RESULTS FROM THE NATIONAL PHYSICAL LABORATORY GPS COMMON-VIEW TIME AND FREQUENCY TRANSFER SERVICE

J. A. Davis, S. L. Shemar, and J. D. Clarke
Centre for Electromagnetic and Time Metrology
National Physical Laboratory
Queens Road, Teddington, Middlesex, TW11 0LW, UK

Abstract

An overview is given of precise frequency and time transfer methods available to UK users. The use of the GPS common-view method to provide time and frequency links, traceable to national standards, is examined. The development of a new GPS common-view receiver is described along with NPL's new GPS common-view service. Methods used to characterize and validate these GPS common-view links are discussed.

INTRODUCTION

The common view of GPS satellites [1] has for many years been used by primary timing laboratories as a high accuracy method of both frequency and time transfer. The method is particularly suitable for comparing the atomic clocks that contribute to International Atomic Time (TAI). The cost of the GPS hardware is, however, relatively high, which has restricted its uptake by other users within the UK. Inexpensive GPS receiver engines, suitable for high accuracy time and frequency applications, appeared in the market in the mid-1990s and have now been used to produce less expensive GPS common-view receivers [2]. NPL has contributed both to the development of less expensive receivers, and in parallel has developed a UK-based GPS common-view frequency and time transfer service. The new service will enable UK users to obtain time and frequency transfers traceable to national standards, at an uncertainty previously only available to primary timing laboratories.

FREQUENCY AND TIME TRANSFER METHODS AVAILABLE TO HIGH-ACCURACY UK USERS

The frequency and time transfer options available to UK users requiring the lowest uncertainties has been somewhat limited. Portable atomic clocks used as transfer standards will provide a high accuracy calibration with uncertainties better than 20 ns. Unfortunately, this form of calibration provides only a "spot" measurement, and regular expensive recalibrations are required. UK terrestrial standard frequency and time signals, for example MSF 60kHz and Droitwich 198kHz, are often used as sources of precise frequency and time. These standard frequency and time transmissions offer continuous frequency signals traceable to UTC (NPL). Normalized frequency uncertainties of 1×10^{-12} and 1×10^{-11} for an averaging time (τ) of 1 day are obtainable with the MSF and Droitwich transmissions respectively.

The Global Positioning System (GPS) signals may be used directly as a standard frequency and time reference. GPS-Disciplined Oscillators provide convenient high-accuracy real-time laboratory reference standards [2] with a potential frequency uncertainty of a few parts in 10^{13} over an averaging time (τ) of 1 day. Alternatively, a UK user may use the GPS common-view method to make traceable differential time and frequency measurements against UTC (NPL).

DEVELOPMENT OF THE TFS/NPL GPS COMMON-VIEW RECEIVER

NPL and Time & Frequency Solutions (TFS) have jointly developed an eight-channel GPS common-view receiver using Motorola's VP Oncore GPS engine. The receiver was initially designed for UK users requiring the lowest uncertainty time and frequency traceable to UTC (NPL); however, the receiver has also proved to be valuable for GPS common-view links between primary timing laboratories.

