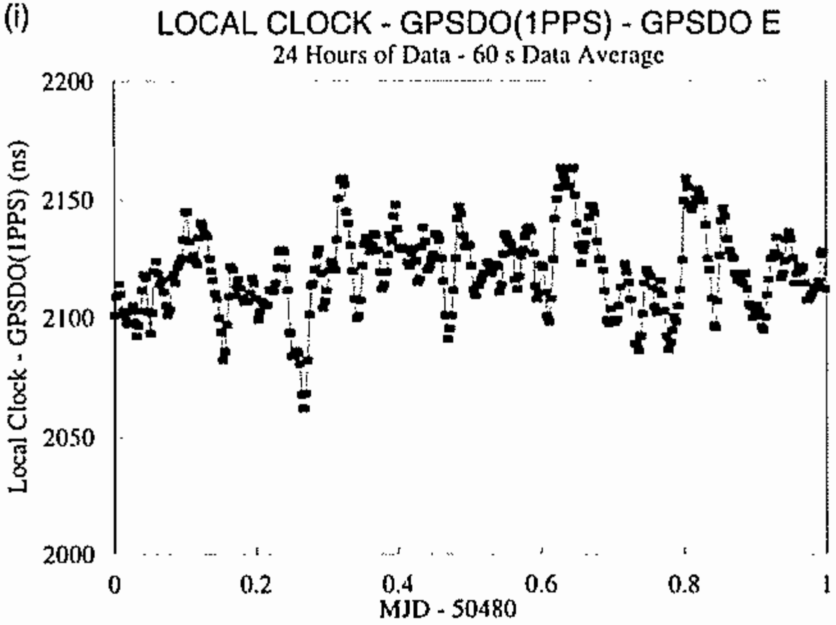
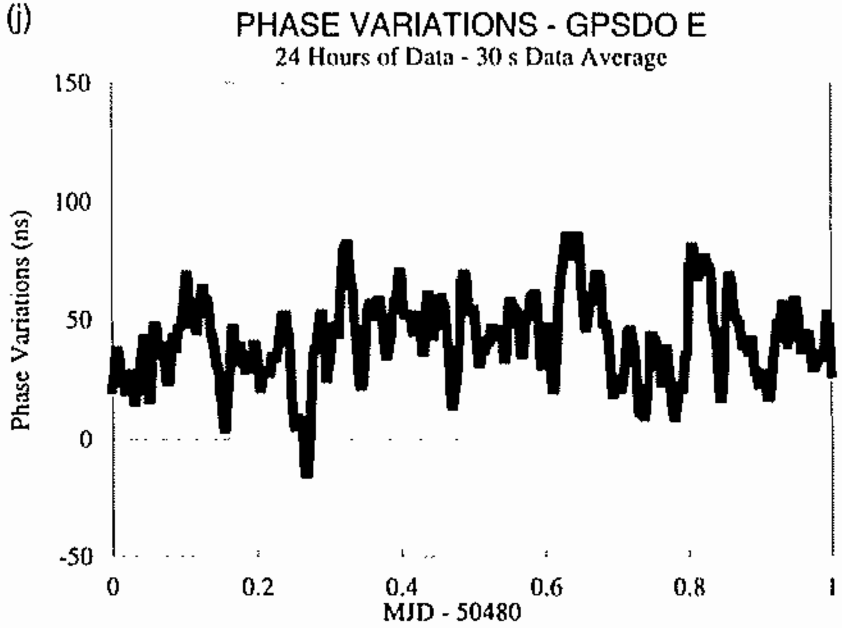

(e)
LOCAL CLOCK - GPSDO(1PPS) - GPSDO C
24 Hours of Data - 60 s Data Average
Local Clock - GPSDO(1PPS) (ns)
2020
2010
2000
1990
1980
0
0.2
0.4
0.6
0.8
1
MJD - 50480
(f)
PHASE VARIATIONS - GPSDO C
24 Hours of Data - 30 s Data Average
Phase Variations (ns)
85
80
75
70
65
60
55
50
45
0
0.2
0.4
0.6
0.8
1
MJD - 50480
(g)
LOCAL CLOCK - GPSDO(1PPS) - GPSDO D
24 Hours of Data - 60 s Data Average
Local Clock - GPSDO(1PPS) (ns)
4070
4060
4050
4040
4030
0
0.2
0.4
0.6
0.8
1
MJD - 50480
(h)
PHASE VARIATIONS - GPSDO D
24 Hours of Data - 30 s Data Average
Phase Variations (ns)
5
0
-5
-10
-15
-20
-25
-30
-35
0
0.2
0.4
0.6
0.8
1
MJD - 50480

FIGURE 18 (i-k)

(i)



(j)



(k)

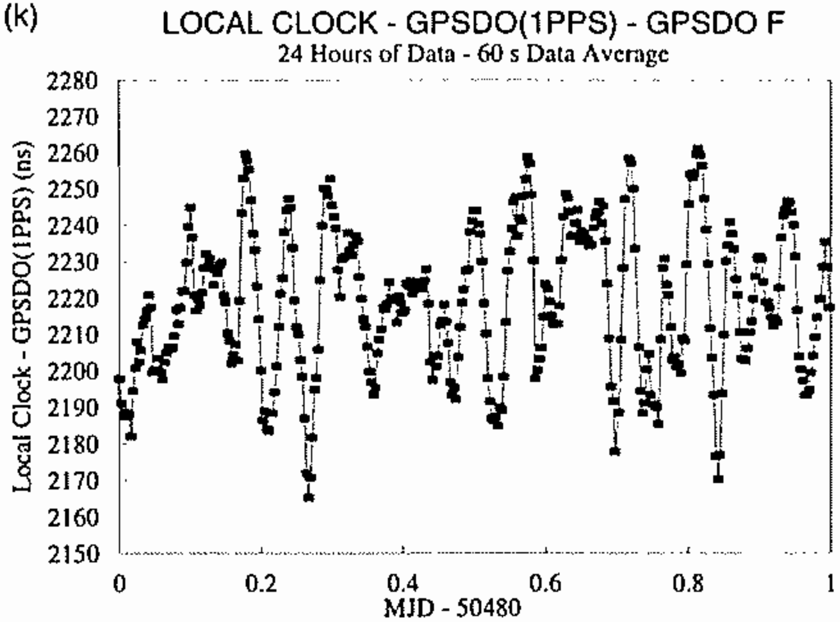
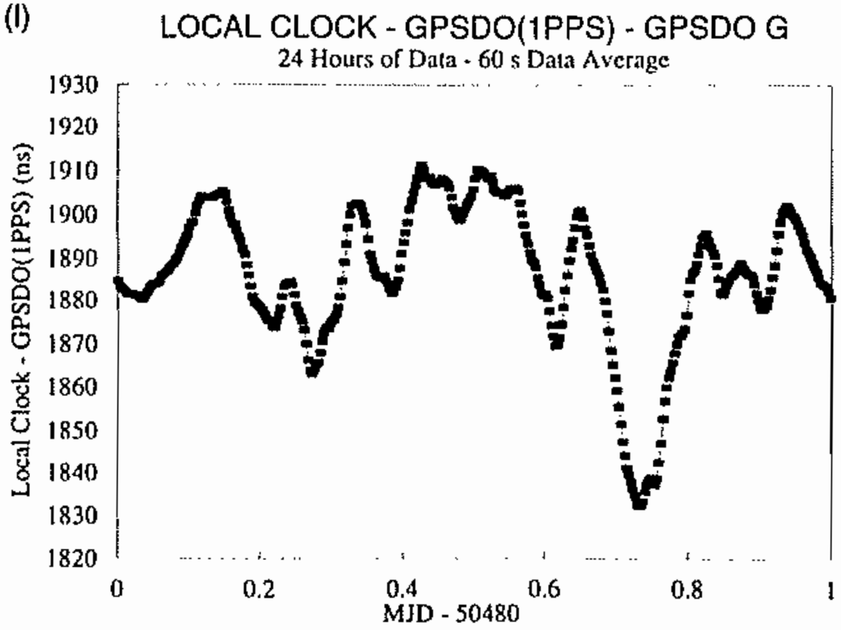
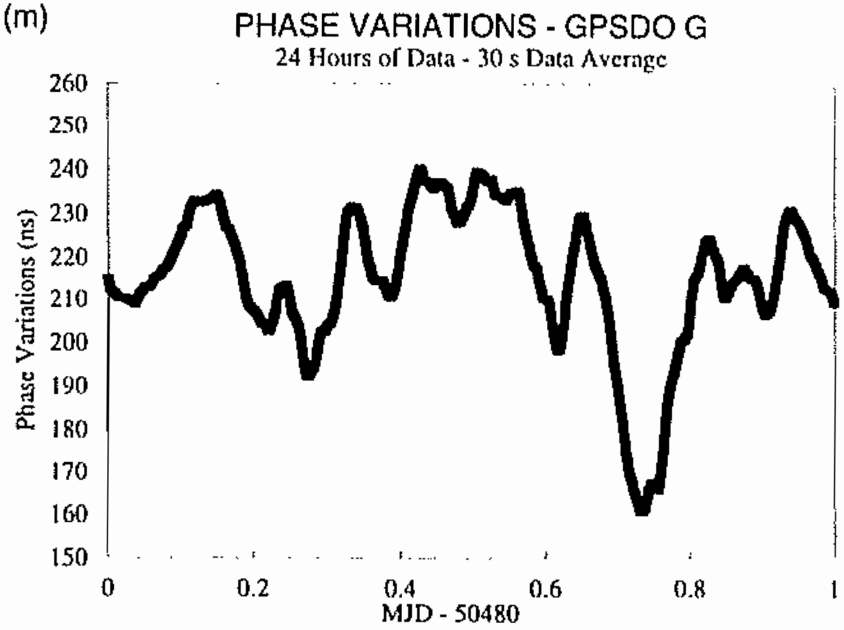


FIGURE 18 (l-o)

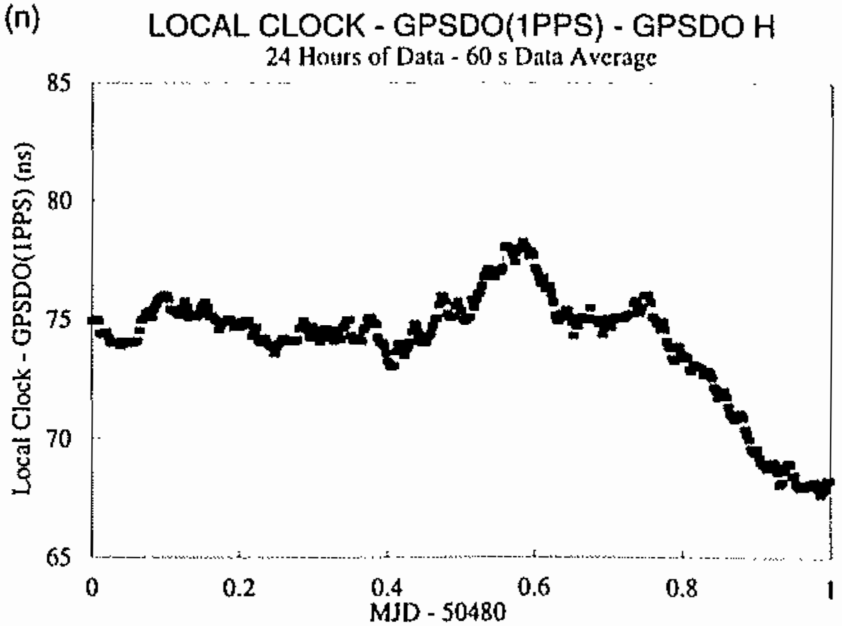
(l)



(m)



(n)



(o)

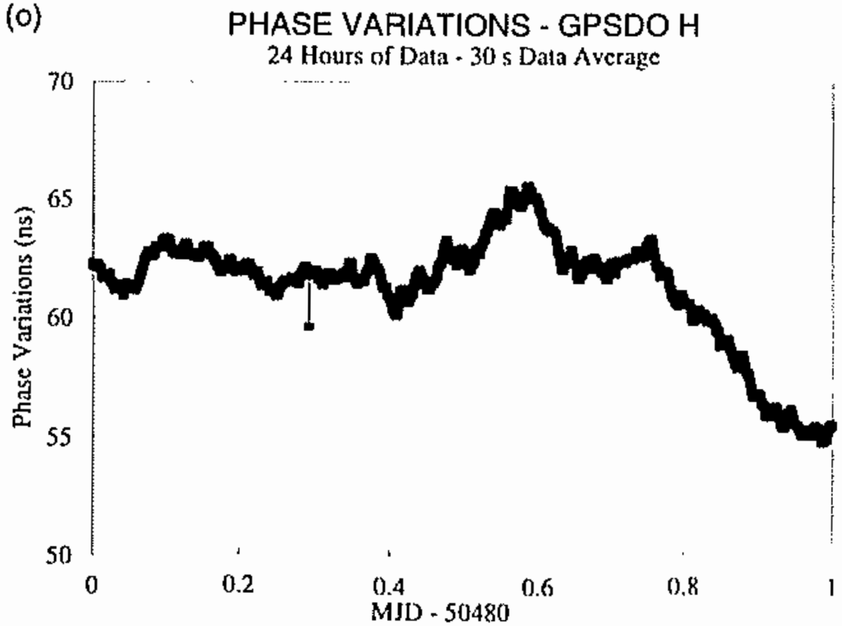
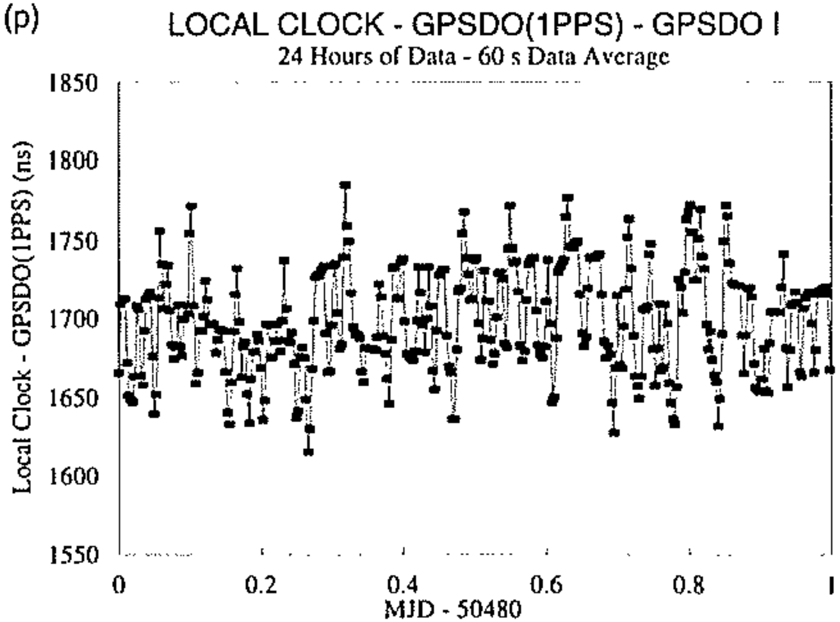
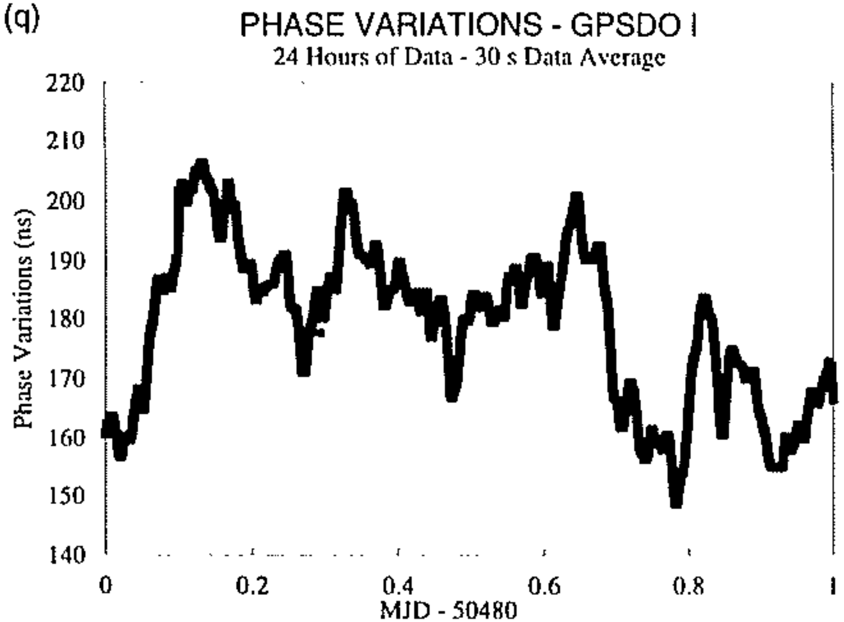


FIGURE 18 (p-r)

(p)



(q)



(r)

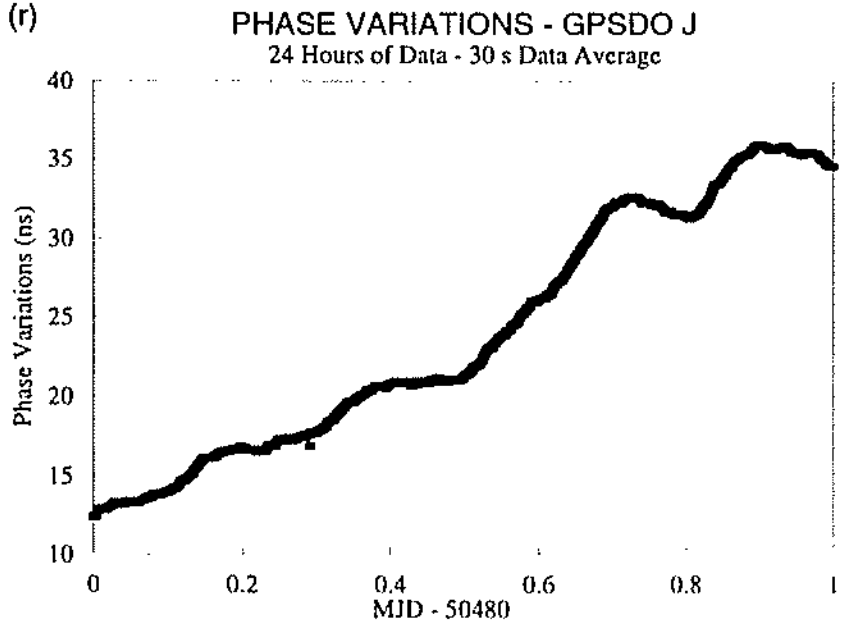
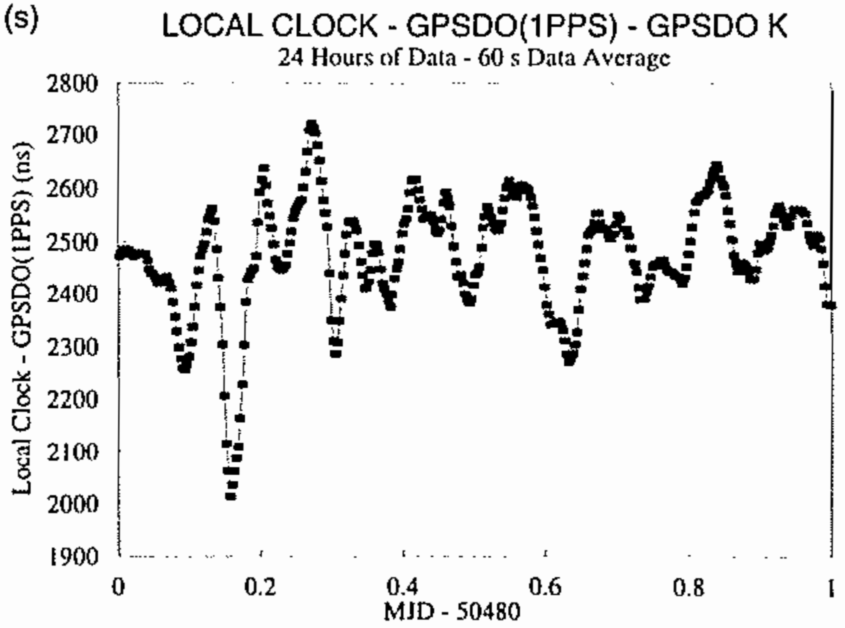
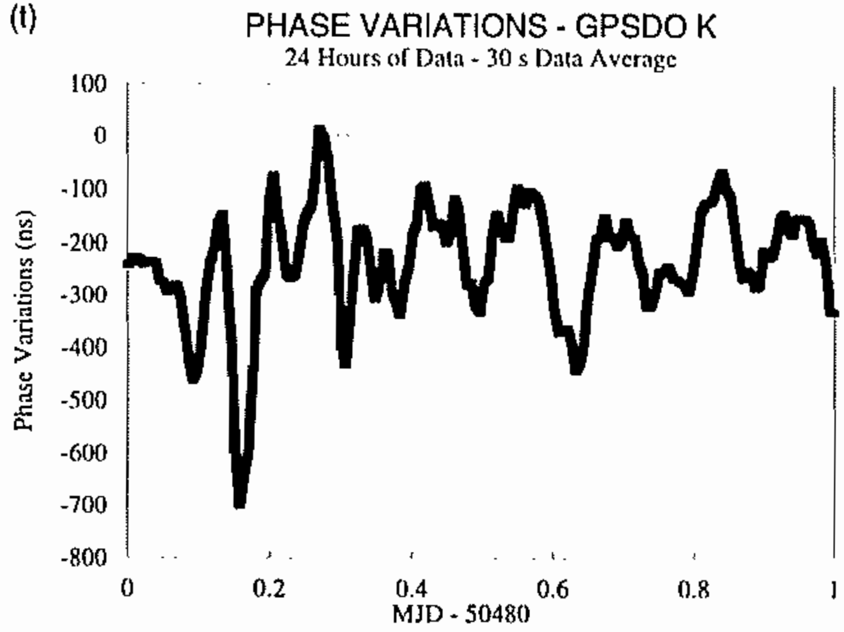


FIGURE 18 (s-v)

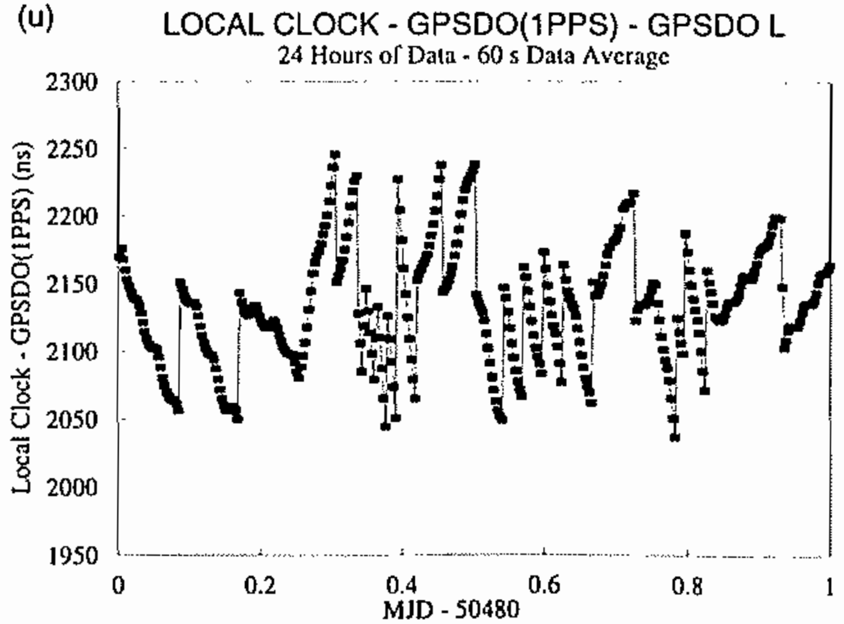
(s)



(t)



(u)



(v)

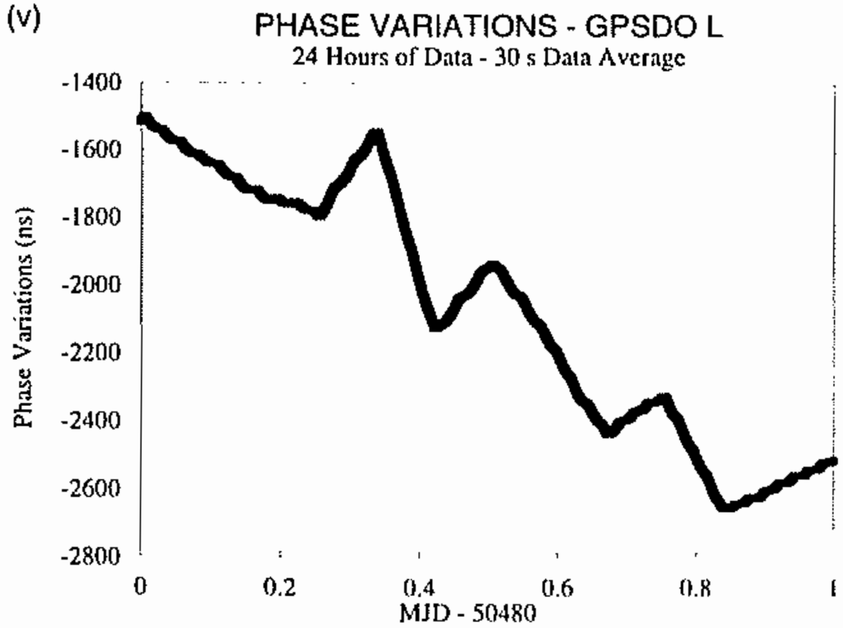


FIGURE 18 (w-z)

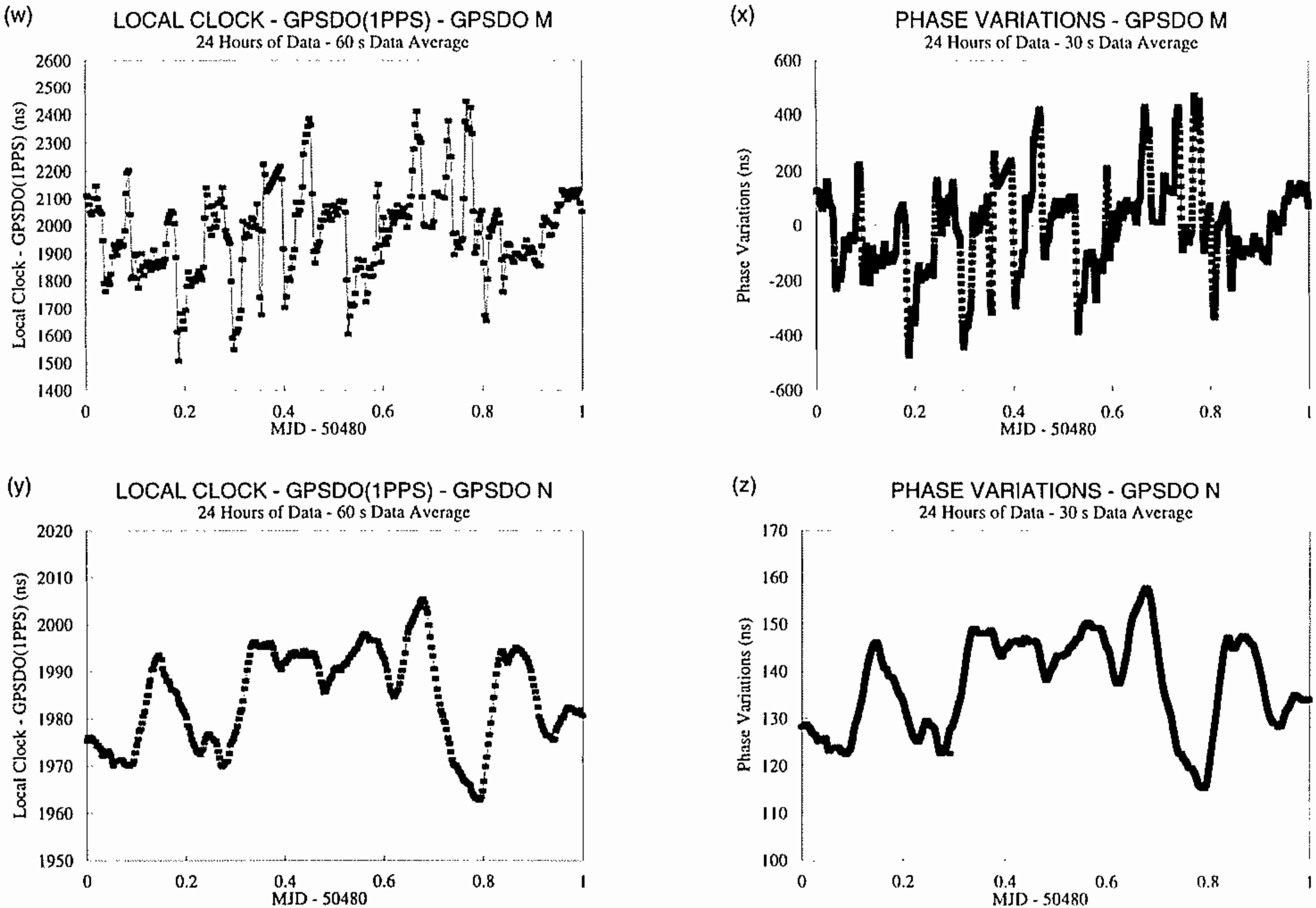
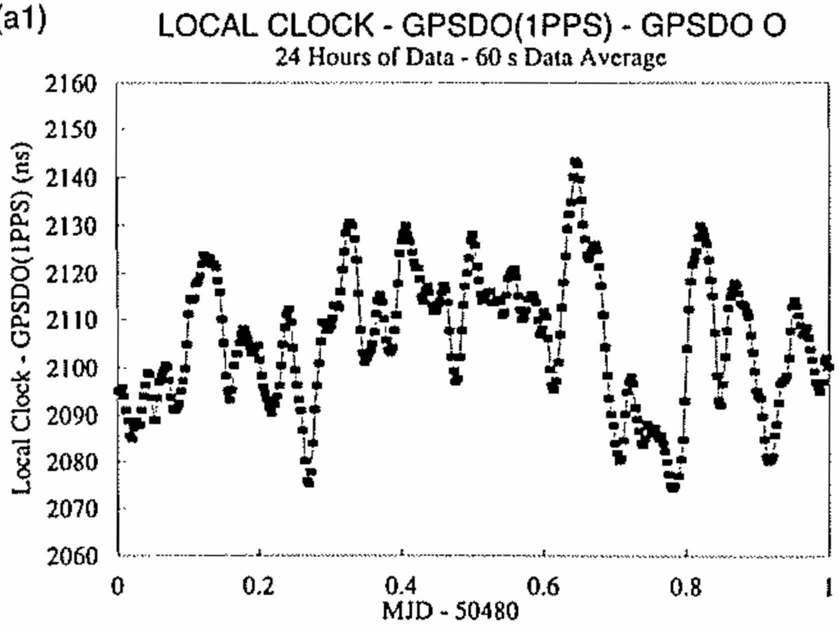

(w)
LOCAL CLOCK - GPSDO(1PPS) - GPSDO M
24 Hours of Data - 60 s Data Average
Local Clock - GPSDO(1PPS) (ns)
MJD - 50480
(x)
PHASE VARIATIONS - GPSDO M
24 Hours of Data - 30 s Data Average
Phase Variations (ns)
MJD - 50480
(y)
LOCAL CLOCK - GPSDO(1PPS) - GPSDO N
24 Hours of Data - 60 s Data Average
Local Clock - GPSDO(1PPS) (ns)
MJD - 50480
(z)
PHASE VARIATIONS - GPSDO N
24 Hours of Data - 30 s Data Average
Phase Variations (ns)
MJD - 50480

FIGURE 18 (a1-b1)

(a1)



(b1)

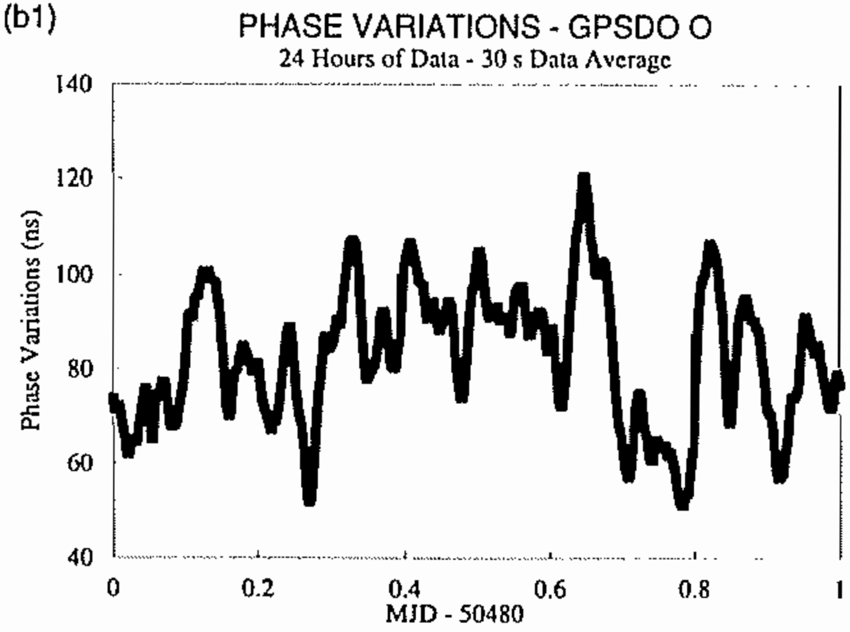


FIGURE 19 (a-d) TIME AND FREQUENCY STATISTICS CALCULATED FROM AN EXTENDED RUN OF 1PPS DATA

(a) Graph of Log 10 Sigma Y against Log 10 Tau
Extended run of 1PPS measurements

(b) Graph of Log 10 Sigma Y against Log 10 Tau
Extended run of 1PPS measurements

(c) Graph of Log 10 Sigma Y against Log 10 Tau
Extended run of 1PPS measurements

(d) Graph of Log 10 Sigma Y against Log 10 Tau
Extended run of 1PPS measurements

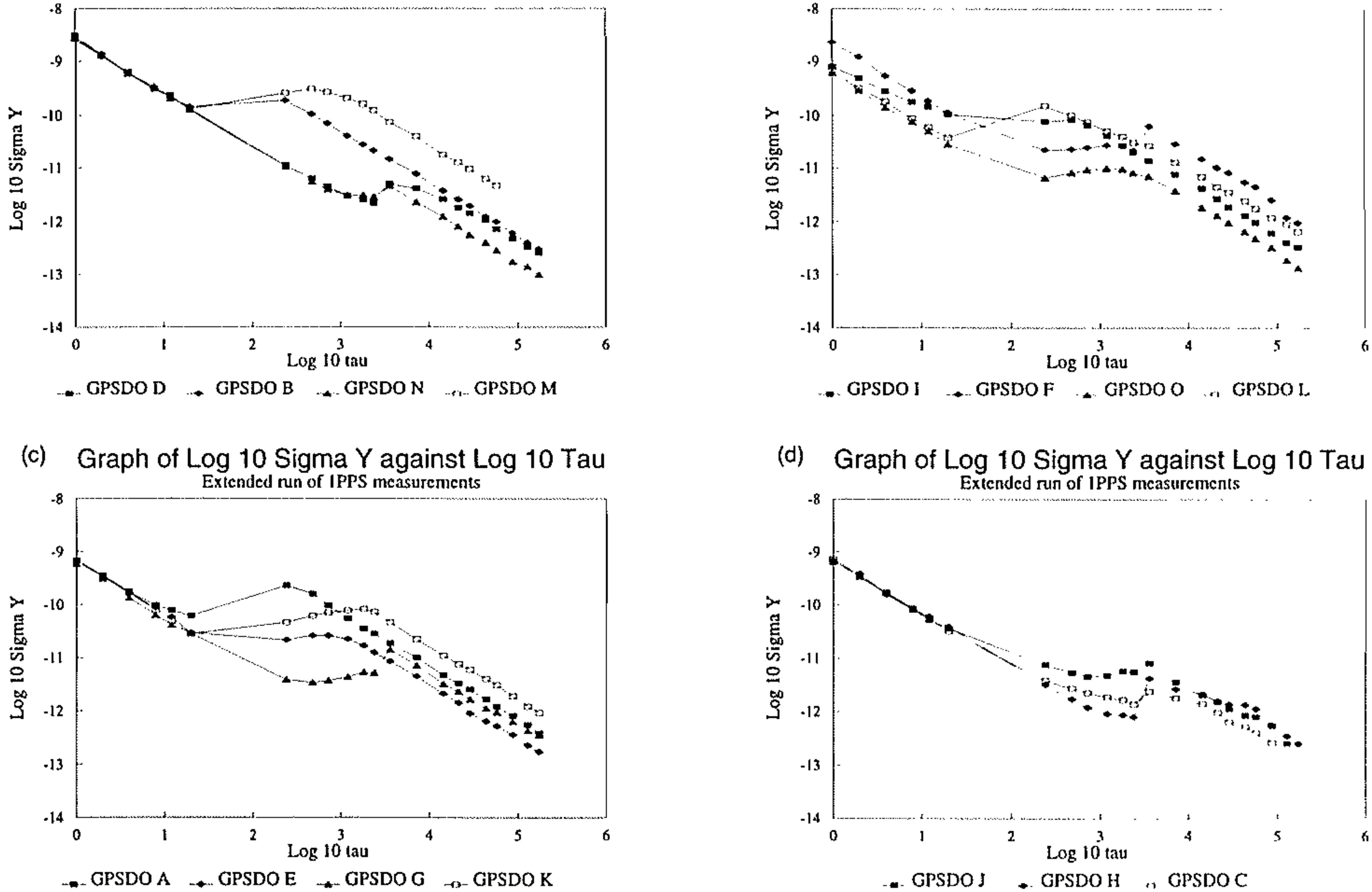


FIGURE 19 (e-h)