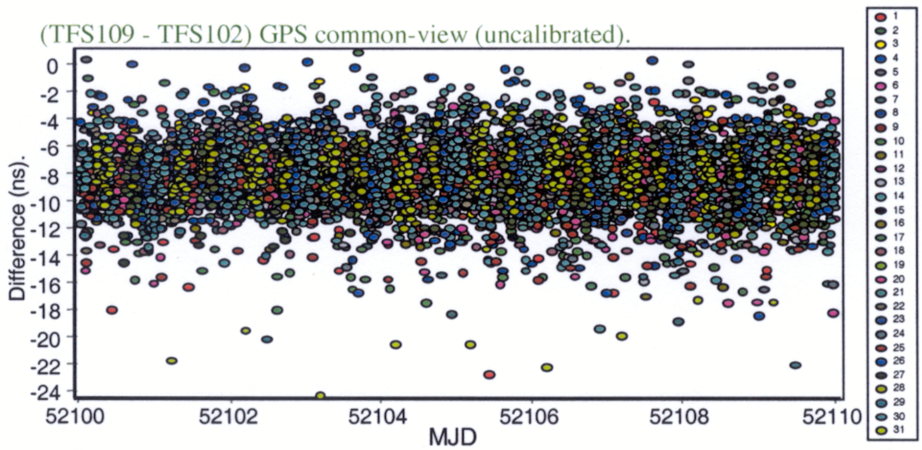

Figure 1 showing GPS common-view common-clock measurements made at NPL between two TFS common-view receivers. The individual GPS satellites are identified by their PRN values.

TFS developed the instrument hardware and NPL the data processing software. The receiver is operated via a laptop PC. In addition to the GPS engine, the receiver hardware consists of a purpose-designed counter timer card, hardware to generate a 1PPS signal from a 5 or 10 MHz standard frequency input, and the required interfaces. The receiver will operate from either a 1PPS timing pulse and/or a standard 5 or 10 MHz standard frequency input. This enables the user to perform both time and frequency transfer common-view measurements using the 1PPS input, or frequency transfer measurements using only the 5 or 10 MHz input. A standard (non-choke-ring) antenna is used with this receiver.

The common-view software was developed at NPL. Daily output files are produced. These consist of data in the recognized CGGTTS format **[3]**. Additional information on the GPS system, and on the status of the GPS receiver is output daily to a separate file. The logging software will run continuously. The PC used to control the receiver may be connected via a modem to a local telephone. A second software package will automatically transfer the data files once per day from the receiver to an FTP site at NPL for processing.

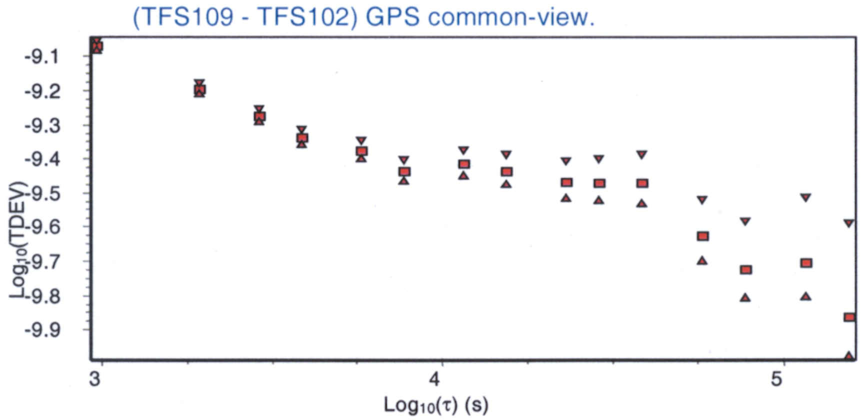

Figure 2 showing plots of $\mathrm{Log}_{10}(\sigma_x)$ against $\mathrm{Log}_{10}(\tau)$ determined from the mean of each epoch's time transfer measurements shown in Figure 1.

The performance of the TFS GPS common-view receiver has been evaluated using common-clock common-view measurements. Individual satellite common-view measurements are plotted in Figure 1. The mean offset of approximately –8 ns is due to the difference in the internal delay of the two receivers, which had not yet been calibrated. The underlying noise type is close to White Phase Modulation (WPM) and there is no obvious daily cycling of the delay. Plots of $\mathrm{Log}_{10}(\sigma_x)$ against $\mathrm{Log}_{10}(\tau)$ are shown in Figure 2 determined from the mean of each epoch's time transfer measurements. The underlying gradient of –1/2 verifies that the noise type is principally WPM. There is a slight but noticeable increase in the values of σ_x extending above the –1/2 gradient trend line at an averaging time of approximately 1/2 day. This is probably due to daily temperature cycling. The value obtained of 0.2 ns for σ_x at an averaging time of approximately 1 day was particularly encouraging and illustrated the intrinsic delay stability possible for GPS common-view receivers when based on the Motorola VP Oncore engine.

TRACEABILITY TO NATIONAL STANDARDS

Traceability is the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. NPL's GPS common-view service offers traceability to UTC via UTC (NPL). Frequency transfer uncertainties (relative to UTC(NPL) and UTC) of $5\mathrm{x}10^{-14}$ (1σ) and time transfer uncertainties of 10 ns (1σ) relative to UTC(NPL) and 20 ns (1σ) relative to UTC at an averaging time (τ) of 1 day are achievable using the service.

The common-view service also provides extensive validation of the common-view link to provide confidence in the traceability of the user's time measurements or reference standards.

OPERATION OF NPL'S GPS COMMON-VIEW SERVICE

The NPL GPS common-view service is designed as a complete package offering a UK user lower frequency and time transfer uncertainties and a higher integrity than may be achieved through direct reception of the GPS signals. Data are transferred on a daily basis to NPL via the Internet, and is processed on a weekly basis. NPL will provide data, plots, statistics, and detailed reports. Although the service is primarily designed with the TFS/NPL common-view receiver, NPL will process data from any receiver output in the CGGTTS format [3].

The setting up and operation of a GPS common-view installation may be considered in four parts:

a) Initial characterization and calibration of the GPS common-view receiver

This is usually performed at NPL. A differential receiver delay calibration is performed against NPL's reference GPS common-view receiver. In addition, extensive measurements are made of the receiver's performance characteristics. These characteristics are then used as a "benchmark" against which to compare the receiver's performance when operating at a user's laboratory. Examples of the initial characterization of a TFS receiver are shown in Figures 1 and 2.

b) Installation and validation of the new GPS common-view link

The installation of a GPS common-view receiver is relatively straightforward and may easily be undertaken by the user. A key principle is to validate as much as possible of the new GPS common-view link using regularly obtained GPS common-view data rather than measurements made specifically for validation purposes. The initial characterization measurements are repeated at the user's laboratory, from which the performance of the receiver in its new operating environment may be evaluated.

c) Routine operation and performance validation of the GPS common-view link

GPS common-view data are forwarded to NPL on a daily basis. NPL applies a series of validation tests in its data processing that will confirm the integrity of the GPS common-view measurements during routine operation.

d) Regular re-calibration of the GPS receiver's time offset

Frequency transfer measurements do not require the calibration of the user's GPS receiver. Regular recalibrations of the receiver are, however, required for time measurement. The duration between re-calibrations will depend on the measurement uncertainty required. There are two recalibration methods. The user's common-view receiver may be sent to NPL. Alternatively, NPL may send a second common-view GPS receiver to the user's laboratory as a transfer standard. The latter method has the advantage that the user's receiver remains operational during the recalibration process.

The use of NPL's GPS common-view service to perform frequency transfers between a passive hydrogen maser at Quartzlock, Totnes, Devon, and UTC (NPL), a baseline of approximately 300 km, is shown in Figure 3. The underlying rate of the Quartzlock maser may clearly be observed from the plots. The short-term scatter on Figure 3 is due to noise on the GPS common-view link and is similar to the scatter obtained on the benchmark common-clock common-view measurements shown in Figure 1. Plots of $\mathrm{Log}_{10}(\sigma_x)$ against $\mathrm{Log}_{10}(\tau)$ determined from the mean of each epoch's individual satellite time-transfer measurements are shown in Figure 4. These results are very encouraging for, at averaging times greater than 1000 s, frequency transfer measurements are being made with a precision better than 1 nanosecond. This illustrates the potential of NPL's GPS common-view service for making sub-nanosecond precision frequency and time transfers to customers within the UK. The values of σ_x were, however, noticeably higher than those obtained from the common-clock measurements shown in Figure 2, showing that some additional noise has been added through the use of an extended baseline. Plots of $\mathrm{Log}_{10}(\mathrm{Mod}\ \sigma_y)$ against $\mathrm{Log}_{10}(\tau)$ show that frequency transfers with a stability better than $1\mathrm{x}10^{-14}$ for an averaging time (τ) of 1 day