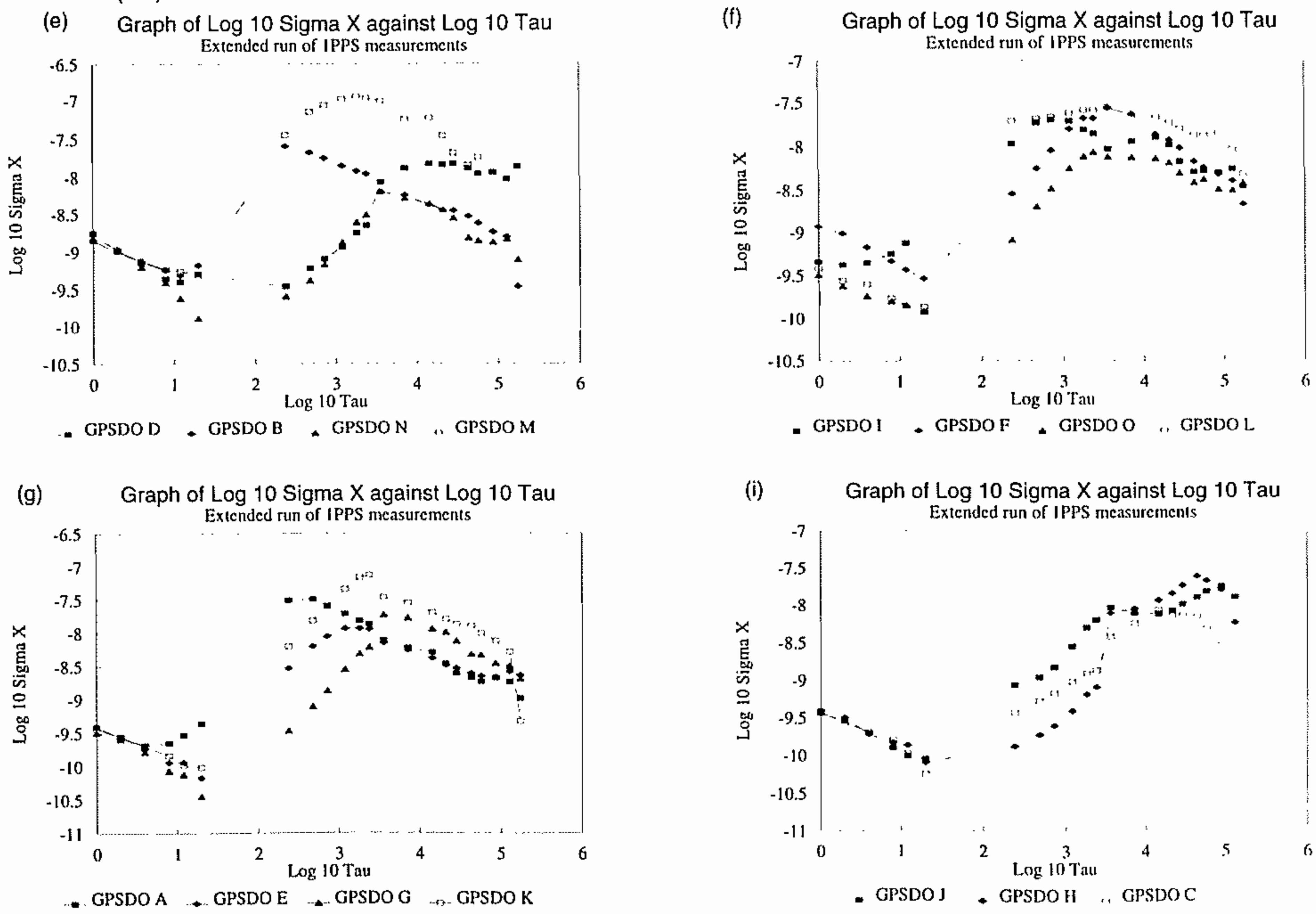
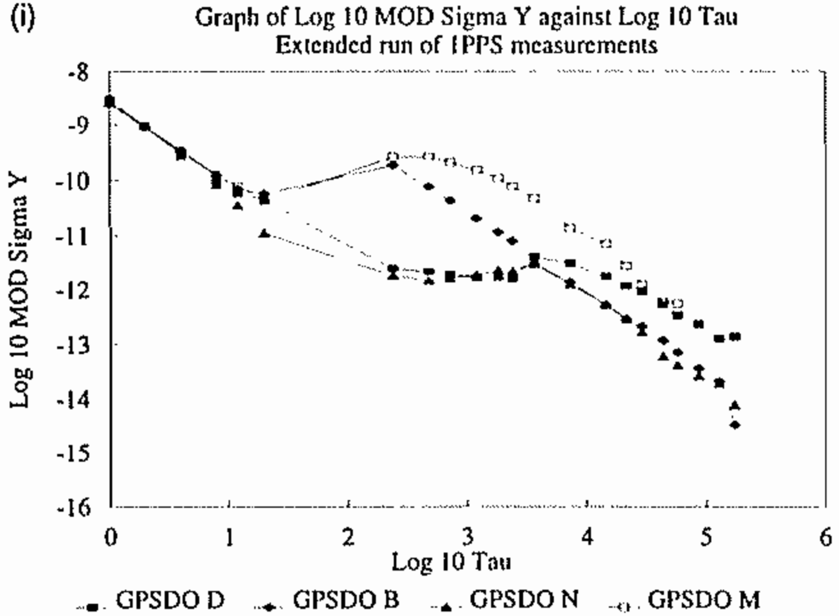
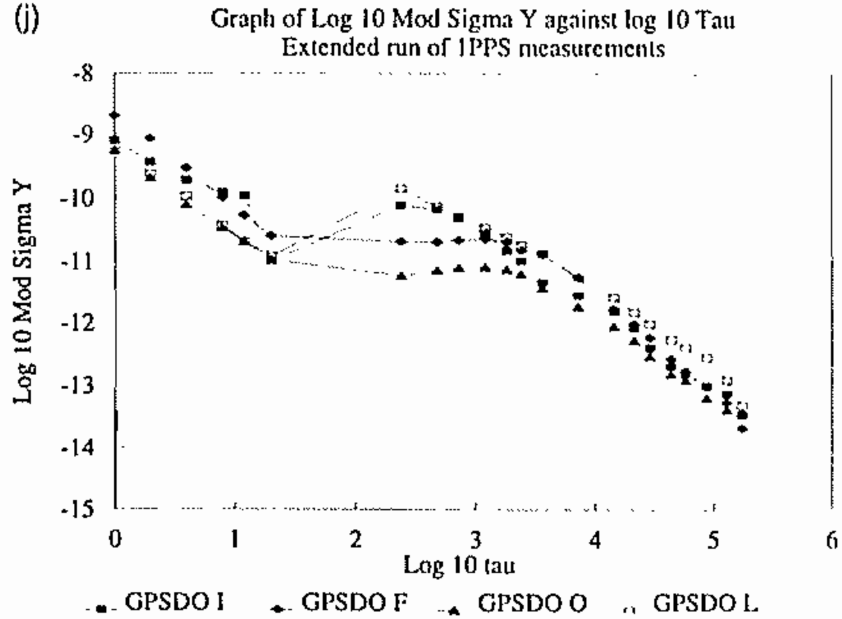

(e)
Graph of Log 10 Sigma X against Log 10 Tau
Extended run of 1PPS measurements
Log 10 Sigma X
Log 10 Tau
GPSDO D
GPSDO B
GPSDO N
GPSDO M
(f)
Graph of Log 10 Sigma X against Log 10 Tau
Extended run of 1PPS measurements
Log 10 Sigma X
Log 10 Tau
GPSDO I
GPSDO F
GPSDO O
GPSDO L
(g)
Graph of Log 10 Sigma X against Log 10 Tau
Extended run of 1PPS measurements
Log 10 Sigma X
Log 10 Tau
GPSDO A
GPSDO E
GPSDO G
GPSDO K
(i)
Graph of Log 10 Sigma X against Log 10 Tau
Extended run of 1PPS measurements
Log 10 Sigma X
Log 10 Tau
GPSDO J
GPSDO H
GPSDO C

FIGURE 19 (i-l)

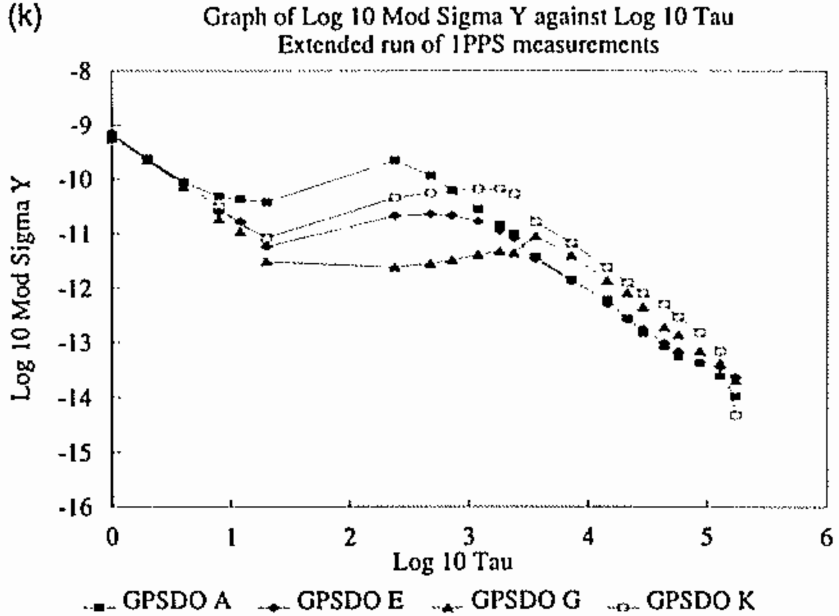
(i)



(j)



(k)



(l)

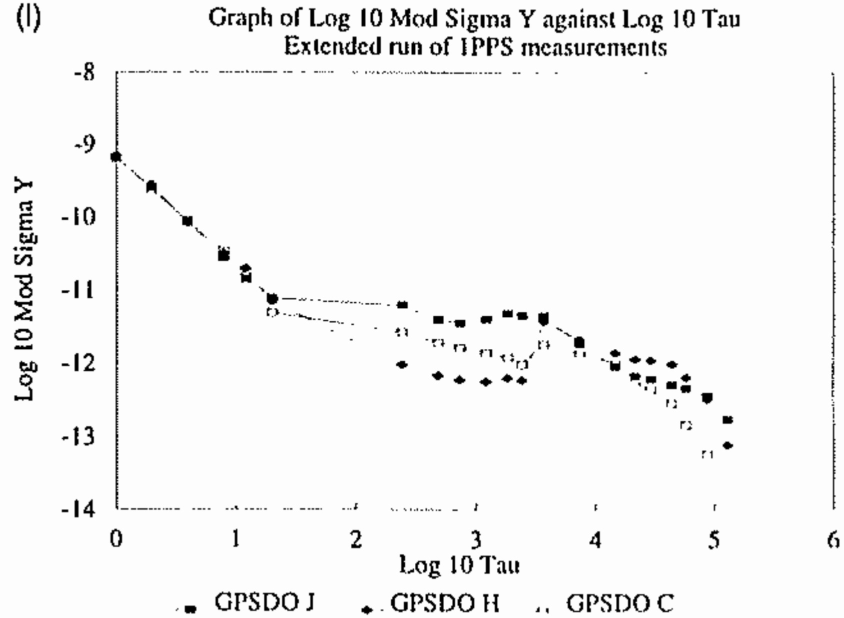
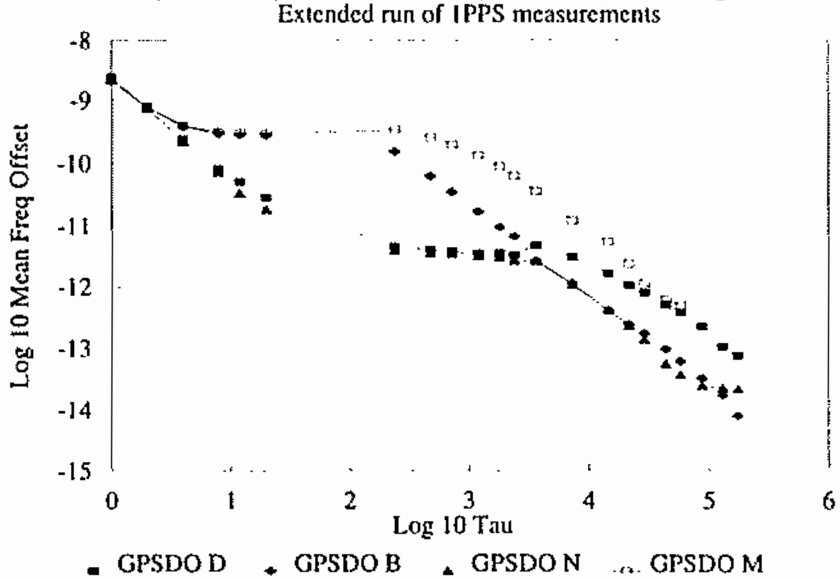
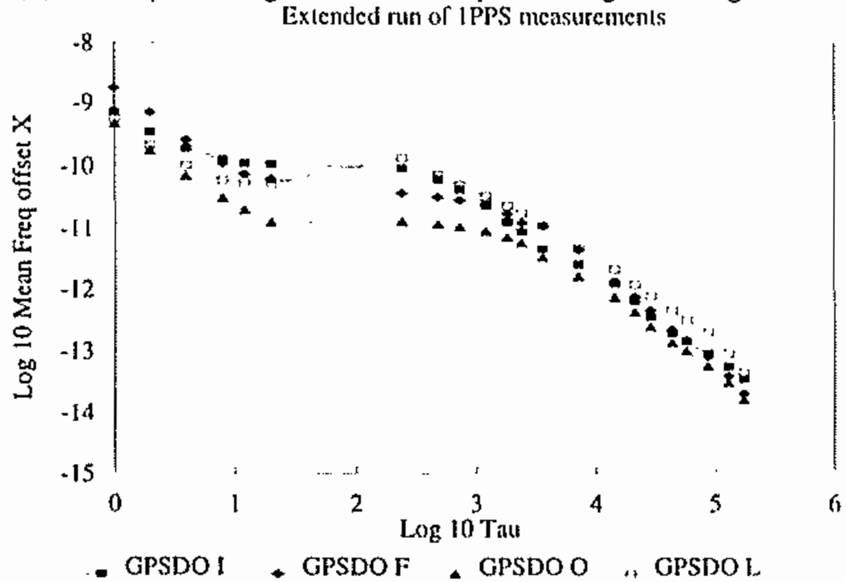


FIGURE 19 (m-p)

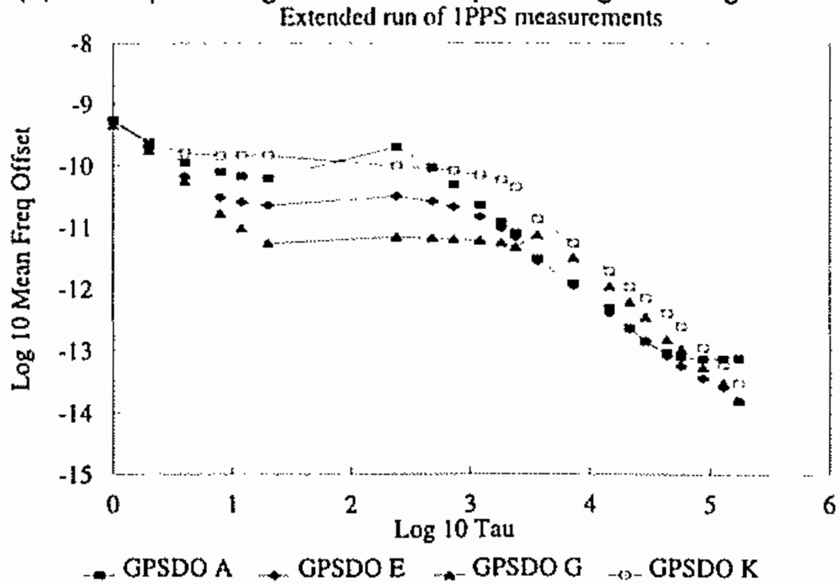
(m) Graph of Log 10 Mean Freq offset against log 10 Tau



(n) Graph of Log 10 Mean Freq Offset against Log 10 Tau



(o) Graph of Log 10 Mean Freq Offset against Log 10 Tau



(p) Graph of Log 10 Mean Freq Offset against Log 10 Tau

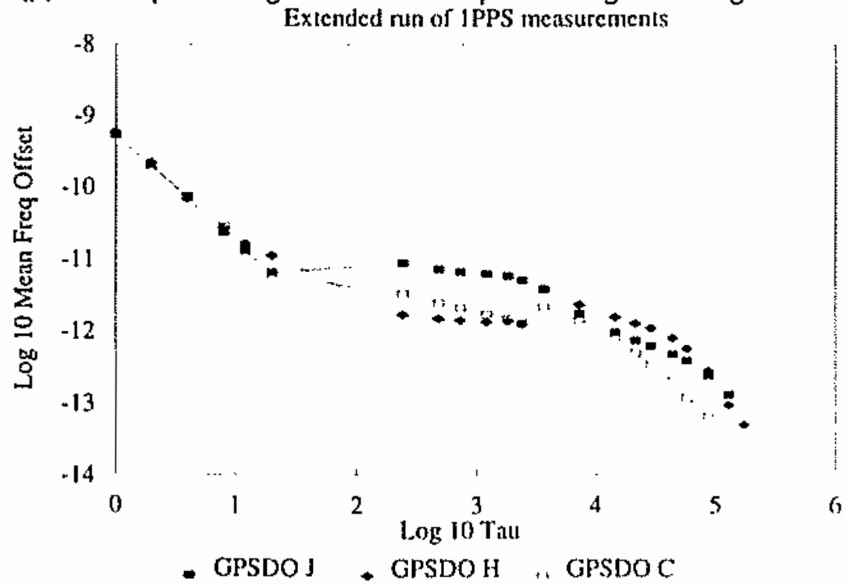


FIGURE 20 (a-d) TIME AND FREQUENCY STATISTICS CALCULATED FROM AN EXTENDED RUN OF PHASE DATA

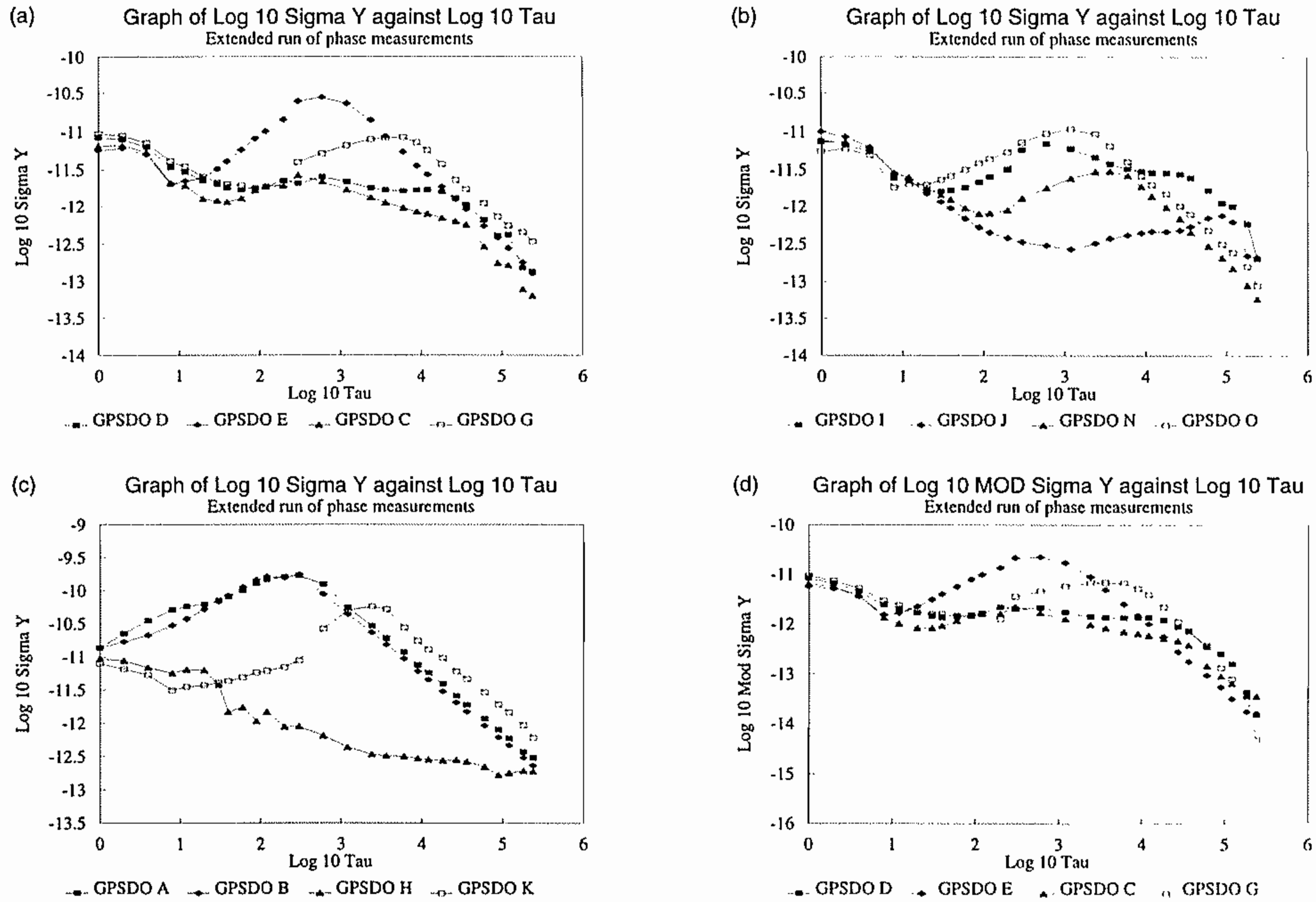
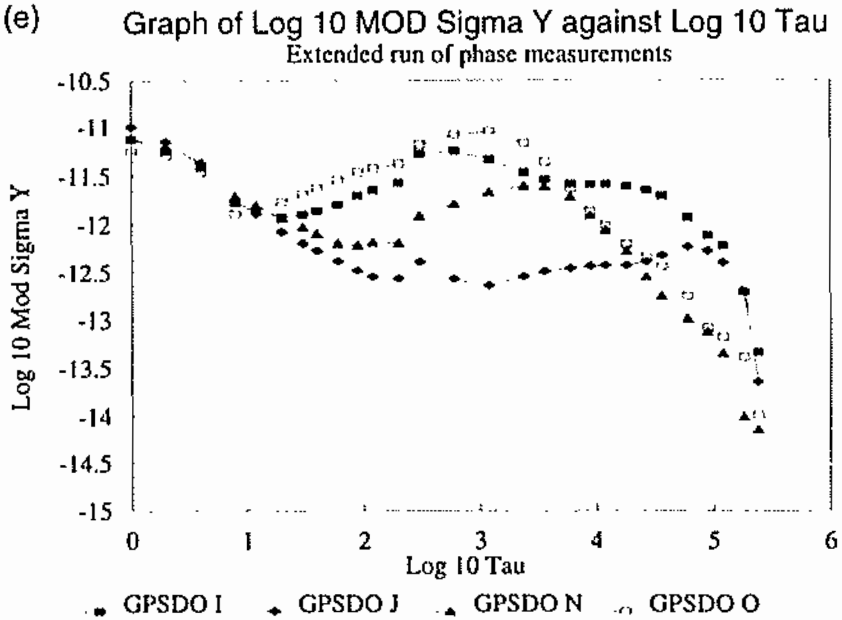
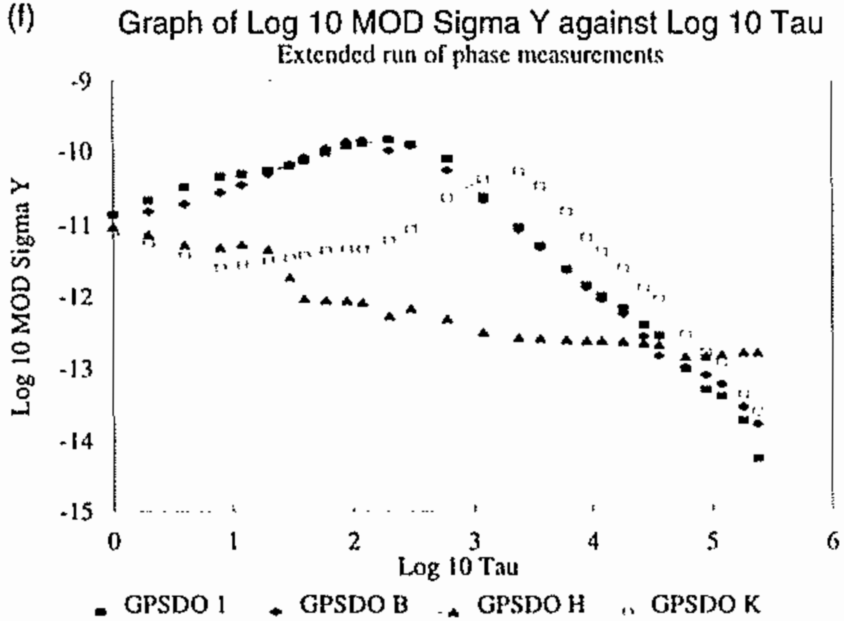


FIGURE 20 (e-h)

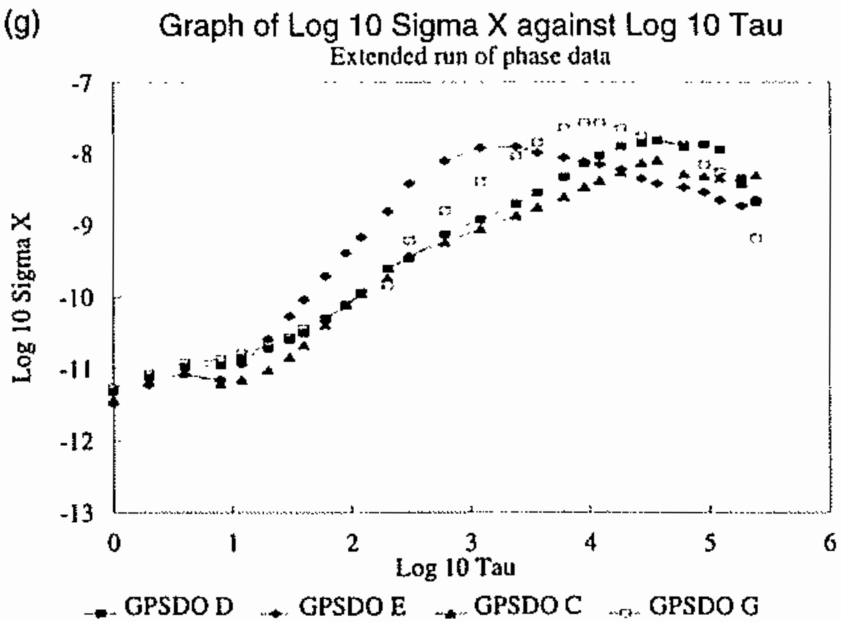
(e)



(f)



(g)



(h)

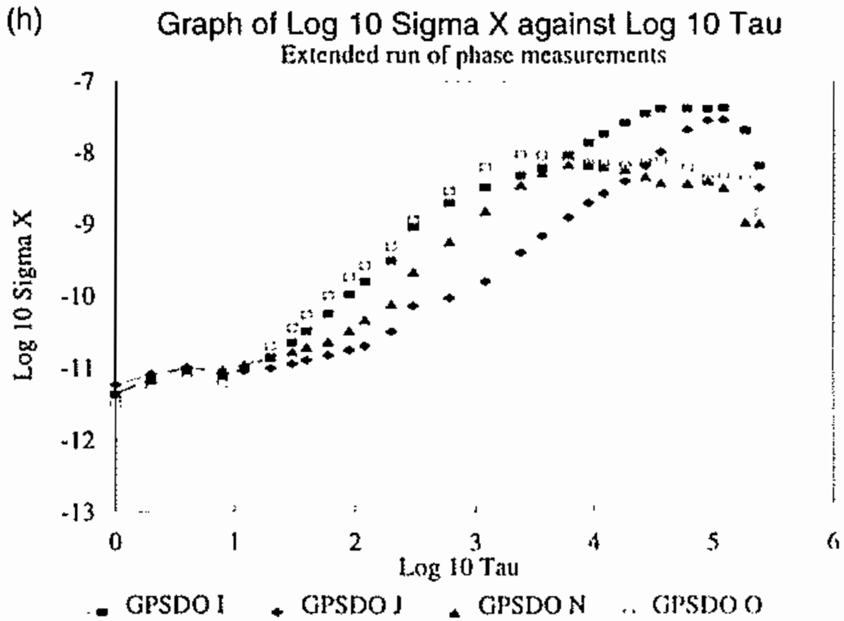
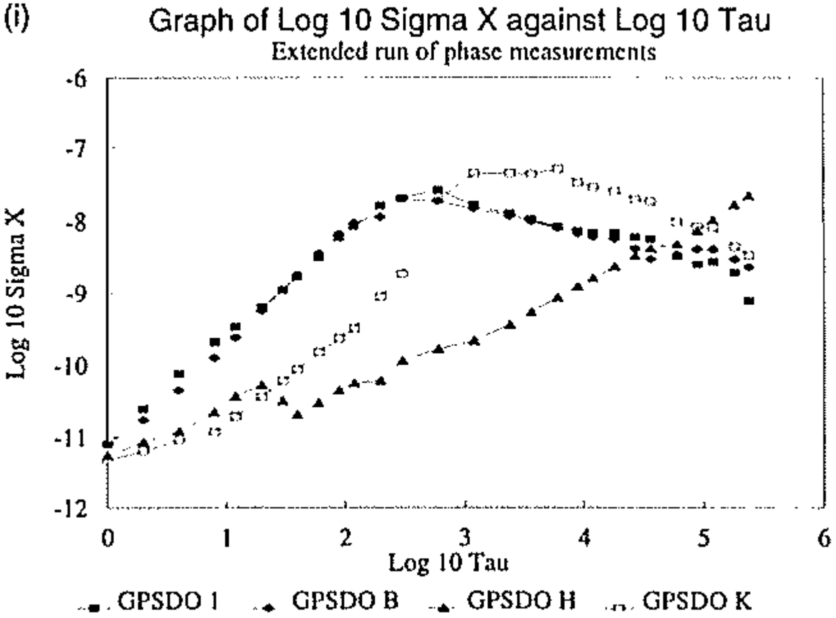
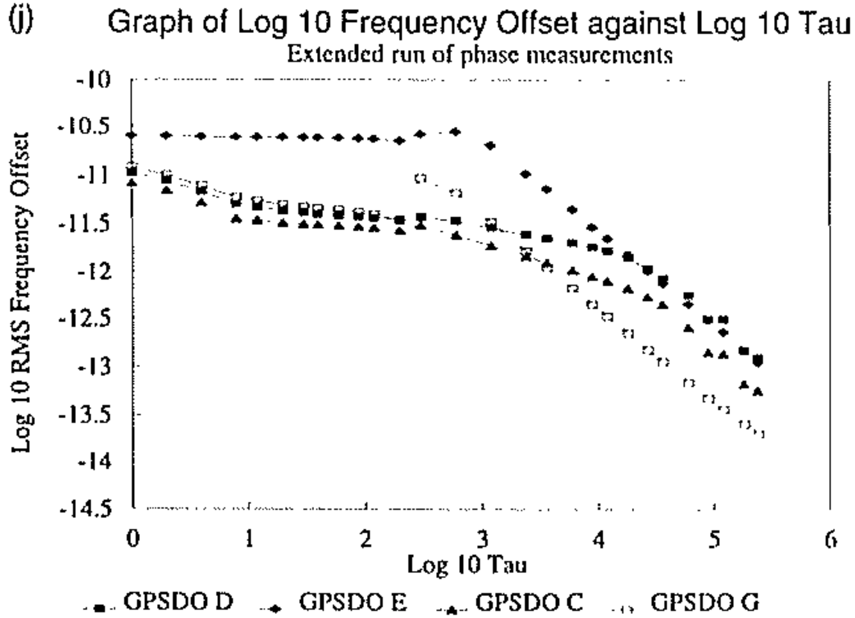


FIGURE 20 (i-l)

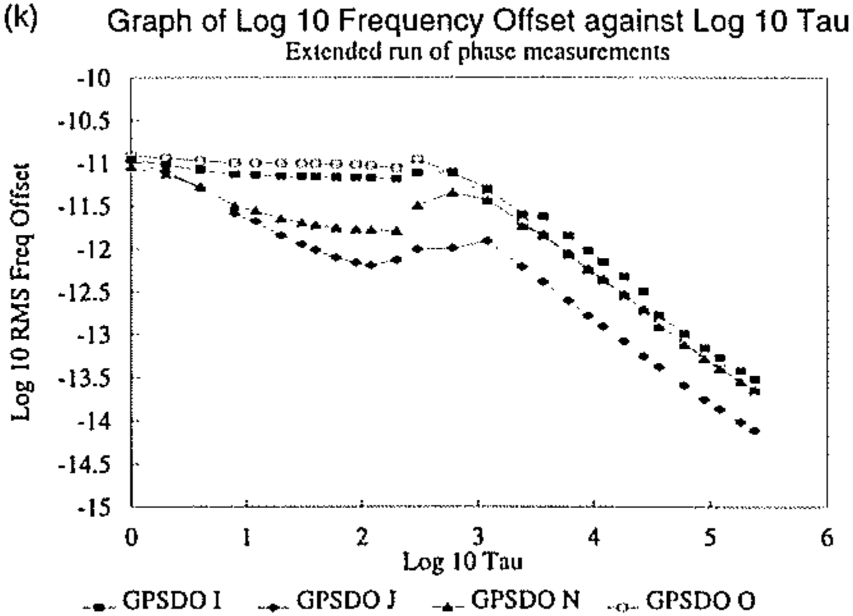
(i)



(j)



(k)



(l)

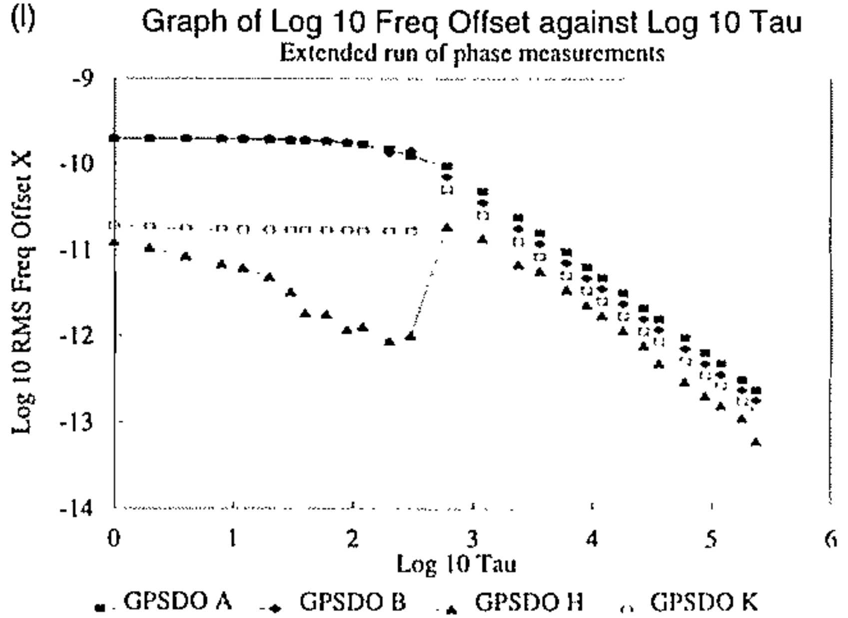
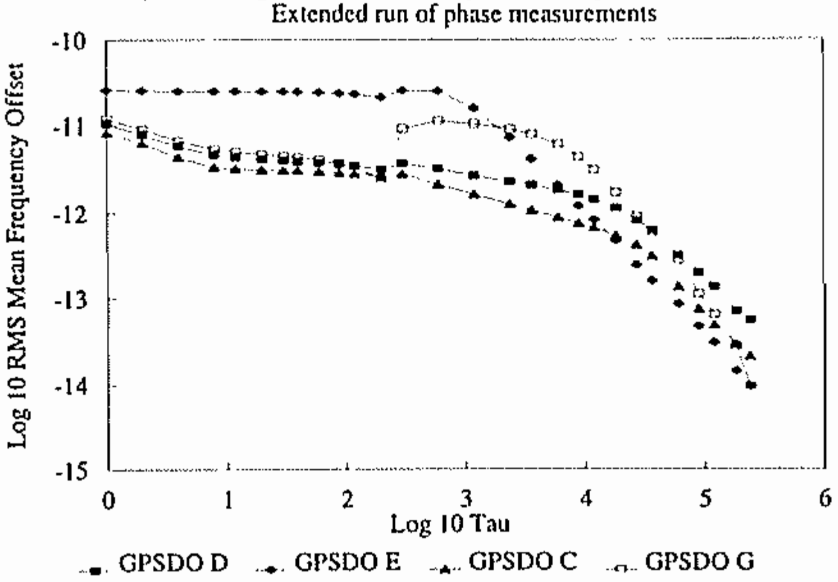
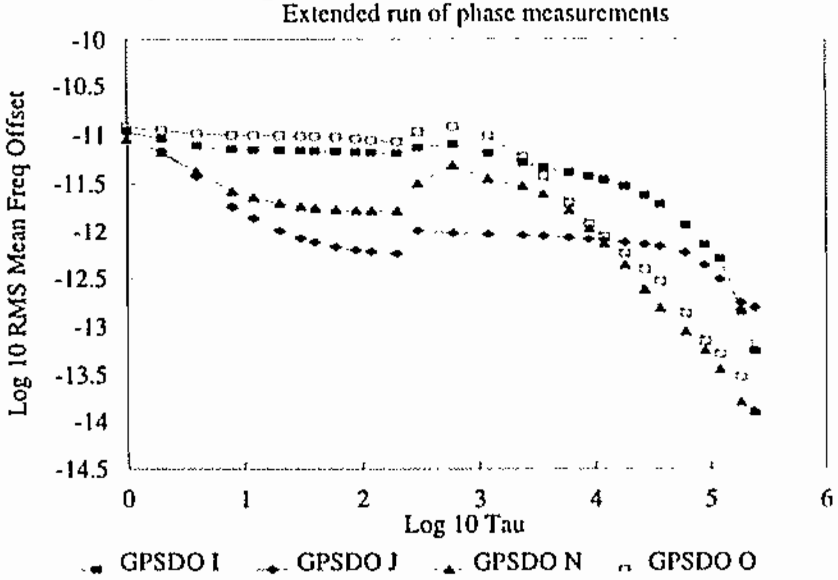


FIGURE 20 (m-o)

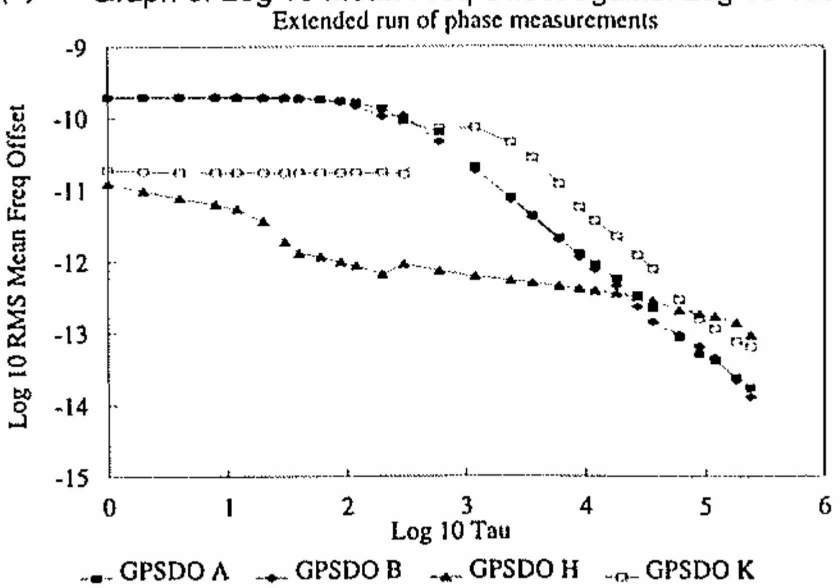
(m) Graph of Log 10 Mean Freq Offset against Log 10 Tau



(n) Graph of Log 10 Mean Freq Offset against Log 10 Tau



(o) Graph of Log 10 Mean Freq Offset against Log 10 Tau



There are discrete steps on some of the curves shown in figures 19 and 20, notably at averaging times of 4,000 s in figure 19 and 600 s in figure 20. This is due to the data set used to calculate long and short averaging times being significantly different. Discrete events, for example transients may be present in the longer data set but also in the shorter, resulting in a discrete step in the curves.

4.10) Frequency stability measurements

The plots of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ obtained from the 1PPS measurements show several distinct regions (Figure 19(a-d)). For short averaging times (τ<30 s), the curve display gradients of -1. The gradient is consistent with white noise originating from the generation and measurement of the 1PPS pulses. In the long term the plots of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ often show gradients of -1. Under these conditions it appears that the GPSDO disciplining is effectively averaging out the effects of SA and the local oscillator noise. At τ = 100,000 s the values of σ_y for all of the GPSDOs are around $1x10^{-13}$. This shows that in the long term the GPSDOs are being effectively disciplined by the GPS.

There was a substantial variation in the values of σ_y for medium averaging times between 50 s and 10,000 s. The performance of the GPSDOs is limited principally by the disciplining of the local oscillator. Where the local oscillator is highly stable, the GPSDO performance is limited principally by the free running local oscillator for example GPSDOs (N) and (H). When the local oscillator is less stable, the performance of the GPSDO is significantly degraded over these averaging times (50-10,000 s), for example GPSDOs (A), (M) and (L). Over these averaging times the GPS is not a stable time and frequency source due to the effects of SA. The combination of a relatively poor local oscillator and a SA limited GPS system results in a poor performing GPSDO over medium averaging times. The curves of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ are similar when calculated from the phase data (figure 20(a-c)), except that for short averaging times the noise is dominated by the local oscillator rather than by the generation of the 1PPS signal. The lack of short term noise on the phase data curves results in the medium and long term variations in figure 20 being noticeably more visible.

There was little or no correlation between the medium term stability and long term performance of the GPSDOs. The medium term performance depends on both the local oscillator and the disciplining algorithm. The long term performance is determined principally by the disciplining algorithm. Some GPSDOs showing relatively poor medium term performance showed excellent long term performance for example GPSDOs (E) and (O), while others showing good medium term performance were not so good in the long term, for example GPSDOs (H) and (J). Quartz based GPSDOs were amongst the best long term performers for example GPSDOs (E) (B) and (O).

Curves of $Log_{10}(MOD\sigma_y)$ against $Log_{10}(\tau)$ show similar trends (see figure 19(e-i) and figure 20(d-f)). For short averaging times (τ < 20s) the curves generated from the 1PPS data had gradient -3/2 , confirming that the noise from the 1PPS generation is white noise. For longer averaging times many of the curves had gradient -3/2 e.g. GPSDOs (A) and (B). This demonstrated the effectiveness of the GPSDO disciplining as shorter term variations were averaged out as if they were white noise. The performance variation in the medium term (τ =1000 s) was even more varied than had been observed with plots of σ_y.

4.11) Frequency offset measurements

The fractional frequency offset of the GPSDOs was studied in a similar way to the frequency stability using both the 1PPS and the phase data. Plots of Log_{10} (fractional frequency offset) against Log_{10} (τ) (figures 20(j-l)) and Log_{10} (mean fractional frequency offset) against Log_{10} (τ), (see figures 19(m-p) and figures 20(m-o)) show three distinct regions. In the short term the curves generated from the 1PPS data have gradient of -1 and -3/2 respectively, this is again caused by the averaging out of the white noise associated with the 1PPS generation. In many cases, with medium term averaging the curves are essentially flat, this region is dominated by the RMS offset of the GPSDO local oscillator. A third region is observed for longer averaging times (τ >1000 s). Here the disciplining of the local oscillator is averaging out the frequency offset of the local oscillator. In this region the majority of the curves have gradients -1 and -3/2 respectively, effectively averaging out the shorter term variations as if they were white noise. The curves generated from the phase data are essentially similar in both the medium and long term. In the short term the curve remains flat as there is no noise introduced by the 1PPS system.

The medium term performance of curves of Log_{10} (Fractional frequency offset) and Log_{10} (Mean fractional frequency offset) against $Log_{10}(\tau)$ give an insight into the performance of the GPSDOs. The averaging time at which the gradient of the graph changes is the averaging time at which the disciplining becomes effective. This is likely to be related to the time constant of the disciplining algorithm. The gradient of the later slope is a measure of the effectiveness of the disciplining. The levels of the "flat line" frequency offset will depend on both the local oscillator and the short term disciplining.

Several examples are given. GPSDOs (A) and (B) have relatively poor local oscillators and hence large short term frequency offsets. There is an effective disciplining mechanism implemented employing a short time constant. The result is very good long term performance. Other GPSDOs for example (H) and (J) have excellent local oscillators and small frequency offsets. Their GPSDO disciplining is less good and so is the long term performance.

4.12) Conclusions

The long term frequency dissemination performance of GPSDOs (τ > 10,000 s) is similar for most of the GPSDOs. This performance is not strongly dependent on the performance of the local oscillator. The short term (τ<100 s) frequency dissemination performance of the GPSDOs was in most cases very similar. In the medium term (100 s < τ < 10,000 s) there was an extremely wide (over a factor of 100) variation in the performance of the GPSDOs. The medium term performance is strongly dependent on the GPSDOs local oscillator combined with the performance of the disciplining algorithm.

A consequence of the above conclusion, is that:

(1) For applications requiring good medium term stability, a GPSDO be used that contains a high quality (e.g., rubidium) local oscillator and a proven disciplining algorithm will be the most appropriate.

(2) For applications requiring only high long term stability, a GPSDO that contains a quartz - based local oscillator would be sufficient provided that the GPSDO still uses a proven disciplining algorithm.

4.13) Recommendations

It is recommended that the frequency stability and accuracy of a GPSDO be specified at the averaging time appropriate for the measurement process, and that the specified performance is validated by measurements traceable to the national time standard.

In the short term such a recommendation will probably require manufacturers or users to characterise the performance of a given GPSDO against a primary time scale (eg UTC(NPL)) but as the national measurement system for GPSDOs matures, such validation processes may well devolve to UKAS accreditation laboratories.

4.14) References

[1] E A Gerber and A Ballato, *Precision Frequency Control, vol 2, Oscillators and Standards*, pp 193-217, Academic Press, Inc 1985.

[2] M Wolf, *The Applicability of MTIE and TDEV for assessing the quality of telecom services*, Proceedings 11 th EFTF, Neuchatel, Switzerland, March 1997.

5) Transients

5.1) Introduction.

The occurrence of time and frequency transients degrade both the accuracy and the integrity of GPSDO time and frequency disseminations. Transients may therefore seriously undermine the use of GPSDOs as traceable standards.

5.2) Characteristics of time and frequency transients

Several GPSDOs exhibited transient time and frequency variations during the course of the extended measurements. In most cases the transients occurred as changes in both the 1PPS and phase outputs of the GPSDO (figure 21). These changes would take the phase and 1PPS outside their normal range of values. The phase and 1PPS values later returned to their normal operating range. Some of these transients occurred for several hours. There was little or no correlation between the transients occurring on different GPSDOs. The occurrence of some of the transients are tabulated in table 8. Transient amplitudes varied between 100 ns and 1,600 ns. The maximum fractional frequency offset occurring was 3×10^{-9} (τ= 240 s) on GPSDO (F). This is a very significant offset and should be taken into account when considering the use of GPSDOs as traceable frequency standards.

The transients had a wide range of durations and amplitudes, similarly there was the range of frequency offsets occurring during the study. During the operation over an extended period, no transients occurred in 10 of the 15 GPSDOs. Transients occurred on GPSDOs (F),(G),(H),(L) and (O). GPSDOs operating from quartz rather than rubidium oscillators were more susceptible to transients. Only one rubidium based GPSDO (H) displayed transients, which were of a relatively small amplitude. The longer time constants in the disciplining algorithms of rubidium GPSDOs may be able to average out these transient effect. The transient effects occur for a relatively small proportion of the total operating time. An intense study is underway to investigate the GPSDO RS232 data to determine both the origins of the transients and any warning of their occurrence.

The plots of GPSDO transients (figures 21) show 1PPS variations and fractional frequency offsets, calculated by numerically differentiating the 1PPS data. Most of the transients follow a similar pattern. There is a sudden discrete change in the GPSDO frequency offset, caused most probably by an unexpected change in the GPSDO DAC value. The GPSDO disciplining process then returns the 1PPS and standard frequency outputs to their normal operating range. Examples are shown in figure 21 for GPSDOs (G), and (O). Transients observed on GPSDO (L) , and on NPL's Motorola Oncore receiver (figure 21(m)) occur by a different mechanism.

There was a correlation observed on MJD 50497(figure 21(i-l)), when two GPSDO transients on separate GPSDOs (I) and (J) were all triggered at the same instant. This time correlated with an instantaneous power failure at NPL. There were no other observed correlations between the occurrence of transients.

Table 8: Examples of transients observed on the 1PPS outputs of the GPSDO during the period of extended measurements.

GPSDO	MJD	Duration hh:mm	Amplitude / ns
F	50466-50467	3:54	-1770 to +1,920
F	50471	6:08	-813 to +963
F	50473	1:36	-450 to +1,600,
F	50475	1:04	-40 to +250
G	50476	3:50	-190
G	50486	6:37	-160 to +217
H	50498	1:23	±50
L	50482	7:12	-92 to +342
L	50485	1:01	-467
O	50468	3:43	262
O	50469	3:25	188
O	50471	4:51	-210

FIGURE 21 (a-d) TIME AND FREQUENCY TRANSIENTS

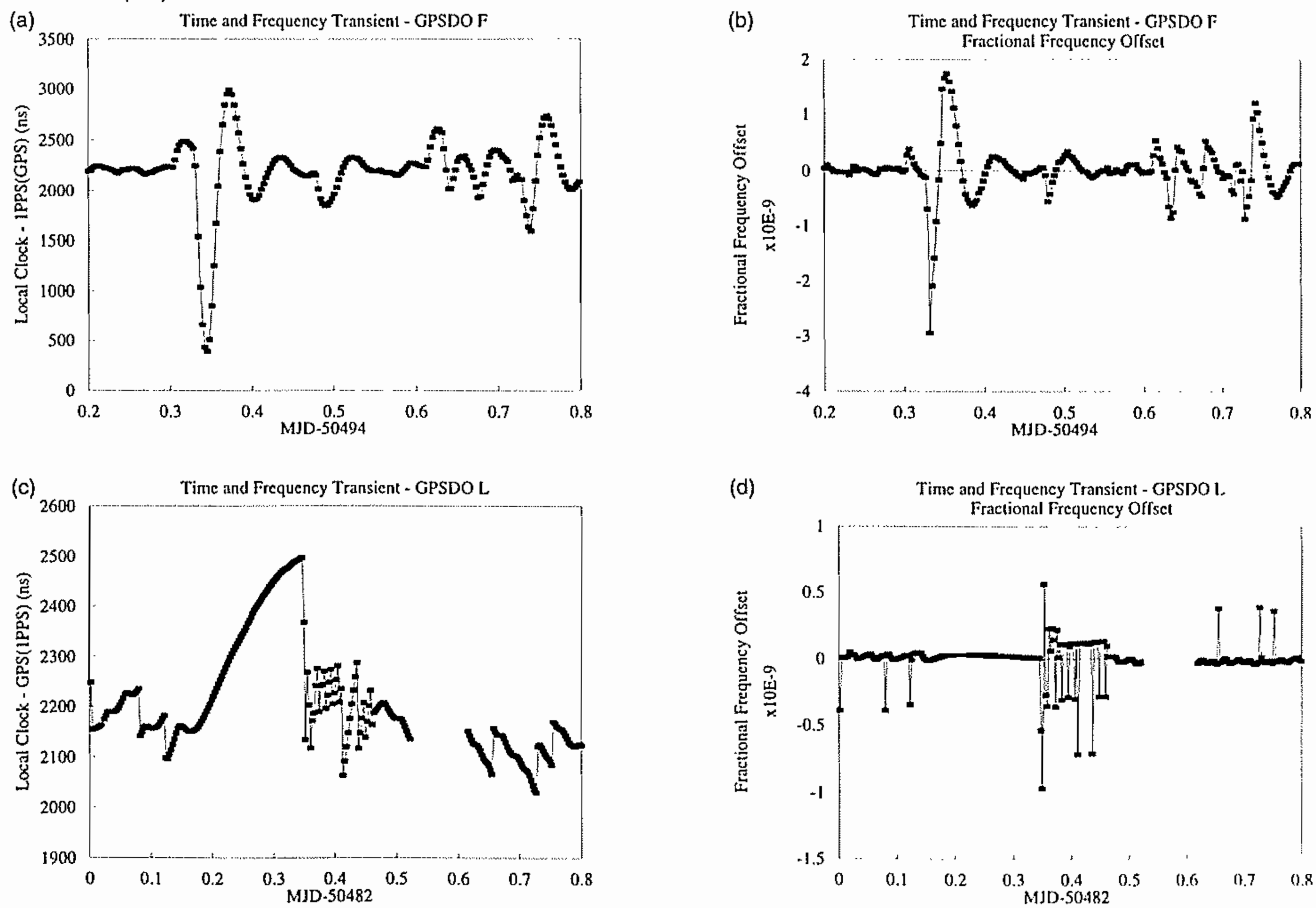


FIGURE 21 (e-h)

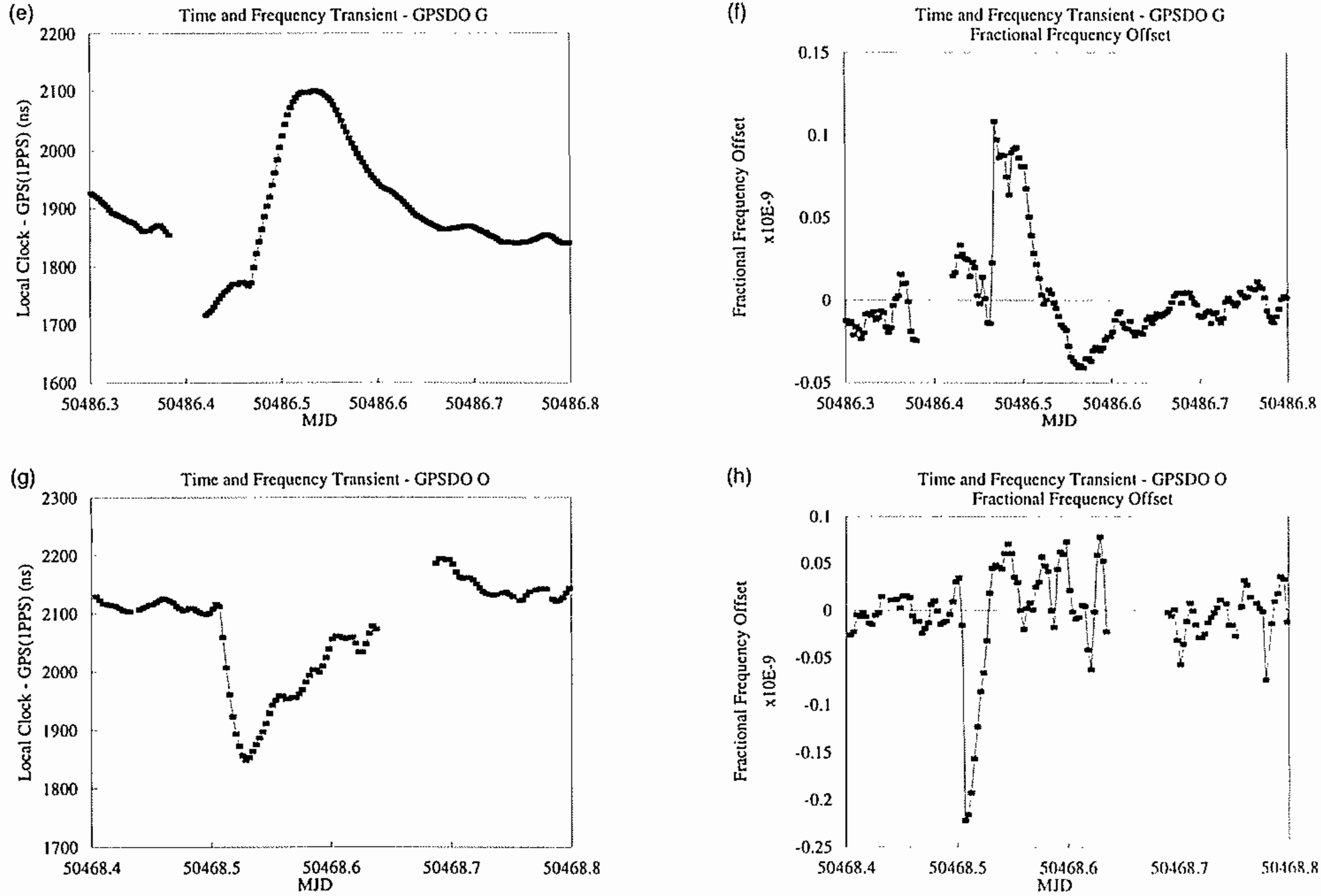

(e)
Time and Frequency Transient - GPSDO G
Local Clock - GPS(1PPS) (ns)
2200
2100
2000
1900
1800
1700
1600
50486.3
50486.4
50486.5
50486.6
50486.7
50486.8
MJD
(f)
Time and Frequency Transient - GPSDO G
Fractional Frequency Offset
Fractional Frequency Offset
x10E-9
0.15
0.1
0.05
0
-0.05
50486.3
50486.4
50486.5
50486.6
50486.7
50486.8
MJD
(g)
Time and Frequency Transient - GPSDO O
Local Clock - GPS(1PPS) (ns)
2300
2200
2100
2000
1900
1800
1700
50468.4
50468.5
50468.6
50468.7
50468.8
MJD
(h)
Time and Frequency Transient - GPSDO O
Fractional Frequency Offset
Fractional Frequency Offset
x10E-9
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
50468.4
50468.5
50468.6
50468.7
50468.8
MJD

FIGURE 21 (i-l)

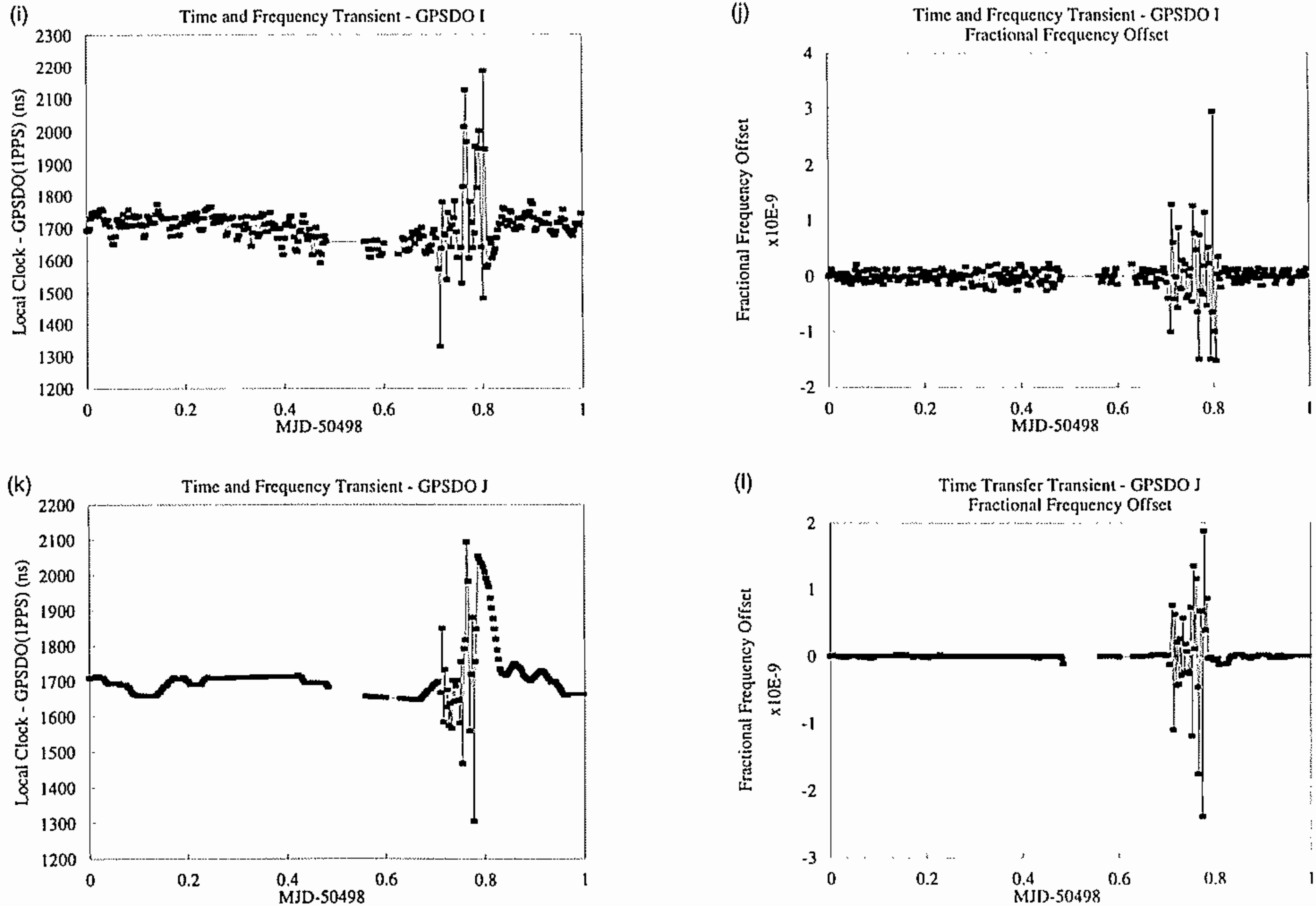
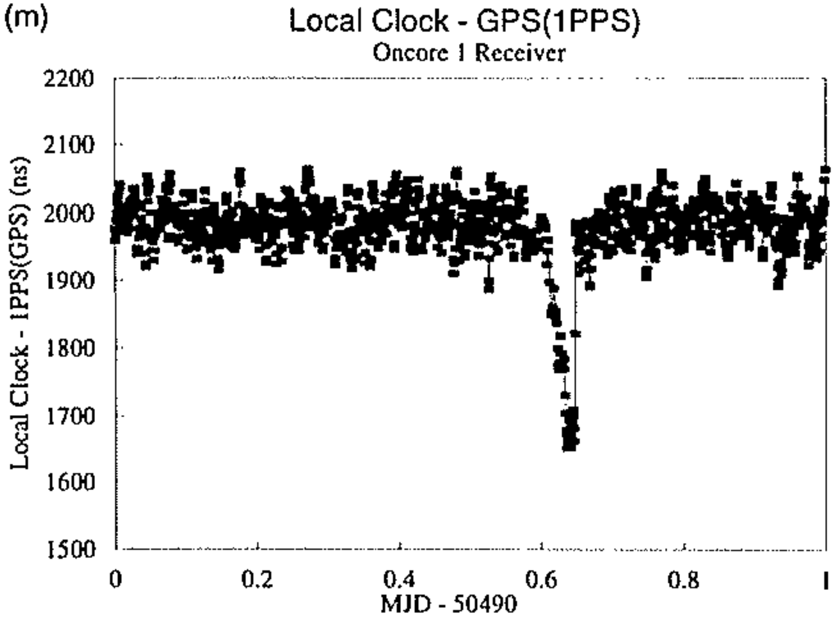
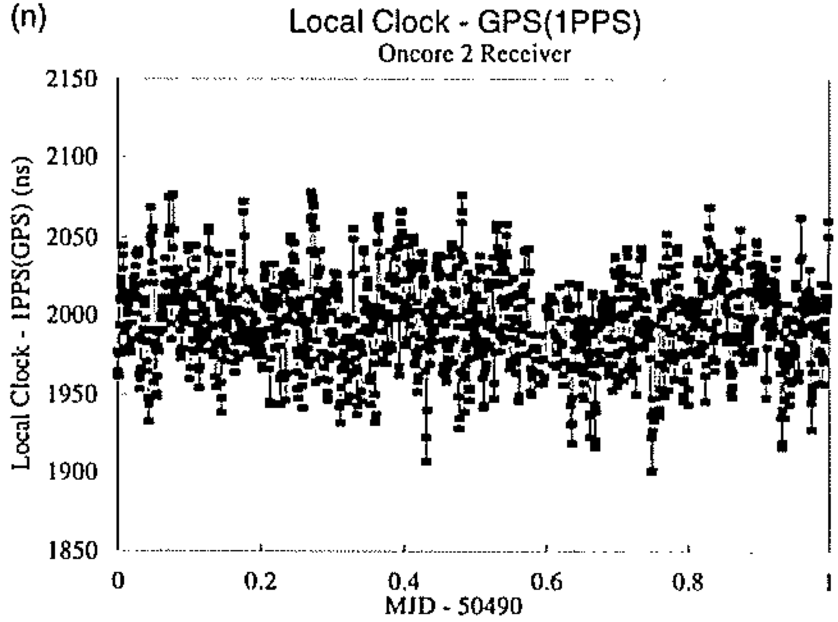

(i)
Time and Frequency Transient - GPSDO I
Local Clock - GPSDO(1PPS) (ns)
MJD-50498
(j)
Time and Frequency Transient - GPSDO I
Fractional Frequency Offset
Fractional Frequency Offset x10E-9
MJD-50498
(k)
Time and Frequency Transient - GPSDO J
Local Clock - GPSDO(1PPS) (ns)
MJD-50498
(l)
Time Transfer Transient - GPSDO J
Fractional Frequency Offset
Fractional Frequency Offset x10E-9
MJD-50498

FIGURE 21 (m-n)

(m)



(n)



5.3) Conclusions and recommendations

The occurrence of transients causes a problem when considering the performance of GPSDOs. The amplitudes of the transients were found to range from a hundred ns to several thousand ns with associated maximum fractional frequency offsets of $3x10^{-9}$ (τ=240 s) . However the size of the transient is usually dependent on the individual GPSDO. There is very little correlation between either the amplitude or occurrence of the GPSDO transients.

It would seem that there are two possibilities when considering GPSDOs as traceable standards in the context of transients. One possibility is to expand the uncertainty limits associated with the standard so that they are able to tolerate the occurance of typical transients. However, such a route could well remove any benefit from the GPS disciplining process, making it an unviable option. The alternative, more practical approach, would be to use the GPSDO alongside a second stable oscillator. This would help identify the occurrence of transients and would therefore improve both the accuracy and integrity of the resulting time and frequency transfers.

6) Free Running Oscillator

6.1) Introduction

Information on the performance of complete GPSDO units may be obtained by examining their component parts. In this GPSDO study, the performance of the GPSDO internal oscillators, and the determination of antenna coordinates are examined in depth. The performance of the front end GPS receiver may be examined by considering correlation effects between different GPSDOs. The integrity and accuracy associated with each component of the GPSDO is important when considering the performance of the complete unit, and hence its usefulness as a traceable standard.

6.2) Performance of the free running oscillator

The stability of the free running local oscillator is vital for the effective performance of the GPSDO. The GPSDOs were operated for several days in the absence of GPS signals, in order to assess the performance of the free running oscillator. Only where explicitly stated in the GPSDO manual was the receiving antenna removed. In most cases the GPSDO antenna were left connected to the GPSDOs but removed from the antenna pole and placed in an absorbing environment free from GPS signals. In several cases the GPS signals were eliminated through software changes, either by setting the satellite mask angle to 90° or by deselecting all of the satellites.

Variation of the GPSDO output phase and associated frequency offset (τ=300s) is shown in figure 22. The GPS signals were removed during the afternoon of MJD 50507. The DAC values are likely to frozen at the time of their last correction. Where possible this was confirmed by examining the available RS232 data. For some GPSDOs, DAC corrections had been applied in the absence of signals from the GPS satellites (see figure 22). Examples being GPSDOs (B), (C) and (L). These changes have been taken into account when applying statistics to the free running oscillator data. Both the 1PPS and the phase data were recorded during this period. It was noted that several of the GPSDOs 1PPS signals failed to operate in the absence of the GPS satellite signals. All of the GPSDOs did however provide a 5/10 MHz reference in the absence of the GPS signal.

Examination of GPSDOs (D),(E) and (K) (figure 22) revealed that while the GPSDOs have a more stable long term performance, the free running oscillators will almost always have better medium term performance (τ = 1,000s). This is shown by a obvious reduction in the scatter on the fractional frequency offset plots, following the removal of the GPS disciplining signal. The phase data has been used for calculation of σ_y and similar statistics. It is not possible to obtain meaningful free running oscillator statistics from some of the GPSDOs because of residual modulation to the output phase data by the GPSDOs electronics (see figure 22 (q),GPSDO (G)).

Figure 22 reveals a large variation in the performance of the free running GPSDOs, both in the phase (delay) variations and the fractional frequency offset. The GPS signal was removed on the afternoon of MJD 50507. In many examples e.g., figure 22 (b) to (f), the frequency stability of

FIGURE 22 (a-d) FREE RUNNING OSCILLATOR PHASE CHANGES AND FREQUENCY OFFSETS

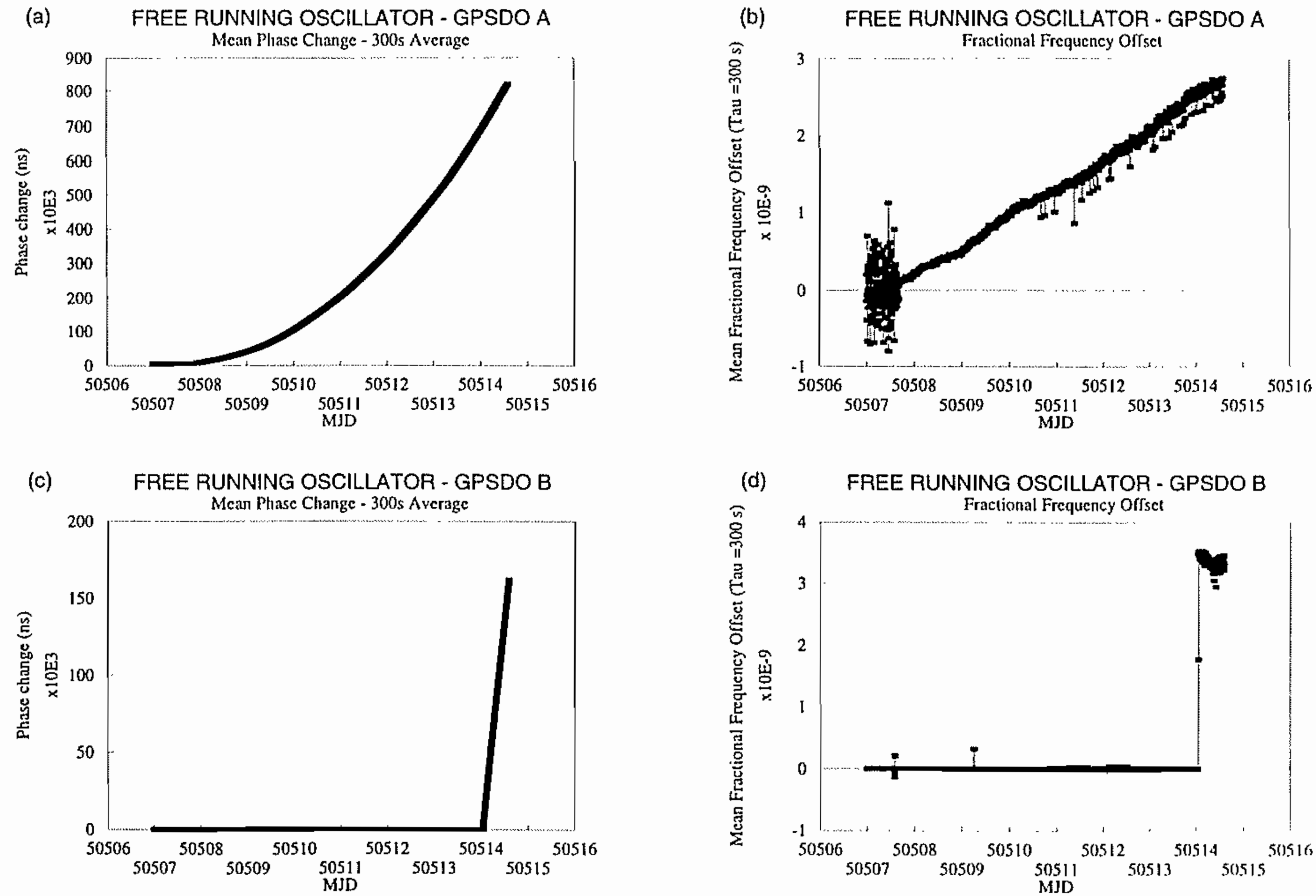


FIGURE 22 (e-h)

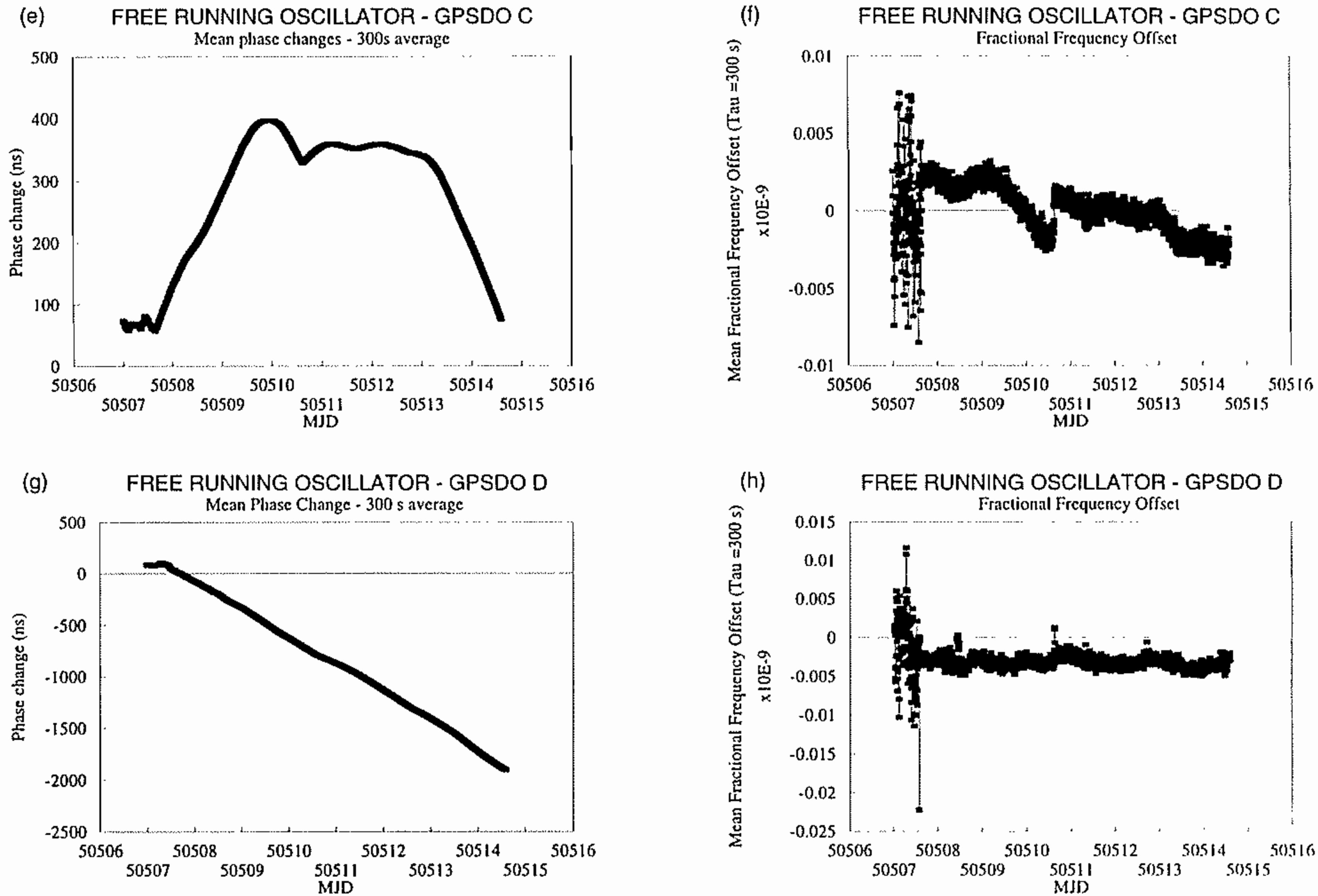
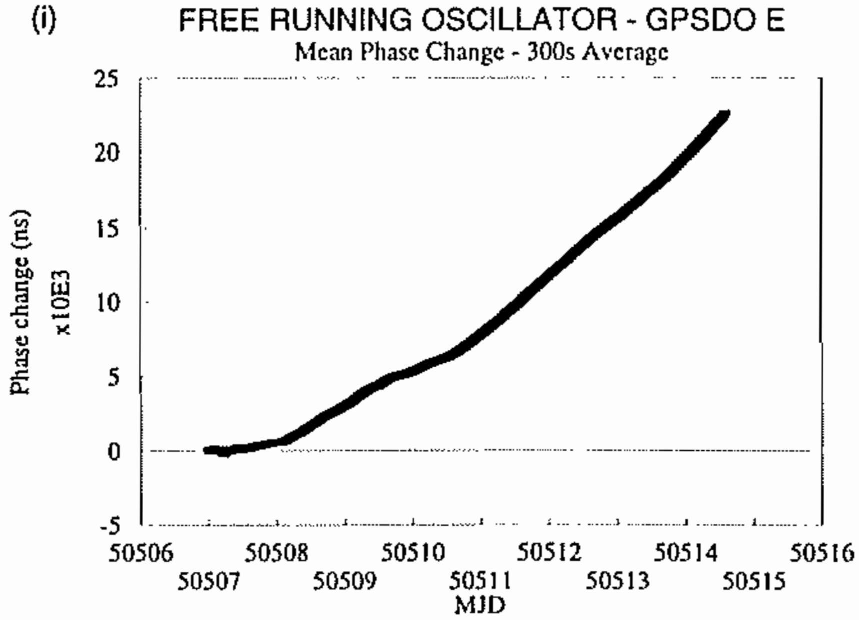
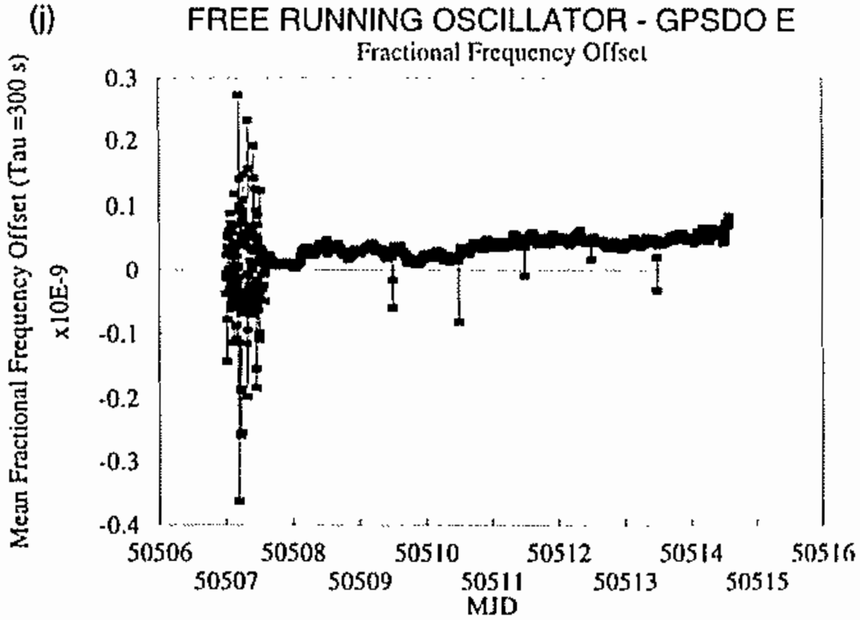

(e)
FREE RUNNING OSCILLATOR - GPSDO C
Mean phase changes - 300s average
Phase change (ns)
500
400
300
200
100
0
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(f)
FREE RUNNING OSCILLATOR - GPSDO C
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau =300 s)
x10E-9
0.01
0.005
0
-0.005
-0.01
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(g)
FREE RUNNING OSCILLATOR - GPSDO D
Mean Phase Change - 300 s average
Phase change (ns)
500
0
-500
-1000
-1500
-2000
-2500
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(h)
FREE RUNNING OSCILLATOR - GPSDO D
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau =300 s)
x10E-9
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD

FIGURE 22 (i-l)