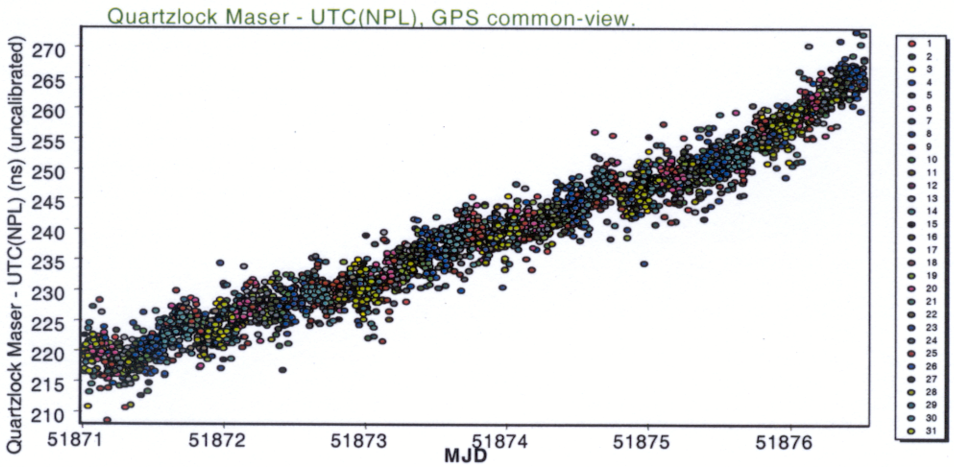

Figure 3 showing individual satellite time offset measurements of a (Quartzlock Maser – UTC(NPL)) frequency transfer.

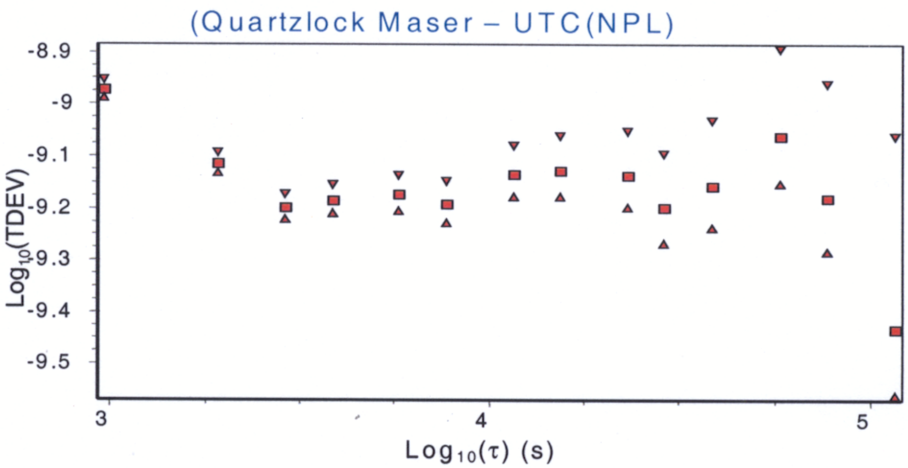

Figure 4 showing plots of $Log_{10}(\sigma_x)$ against $Log_{10}(\tau)$ determined from the mean of each epoch's time transfer measurements shown in Figure 3 (1σ confidence interval).

have been achieved.