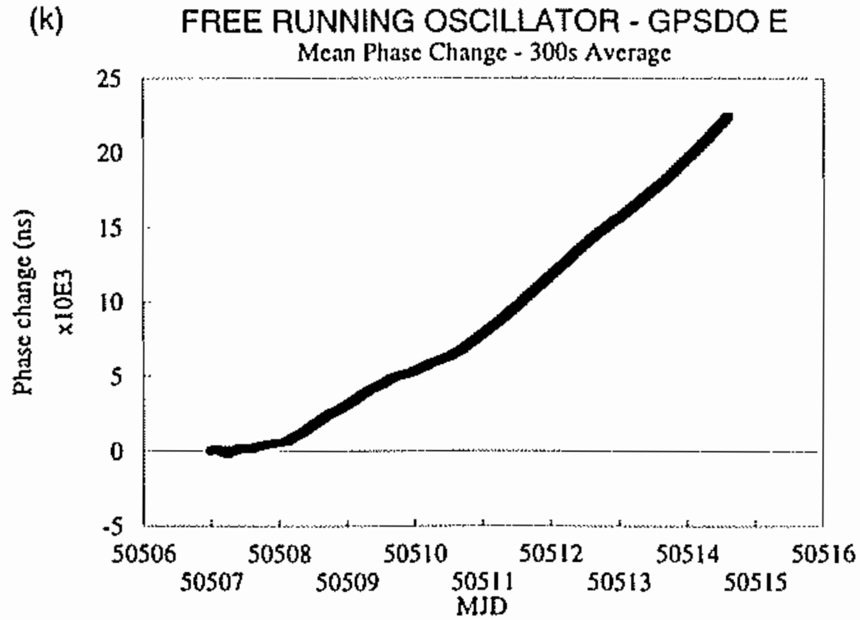
(i)



(j)



(k)



(l)

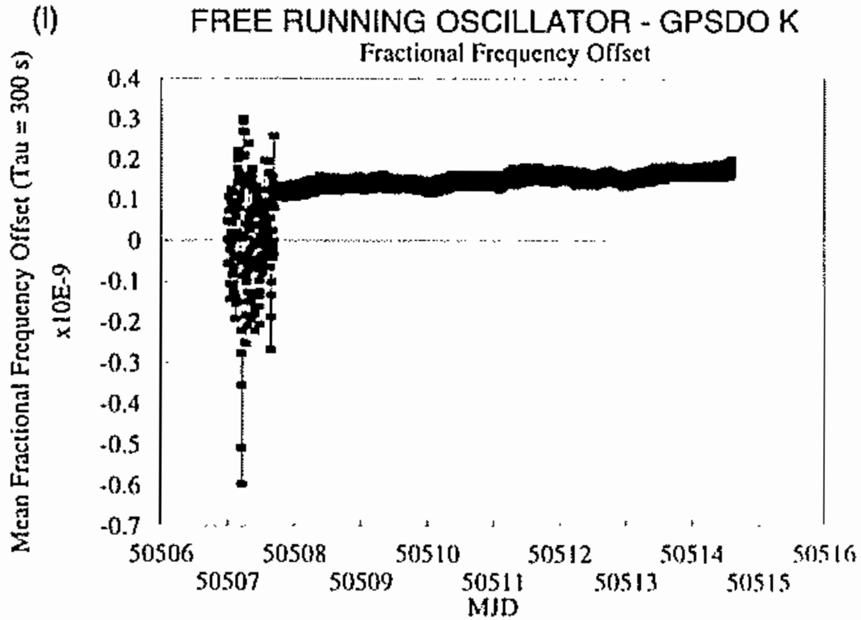
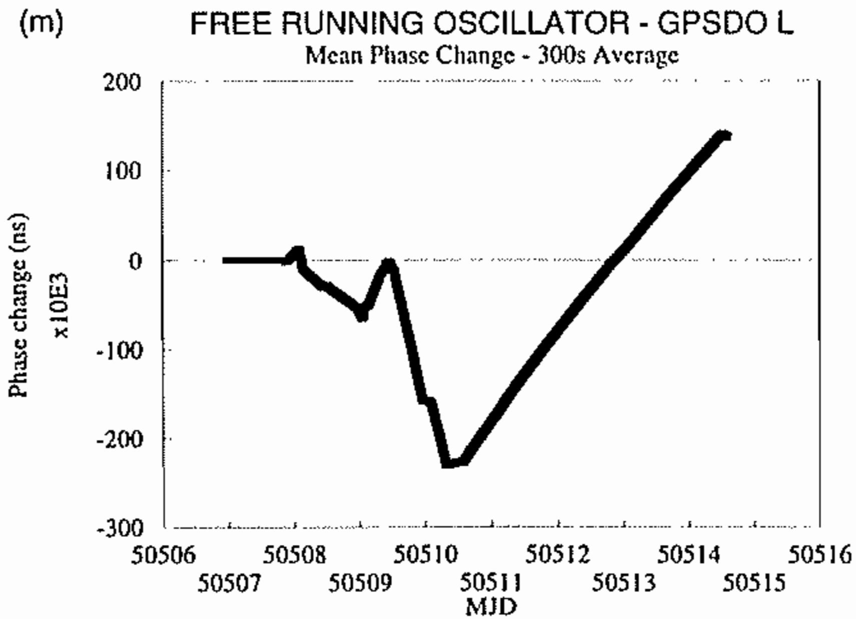
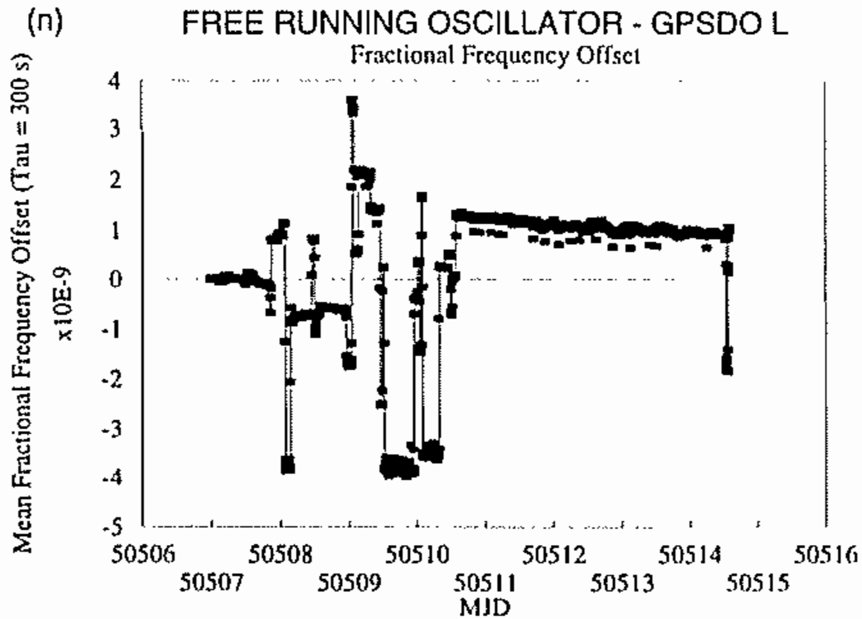


FIGURE 22 (m-o)

(m)



(n)



(o)

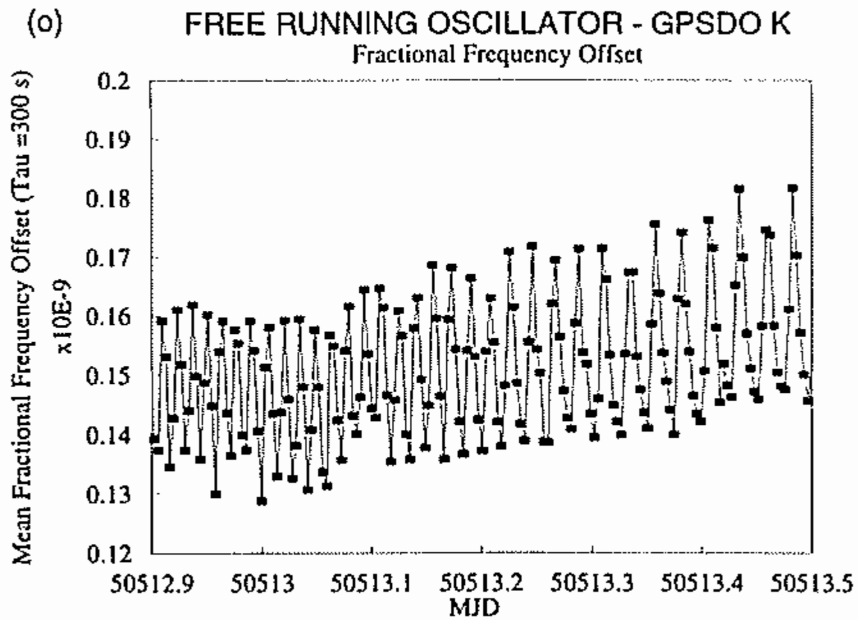


FIGURE 22 (q-t)

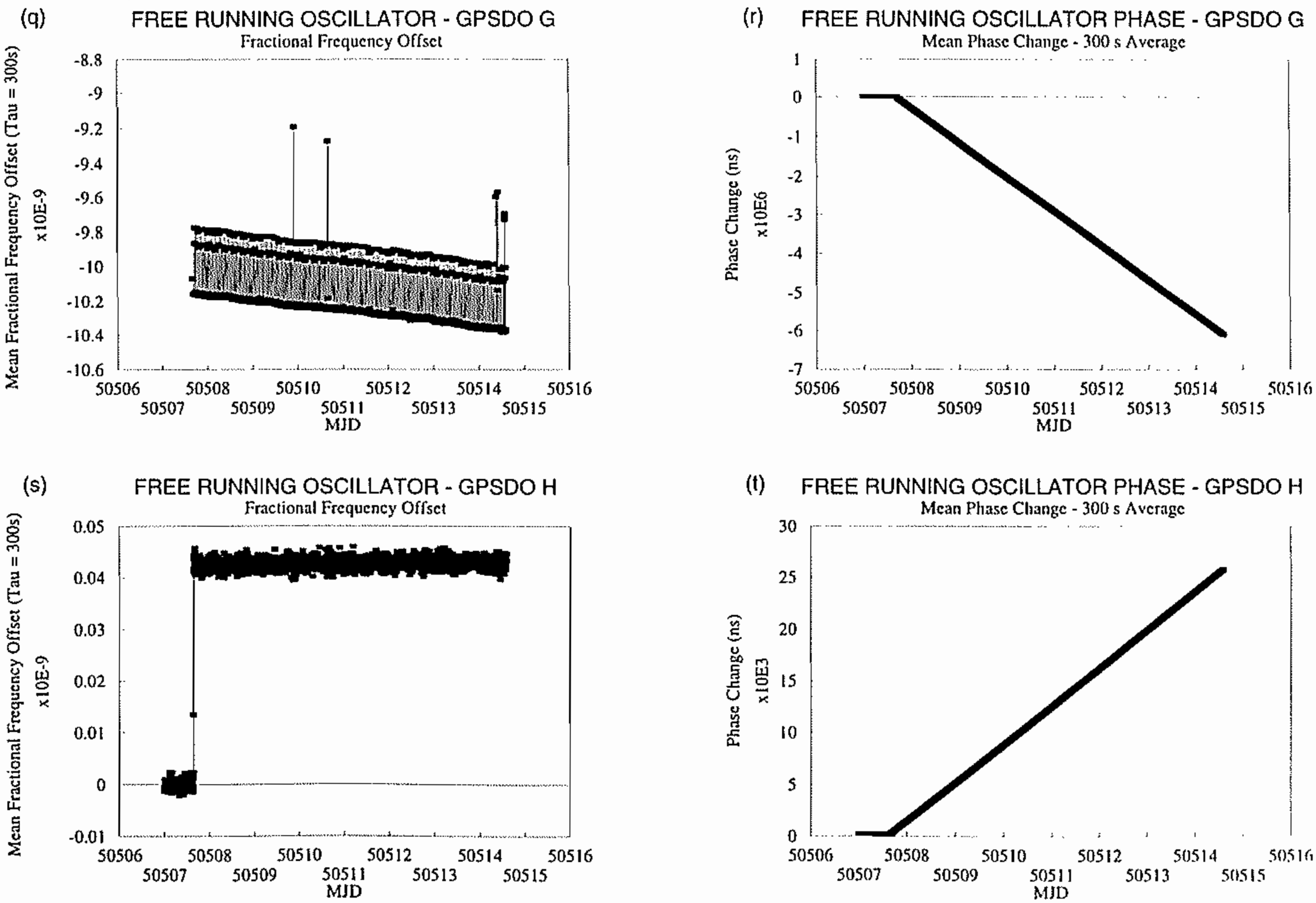
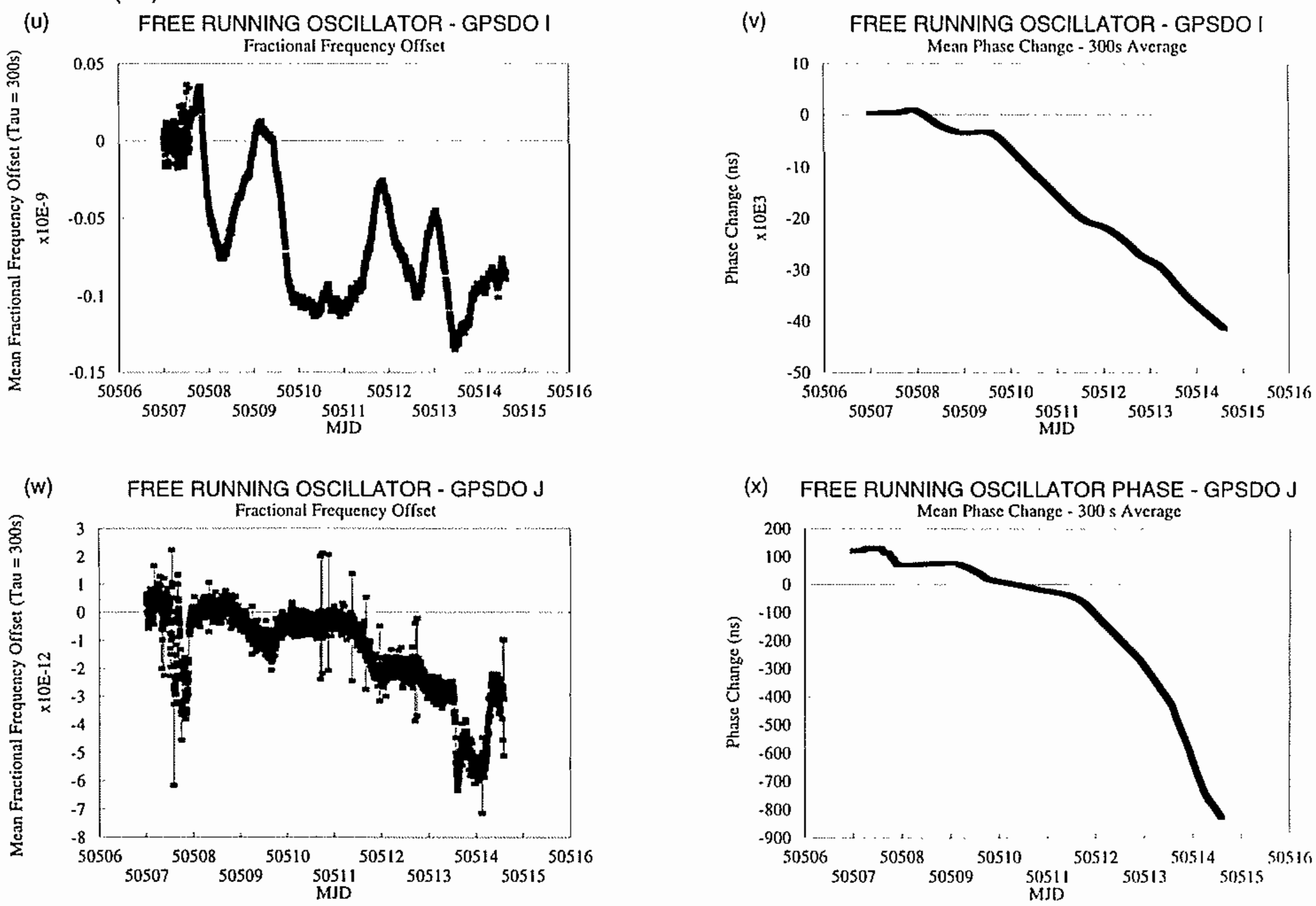

(q)
FREE RUNNING OSCILLATOR - GPSDO G
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau = 300s)
x10E-9
-8.8
-9
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
-10.6
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(r)
FREE RUNNING OSCILLATOR PHASE - GPSDO G
Mean Phase Change - 300 s Average
Phase Change (ns)
x10E6
1
0
-1
-2
-3
-4
-5
-6
-7
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(s)
FREE RUNNING OSCILLATOR - GPSDO H
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau = 300s)
x10E-9
0.05
0.04
0.03
0.02
0.01
0
-0.01
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(t)
FREE RUNNING OSCILLATOR PHASE - GPSDO H
Mean Phase Change - 300 s Average
Phase Change (ns)
x10E3
30
25
20
15
10
5
0
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD

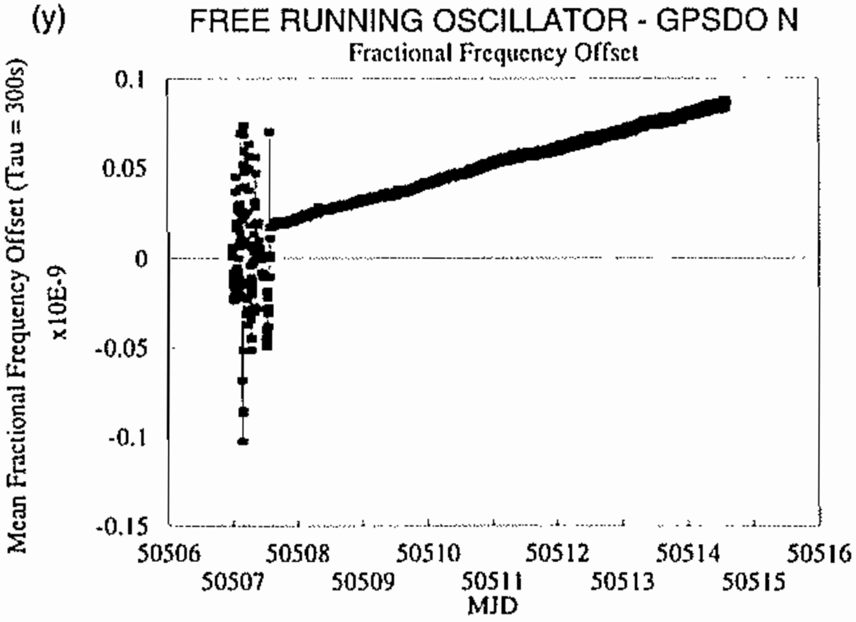
FIGURE 22 (u-x)



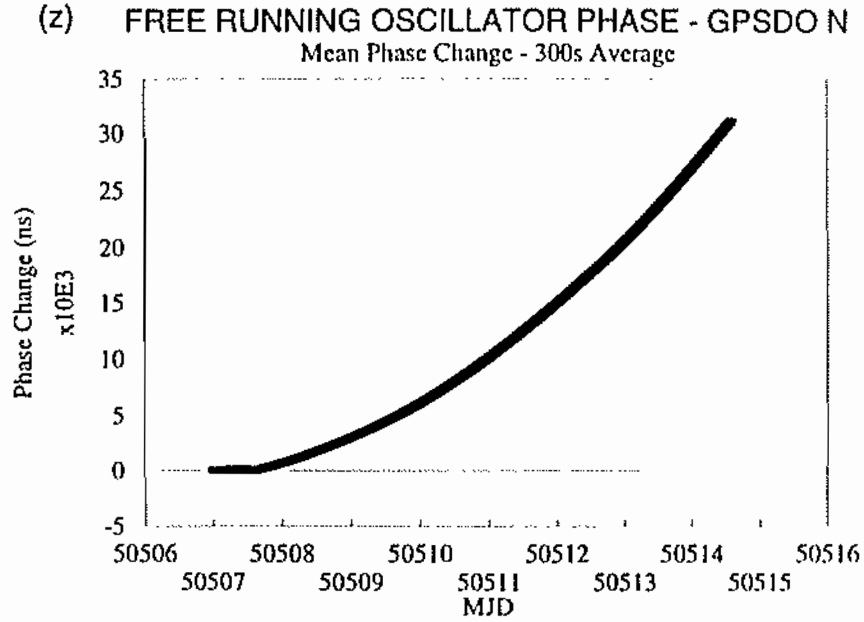
(u)
FREE RUNNING OSCILLATOR - GPSDO I
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau = 300s)
x10E-9
0.05
0
-0.05
-0.1
-0.15
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(v)
FREE RUNNING OSCILLATOR - GPSDO I
Mean Phase Change - 300s Average
Phase Change (ns)
x10E3
10
0
-10
-20
-30
-40
-50
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(w)
FREE RUNNING OSCILLATOR - GPSDO J
Fractional Frequency Offset
Mean Fractional Frequency Offset (Tau = 300s)
x10E-12
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD
(x)
FREE RUNNING OSCILLATOR PHASE - GPSDO J
Mean Phase Change - 300 s Average
Phase Change (ns)
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
50506
50507
50508
50509
50510
50511
50512
50513
50514
50515
50516
MJD

FIGURE 22 (y-b1)

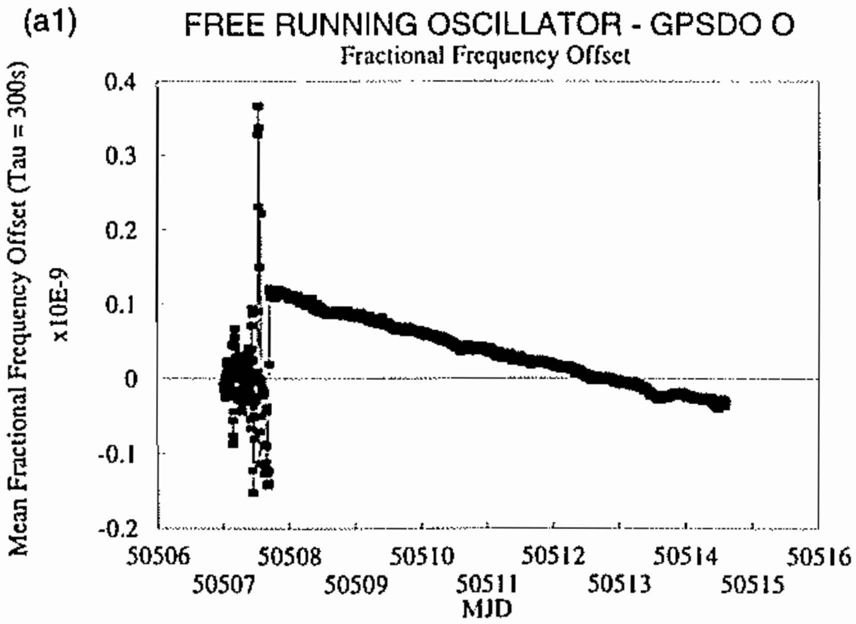
(y)



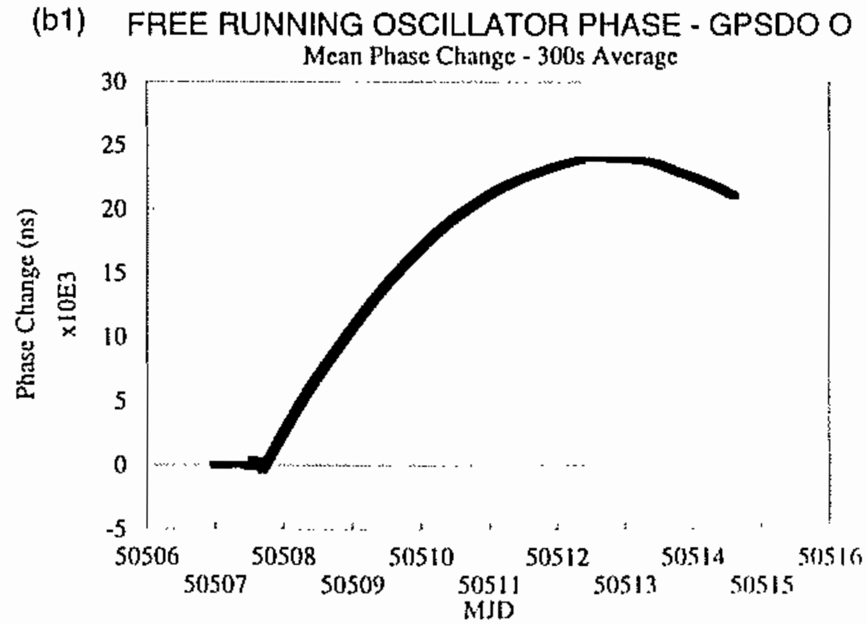
(z)



(a1)



(b1)



the free running oscillator (τ = 300 s) is far better than the stability of the oscillator (τ = 300 s) when disciplined. The DAC values of GPSDOs (G) and (H) were not frozen on loosing the GPS signal. However, because of the short term frequency instabilities of the disciplined oscillators compared with the free running oscillators, the 'frozen' DAC values may often not be optimum. This resulted in a large frequency offset and a rapid phase drift, following the loss of the GPS signal. The drift of the GPSDO phase following the loss of the disciplining signal was extremely varied. After 7 days GPSDO (C) had a maximum phase excursion of only 300 ns. In contrast GPSDO (G) had a maximum phase excursion of 6,000,000 ns.

Plots of $Log_{10}(\sigma_y)$ against $Log_{10}(\tau)$ are shown in figure 23(a-c). The oscillators have similar properties at short averaging times (τ < 10 s). At medium and longer averaging times there is a substantial variation in the performance of the free running oscillators. As expected, the rubidium oscillators show themselves to be more stable than the quartz oscillators. A residual disciplining modulation was observed on GPSDO (K), see figure 23(d), resulting in a peak in the curve at τ = 800s. Similar properties were observed with plots of $Log_{10}(MOD\sigma_y)$ against $Log_{10}(\tau)$ and $Log_{10}(\sigma_x)$ against $Log_{10}(\tau)$ (figure23(d-i)). Again it can be seen that the GPSDO free running oscillators have similar characteristics at short averaging times but a wide range of performances at longer averaging times. Values of σ_y, $MOD\sigma_y$ and σ_x for τ =1000 s are shown in table 9. An averaging time of 1,000 s is when there is the greatest variation in performance between the GPSDOs and when the selective availability (SA) applied to the satellite is at it greatest.

Figure 24 shows plots of $Log_{10}(\sigma_x)$, $Log_{10}(\sigma_y)$,and $Log_{10}(MOD\sigma_y)$, against $Log_{10}(\tau)$, obtained from the GPSDOs and their free running oscillators. Several interesting trends emerged from the results. In the long term the frequency stability of the GPSDO is significantly better when compared with the frequency stability of the free running oscillator. In the medium term the frequency outputs of almost all of the GPSDOs is significantly less stable than the corresponding free running oscillators, particularly in the case of the less stable quartz based oscillators (figure 24). In the short term the frequency stability of the GPSDO and of the free running oscillators are similar. The GPSDO characteristics depend on the performance of the free running oscillator and how it is disciplined. For GPSDOs with very stable rubidium oscillators, the short and medium term performance is limited by the oscillator. The disciplining takes place with a relatively long time constant, resulting in some degradation in the performance of the free running oscillator in the medium to long term. In the case of GPSDOs (H) and (J), very little of the free running oscillator stability is lost on disciplining. However it is only after a period of a day or longer that the GPSDO disciplining becomes effective.

When the performance of the free running oscillator is less good the disciplining process takes place with a much shorter time constant. This time constant, typically 1,000 s is not sufficient to average out much of the SA applied to the GPS signals which discipline the GPSDO. The result of GPS disciplining can be severe degrading of both the short and medium term stability of the GPSDOs, examples being GPSDO (K) shown in figure 24 (h).

Several GPSDOs operating with relatively poor local oscillators, for example (E), (A), (B) have excellent long term performance. In order to achieve this there has been significant degrading of the GPSDOs short/medium term frequency stability.

6.3) Conclusions and recommendations

FIGURE 23 (a-d) TIME AND FREQUENCY STATISTICS CALCULATED FROM THE FREE RUNNING OSCILLATOR PHASE DATA

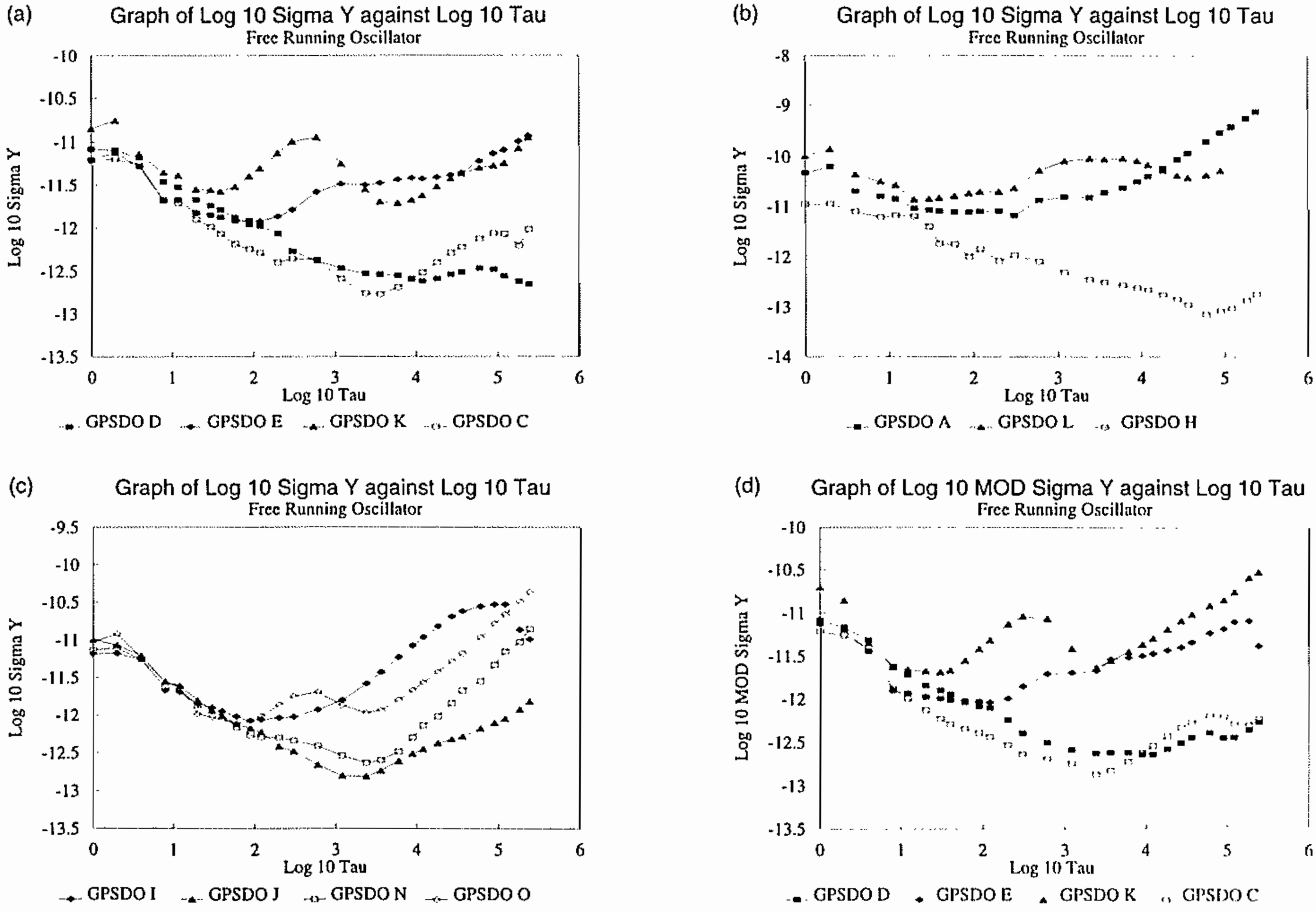
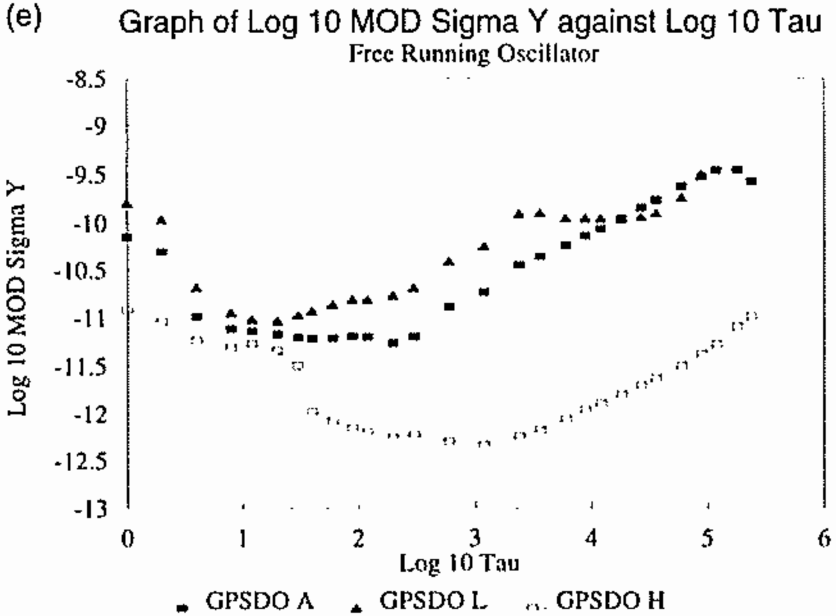
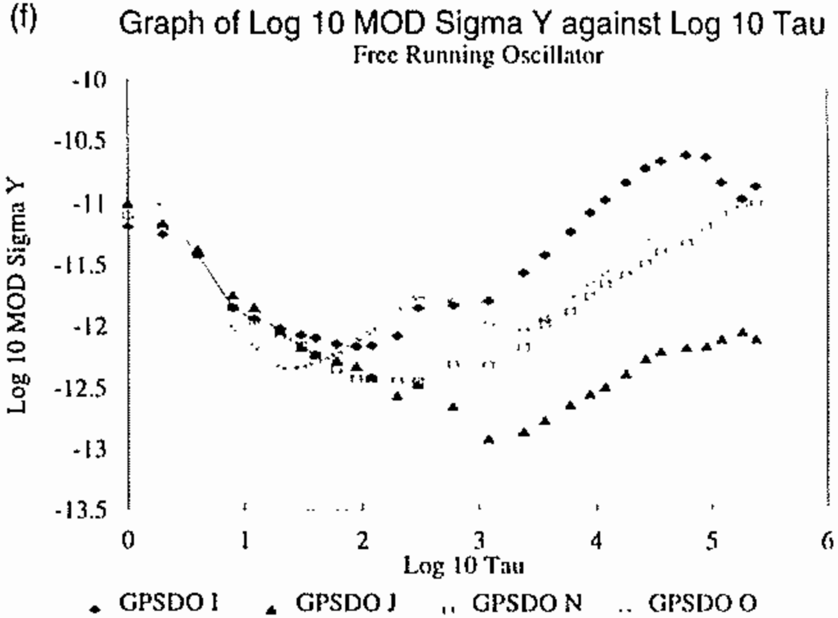


FIGURE 23 (e-h)

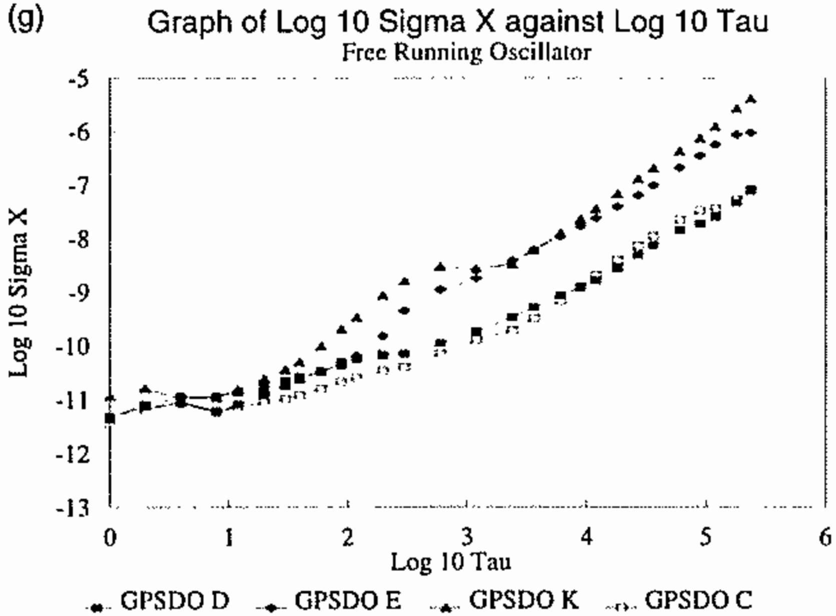
(e)



(f)



(g)



(h)

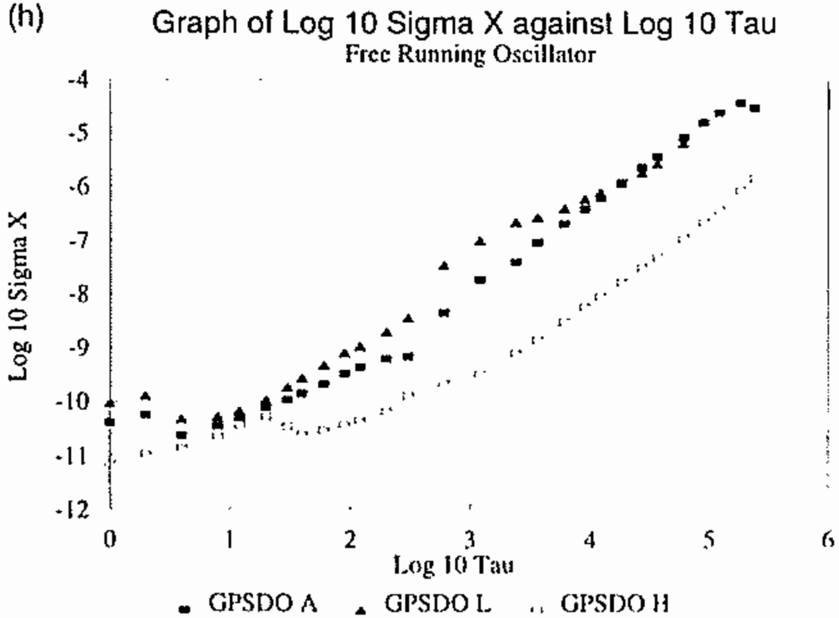


FIGURE 23 (i)

(i) Graph of Log 10 Sigma X against Log 10 Tau

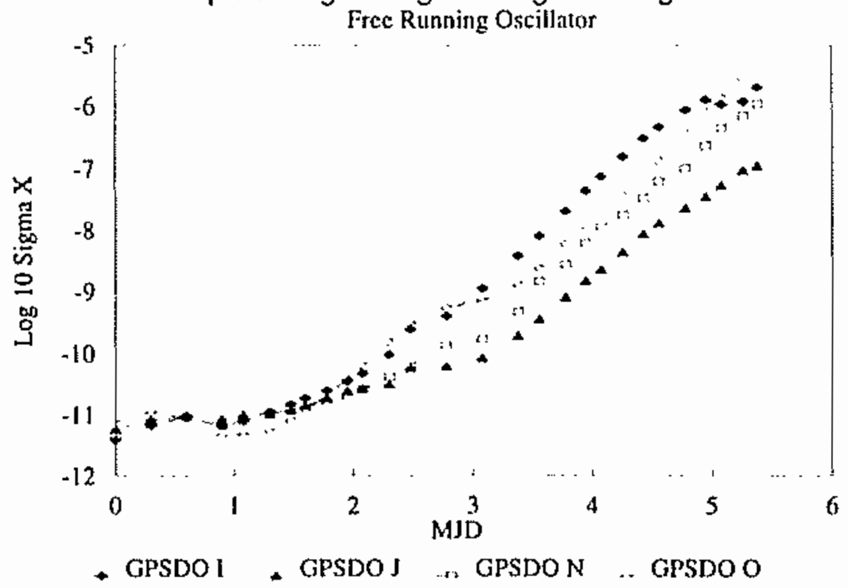


Table 9 : Frequency stability characteristics of GPSDO free running local oscillator at τ = 1,000s averaging time calculated from phase data.