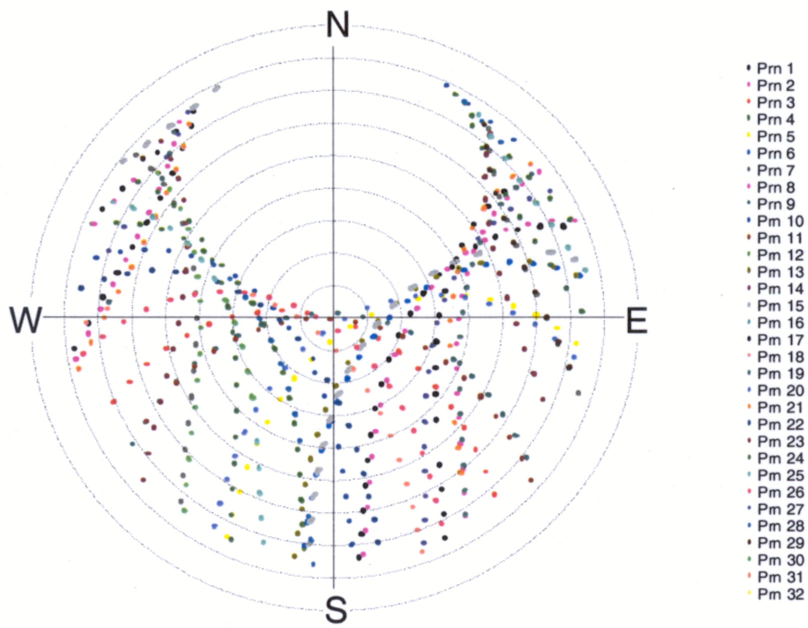

Figure 5 showing the skymap for benchmark GPS stand-alone measurements made at NPL using a GPS common-view receiver.

VALIDATION OF THE GPS COMMON-VIEW MEASUREMENTS

VALIDATION PRINCIPLES

NPL will be setting up GPS common-view installations at some locations in the UK where the laboratory operators will not be experts in setting up GPS common-view receivers. NPL has adopted the principle that as much as possible of the optimization and validation of the GPS common-view links are performed using regular GPS common-view measurements, rather than by performing separate validation measurements. In this section several of the validation techniques employed in NPL's GPS common-view service will be outlined.

USE OF SKYMAPS

Skymaps provide a plot of the trajectory of each satellite tracked by a GPS receiver as a function of satellite azimuth and elevation angle. An example of a skymap for GPS common-view receiver operating at NPL is shown in Figure 5 above. Satellites directly overhead are shown at the center of the map. Noticeable is the "hole" in the GPS constellation that occurs in the sky to the north of the receiver, and the absence of satellites with elevation angles below 10°. This is due to a mask angle being applied by the receiver. Sky maps are ideal for checking that there is visibility of GPS satellite in all directions. Sky maps may also be composed of the GPS satellites actually used in common-view time transfer, as this will provide a useful indication of the effect on the usable GPS constellation of the extended GPS common-view baseline.