GPSDO	σ_y	MOD σ_y	σ_x
A	2.6×10^{-11}	2.6×10^{-11}	1.5×10^{-8}
B	-	-	-
C	3.0×10^{-13}	2.0×10^{-13}	1.3×10^{-10}
D	3.6×10^{-13}	2.7×10^{-13}	1.6×10^{-10}
E	3.4×10^{-12}	2.7×10^{-12}	1.6×10^{-9}
F	3.5×10^{-11}	2.0×10^{-11}	1.2×10^{-8}
G	-	-	-
H	5.5×10^{-13}	5.0×10^{-13}	3.0×10^{-10}
I	1.5×10^{-12}	1.5×10^{-12}	1.0×10^{-9}
J	1.7×10^{-13}	1.3×10^{-13}	8.0×10^{-11}
K	7.0×10^{-12}	5.0×10^{-12}	2.8×10^{-9}
L	-	-	-
M	-	-	-
N	2.4×10^{-13}	6.0×10^{-13}	4.0×10^{-10}
O	1.4×10^{-12}	1.1×10^{-12}	7.0×10^{-10}

FIGURE 24(a-d) COMPARISONS OF GPSDOS AGAINST THEIR FREE RUNNING OSCILLATORS

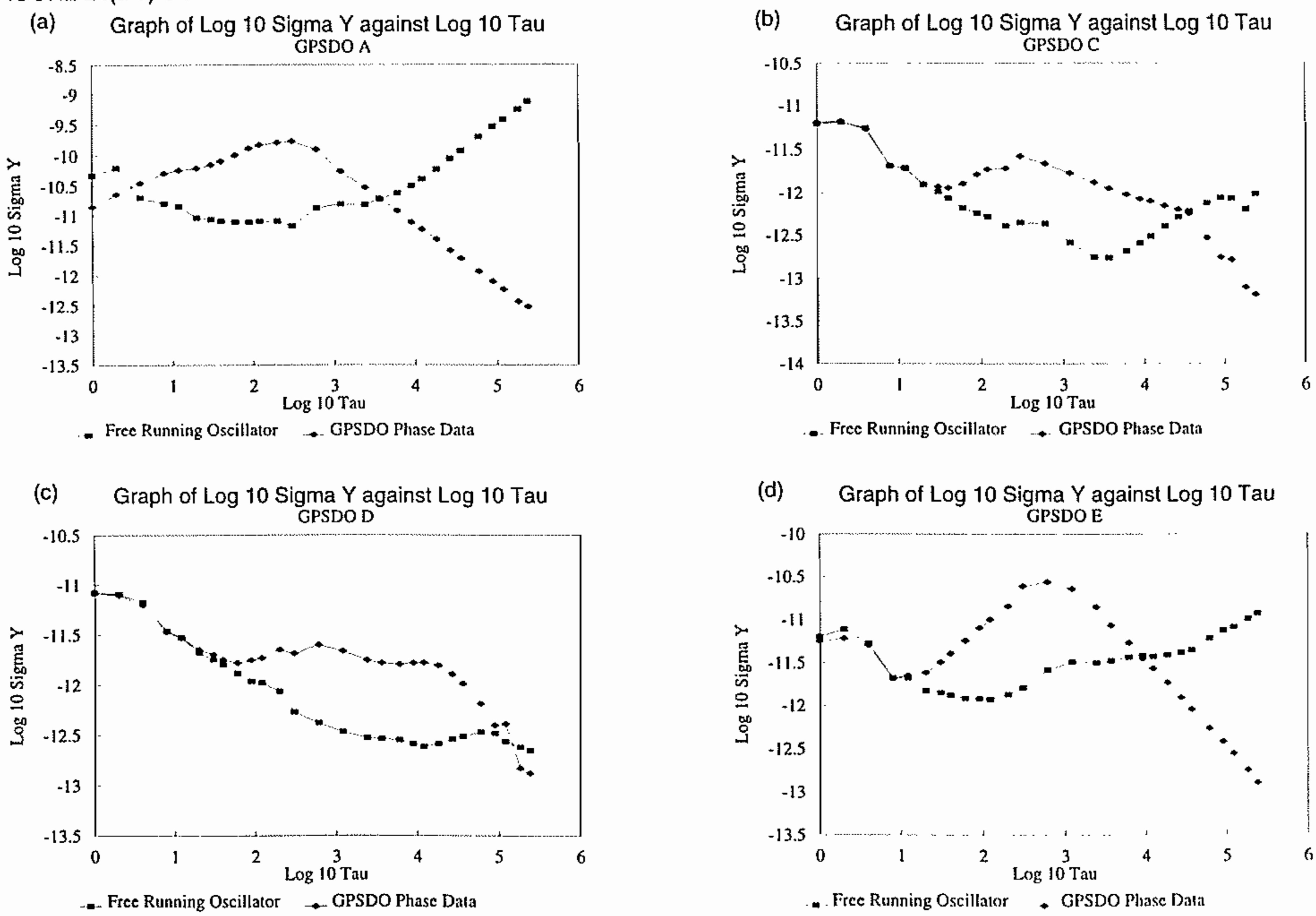
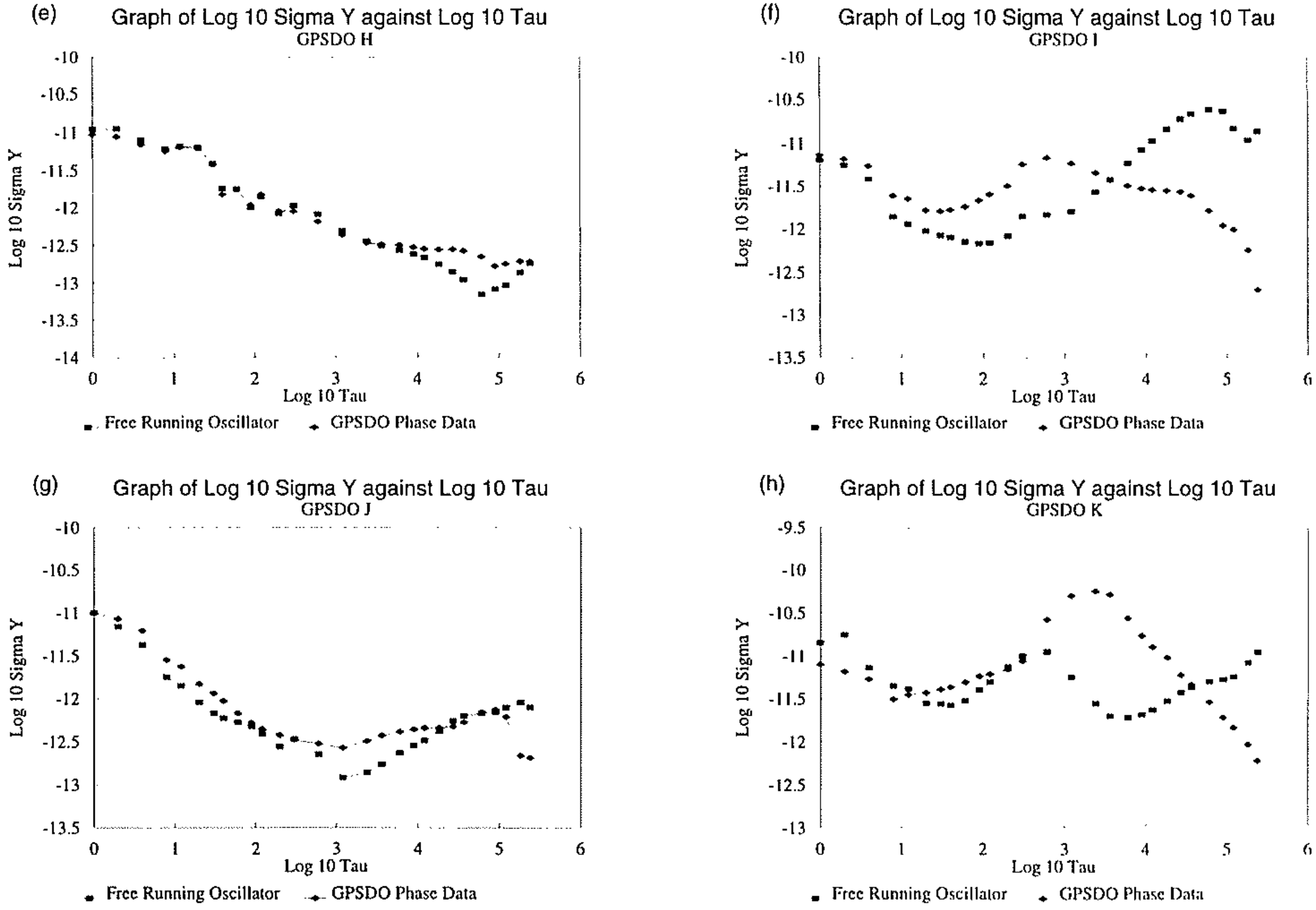


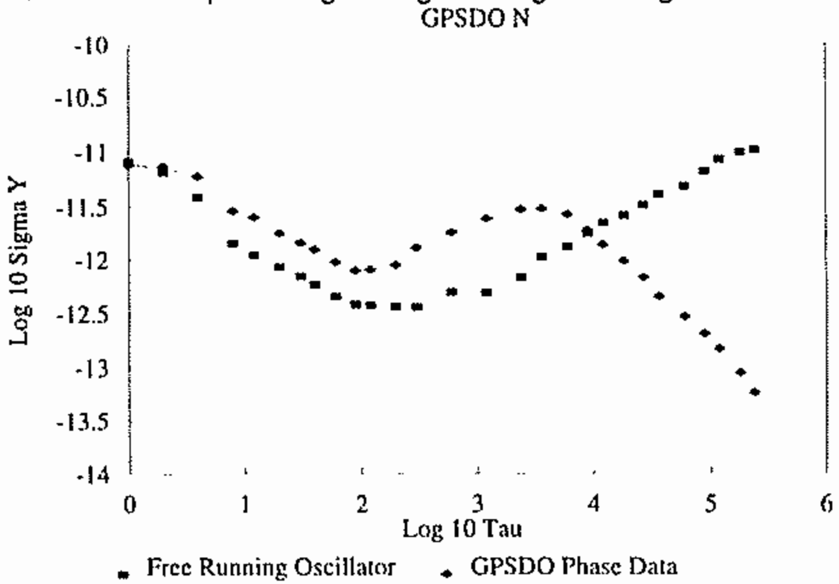
FIGURE 24(e-h)



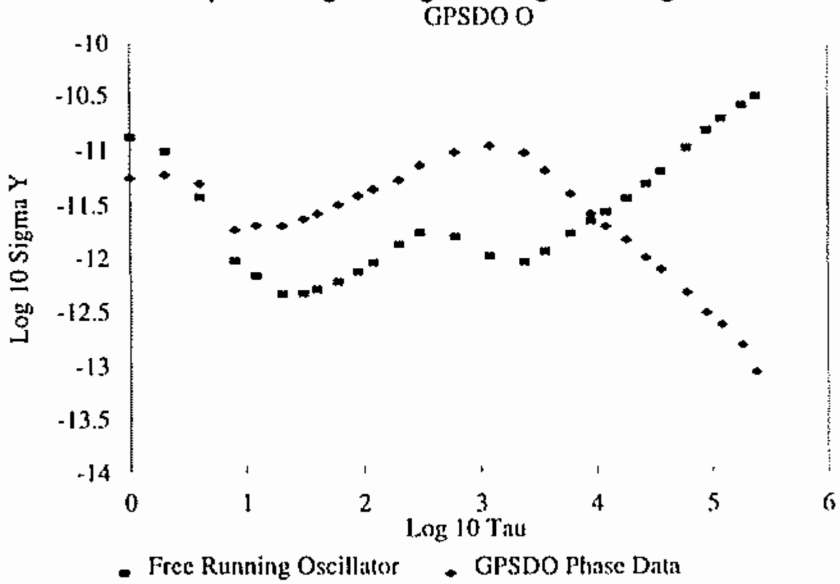
(e)
Graph of Log 10 Sigma Y against Log 10 Tau
GPSDO H
Log 10 Sigma Y
-10
-10.5
-11
-11.5
-12
-12.5
-13
-13.5
-14
0
1
2
3
4
5
6
Log 10 Tau
Free Running Oscillator
GPSDO Phase Data
(f)
Graph of Log 10 Sigma Y against Log 10 Tau
GPSDO I
Log 10 Sigma Y
-10
-10.5
-11
-11.5
-12
-12.5
-13
-13.5
0
1
2
3
4
5
6
Log 10 Tau
Free Running Oscillator
GPSDO Phase Data
(g)
Graph of Log 10 Sigma Y against Log 10 Tau
GPSDO J
Log 10 Sigma Y
-10
-10.5
-11
-11.5
-12
-12.5
-13
-13.5
0
1
2
3
4
5
6
Log 10 Tau
Free Running Oscillator
GPSDO Phase Data
(h)
Graph of Log 10 Sigma Y against Log 10 Tau
GPSDO K
Log 10 Sigma Y
-9.5
-10
-10.5
-11
-11.5
-12
-12.5
-13
0
1
2
3
4
5
6
Log 10 Tau
Free Running Oscillator
GPSDO Phase Data

FIGURE 24(i-j)

(i) Graph of Log 10 Sigma Y against Log 10 Tau



(j) Graph of Log 10 Sigma Y against Log 10 Tau



The short term frequency stability of all of the GPSDO free running oscillators is very similar, however there is wide variation in their long term performance. The long term performance of all free running oscillators is improved by disciplining. Many of the GPSDOs with less good local oscillators require disciplining with medium or short term time constants. The GPSDOs performance is significantly degraded over these averaging times, compared with the free running oscillator. However the long term disciplined performance can still be excellent.

GPSDOs (J) and (H) do not significantly degrade the performance of their free running oscillator. These GPSDOs have excellent medium term stability, but not quite so good long term stability.

The phase drift and frequency offset of the free running oscillators varies dramatically between those tested at NPL The maximum phase offset over a 7 day period varies between 300 ns and 6,000,000 ns. Likewise the maximum frequency offset varies between $3x10^{-12}$ and $1x10^{-8}$.

GPSDOs (G) and (H) did not freeze their DAC values on loss of the GPS signal. Many of the remaining GPSDOs freeze their DAC values at sub optimum values, due to short term GPSDO frequency instabilities.

We note that for applications where the user wishes to flywheel on the free running oscillator during the loss of GPS signal, that simply freezing the DAC value at the point the signal is lost does not offer the optimum solution. Schemes that monitor the average DAC values before signal loss may be preferable.

7) Correlations between GPSDOs

7.1) Introduction

It is interesting to examine the presence of any correlation between the outputs of GPSDOs, for example due to the reception of common GPS signals, or the presence of a common temperature and humidity environment. This is useful in separating errors originating within the GPSDO units, and those originating in the external environment, for example the GPS, the laboratory power supply and the local environment.

7.2) Study of correlation effects

A simple technique to study correlations between the outputs of the GPSDOs was applied, using a single day's 1PPS and phase data. GPSDOs were considered in pairs. The sums and differences of the 1PPS data (minute averages) and phase data (minute averages) were determined. The standard deviation of both the data sum and difference were calculated. A correlation between the outputs of two GPSDOs would result in a decrease in the scatter on the difference data and a corresponding increase in the scatter on the data sum. Results are tabulated below, several strong correlations are clearly observed in figure 25(a-d). In the case of the data sets consisting of non correlating white noise the following relationship would be expected to hold.

$$\sigma_{x+y}=\sigma_{x-y}=(\sigma_x^2+\sigma_y^2)^{1/2}$$

where σ_x and σ_y are the standard deviations of the original data sets, σ_{x+y} and σ_{x-y} are the standard deviations of the sums and differences respectively. Several relationships of this type were observed indicating that in this case there was no correlation between the outputs of the two GPSDOs.

Table 10: Correlation between GPSDO outputs (Phase Data).

GPSDO (X)	GPSDO (Y)	STANDARD DEVIATION (ns)			
		GPSDO (X)	GPSDO (Y)	Sum	Difference
A	B	36.6	8.63	58.8	27.6
E	O	17.0	14.3	29.5	12.4
A	K	36.6	107.0	111.7	114.4
A	D	36.6	7.3	36.4	37.4
E	G	17.0	17.4	28.6	19.2
E	I	17.0	14.0	26.4	16.9

FIGURE 25 (a-d) CORRELATION EFFECTS BETWEEN GPSDOS

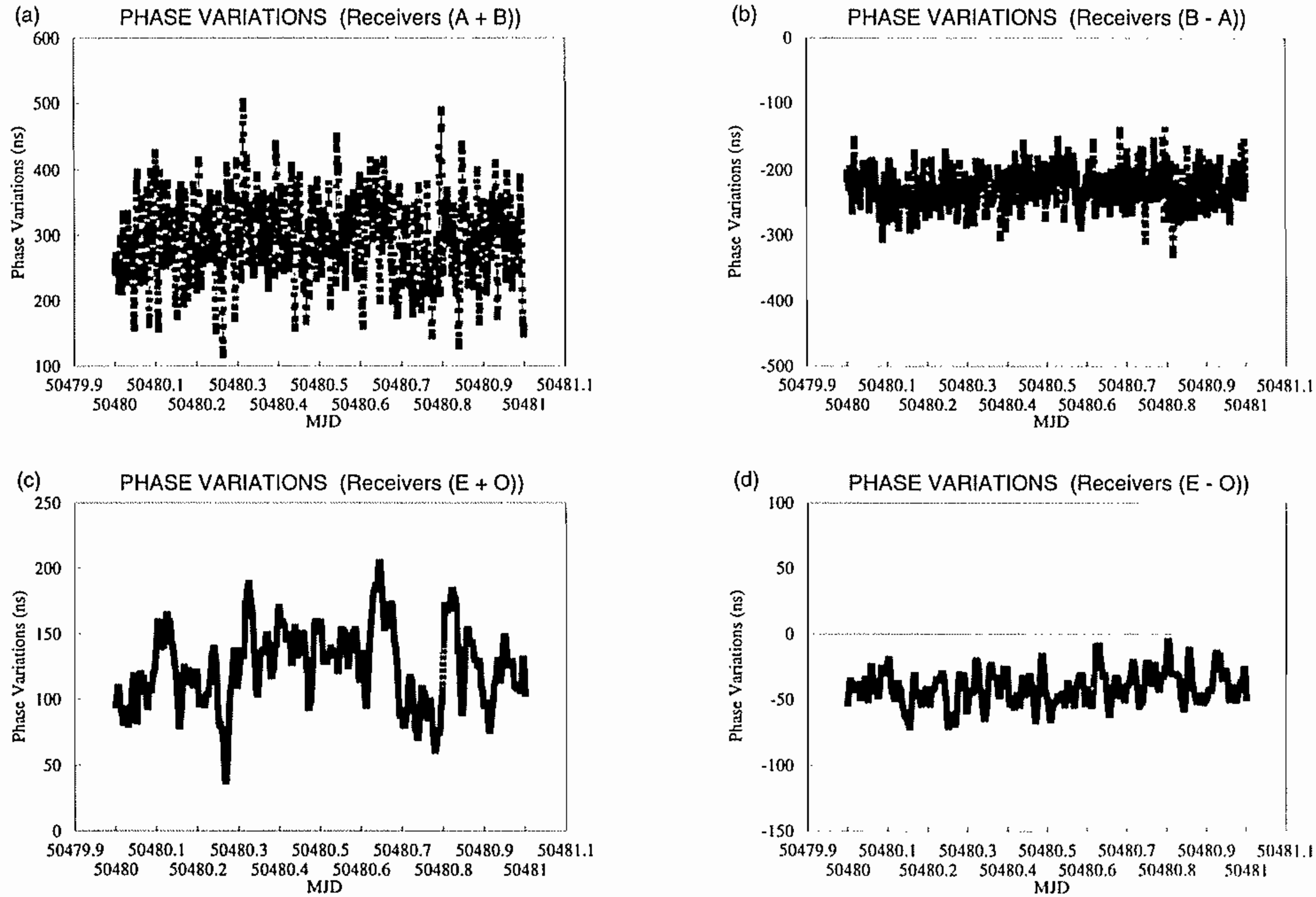
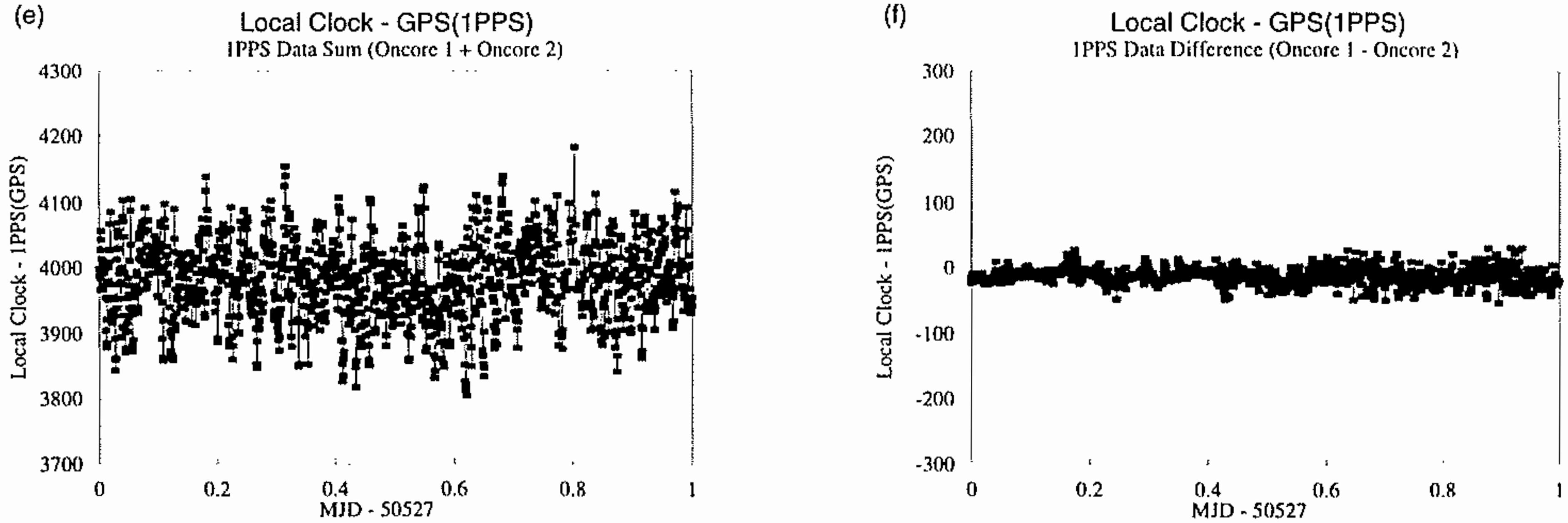


FIGURE 25 (e-f)


(e)
Local Clock - GPS(1PPS)
1PPS Data Sum (Oncore 1 + Oncore 2)
Local Clock - 1PPS(GPS)
4300
4200
4100
4000
3900
3800
3700
0
0.2
0.4
0.6
0.8
1
MJD - 50527
(f)
Local Clock - GPS(1PPS)
1PPS Data Difference (Oncore 1 - Oncore 2)
Local Clock - 1PPS(GPS)
300
200
100
0
-100
-200
-300
0
0.2
0.4
0.6
0.8
1
MJD - 50527

Sample results are shown in table 10. There was little or no correlation between GPSDOs (A and D) and (A and C). Strong correlations were observed between the GPSDO pairs (A and B), (E and O), (F and G) and (E and I).

Several trends were observed: There was very little or no correlation between the rubidium based GPSDOs over a period of up to one day, these GPSDOs appear to be using long time constant disciplining of their local oscillators. All the quartz based GPSDOs showed correlation effects with each other except GPSDO (K). It appears that the correlation effect was strongest when the time constants of the two disciplining algorithms are similar.

GPSDO (K) had a relatively large data scatter and used instantaneous coordinates. It is thought that in this case errors due to the use of instantaneously determined coordinates, which also originate from the effects of SA masked the correlation effects.

It is noticeable that the correlation effects between two co-located GPS receivers (figures 25 (e) and (f)) are much stronger than between the GPSDOs. This suggests that internal elements of the GPSDO, for example the oscillator and disciplining processes are contributing to the noise. Hence it also suggests that SA is the major contribution to instabilities common to different GPSDOs. It appears that the performance of the front end GPS receivers is not a limitation to the short or medium term performance of the GPSDOs.

7.3) Conclusions and recommendations

The correlation effects are due to the presence of SA which is applied to all but one of the GPS satellites. The correlation will not be complete because the GPSDO may not always be observing the same satellites, and the averaging effects of the local oscillator will be different for each GPSDO, even when observing the same constellation.

Evidence from the rubidium and quartz based GPSDOs, along with that from GPS timing receivers, indicate that the effect of SA can be almost completely eliminated with the appropriate combination of disciplining algorithm and stable oscillator. This result has significant implications for assigning uncertainty budgets for GPSDOs as traceable standards. Chapter 2 showed that SA is the dominant uncertainty in instantaneous GPS position calculations. Given the complicated interaction between the GPS information and the oscillator, a convenient starting point for uncertainty calculations is to take worst case figures for GPS timing solutions. For those units where the reduction of the effects of SA can be demonstrated there is a sound basis for reducing uncertainty figure below the worst case figure.

8) Antenna Coordinate Determination

8.1) Introduction

The determination of accurate antennae coordinates is vital for the optimum performance of GPSDOs. Because GPSDOs may be set up as traceable standards at a wide variety of possible antennae sites in the UK, there is always the possibility of the GPSDOs operating with degraded performance due to the use of inappropriate antenna locations. Antenna sites may vary both in the amount of clear sky available, and also in the presence of local obstacles, that may contribute to multipath effects. In this section, the normal coordinate determination of the GPSDOs under study will be examined. In chapter 10, the effect of GPSDO s operating with a reduced GPS satellite constellation and operating from erroneous coordinates, will also be examined. It is hoped that ultimately a guidance document will be produced outlining the procedures to follow when setting up GPSDOs as traceable standards at new locations.

8.2) GPSDO coordinates determined in this experiment

In this study, the GPSDOs were set up to initially determine their own coordinates. The GPSDOs may operate in one of several modes, these are outlined below:

a) Position hold mode
In this mode the initial determination of antenna coordinates is separated from the regular operation of the GPSDO. This is the most common mode of GPSDO operation. After performing a cold start, the GPSDO will receive GPS signals for an extended period, typically 24 hours. The GPSDO will then determine the mean antenna co-ordinates from the data. The GPSDO will then operate from fixed coordinates, based on its initial determination. This mode of operation also permits pre-determined coordinates to be entered into the GPSDO.

b) Position average mode
In position average mode the GPSDO will obtain an average of the antenna co-ordinates through averaging typically the last 24 hours data or data since the last cold restart.

c) Instantaneous position mode
The simplest mode is to use the instantaneously determined antennae co-ordinates.

The GPSDO coordinates have been determined by measuring the distance from the GPSDO antenna to a reference point whose coordinates have been previously determined by the Ordnance Survey. It is estimated that the coordinates of NPL's reference points has been determined with an uncertainty of a few cm [1]. The relative positions of the GPSDO antennae have been described in Appendix B. Their relative location on the laboratory roof is shown in figure 26.

Table 11(a)(columns 5-7) gives the coordinates determined by the GPSDO by using their internal GPS receivers. The same coordinates determined by measuring from NPL's surveyed points are

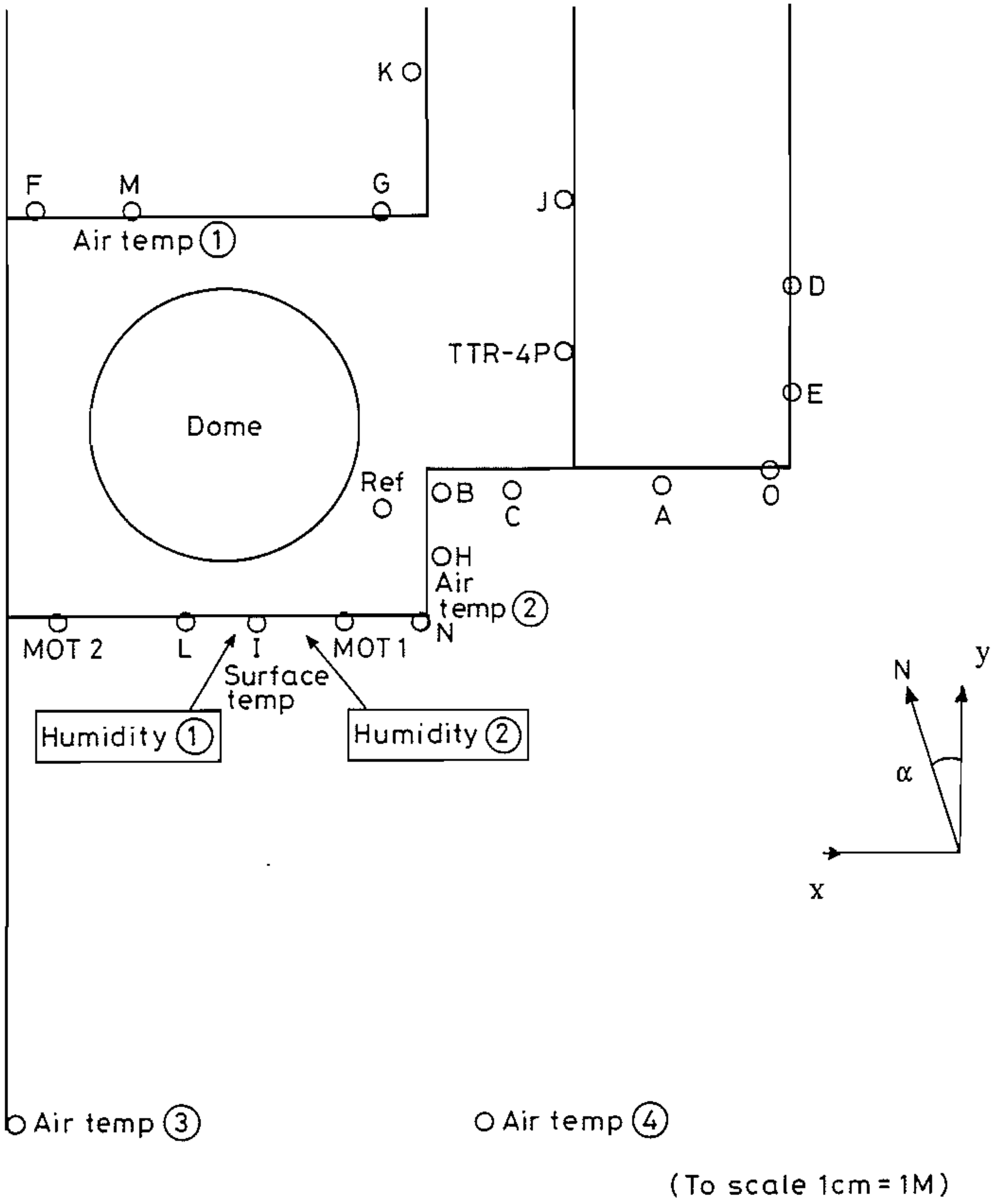


Figure 26: Location of GPS antennae, temperature and humidity probes on the roof of building(2)

Table 11a: GPSDO Antenna coordinates determined from site surveys and by the GPSDO receivers.

GPSDO	GPSDO Coordintes determined from Ordance Survey site survey			GPSDO coordinates determined by GPSDO receivers.		
	Latitude (N) - (51° 25') (Seconds of arc)	Longitude (W) - (0°20') (Seconds of arc)	Height above ellipsoid (m)	Latitude (N) - (51°25') (Seconds of arc)	Longitude (W) - (0°20') (Seconds of arc)	Height above ellipsoid (m)
A	15.37	23.02	74.1	15.4	22.56	94
B	15.41	23.11	72.3	15.54	22.79	46
C	15.4	23.08	72.3	15.68	22.67	118
D	15.46	22.97	74.1	15.0	22.2	74
E	15.4	22.98	74.1	15.59	22.54	79
F	15.62	23.22	72.3	15.61	23.22	75.2
G	15.56	23.11	72.1	15.36	23.04	80
H	15.37	23.11	72.3	15.3	23.16	77
I	15.35	23.18	72.3	15.54	23.34	83.4
J	15.55	23.03	74.9	15.72	23.1	83.7
K	15.63	23.09	72.1	15.84	23.28	112
L	15.29	23.08	72.3	15.0	23.0	81.9
N	15.32	23.12	72.3	15.3	23.1	73
O	15.36	22.99	72.4	14.4	22.7	81

Table 11b: GPSDO Antenna coordinate errors and method of coordinate determination.

GPSDO	Method of coordinate determination	GPSDO Coordinate Errors (m)			
		Latitude North - South	Longitude East - West	Height above ellipsoid	Total Error
A	Position Hold	1.01	24.4	19.9	31.5
B	Position Hold	3.99	16.4	26.3	31.2
C	Position Hold	8.75	21.8	45.8	51.4
D	Position Hold	14.4	14.8	0.1	20.6
E	Position Hold	6.04	23.4	4.9	24.6
F	Unknown	0.32	0.09	2.92	2.94
G	Position Hold	6.18	3.65	7.92	10.7
H	Position Hold	2.21	2.51	4.72	5.79
I	Position Hold	5.79	8.42	11.1	15.1
J	Position Hold	5.43	3.48	8.82	10.9
K	Instantaneous Position	6.44	10.3	39.9	41.7
L	Unknown	9.06	3.63	9.6	13.7
N	Position Average	0.75	1.28	0.72	1.65
O	Position Average	29.8	15.2	8.62	34.5
MR1	Position Hold	9.86	11.3	3.12	15.32
MR2	Position Hold	1.26	2.49	9.66	10.05
TTR-4P	Position Hold	7.49	15.9	3.52	17.93

shown in columns 2-4. The mode of GPSDO coordination determination and the errors in the GPSDOs determination of their own coordinates are shown in table 11(b). WGS 84 coordinates are assumed.

8.3) Errors in the GPSDO coordinate determination.

The coordinate determination errors ranging between 1.7 m and 51 m. The wide range of GPSDO coordinate errors was particularly surprising. There was no correlation between the frequency performance of GPSDOs and the determination of their antennae coordinates. Several of the most stable GPSDOs for example (C) have relatively badly determined antenna coordinates. In contrast several of the GPSDOs with excellent antennae coordinates (F) are relatively poorly performing GPSDOs.

Where there is a combination of poorly determined antennae coordinates and highly stable GPSDOs, the frequency transfer performance of the GPSDO is limited by the coordinate determination. This may be demonstrated by averaging data from the same sidereal time of successive days. Figure 28 illustrates a repeating daily time transfer variation, most probably caused by poor antennae coordinates. A good example of daily variations is shown by GPSDO C where an otherwise extremely good performing GPSDO is limited by relatively poor coordinate determination. Where the antennae coordinates are well determined, or when the GPSDO is of less high quality, the GPSDO performance is not limited by the antennae coordinate determination.

There was a relationship between the method of antennae coordinate determination and the accuracy of the coordinates. When the GPSDOs were using instantaneously determined coordinates, these were usually poorly determined. GPSDOs operating using "position hold" mode had a wide variation of coordinate errors. The dependence of these errors on the initial coordinate determination, especially the quantity of data averaged, requires further examination.

Erroneous antennae coordinates will degrade the absolute time transfer characteristics of the GPSDOs. However in practice , the study did not reveal a correlation between large coordinate errors and errors in the time dissemination, indicating that the time dissemination errors are being dominated by unknown delays, probably related to GPSDO hardware delays.

8.4) Conclusions and recommendations.

There was a very wide variation in the GPSDO coordination errors. Only when there is a combination of poor coordinate determination and otherwise excellent GPSDO performance, was the antennae coordinate determination limiting the performance of the GPSDOs.

There are several implications regarding the traceability of GPSDOs:

1) When considering time dissemination traceability, there is a need to calibrate the GPSDO internal delays as these can, from the evidence in this chapter, dominate the error budget.

2) When considering both time and frequency traceability, there is a need to assess the magnitude of the local position errors, and to determine when these first become significant in the overall uncertainty budget.

3) Where position errors are important, the cost of GPSDO installation could be reduced if appropriate self validation schemes are possible.

8.5) References

[1] PH Denys, Paul A Cross, *The Ordnance Survey Scientific GPS Network 1992 Scinet*, University of Newcastle upon Tyne, Newcastle upon Tyne, Final report - Version 3.0 Report Number 93/0602, page 28, 1993.

9) Case Studies

9.1) Introduction

In sections 3-8 of this report various aspects of the performance of the GPSDOs under test have been studied, and the results related to the traceability of GPSDOs to UTC(NPL). In this section the performance characteristics of individual GPSDOs are brought together, in order to give an overall picture of several typical GPSDO units. The characteristics of each GPSDO is summarised in Table 12.

Table 12: Performance characteristics of GPSDOs (E),(H), (N) and (K).

CHARACTERISTIC	GPSDO E	GPSDO H	GPSDO N	GPSDO K
UTC(USNO) -GPSDO(1PPS)	34 ns	-104.5 ns	22 ns	397 ns
Standard Deviation (Individual 1PPS readings)	18 ns	31.2 ns	9.9 ns	97.7 ns
Standard Deviation (Hourly Means, 1PPS readings)	11.4 ns	31.4 ns	9.5 ns	67.5 ns
Phase Data $\sigma_y(\tau=1s)$	$6.0x10^{-12}$	$8.0x10^{-12}$	$6.0x10^{-12}$	$4.6x10^{-12}$
Phase Data $\sigma_y(\tau=1,000s)$	$2.5x10^{-11}$	$4.0x10^{-13}$	$2.5x10^{-12}$	$7.5x10^{-11}$
Phase Data $\sigma_y(\tau=100,000s)$	$2.5x10^{-13}$	$2.0x10^{-13}$	$1.6x10^{-13}$	$1.8x10^{-12}$
Mean Frequency Offset (τ=1s).	$2.0x10^{-11}$	$1.2x10^{-11}$	$1.0x10^{-11}$	$2.0x10^{-11}$
Mean Frequency Offset (τ=1,000s).	$1.6x10^{-11}$	$5.0x10^{-13}$	$3.0x10^{-12}$	$2.0x10^{-11}$
Mean Frequency Offset (τ=100,000s).	$3.0x10^{-14}$	$1.6x10^{-13}$	$4.0x10^{-14}$	$2.0x10^{-14}$
Free Running Oscillator σ_y (τ=1s)	$6.0x10^{-12}$	$1.2x10^{-11}$	$6.0x10^{-12}$	$2.0x10^{-11}$
Free Running Oscillator σ_y (τ=1,000s)	$2.0x10^{-12}$	$6.0x10^{-13}$	$4.0x10^{-13}$	$4.5x10^{-12}$
Free Running Oscillator $\sigma_y(\tau=100,000s)$	$6.0x10^{-12}$	$6.0x10^{-14}$	$5.0x10^{-12}$	$1.5x10^{-11}$
Transients	No	Yes	No	No
Maximum Amplitude	-	100 ns	-	-

CHARACTERISTIC	GPSDO E	GPSDO H	GPSDO N	GPSDO K
Correlation Effects	Yes	No	No	No
Coordinate Errors	24.6 m	5.8 m	1.7 m	41.7 m
Approximate time constant of disciplining	1,000 s	1 Day	4,000 s	2,000 s
Mode of Operation	Position Hold	Position Hold	Position Average	Position Average
Phase / 1PPS correlation	Yes	Yes	Yes	Yes

9.2) GPSDO (E)

GPSDO (E) is based on a medium quality quartz oscillator. The unit is well manufactured, allowing substantial information to be obtained via the RS232 port. The GPSDO may be easily controlled via either the front panel or the RS232 port. The GPSDO operates in a position hold mode . There is substantial user control of the GPSDO operating parameters . A loss of GPS signal is reported via a front panel warning light.

The GPSDO displays excellent long term performance, close to the performance of the best GPSDOs. The short and medium term performance is not so good , particularly with averaging times (τ) of around 1,000 s. There have been shown to be significant degrading of the free running oscillator performance around this averaging time. The frequency offsets are correspondingly high for medium averaging times, but are good in the long term. The GPSDO disciplining becomes effective with averaging times of around 1,000 s. Phase and 1PPS outputs are correlated.

There are strong, short and medium term correlation effects with other quartz based GPSDOs. The unit under test has shown no transients, long term delay drifts or delay steps. The mean absolute time dissemination error (UTC(USNO) - GPSDO(1PPS)) of 34 ns was excellent. The coordinate determination error of 24.6 m was large. This does not limit the frequency determination accuracy, but may limit the time dissemination accuracy, because other contributions to this error appear to be small.

In summary GPSDO (E) is a well engineered quartz based GPSDO with excellent long term performance. Short and medium term performance is limited by the disciplining of the quartz oscillator, which is probably required to achieve this long term performance.

9.3) GPSDO (H)

GPSDO (H) is based on a high quality Rubidium oscillator. The unit provides significantly less information via its RS232 port than either GPSDO E or N. An improved software upgrade did however become available towards the end of the study. The GPSDO operates in a position hold mode. Although the user has some control on the operating parameters, for example antenna coordinates, this is not comparable to the control available via GPSDOs E and N. The loss of GPS signal was flagged by a front panel warning light.

GPSDO (H) has excellent medium term stability (τ = 1,000 s - 10,000 s), this has been attributed to the use of an extremely high quality Rubidium oscillator. There is very little short or medium term degrading of the free running oscillator performance, Only at averaging time close to 1 day are there any significant effects. Despite this excellent medium term performance, the long term performance was slightly disappointing. The mean frequency offset is excellent over the medium term but again slightly disappointing over the longer term. GPSDO (H) may be operating with time constants as long as 1 day. Phase and 1PPS outputs are correlated.

The absolute time error (UTC(USNO) - GPS(1PPS)) of 104.5 ns is typical for the GPSDOs under study. There were no noticeable correlation effects with other GPSDOs . These would not be expected due to the long time constant of the disciplining algorithm. The coordinate determination errors of 5.8 m was better than average , and is unlikely to contribute significantly to the overall error budget.

Several small transients of around 100 ns amplitude were observed. This was unusual for a Rubidium based GPSDO, and may be due to a fault in the disciplining algorithm. The GPSDO did occasionally "hang up" although this did not happen with the latest software version.

In summary, GPSDO (H) gives excellent medium term performance, which may be achieved at the expense of the longer term performance. The occurrence of transients is disturbing and requires further investigation by the manufacturer.

9.4) GPSDO (N)

GPSDO (N) is a high performing Rubidium based GPSDO. The unit is well manufactured, with an excellent RS232 interface, and substantial user control via either the front panel or RS232 port. The loss of the GPS signal, while being recorded in the RS232 data does not however trigger a front panel warning light.

The short, medium and long term performances of the GPSDO are all excellent although the medium term performance is not quite as stable as GPSDO (H). The mean frequency offset performance was similarly excellent. The disciplining becomes effective at averaging times around 4,000 s. There is some medium term degrading of the free running oscillator performance by the GPSDO disciplining process.

The GPSDO operates under a position average mode. This resulted in the GPSDO having extremely small coordinate determination errors, presumably due to calculating the antennae coordinate from an extended set of GPSDO data. The absolute time error (UTC(USNO) - GPSDO(1PPS)) of 22 ns was small. There were no significant correlation effects, with other GPSDOs . There were no transients, delay steps or long term delay drifts. Phase and 1PPS outputs are correlated.

In summary GPSDO (N) would behave excellently as a standard traceable to UTC(NPL).

9.5) GPSDO (K)

GPSDO K is a less expensive quartz based GPSDO. The GPSDO is well manufactured, information may be obtained either directly from the RS232 port or via software supplied with the unit. There was however little possibility of user control of the unit operating parameters. A loss of GPS signal is reported via a front panel warning light.

The short term frequency stability (τ = 1s) was typical, however the medium term frequency stability (τ=1,000 s) and frequency offset were noticeably less good when compared with the other GPSDOs reported in this section. In the long term (τ > 100,000 s) the disciplining process is effective.

GPSDO (K) operates using an instantaneous position mode. This may explain both the relatively large medium term GPSDO instabilities and the lack of correlations between the output of GPSDO (K) and other GPSDOs. The antennae coordinate errors were both large and varying. It is the variability rather than the magnitude of this error that may be degrading the GPSDO performance.

The phase and 1PPS outputs are correlated, there were no transients or delay steps. The value of UTC(USNO) - GPSDO(1PPS) was large but not untypical for the GPSDOs under test. The performance of the free running oscillator was obscured by a residual modulation, presumably applied to the DAC voltage. Despite this, it is clear that the performance of the free running oscillator is significantly degraded by the disciplining process. This is particularly evident for averaging times (τ) between 1,000 and 10,000s. The time constant of the disciplining algorithm appears to be around 2,000 s.

In summary GPSDO (K) performs satisfactory, however the design may not be optimum, particularly in the use of instantaneously determined coordinates.

9.5) Conclusion

The GPSDOs discussed above were typical of the GPSDOs studied. It is hoped that a complete picture may be determined for each GPSDO from which an assessment may be made as to its suitability as a standard traceable to UTC(NPL).

10) Performance of GPSDOs under 'Non-Ideal' Operating Conditions

10.1) Introduction

In this section, preliminary results are presented on the time and frequency output characteristics of the GPSDOs under a selection of 'non-ideal' operating conditions, e.g., if the antenna location has a restricted view of the sky or if inaccurate antenna coordinates are used. In particular studies of trends and variations in the performance of the GPSDOs are made for a reduced satellite constellation, a change of antenna coordinates, a complete loss of GPS satellite signal and also when there is a temporary loss of mains power. For each test made, a description of the test and the outcome is discussed. Recommendations are made for procedures to be followed when setting up GPSDOs at new installations and on their operation.

10.2) Operational characteristics with a reduced GPS satellite constellation

10.2.1) Introduction

A key part of the study is to determine the effect of operating the GPSDO from a reduced satellite constellation. A number of GPSDOs were selected which had the capability of changing the number of satellites being tracked. Receivers without this capability, were left to run as a control group. Two techniques (e.g., change of mask angle or deselection of satellites) were used to reduce the number of satellites in view depending on the capabilities of the GPSDO. Both methods are described in turn.

10.2.2) Change of receiver mask angle

Six of the GPSDOs under test: (A), (B), (C), (E), (I) and (J), could be programmed for a change of mask angle. Four of these receivers were selected and the mask angle was changed in increments of 10° or each change in mask angle, the GPSDO was left to run continuously for forty-eight hours. The measurement schedule used is given in table 12, along with mean and standard deviation values calculated from the 1PPS data. For GPSDOs (A) and (E), it was noticeable that as the mask angle was increased, this had very little effect on the average value of the 1PPS data, and only a gradual increase in the standard deviation. The 1PPS output from GPSDO (B) became unstable after a mains power failure and the 1PPS output was no longer usable. Problems were experienced with GPSDO (C); new mask angles programmed into the front panel of the receiver had very little effect on the phase and 1PPS output, even for mask angles of 60° where it became noticeable for other GPSDOs. This suggests that either the receiver was not responding to these new changes or that more information is necessary for the user to operate the GPSDO.

Graphs of variation in the phase data (Local clock - GPSDO (E)) as a function of mask angle are shown in figures 27(a) to (c). For GPSDO (E), the effect of increasing the mask angle resulted in an increase in the standard deviation in the 1PPS data. On MJD 50503 when the mask angle was increased to 50°, a large step, i.e., -100 ns, was introduced in the phase output.

Table 13: Mean (Local Clock-GPSDO) and standard deviation results as a function of change in mask angle for each receiver.

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	Mask angle
A	50496	12,060	13:32	1861	37	15°
A	50496	5,700	6:16	1869	41	20°
A	50497	21,360	23:56	1867	45	20°
A	50498	10,260	11:36	1871	40	20°
A	50498	8,640	10:28	1879	52	30°
A	50499	21,420	23:56	1877	46	30°
A	50500	9,060	10:00	1877	46	30°
A	50500	9,780	11:28	1873	56	40°
A	50501	21,480	24:00	1872	57	40°
A	50502	21,480	24:00	1871	60	40°
A	50503	11,940	13:12	1881	57	40°
A	50503	7,680	10:04	1879	76	50°
A	50504	9,300	10:36	1886	72	50°
A	50505	2,400	2:36	1867	75	60°
A	50505	6,480	8:36	1830	287	60°
A	50506	12,360	23:56	1872	95	60°

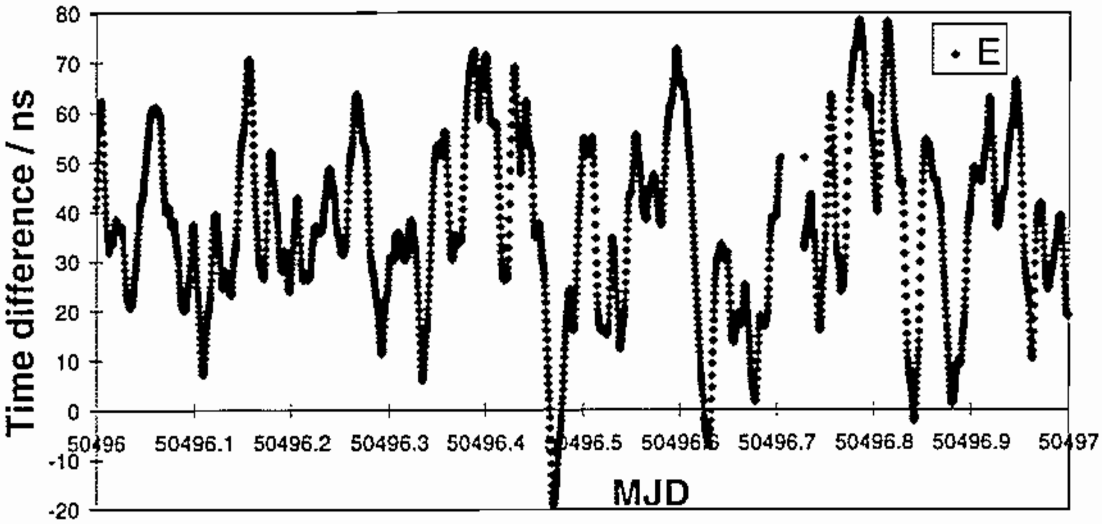
GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	Mask angle
B	50496	12,060	13:33	2659	29	10°
B	50496	5,700	6:16	2667	31	10°
B	50497	21,360	23:56	2670	33	10°
B	50498	10,200	11:32	2664	31	30°
B	50498**	-	-	-	-	-

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	Mask angle
C	50496	10,020	17:36	1996	4	10°
C	50496	5,640	6:12	2005	4	20°
C	50497	19,380	23:56	2004	11	20°
C	50498	9,180	14:24	1996	8	20°
C	50498	1,080	1:08	1996	2	30°
C	50498**	3,660	5:16	1995	3	30°
C	50499	12,900	23:56	1994	7	30°
C	50500	8,940	9:56	1997	5	30°
C	50500	3,120	4:52	2010	4	40°
C	50501	15,060	18:24	1998	8	40°
C	50502	15,300	3:40	2007	9	40°
C	50503	4,020	8:00	2002	4	40°
C	50503	7,680	10:08	2002	3	50°
C	50504	2,460	3:36	2003	2	50°
C	50505	4,980	8:40	1999	6	60°
C	50506	18,000	23:56	1996	9	60°

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	Mask angle
E	50496	12,060	13:32	2114	19	10°
E	50496	5,700	6:16	2118	19	20°
E	50497	21,360	23:56	2121	21	20°
E	50498	10,200	11:32	2124	20	20°
E	50498	8,760	10:28	2119	17	30°
E	50499	21,360	23:56	2117	21	30°
E	50500	9,060	10:00	2119	20	30°
E	50500	9,840	11:28	2120	28	40°

Figure 27: Variation on the phase data (Local Clock - GPSDO (E)) as a function of mask angle

(a) 20 degree mask angle



(b) 30 degree mask angle

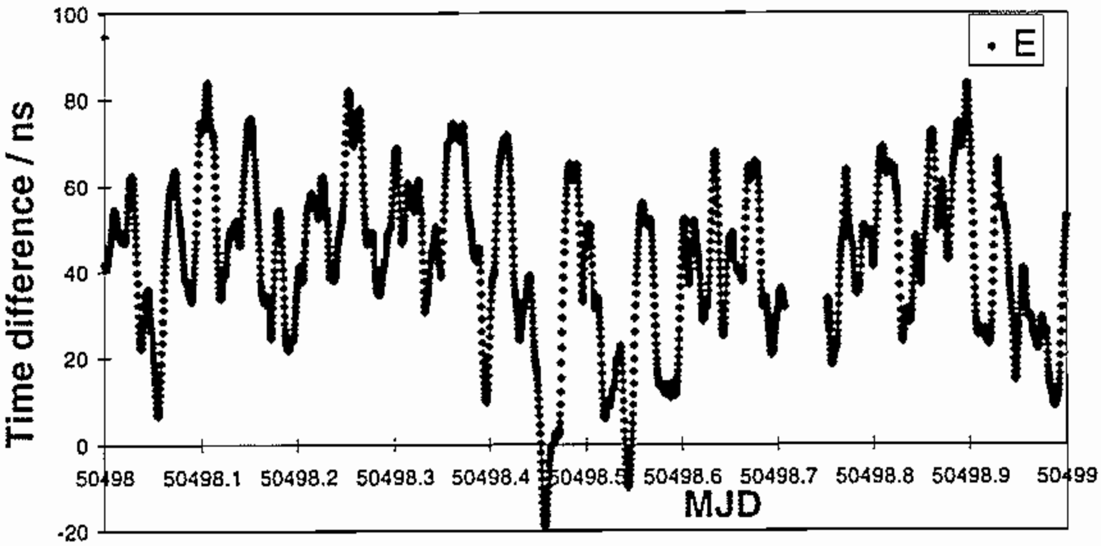
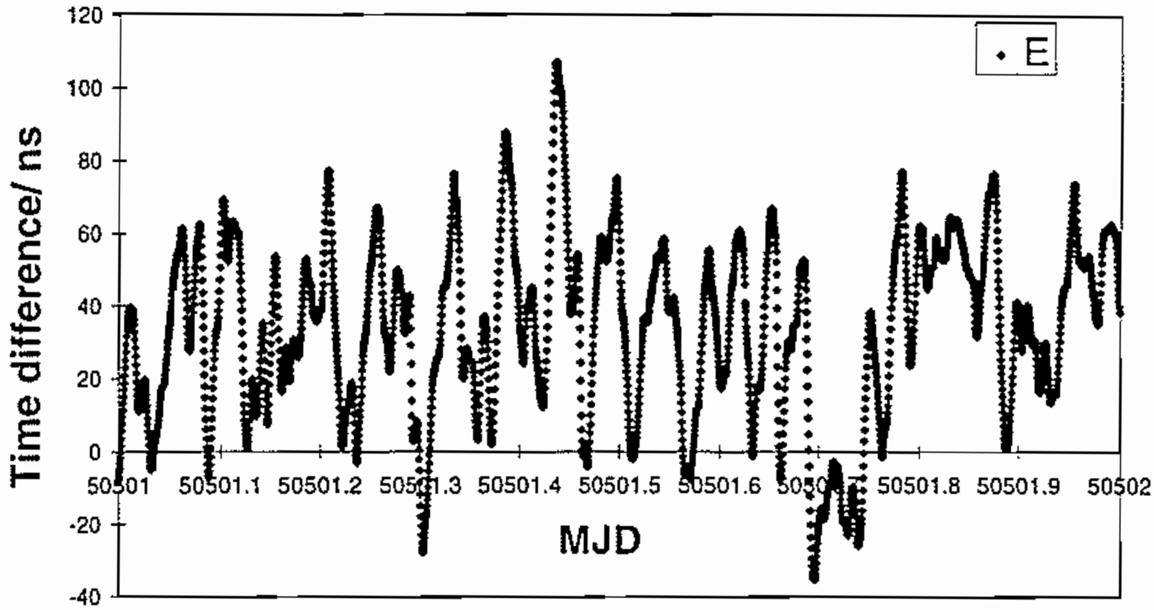


Figure 27(cont...): Variation on the phase data (Local Clock - GPSDO (E)) as a function of mask angle

(c) 40 degree mask angle



(d) 50 degree mask angle

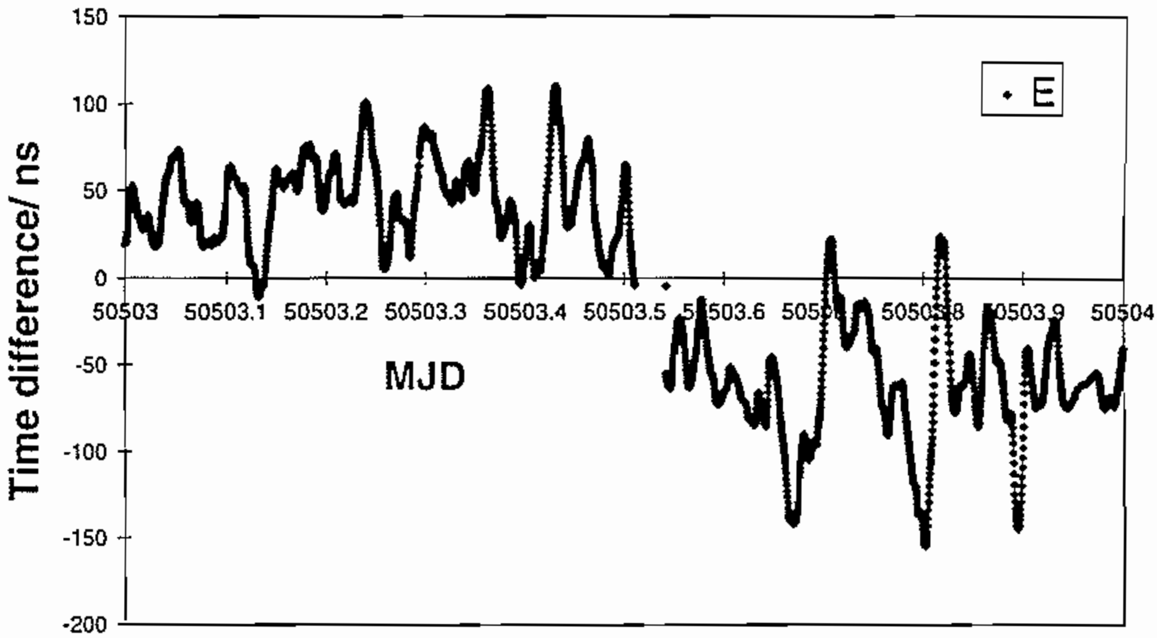


FIGURE 27 (cont...): Variation on the phase data (Local Clock - GPSDO (E)) as a function of mask angle

(e) 60 degree mask angle

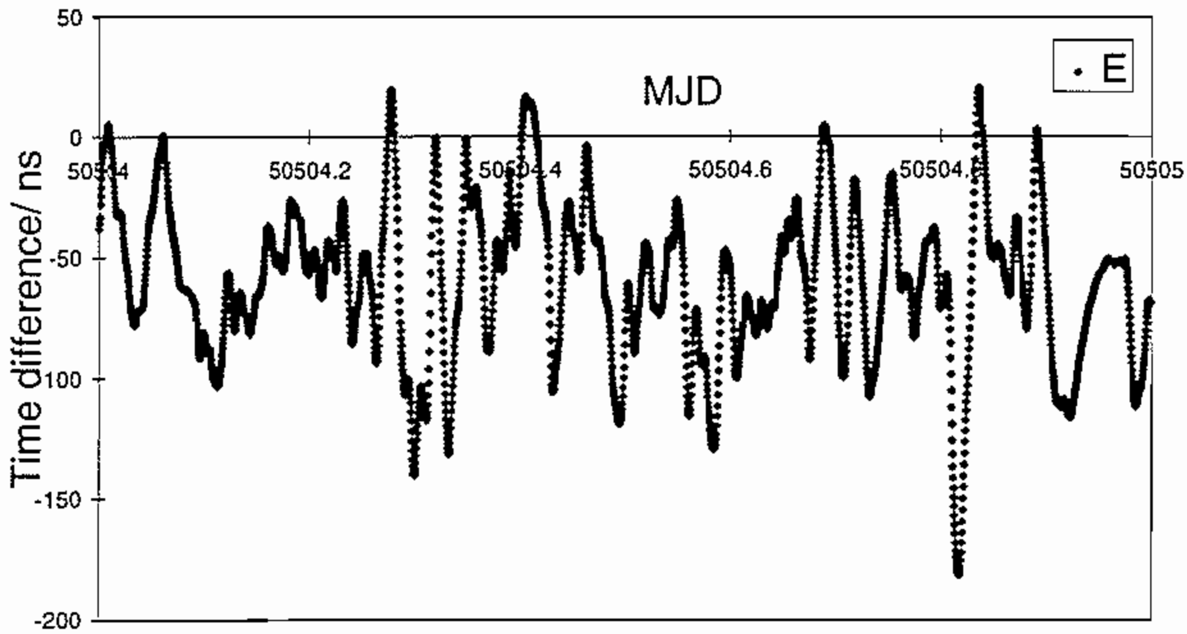
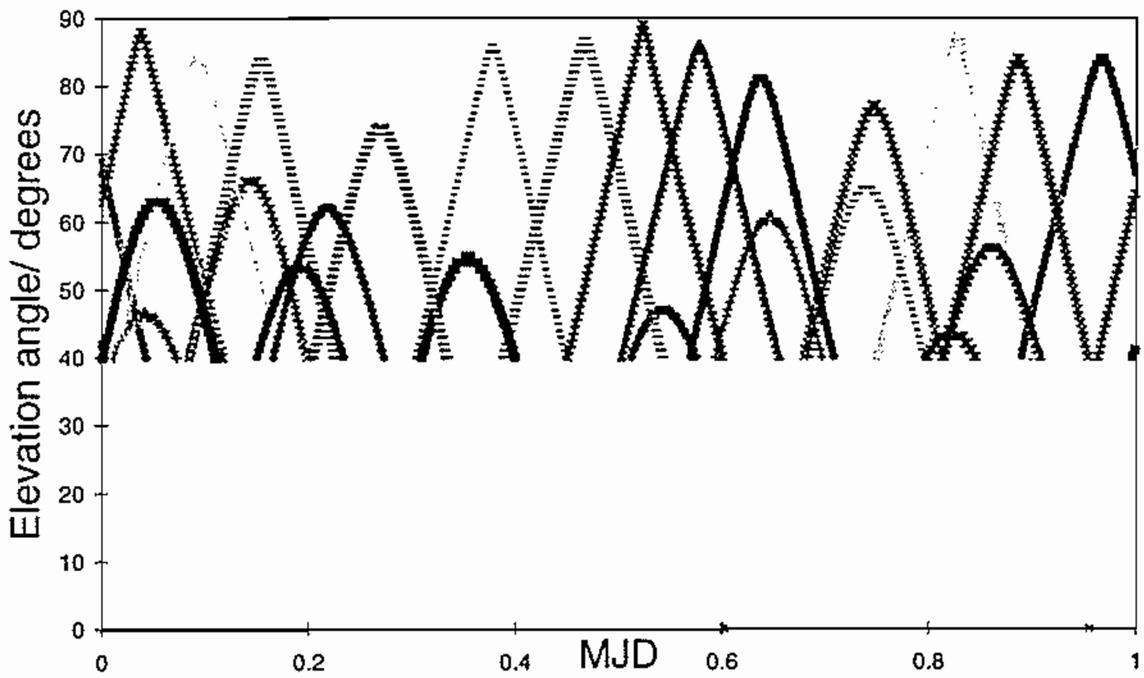


FIGURE 28: Elevation angles plotted for each satellite during the course of the day, GPSDO (E), mask angle = 40 degrees, MJD = 50501



GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	Mask angle
E	50501	21,360	23:56	2111	25	40°
E	50502	21,420	23:56	2116	25	40°
E	50503	11,940	13:12	2122	25	40°
E	50503	7,560	10:04	2114	38	50°
E	50504	21,480	23:56	2118	33	50°
E	50505	11,880	13:29	2116	28	50°
E	50505	7,800	8:36	2105	50	60°
E	50506	21,420	23:56	2121	52	60°

** power failure at 17:00 on MJD 50498

Figure 28 is a typical plot showing the satellite constellation tracked by the receiver as a function of time for MJD 50501 obtained for GPSDO (E). This plot illustrates the performance of the receiver after a mask angle of 40° had been programmed into the receiver. For some receivers, e.g., GPSDO (C), the receiver did not correspond to changes made to the software, and it was important to keep a record of all changes made to the receiver via the RS232 port.

10.2.3) Deselection of satellites

A second technique of reducing the available satellite constellation was to deselect satellites. Four of the GPSDOs: (I), (J), (N) and (O), could be programmed to allow the deselection of satellite vehicles. Typically two to four satellites were incremently removed from the available satellite constellation. The measurement schedule is listed in table 14(a). All the satellites deselected had been chosen from the recorded satellite constellation of the GPSDO. Typically once the satellites had been deselected, the GPSDOs were left to run for approximately forty-eight hours before any further changes were made. Table 14(b) gives values for the mean and standard deviation for the 1PPS output from the four receivers studied.

Graphs which show the vaiation in phase data (Local Clock-GPSDO(O)) as a function of the number of satellites deselected are shown in figures 29 (a) to (e). As the number of deselected satellites increases the offset in the phase data becomes larger. The occurrence of a large deviation on MJD 50504 (figure 29 (d)) also occurs in the 1PPS output for the receiver, and is probably due to a transient. The source of this transient remains to be investigated further.

Figure 29: Variation in the phase data (Local Clock-GPSDO(O)) during the deselection of satellites

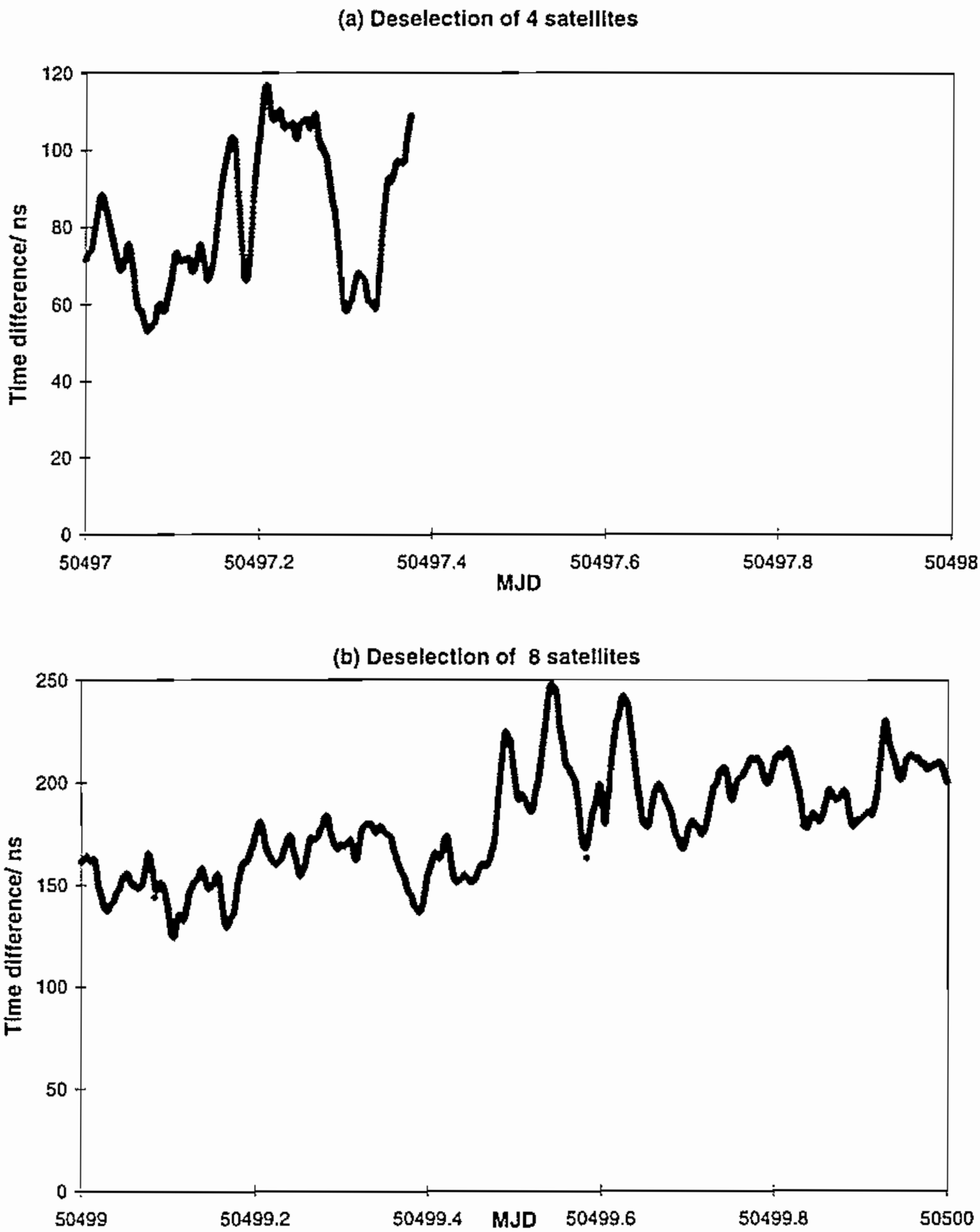
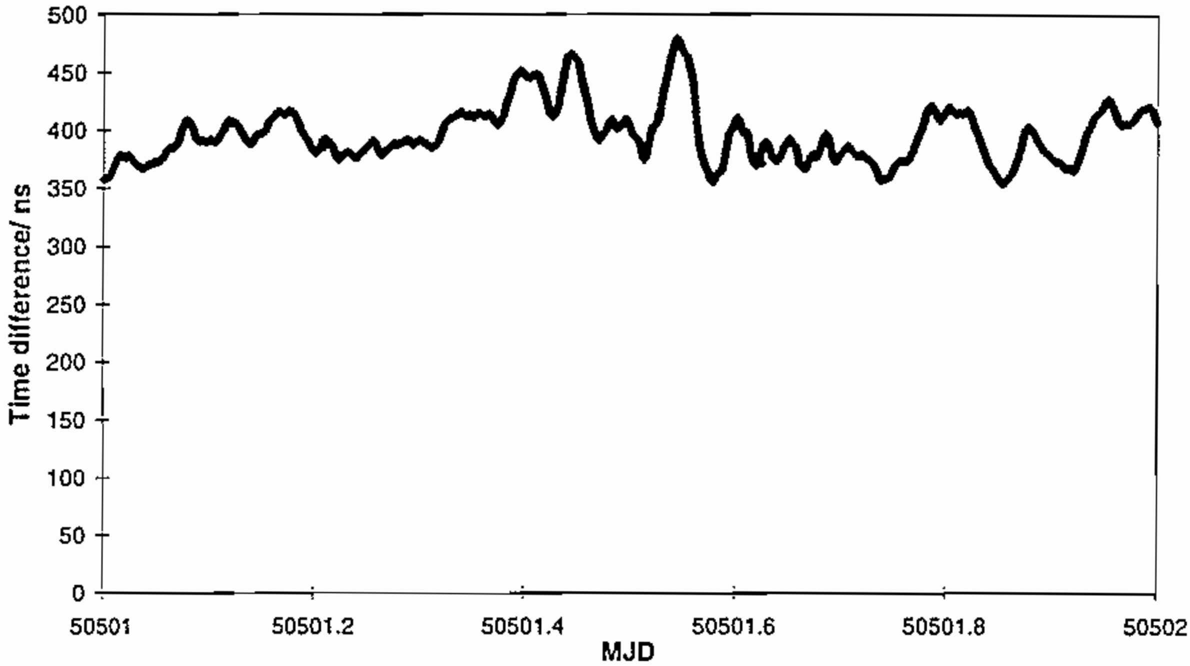


Figure 29 (cont...): Variation on the phase data (Local Clock-GPSDO (O)) during the deselection of satellites.

(c) Deselection of 10 satellites



(d) Deselection of 12 satellites

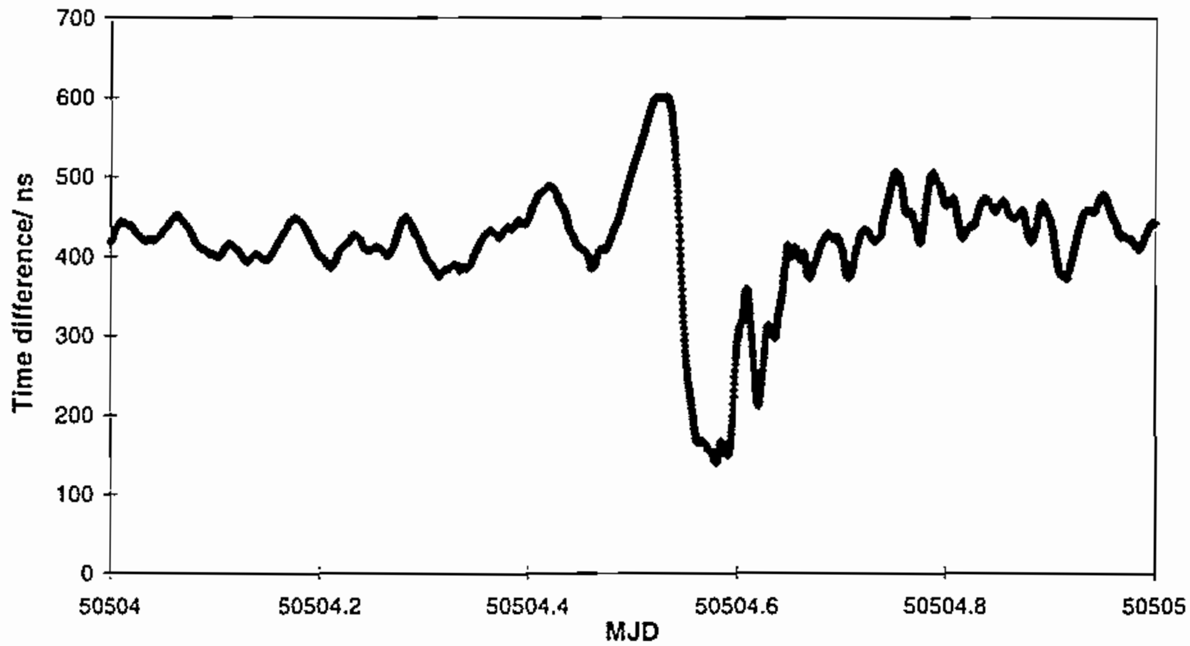


Figure 29 (cont...): Variation in the phase data (Local Clock- GPSDO(O)) during the deselection of satellites.

(e) Deselection of 15 satellites

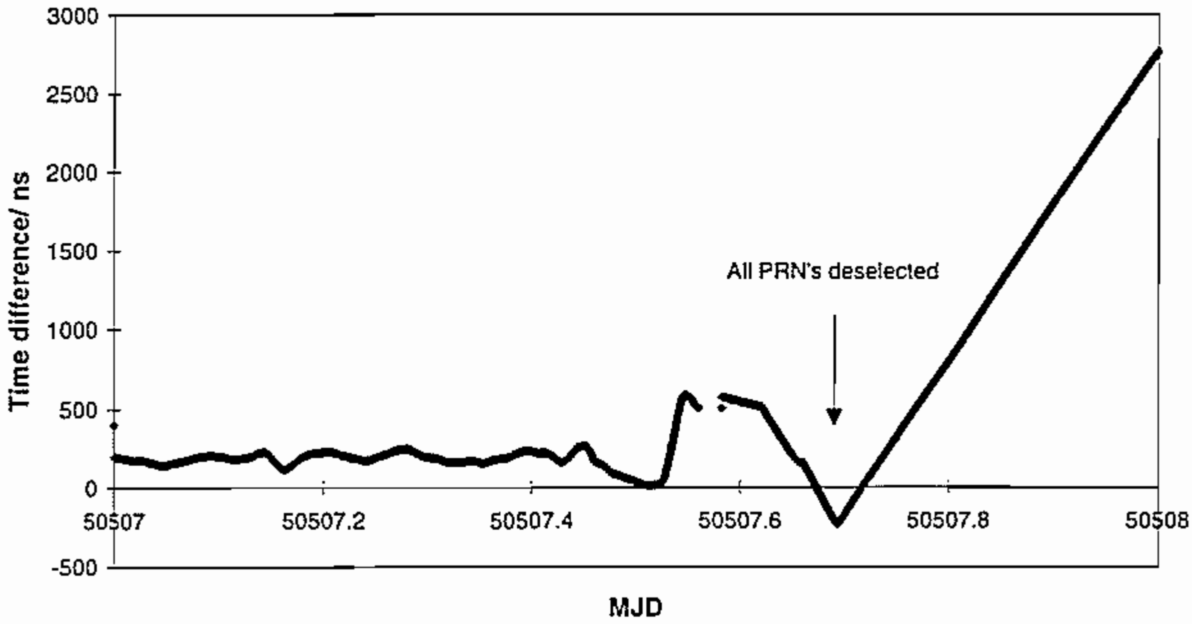


Table 14(a): De-selected PRN numbers for each satellite.

MJD	GPSDO (I)	GPSDO (J)	GPSDO (N)	GPSDO(O)
>50496	normal constellation	normal constellation	normal constellation	normal constellation
50496-50498	6, 7, 23 & 24	6, 7, 23 & 24	6, 7, 23 & 24	6, 7, 23 & 24
504098**-50500	6, 7, 23, 24, 1, 2, 4 & 21	6, 7, 23, 24, 1, 2, 4 & 21	6, 7, 23, 24, 1, 2, 4 & 21	6, 7, 23, 24, 1, 2, 4 & 21
50500-50503	6, 7, 23, 24, 1, 2, 4, 21, 9 & 30	6, 7, 23, 24, 1, 2, 4, 21, 9 & 30	6, 7, 23, 24, 1, 2, 4, 21, 9 & 30	6, 7, 23, 24, 1, 2, 4, 21, 9 & 30
50503-50505	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5 & 19	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5 & 19	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5 & 19	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5 & 19
50506-50507	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5, 19, 16, 22 & 26	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5, 19, 16, 22 & 26	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5, 19, 16, 22 & 26	6, 7, 23, 24, 1, 2, 4, 21, 9, 30, 5, 19, 16, 22 & 26
>50507	all PRN no.s and 90° mask	all PRN no.s and 90° mask	all PRN no.s	all PRN no.s

**Power failure at 17:00 on MJD 50498

Table 14(b): Mean (Local clock- GPSDO) and standard deviation 1PPS values as a function of satellite de-selection.