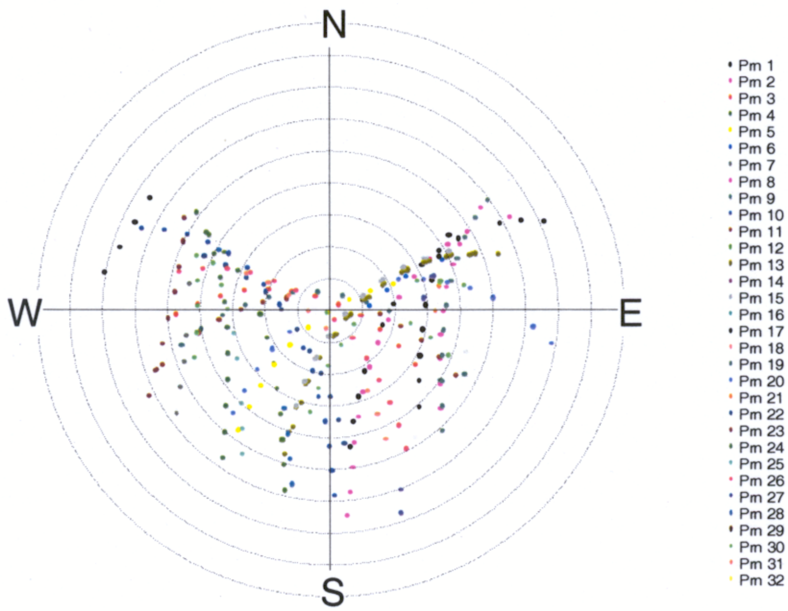

Figure 6 showing the skymap for GPS stand-alone measurements made during a period where the receiver was experiencing reception difficulties.

Figure 6 shows a skymap constructed from measurements made by a GPS common-view receiver during a period when there were signal reception problems. Almost all of the satellite tracks below an elevation angle of 20° have been lost. The use of the skymap confirms that the east-west symmetry of the satellites tracked has been maintained. The loss of satellites may then be identified as a signal reception problem and is independent of the satellite azimuth angle, rather that the obscuration of part of the sky that will be azimuth-dependent.

Use of Difference from Mean Measurements

Many of the users of NPL's GPS common-view service will not be using the highest stability atomic clocks as their laboratory reference standard, and their standards will almost certainly not be steered to UTC (NPL). A simple method is developed to validate the performance of a GPS common-view link when the customers' clocks may either be significantly less stable than the common-view link itself or when the clocks possess a significant frequency offset.

At each measurement epoch, both GPS receivers contributing to the common-view link are simultaneously tracking between five and eight satellites. A mean value of the common-view measurements t_m is determined from all individual satellite common-view measurements made in a single epoch. For each individual satellite common-view measurement t_i, the Difference From Mean (DFM) value t_{DFM} is determined using:

$$t_{DFM} = (t_i - t_m) . \qquad (1)$$

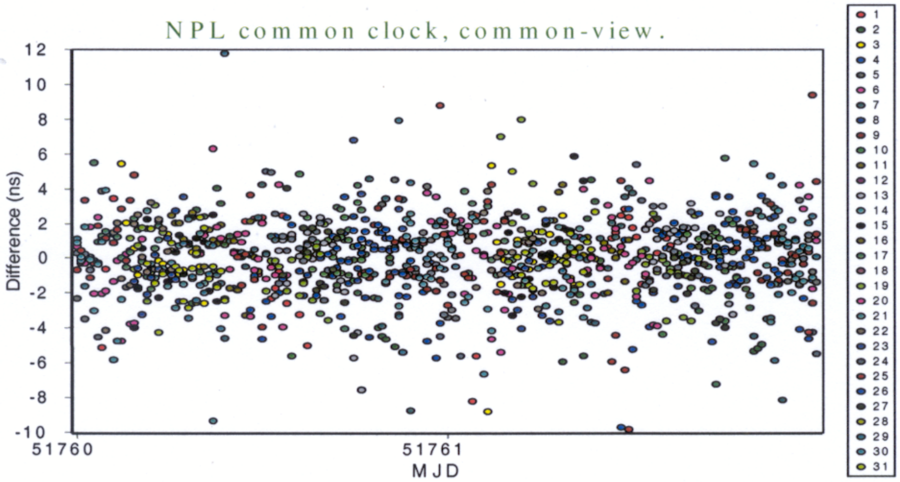

Figure 7 shows benchmark Difference From Mean (DFM) measurements obtained from common-clock, common-view measurements made at NPL.

The DFM values will be independent of the clocks at both the customer's laboratory and at NPL. Figure 7 shows benchmark DFM values made from NPL's common-clock common-view measurements. Figure 8 shows the time transfer between a poorly functioning rubidium GPSDO being tested at the National Metrology Laboratory in Dublin using NPL's GPS common-view service. The GPSDO's output will varied by several hundred nanoseconds. This is far greater than the instability of the GPS common-view receiver. Figure 9 shows the DFM values obtained from the common-view measurements shown in Figure 8. The scatter of these DFM values is very similar to benchmark common-clock common-view DFM values shown in Figure 7.