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats. deselected
I	50496	12,060	13:32	1688	29	NONE
I	50496	5,700	6:16	1670	31	4
I	50497	21,360	23:56	1719	35	4
I	50498	10,260	11:36	1709	34	4
I	50498	3,060	4:16	1648	60	8
I	50498**	5,520	6:08	1728	107	8
I	50499	21,420	23:56	1704	37	8

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats. deselected
I	50500	9,060	10:00	1701	34	8
I	50500	9,720	11:24	1706	39	10
I	50501	21,420	23:56	1701	40	10
I	50502	21,420	23:56	1706	35	10
I	50503	11,940	13:12	1716	40	12
I	50503	7,680	10:04	1671	31	12
I	50504	21,060	23:56	1706	37	12
I	50505	10,620	11:48	1720	40	12
I	50506	8,820	9:44	1679	51	15

GPSDO	MJD	No. of data points	Duration	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats. deselected
J	50496	12,060	13:32	1688	15	NONE
J	50496	5,700	6:16	1696	18	4
J	50497	21,360	23:56	1706	19	4
J	50498	10,260	11:36	1697	17	4
J	50498**	7,740	8:48	1723	117	8
J	50499	21,420	23:56	1677	24	8
J	50500	9,060	10:00	1703	18	8
J	50500	9,720	11:24	1716	17	10
J	50501	21,420	23:56	1716	19	10
J	50502	21,420	23:56	1733	13	10
J	50503	11,940	13:12	1700	20	10
J	50503	7,680	10:04	1686	22	12
J	50504	18,900	23:56	1698	20	12
J	50505	10,800	11:56	1699	28	12
J	50506	8,760	9:40	1703	11	15

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats Deselect.
N	50496	10,380	12:28	1977	8	NONE
N	50496	5,700	6:16	1979	13	4
N	50497	19,260	23:56	1986	16	4
N	50498	10, 440	11:32	1996	9	4
N	50498**	4,980	8:36	1989	7	8
N	50499	20,940	23:52	1992	11	8
N	50500	17,220	23:56	1984	11	10
N	50501	19,200	23:56	1985	19	10
N	50502	19,140	23:56	1996	13	10
N	50503	9,480	13:12	2003	11	12
N	50504	12,420	14:16	1995	23	12
N	50504	6,780	7:52	2030	31	12
N	50505	12,060	13:20	1991	17	12
N	50505	5,220	8:40	1946	47	12
N	50506	12,840	14:12	2035	147	15

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats. Deselect.
O	50496	10,380	12:28	2109	12	NONE
O	50496	5,700	6:16	2112	16	4
O	50497	19,260	23:56	2107	17	4
O	50498	10,440	11:32	2109	15	4
O	50498**	5,940	10:32	2158	93	8
O	50499	20,940	23:56	2102	26	8
O	50500	7,200	9:56	2119	19	8

GPSDO	MJD	No. of data points	Duration (hh:mm)	Mean 1PPS (ns)	1σ 1PPS (ns)	No. of sats. Deselect.
O	50500	10,020	11:28	2118	21	10
O	50501	19,200	23:56	2119	26	10
O	50502	19,140	23:56	2121	20	10
O	50503	9,480	13:12	2133	28	10
O	50503	7,620	8:24	2092	50	12
O	50504	19,200	23:56	2152	59	12
O	50505	12,060	13:20	2158	100	12
O	50506	12,840	14:12	2137	74	15

** power failure at 17:00 on MJD 50498

For GPSDOs (I) and (J), the effect of removing satellites from their respective constellations had little effect on the output of the 1PPS data. This may be either a problem with the receiver or a with its usage. The situation remains to be investigated further. This was not the case for GPSDO (N) and (O), where a slow degradation in the 1PPS output was observed as the number of satellites was reduced. A detailed study on the signal strengths and the coverage of the remaining constellation needs to be examined in greater depth.

10.3) Discussion

Two methods were used to reduce the satellite constellation in the field of view of the receiver, and it was found that they both gave very similar results. In all cases reducing the number of satellites by 50% resulted in very little or no change in the performance of the GPSDO. This is due to satellite redundancy in the constellation whilst the GPSDOs were operated in a position hold mode. Thereafter, a degradation in the performance of the GPSDOs was observed, due to SA being less effectively averaged out by the remaining constellation.

All of the GPSDO units tested in this section had the advantage that they had fixed their antenna position. If a mean or instantaneous satellite position is used, then the receiver will be more susceptible to problems if less than four satellites are available.

10.4) Recommendations

It is recommended that GPSDOs be operated for several days, during this time a record of the satellites observed should be recorded to check on the satellite visibility for that location. The GPSDOs should be able to see sufficient satellites to maintain continuous operation. It is also recommended that the receiver is used in a position hold or position average mode, and not an instantaneous position.

10.5) Operational characteristics with erroneous antenna coordinates

10.5.1) Introduction

The accuracy with which the GPSDO antenna coordinates are known is important in determining the performance of the GPSDOs. Most of the GPSDOs may be operated in a position hold mode, whereby the antenna coordinates can be programmed into the GPSDO by the user. To investigate the effect of erroneous coordinates, the antenna coordinates determined by each GPSDO were offset by 100 m in altitude, latitude and longitude. The GPSDOs were left in each position for approximately 48 hours. Table 15 details the changes made to a selection of GPSDOs used in the study. Figures 30 (a) to (g) show the effects in the output phase values for GPSDO (G) as a function of altitude (MJD 50519-50522), latitude (MJD 50525-50526) and longitude (MJD 50527).

Table 15: Details of offsets made to the receivers antenna coordinates.

MJD	GPSDO (A)	GPSDO (B)	GPSDO (C)	GPSDO (D)	GPSDO (E)
>50519	no change	no change	no change	no change	no change
50519-50525	alt + 100 m	no change	no change	no change	no change
50525-50527	alt reset lat +3"	alt + 100 m	alt + 100 m	no change	alt + 100 m
50528-50530	lat reset long + 5"	alt reset long + 5"	alt reset long + 5"	no change	alt reset long + 5"

MJD	GPSDO (F)	GPSDO (G)	GPSDO (H)	GPSDO (I)	GPSDO (J)
>50519	no change	no change	no change	no change	no change
50519-50525	alt + 100 m	alt + 100 m	alt + 100 m	alt + 100 m	alt + 100 m
50525-50527	alt reset lat + 3"	alt reset lat + 3"	alt reset lat + 3"	alt reset lat + 3"	alt reset lat + 3"
50528-5030	lat reset long + 5"	lat reset long + 5"	lat reset long + 5"	lat reset long + 5"	lat reset long +5"

FIGURE 30

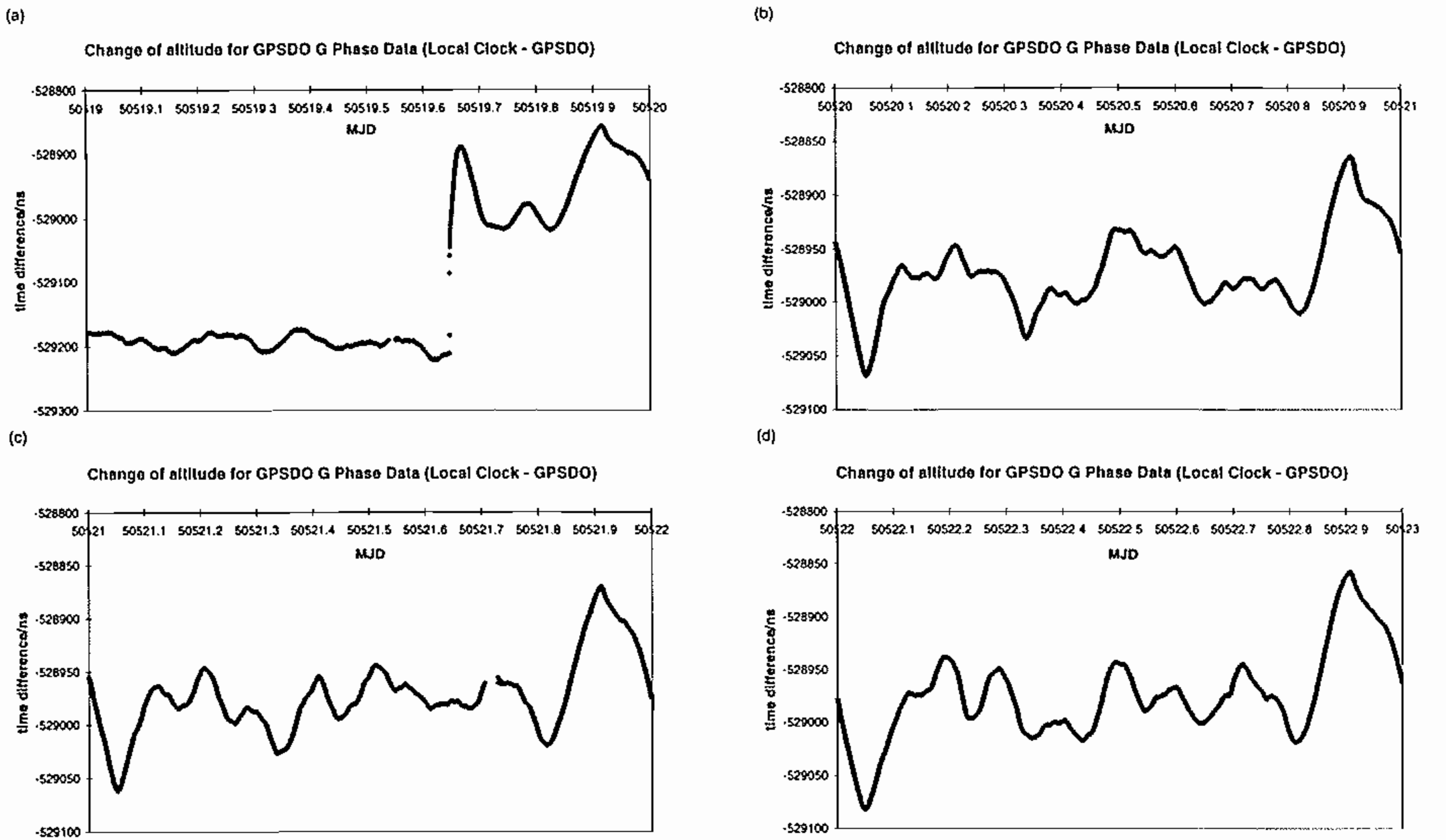
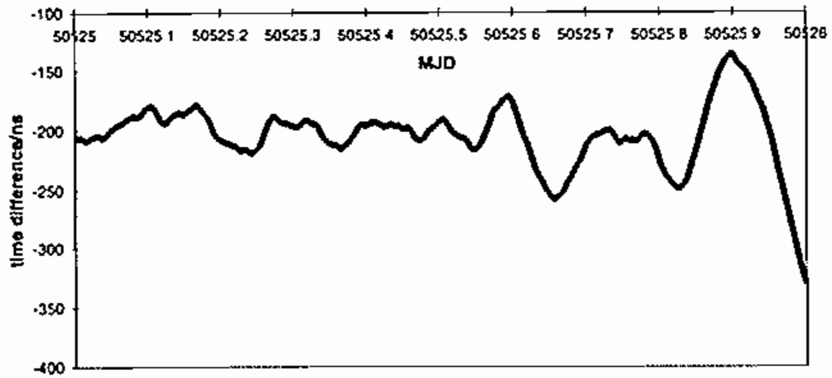

(a)
Change of altitude for GPSDO G Phase Data (Local Clock - GPSDO)
-528800
-528900
-529000
-529100
-529200
-529300
time difference/ns
50519
50519.1
50519.2
50519.3
50519.4
50519.5
50519.6
50519.7
50519.8
50519.9
50520
MJD
(b)
Change of altitude for GPSDO G Phase Data (Local Clock - GPSDO)
-528800
-528850
-528900
-528950
-529000
-529050
-529100
time difference/ns
50520
50520.1
50520.2
50520.3
50520.4
50520.5
50520.6
50520.7
50520.8
50520.9
50521
MJD
(c)
Change of altitude for GPSDO G Phase Data (Local Clock - GPSDO)
-528800
-528850
-528900
-528950
-529000
-529050
-529100
time difference/ns
50521
50521.1
50521.2
50521.3
50521.4
50521.5
50521.6
50521.7
50521.8
50521.9
50522
MJD
(d)
Change of altitude for GPSDO G Phase Data (Local Clock - GPSDO)
-528800
-528850
-528900
-528950
-529000
-529050
-529100
time difference/ns
50522
50522.1
50522.2
50522.3
50522.4
50522.5
50522.6
50522.7
50522.8
50522.9
50523
MJD

FIGURE 30 cont....

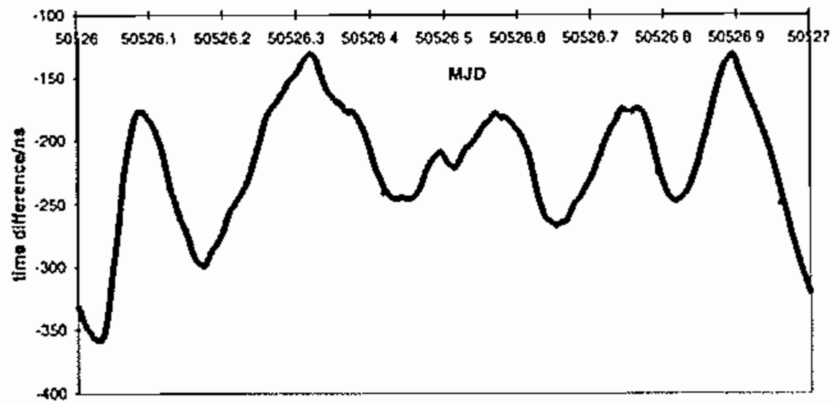
(e)

Change of latitude for GPSDO G Phase Data (Local Clock - GPSDO)



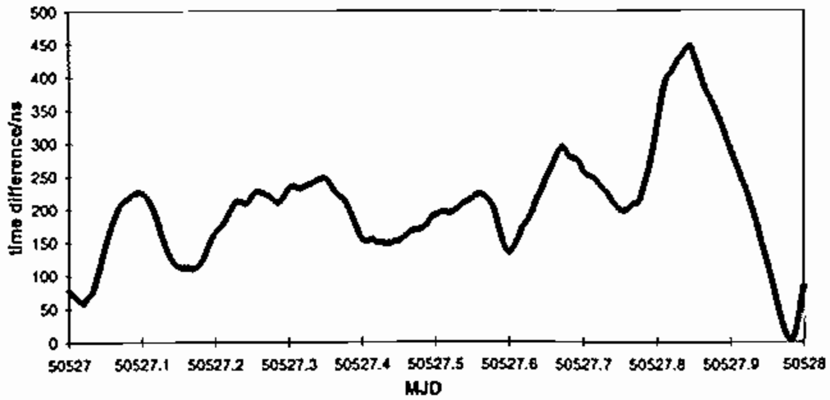
(f)

Change of latitude for GPSDO G Phase Data (Local Clock - GPSDO)



(g)

Change of longitude for GPSDO G Phase Data
(Local Clock - GPSDO)



MJD	GPSDO (K)	GPSDO (L)	GPSDO(M)	GPSDO (N)	GPSDO (O)
>50519	no change	no change	unavailable	no change	no change
50519-50525	no change	no change	unavailable	no change	no change
50525-50527	no change	no change	unavailable	alt + 100 m	no change
50528-50530	no change	no change	unavailable	alt reset long + 5"	no change

10.5.2) Results

Several trends emerged from these changes. All of the GPSDOs operated successfully with 100 m offsets along each coordinate axis. An offset of 100 m is typically twice the normal maximum positioning error. However the data scatter when using the offset coordinates was noticeably larger than when using the receiver determined coordinates. There is a change in the absolute delays typically of the order 230 ns/100 m, in the vertical direction, and only smaller changes in the north-south direction. There was only a minimal change in the east-west direction. This may be explained as follows: consider a receiver coordinate that is 100 m too high. In this case all of the GPSDO signals will arrive later than expected to, from which they will conclude that GPSDO 1PPS is on average 230 ns ahead of GPS time (depending on elevation angle). The north-south asymmetry in the GPS constellation will produce a similar but smaller affect when the receiver coordinates are in error and too far south. The receiver east-west symmetry of the GPS constellation should prevent any sizeable effect from being observed.

The use of offset coordinates resulted in a diurnal cycle in the GPSDO timing outputs. Plots are shown in figure 30 for two successive days showing a clearly repeating cycle in the Local clock-GPSDO(1PPS). The resulting frequency transfer performance of the GPSDOs is degraded by this effect.

GPSDOs may be subject to cumulative errors, as a partly obscured sky may result both in a lack of further satellites, and also in the occurrence of erroneous antenna coordinates. This requires further examination.

10.5.3) Recommendations

For each GPSDO, the magnitude of the coordinate errors need to be determined when they first become significant in the error budget.

The uncertainty to which each GPSDO is able to determine its own position under a clear sky needs to be evaluated.

It is recommended that GPSDOs either be allowed to determine their own position if the overall result does not affect the traceability of the unit, or use accurate known coordinates which can be entered into the receiver.

The accuracy of the antenna coordinates and how it relates to increased levels of timing accuracies will be determined from future studies.

10.6) Operational characteristics after loss of GPS signal

10.6.1) Introduction

The integrity of a GPSDO following the loss of all GPS satellite signals is an important issue which was addressed in this study. A simple experiment was performed whereby the GPSDO was left unchanged and an absorbent material was used to block out the L1 frequency on the GPSDO antenna. This was left in place for periods of between 15 minutes and one hour before allowing the receiver to reset. The time-to-alarm, i.e., the time between the loss of the GPS signal and the reporting of this loss by the GPSDO was carefully monitored for each GPSDO under study. The recovery properties of the GPSDO after the return of signal was also examined.

10.6.2) Preliminary results

Results show that for the GPSDOs tested, nearly all of them successfully recorded the absence of GPS signals (GPSDO (J) and (M) were not available for test). The majority of GPSDOs have a clear visual indicator to show the loss of signal. Where this was not present, the loss of the GPS signal was indicated through either menus on the front panel or via commands through the RS232 connection.

The time elapsed before the performance of the GPSDO continued outside its normal operating range is of clear interest. For several of the GPSDOs, the loss of signal was followed by a loss of the 1PPS signal.The time dissemination characteristics of the GPSDOs after the loss of the GPS signal will be reported at a later stage.

The frequency stability of the GPSDO will change almost instantaneously on loss of the GPS signal (e.g., section 6.2). The frequency offset will change more slowly, assuming that the final DAC correction has been fixed.

The time before the GPSDOs move out of their normal operating range is quite varied. However, results show that the GPSDOs remain within their normal operating ranges for a period significantly longer than the time-to-alarm.

10.6.3) Recommendations

Reporting the loss of GPS lock is essential for traceability, and it is recommended that the GPSDO implement a method of reporting the loss of GPS lock, e.g., either by a light on the front panel, a screen menu on the unit, or via the RS232 port.

10.7) Operational characteristics after a mains power failure

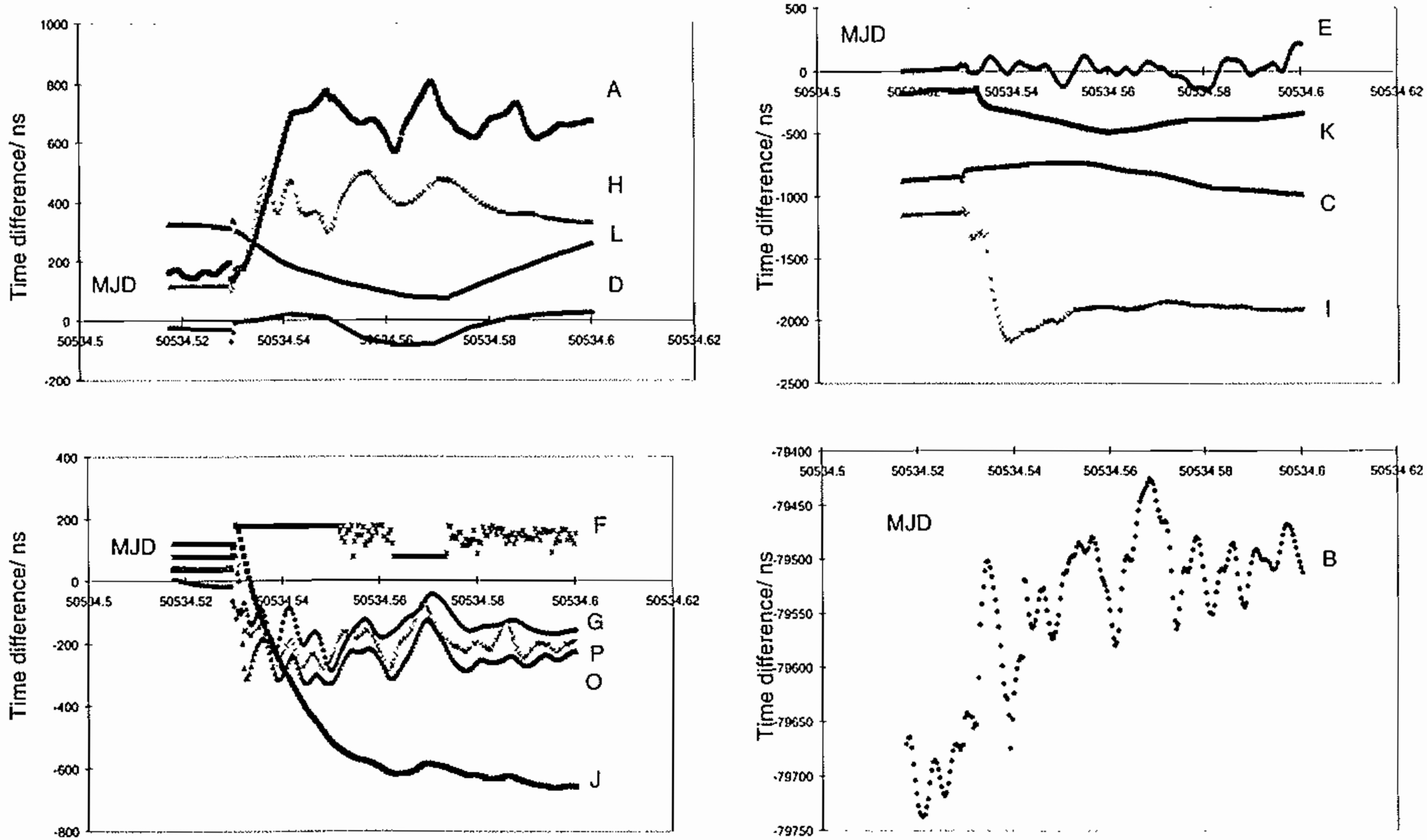
10.7.1) Introduction

A simple experiment was performed to test the response from each GPSDO if a mains power failure occurred during their normal course of operation. The mains power supply to all the GPSDO units is derived from two dedicated distribution boards. This allowed all of the GPSDOs to be switched off simultaneously for a period of thirty seconds. The interruption of the power supply can have serious consequences for the time and frequency stability of the 1PPS and phase output. Table 16 gives values for the mean (Local Clock-GPSDO) and the standard deviation (1σ) values before and after a mains power loss for each GPSDO. In figure 31, plots of variation in the phase data are shown for all the GPSDOs on the day that the loss of power took place (MJD 50534).

Table 16:Mean (Local clock-GPSDO) and standard deviation 1PPS values before and after a loss of mains power for each GPSDO.

GPSDO	MJD	No. of data points	Duration/ hh:mm	Mean 1PPS (ns)	1σ 1PPS (ns)	Comment
A	50534	11,460	12:40	1802	47	before loss
A	50534	1,980	02:56	1809	159	after loss
B	50494	21,300	23:56	2657	31	before loss
B	50534	1,920	02:12	2708	77	after loss
B	50534	9,300	11:16	2733	31	after loss
B	50535	20,100	23:56	2728	28	after loss
B	50536	19,560	23:56	2725	27	after loss
C	50534	1,800	2:00	2071	38	before loss
C	50534	8,700	11:32	2064	41	after loss
C	50535	19,260	19:12	2056	39	after loss
C	50536	19,560	23:52	2053	41	after loss
D	50534	11,460	12:40	4014	29	before loss
D	50534	8,640	11:08	3946	28	after loss
D	50535	19,680	23:56	3977	17	after loss
D	50536	19,860	23:52	3984	56	after loss

FIGURE 31: Variation in PHASE data (Local Clock-GPSDO) at the time of a controlled loss of power to each GPSDO



GPSDO	MJD	No. of data points	Duration/ hh:mm	Mean 1PPS (ns)	1σ 1PPS (ns)	Comment
E	50534	11,460	12:40	2114	21	before loss
E	50534	2,580	03:12	2091	51	after loss
F	50534	11,460	12:40	2205	25	before loss
F	50534	1,260	01:20	2228	75	after loss
F	50534	7,980	09:44	2213	28	after loss
F	50535	19,980	09:48	2211	20	after loss
F	50536	19,620	23:59	2205	20	after loss
G	50532	20,400	23:56	1905	18	before loss
G	50534	6,600	07:56	179	375	after loss
G	50535	19,920	23:56	733	428	after loss
G	50536	20,160	23:56	583	480	after loss
H	50532	10,440	13:24	146	8	before loss
H	50534	6,600	07:48	684	8	after loss
H	50535	19,980	23:56	702	14	after loss
H	50536	19,560	23:56	728	4	after loss
I	50534	11,460	12:40	1715	110*	before loss
I	50534	6,060	07:52	1721	84	after loss
I	50535	19,680	23:56	1737	33	after loss
I	50536	19,800	23:48	1714	41	after loss
J	50534	11,460	12:40	1720	5	before loss
J	50534	6,540	08:36	1729	62	after loss
J	50534	2,160	02:32	1714	24	after loss
J	50535	19,680	23:56	1698	22	after loss
J	50536	19,860	23:12	1722	19	after loss
K	50534	11,160	12:20	2521	93	before loss
K	50534	8,760	11:32	2510	111	after loss

GPSDO	MJD	No. of data points	Duration/ hh:mm	Mean 1PPS (ns)	1σ 1PPS (ns)	Comment
K	50535	19,260	23:56	2500	90	after loss
K	50536	19,260	23:56	2478	85	after loss
L	50534	11,400	12:36	2131	37	before loss
L	50534	8,520	11:12	2154	59	after loss
L	50535	19,260	23:56	2147	48	after loss
L	50536	19,500	23:52	2135	41	after loss
M	-	-	-	-	-	-
N	50534	10,860	12:36	1976	10	before loss
N	50534	9,180	11:12	1974	28	after loss
N	50535	19,920	23:56	1983	11	after loss
N	50536	20,220	23:56	1979	10	after loss
O	50534	840	00:52	2084	7	before loss
O	50534	9,180	11:12	2100	34	after loss
O	50535	19,920	23:56	2103	16	after loss
O	50536	20,220	23:56	2095	14	after loss

* The 1σ 1PPS value for GPSDO I was higher before the loss of mains power due to the occurrence of two time transients.

The phase characteristics on most GPSDOs were severely disrupted for a considerable length of time after the loss in power. Stabilisation times were determined for all the GPSDOs and given in table 17. Although large phase offsets were introduced in the phase output measurements after the mains loss, this is to be expected since the absolute level of the phase output cannot be guaranteed after switching the unit off and on. However, this does not apply to the 1PPS timing output. Large steps in the 1PPS output for at least two of the GPSDOs (G) and (H) were observed after the mains power was returned. The results presented from these measurements need to be investigated further in order to check their repeatability.

10.7.2) Recommendations

It is recommended that warnings should be provided by the GPSDO unit to register any mains power interrupt, knowledge of the duration of the interrupt may also be useful. The user should be informed of when the oscillator has stabilised and when the phase and 1PPS output is working to within the specifications of the unit.

Table 17: Record of stabilisation periods for the phase output and permanent offsets in the 1PPS output for each GPSDO.

GPSDO	Phase stabilisation period (hh:mm)	1PPS step
A	00:25	no
B	-	-
C	10:18	no
D	3:44	no
E	2:24	no
F	9:11	no
G	5:32	yes
H	4:10	yes
I	5:50	no
J	31:31	no
K	7:25	no
L	-	-
M	-	-
N	4:29	no
O	7:12	no

10.8) Environmental monitoring

Recent studies [1] have shown that propagation delays through a GPS antenna are dependent on temperature. In this experiment, both the temperature and humidity of the room containing the GPSDOs and the outside environment were recorded every five minutes. Three multi-probe temperature and humidity loggers (Grant Instruments, Squirrel Loggers model no. 1200), were used to monitor both the laboratory and roof environments. The measurements included both surface and air temperature monitoring. Figure 26 (section 8) and figure 32 show the location of the temperature probes positioned on the roof and inside the laboratory respectively.

Figures 33 (a) to (f) show typical air and surface temperatures and humidity variations both inside the GPSDO laboratory and outside the laboratory where the antennas are sited. Correlations between diurnal temperature fluctuations and the output performance of the 1PPS and phase outputs remain to be examined in greater depth. It is expected that temperature effects on the

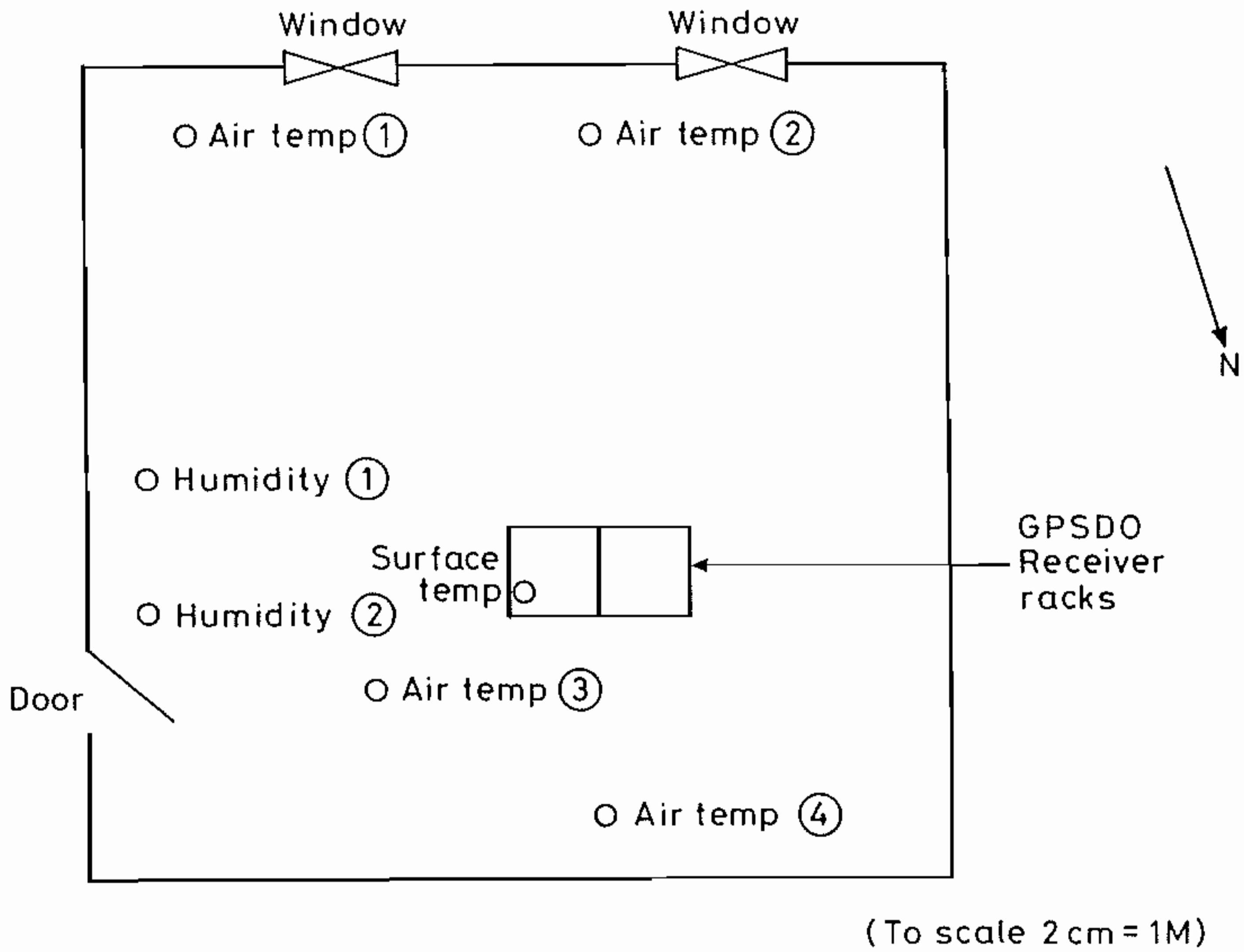
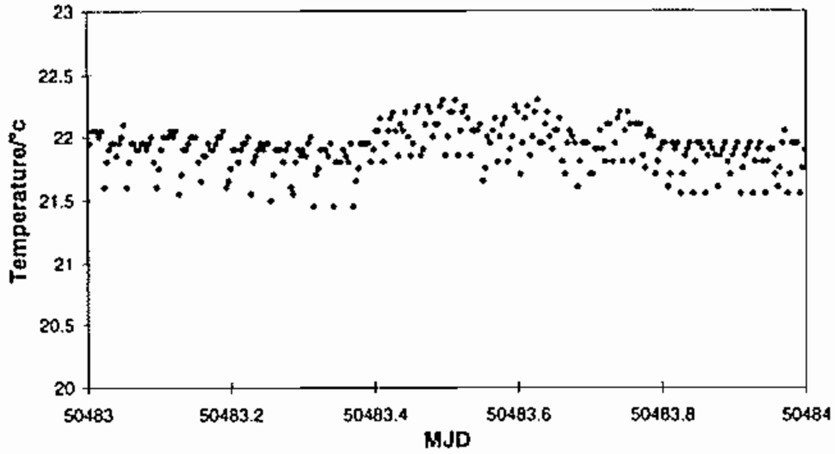


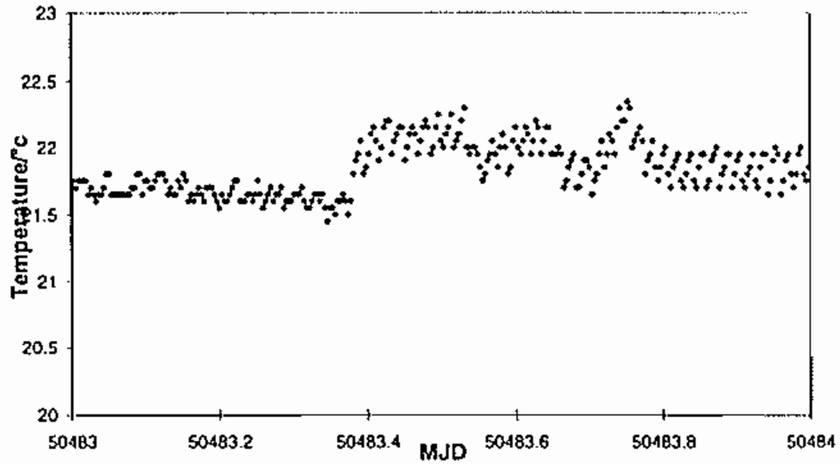
FIGURE 32: Schematic layout of temperature and humidity probes inside the GPSDO laboratory

FIGURE 33

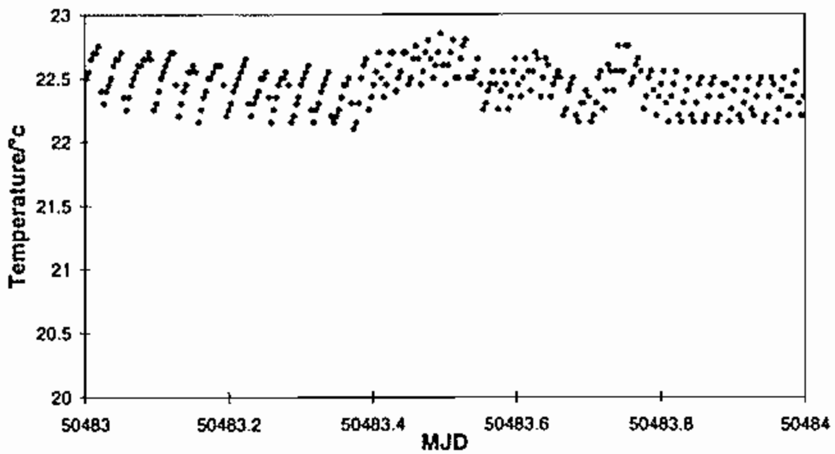
(a) Probe 1: Inside air temperature



(b) Probe 2: Inside air temperature



(c) Probe 3: Inside air temperature



(d) Probe 4: Inside air temperature

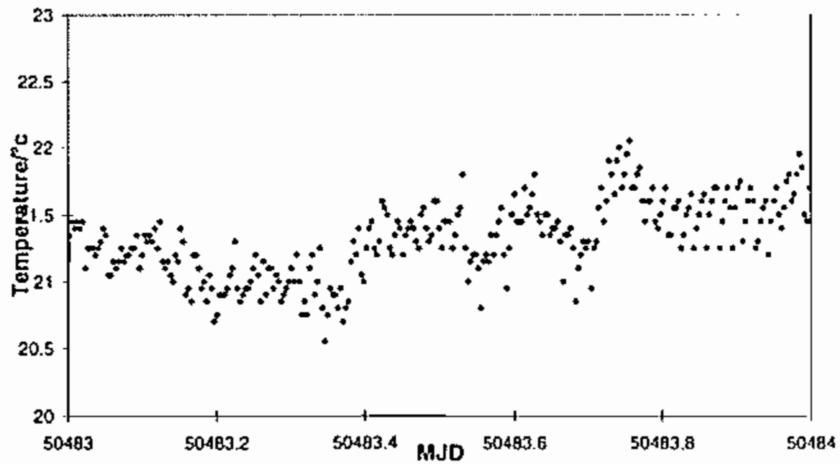
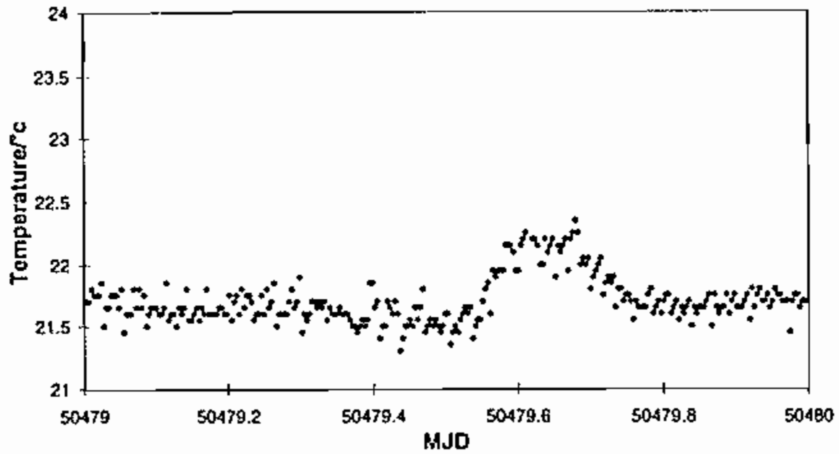
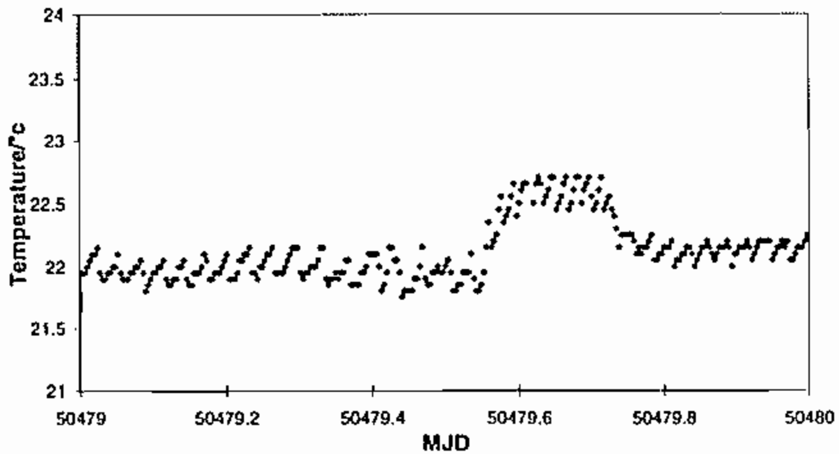


FIGURE 33

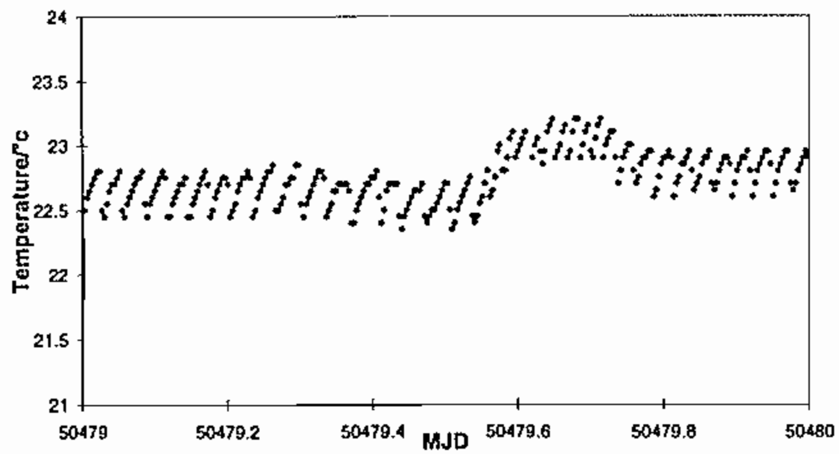
(e) Probe 1: Inside air temperature



(f) Probe 2: Inside air temperature



(g) Probe 3: Inside air temperature



(h) Probe 4: Inside air temperature

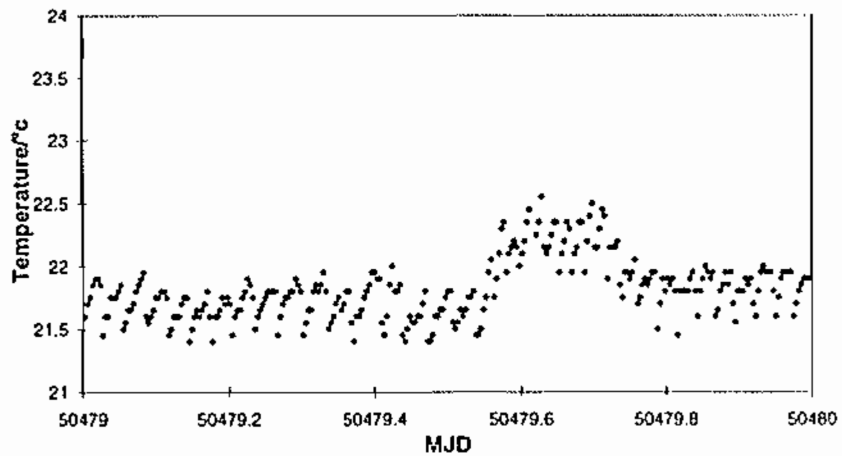
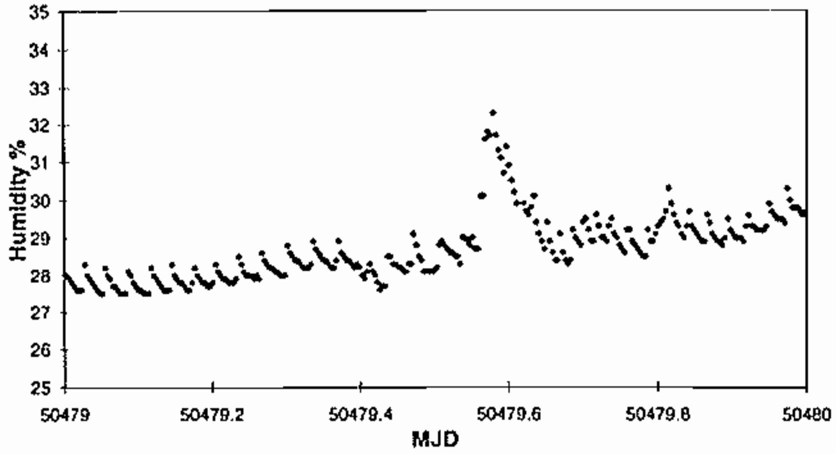
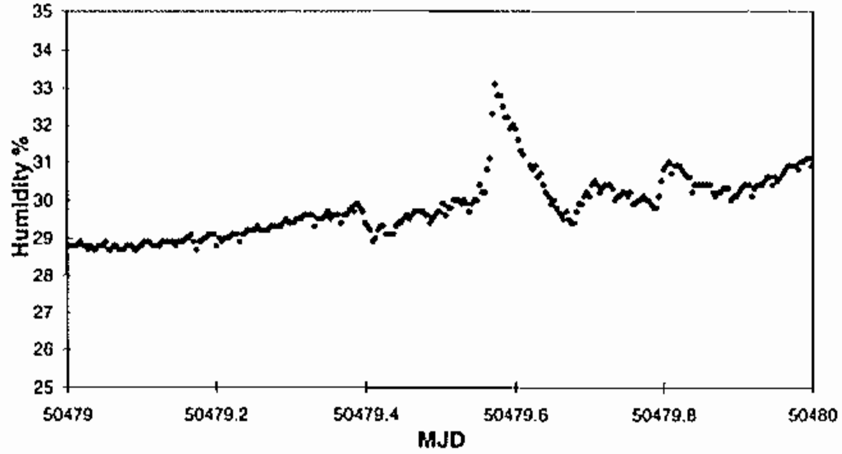


FIGURE 33

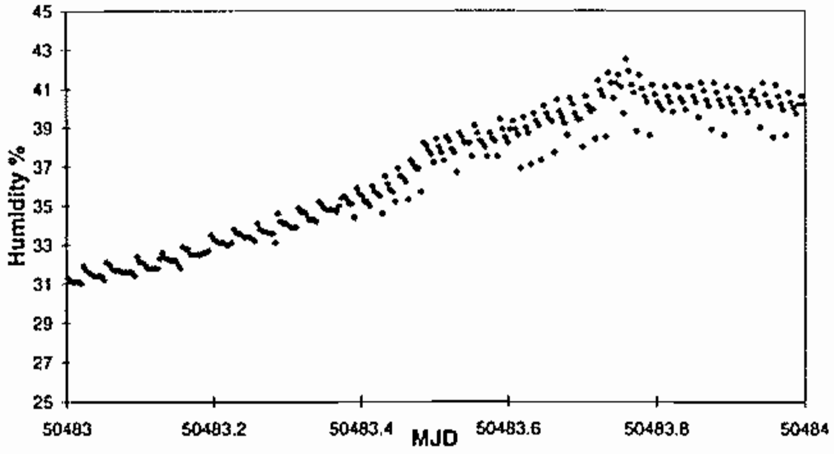
(i) Probe 1 : Inside Humidity



(j) Probe 2 : Inside Humidity



(k) Probe 1 : Inside Humidity



(l) Probe 2 : Inside Humidity

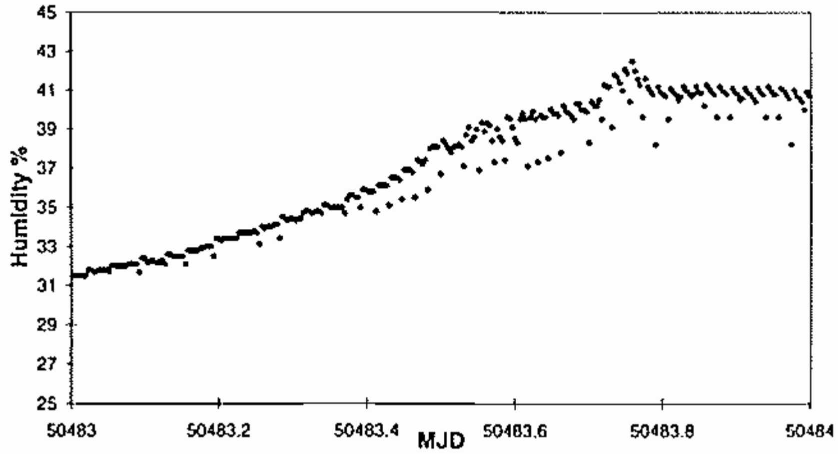


FIGURE 33

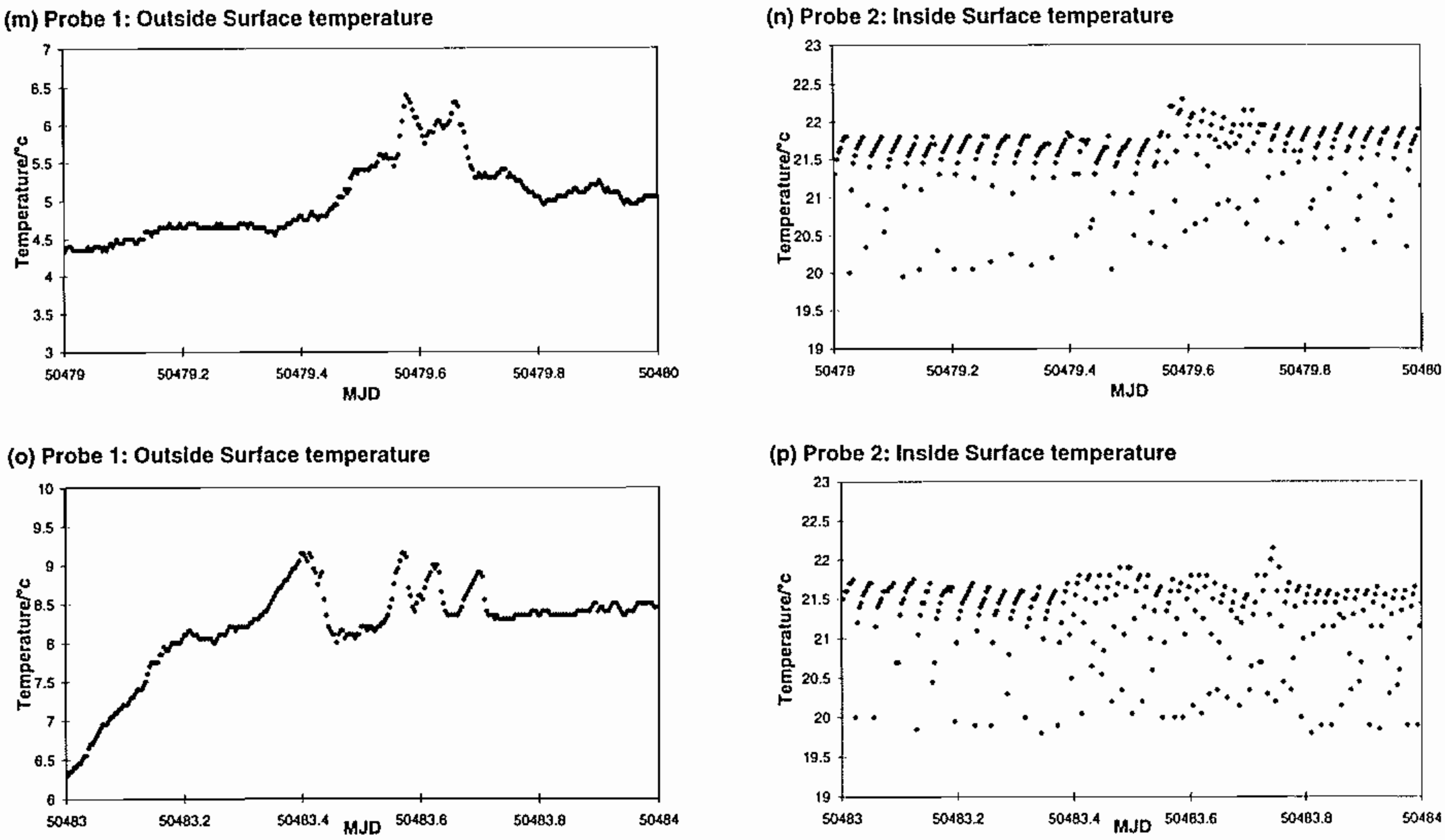
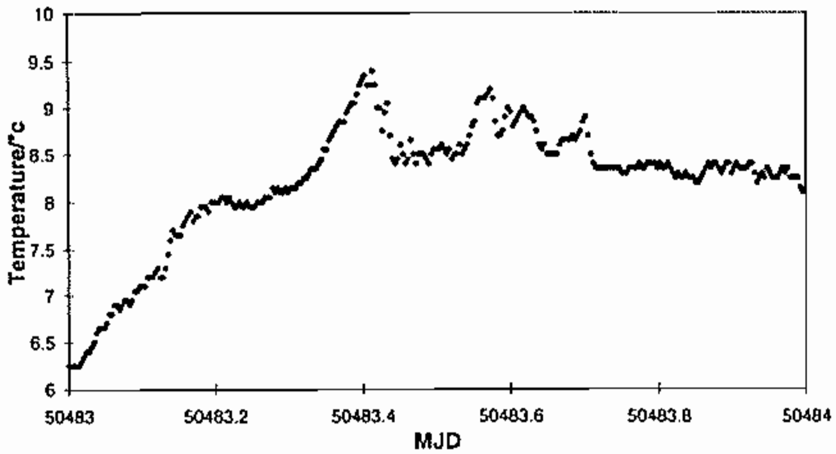
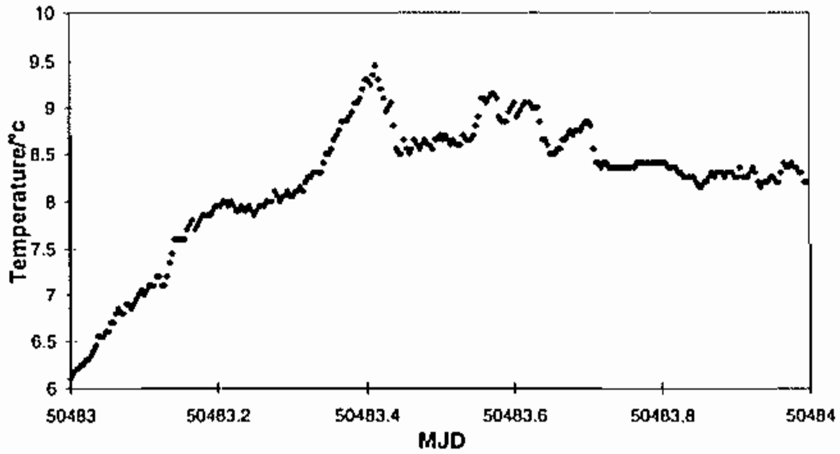

(m) Probe 1: Outside Surface temperature
Temperature/°c
7
6.5
6
5.5
5
4.5
4
3.5
3
50479
50479.2
50479.4
50479.6
50479.8
50480
MJD
(n) Probe 2: Inside Surface temperature
Temperature/°c
23
22.5
22
21.5
21
20.5
20
19.5
19
50479
50479.2
50479.4
50479.6
50479.8
50480
MJD
(o) Probe 1: Outside Surface temperature
Temperature/°c
10
9.5
9
8.5
8
7.5
7
6.5
6
50483
50483.2
50483.4
50483.6
50483.8
50484
MJD
(p) Probe 2: Inside Surface temperature
Temperature/°c
23
22.5
22
21.5
21
20.5
20
19.5
19
50483
50483.2
50483.4
50483.6
50483.8
50484
MJD

FIGURE 33

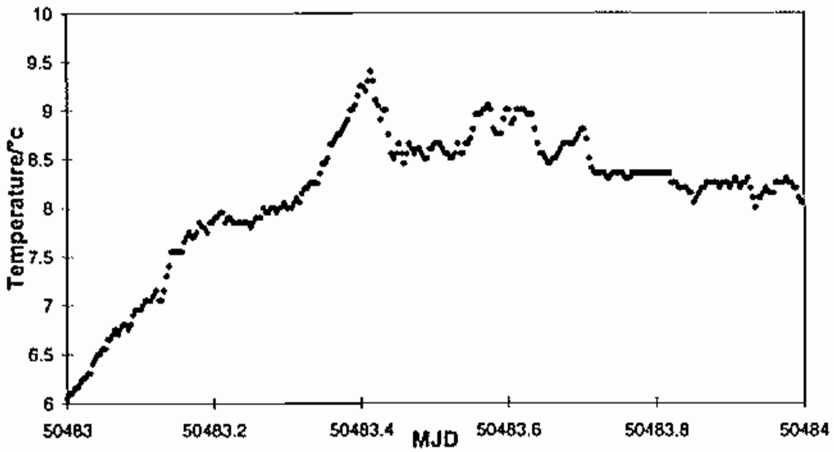
(q) Probe 1: Outside air temperature



(r) Probe 2: Outside air temperature



(s) Probe 3: Outside air temperature



(t) Probe 4: Outside air temperature

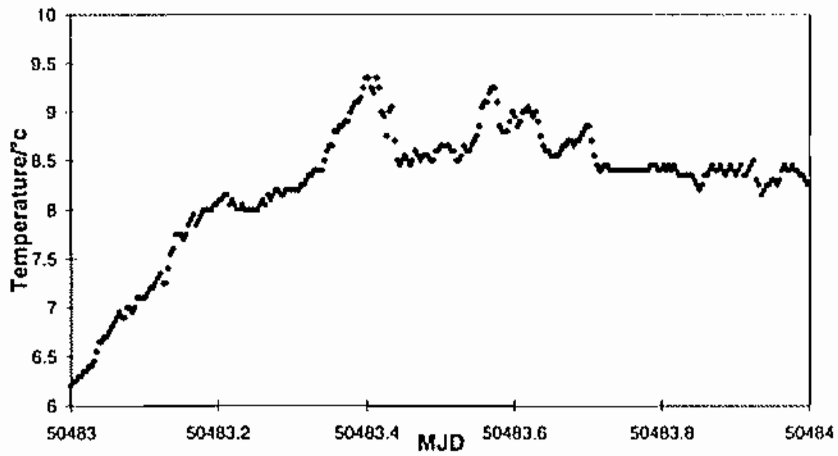
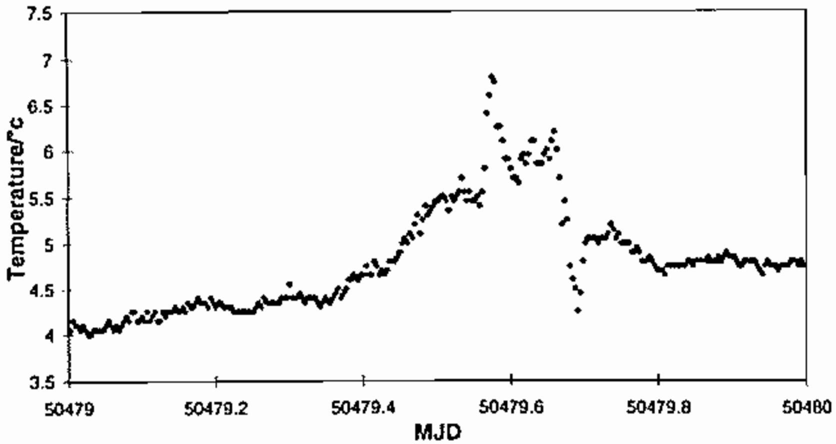
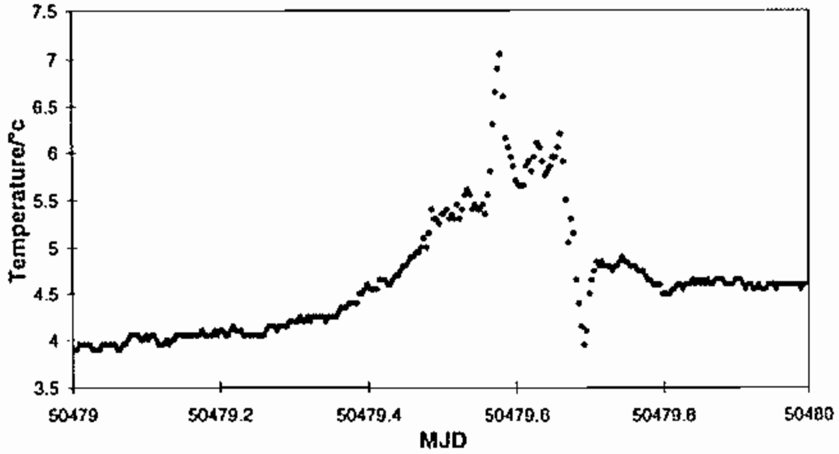


FIGURE 33

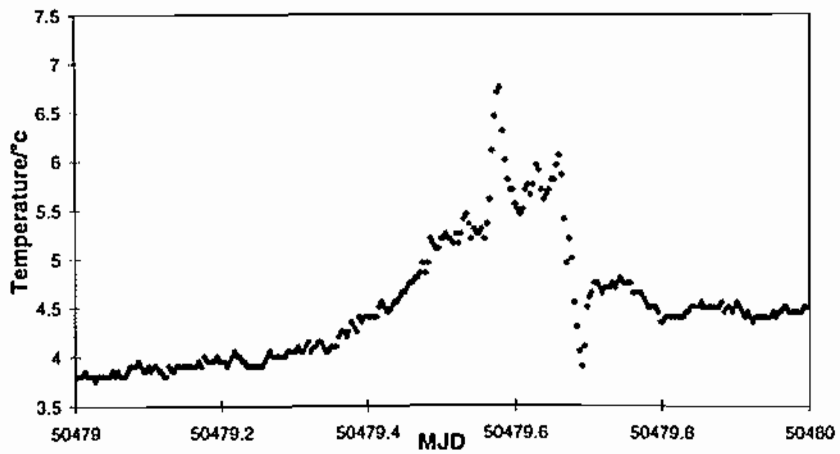
(u) Probe 1 : Outside air temperature



(v) Probe 2 : Outside air temperature



(w) Probe 3 : Outside air temperature



(x) Probe 4 : Outside air temperature

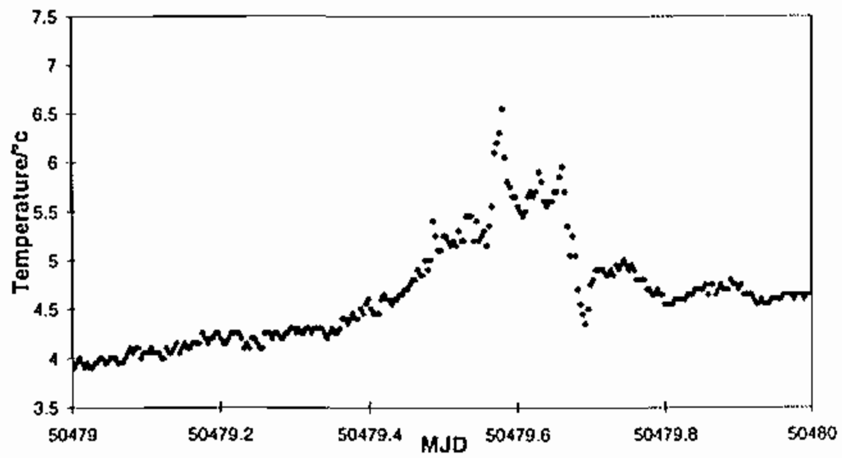
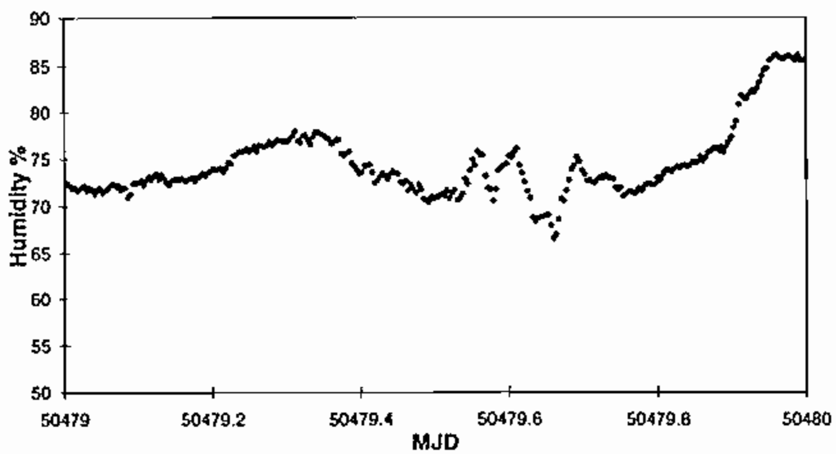
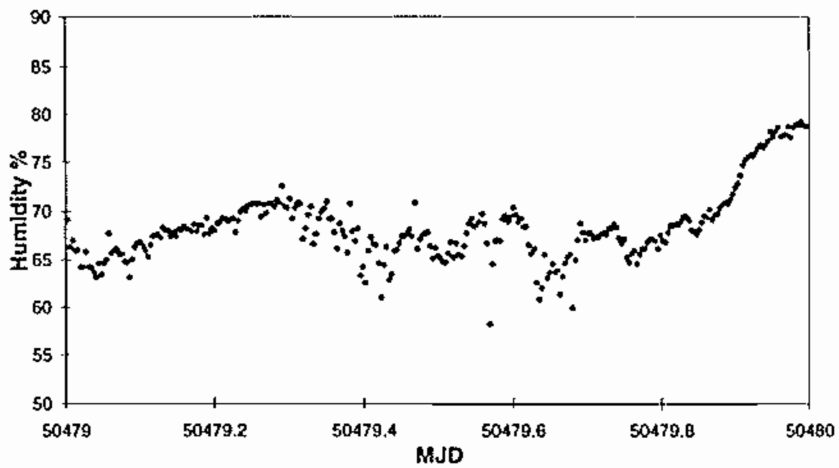


FIGURE 33

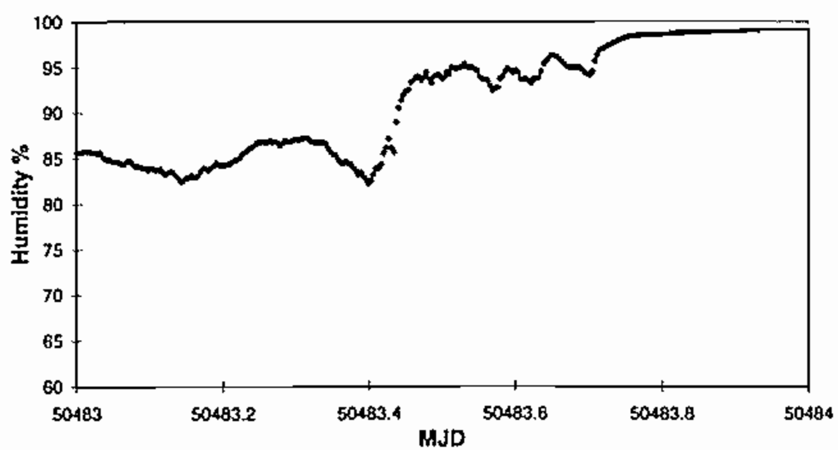
(y) Probe 1: Outside Humidity



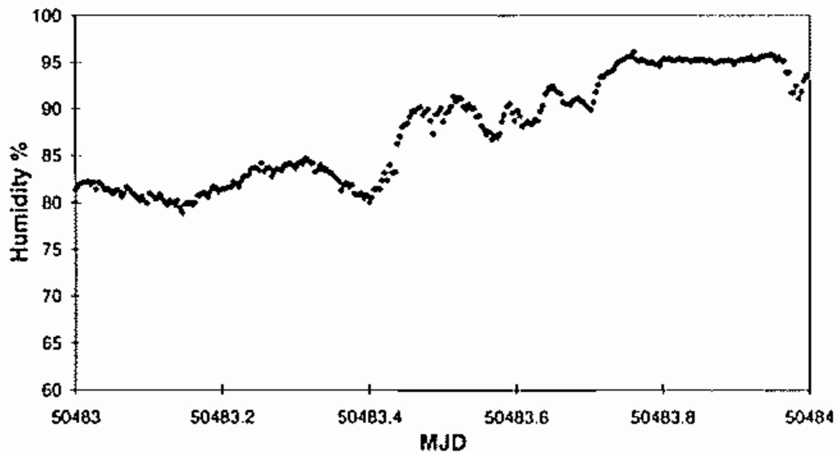
(z) Probe 2: Outside Humidity



(a1) Probe 1: Outside Humidity



(b1) Probe 2: Outside Humidity



receiver will be small, but that temperature fluctuations of the local oscillator used in the GPSDO will give rise to output fluctuations in both the phase and 1PPS measurements.

10.9) References

[1] Lewandowski, W., Moussay, P., Guerin, P., Meyer, F., and Vincent, M., *Testing Motorola Oncore GPS Receiver and Temperature-Stabilised Antennas for Time Metrology*, in Proceed. 28th PTTI, 1996, to be published.

11) Conclusions, Recommendations and Future Work

11.1) Conclusions

The results of this study indicate that when operating under appropriate conditions, and using correctly engineered GPSDOs, GPSDOs may be suitable for use as standards of time and frequency traceable to UTC(NPL).

11.2) Recommendations

During this study a series of recommendations have been made concerning the operation of GPSDOs as standards traceable to UTC(NPL). Two sets of recommendations are provides here, the first group relate directly to traceability issues while the second are of a more general nature.

Recommendation relating directly to traceability issues:

a) NPL should monitor the GPSDO constellation from its Teddington site, and publish to the UK time and frequency community information on any GPS system anomalies.

b) Values of UTC(NPL) - UTC(USNO) should be regularly published by NPL.

c) NPL should produce a sample error budget for a typical GPSDO based on the GPS user range errors and supported by empirical measurements. Error budgets of this type may then be used to set the accuracy levels of the traceability for individual models of GPSDOs.

d) Each manufacturers model of GPSDO should be characterised for both its time dissemination and frequency dissemination properties. The characterisation of individual models of GPSDOs is sufficient if conservative error budgets are used in establishing traceability.

e) It is clear that because of variations between units, to achieve traceability for the highest accuracy time dissemination, (uncertainties < 1,000 ns) each individual GPSDO should be calibrated against a primary time scale. Two co-located GPSDOs should be operated at each location, so as to check for systematic delay changes. When considering time dissemination traceability, there is a need to calibrate the GPSDO internal delays as these can dominate the error budget.

f) It is recommended that the frequency stability and accuracy of a GPSDO be specified at the averaging times appropriate to the measurement process, and that the specified performance is validated by measurement traceable to a primary time scale.

g) Unless a model of GPSDO has been shown not to be vulnerable to transient effects, either two GPSDOs should be operated in parallel, or a single GPSDO should be operated alongside a highly stable local oscillator, so that transients may be identified.

h) Sufficient sky should be visible for the GPSDO to continuous observe the number of satellites required to maintain the GPSDO locked to the GPS system. Hence GPSDOs should be operated for several days at a new installation. During this time a record of the satellites observed should be recorded to check on the satellite visibility at that location.

i) The GPSDOs should provide warning of any mains power interrupt. The GPSDO should provide information on when the local oscillator has stabilized following a power interrupt. The duration of the interrupt should be recorded.

j) The GPSDOs should provide warning of any loss of GPS lock, the method of implementation being at the discretion of the manufacturer.

k) When considering both time and frequency traceability, there is a need to assess the magnitude of the local position errors, and to determine when these first become significant in the overall uncertainty budget. We note that where position errors are important, the cost of GPSDO installation could be reduced if appropriate self validation schemes are possible.

More general recommendations:

l) For applications requiring high medium term frequency stability (τ=1,000 s) a GPSDO should be chosen with a highly stable internal oscillator, combined with an effective disciplining algorithm.

m) For applications requiring only high long term frequency stability (τ >100,000 s) a GPSDO may be chosen based on a quartz rather than rubidium internal oscillator, this being combined with an effective disciplining algorithm.

n) GPSDOs should operate in either a position hold or position average mode, but should not operate using instantaneously determined position. The GPSDO should have the capability of operating from a single satellite if necessary.

o) For applications where the user wishes to flywheel on the free running oscillator during the loss of the GPS signal, the GPSDOs should then control their DAC values on the loss of the GPS signal. A suitable mean rather than instantaneous DAC value is likely to be preferable.

11.3) Future work

This report has described a very extensive characterization study of GPSDO that has taken place at NPL on the subject of using GPSDOs as standards traceable to UTC(NPL). It is important to follow-on from this study with a mechanism for realizing traceability. Table 18 outlines the principal sources of error for both time and frequency dissemination using GPSDOs. It is proposed that a worst case uncertainty budget be constructed for the use of GPSDOs as traceable standards. The uncertainty budget would then be checked, through a series of detailed characterizations of the individual models of GPSDOs. This study may form part of the characterization. A series of on-site tests would then be performed at the GPSDO installations. This route to traceability requires the development of a series of on-site tests to characterise each individual GPSDO. NPL would be pleased to participate in the development of these tests. It is intended to submit a copy of this report to UKAS and seek their advise concerning the next steps.

Table 18: Current limiting factors for GPSDOs.

CURRENT LIMITING FACTORS FOR TIME DISSEMINATION ACCURACY	CURRENT LIMITING FACTORS FOR FREQUENCY DISSEMINATION ACCURACY
Major Limitations SA Antenna coordinates Antenna cable delays Instrumentation delays Disciplining algorithm	**Major Limitations** SA Local oscillator Disciplining algorithm
Minor Limitations Ionosphere corrections Multipath and shadowing Local oscillator GPS time vs UTC	**Minor Limitations** Ionosphere corrections Multipath and shadowing Antenna coordinates Antenna cable delays Instrumentation delays GPS time vs UTC
Non-Limiting Factors Satellite clocks Troposphere Satellite ephemeris	**Non Limiting Factors** Satellite clocks Troposphere Satellite ephemeris

Appendix A

Calibration of GPSDO 1PPS outputs against UTC(NPL)

Each GPSDO 1PPS output has been calibrated against UTC(NPL) by using a HP5071A high performance caesium clock as a transfer standard. This calibration was performed on MJD 50498.

Table 20: Portable clock calibration of UTC(NPL) - Local Clock

GPSDO	UTC(NPL) - Transfer Clock (ns)	Local Clock - Transfer Clock (ns)	UTC(NPL) - Local Clock (ns)
A	5,724	7,707	-1,983
B	5,724	7,699	-1,975
C	5,724	7,697	-1,973
D	5,724	7,699	-1,975
E	5,724	7,705	-1,981
F	5,724	7,716	-1,992
G	5,724	7,706	-1,982
H	5,724	7,699	-1,975
I	5,724	7,716	-1,992
J	5,724	7,699	-1,975
K	5,724	7,761	-2,037
L	5,724	7,764	-2,040
M	5,724	7,699	-1,975
N	5,724	7,700	-1,976
O	5,724	7,715	-1,991

The absolute delay calibration was performed in three parts. The transfer clock was compared directly against UTC(NPL), to give a measurement of (UTC(NPL) - Transfer Clock). The transfer clock was then moved to the GPSDO laboratory in a separate building. Using the same connecting cable the transfer clock was connected to each of the GPSDO inputs to the 1PPS logging system in turn. Measurements were then made of (Local Clock - Transfer Clock) from each GPSDO input. Values of (UTC(NPL) - Transfer Clock) may be obtained by calculating

(UTC(NPL)-Transfer Clock) + (Transfer Clock - Local Clock). Results are shown in table 20.

Cable delays in the 1PPS logging system will cancel during this calibration. The portable transfer clock is returned to the original building and compared against UTC(NPL) to demonstrate that there have been no clock irregularities during the calibration. The results in column 4 of table 19 have been used when calculating the time dissemination accuracy of the GPSDOs.

Appendix B

The Determination of the GPSDO Antenna Coordinate Errors

During 1993 the Ordnance Survey has spent substantial time accurately surveying sites at NPL. One of these sites is located at the centre of the group of GPSDO antenna used in this study. The surveyed site position is given as 51° 25' 15.3933" N , 0° 20' 23.1286" W, 69.8810 m above ellipsoid, in ETRF89 coordinates. These coordinates should agree with WGS84 coordinates to within a metre [1]. This surveyed site is used as the basis for antenna coordinate determination for the GPSDO study. The layout of the GPSDO antennas are shown in Figure 26(a). A local "building orientated" coordinate system is used. There relationship to the surveyed site is shown in Figure 26 (b), where x and y are the axes of the coordinate system , the origin being NPL's surveyed point Aux 2. There are several stages in determining the antenna coordinates. The following transformations were used to convert the x, y coordinates to N, E coordinates, where N is the coordinate offset north of the reference point and E the coordinate offset East of the reference point in metres.

$$E = y\,Sin(\alpha) + x\,Cos(\alpha)$$

$$N = y\,Cos(\alpha) - x\,Sin(\alpha)$$

where $\alpha = 17.2°$. The coordinates N and E may be converted to seconds of arc using

$$\delta\Theta(Seconds\text{-}of\text{-}\mathrm{arc}) = (0.019) * E(metres)$$

$$\delta\theta(Seconds\text{-}of\text{-}\mathrm{arc}) = (0.032) * N(metres)$$

Where $\delta\Theta$ and $\delta\theta$ are the longitude and latitude coordinate offsets of each antenna from the reference location in seconds of arc.

The coordinates of each GPSDO antenna in the "building orientated" x, y coordinates and the associated coordinate offsets E and N are given in table 20. By adding the coordinate offsets to the reference coordinates the GPSDO antenna coordinates given in table 11(a) are obtained.

References

[1] PH Denys, Paul A Cross, *The Ordnance Survey Scientific GPS Network 1992 Scinet*, University of Newcastle upon Tyne, Newcastle upon Tyne, Final report - Version 3.0 Report Number 93/0602, EUREF appendix, section 3.2, page 4, 1993.

Table 20: Building orientated coordinates, and coordinate offsets of each GPSDO antenna.

GPSDO	Building orientated coordinates		Height offset (m)	Coordinate Offsets			
	x(m)	y(m)		E(m)	N(m)	δΘ Seconds of arc	δθ Seconds of arc
A	5.5	0.9	4.2	5.5	-0.8	0.105	-0.026
B	1.0	0.8	2.4	1.2	0.5	0.023	0.015
C	2.3	0.8	2.4	2.4	0.1	0.046	0.003
D	7.4	4.4	4.2	8.4	2.0	0.160	0.065
E	7.4	2.5	4.2	7.8	0.2	0.149	0.006
F	-6.6	5.2	2.4	-4.7	6.9	-0.090	0.223
G	-0.6	5.2	2.2	1.0	5.1	0.019	0.166
H	1.0	-0.4	2.4	0.9	-0.7	0.016	-0.022
I	-2.2	-2.0	2.4	-2.7	-1.2	0.051	-0.040
J	3.4	6.0	5.0	5.0	4.7	0.095	0.152
K	0.0	7.8	2.2	2.3	7.4	0.044	0.239
L	3.2	-2.2	2.4	2.4	-3.1	0.046	-0.099
M	-5.2	5.2	2.4	-3.4	6.5	-0.064	0.210
N	0.85	-2.0	2.4	0.2	-2.1	0.004	-0.069
O	7.38	1.2	2.5	7.4	-1.1	0.140	-0.035