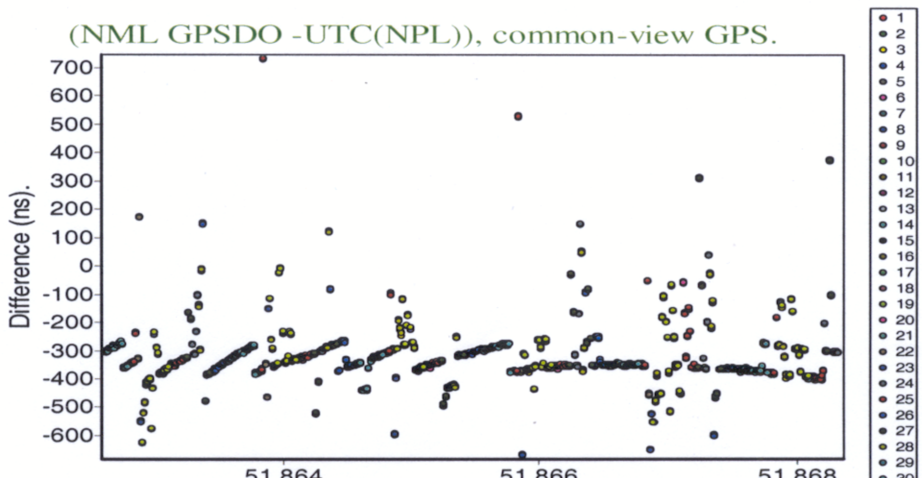

Figure 8 shows individual satellite GPS common-view time transfer measurements between a rubidium GPSDO at the National Metrology Laboratory Dublin and UTC(NPL).

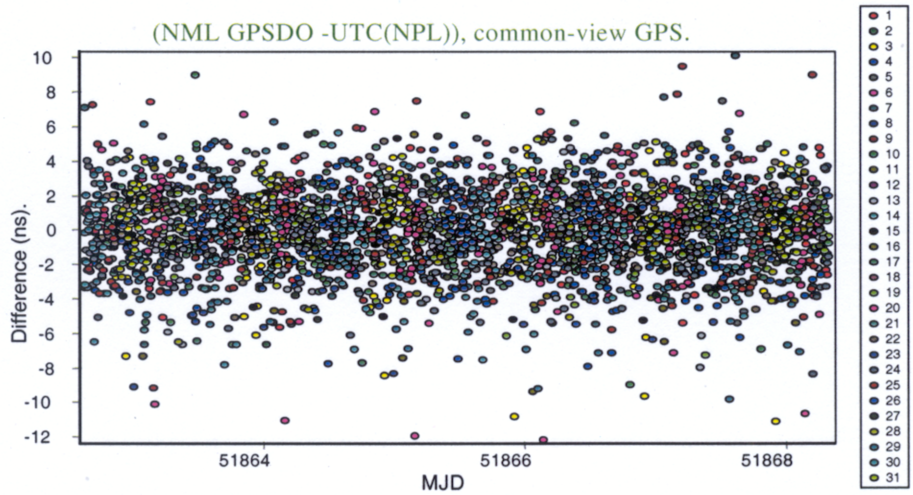

Figure 9 shows Difference From Mean (DFM) values obtained from GPS common-view measurements made between the National Metrology Laboratory in Dublin and NPL.

The standard deviation of DFM values is an excellent method to validate the performance of a GPS common-view link. Physical processes that affect individual GPS satellite time offset measurements, for example ionosphere delay, will change the scatter of the DFM values. Physical processes that affect equally all individual satellite GPS common-view measurements, for example the antenna delay stability, will not affect the DFM values. Table 1 shows the standard deviation of DFM values for both GPS common-clock common-view measurements, and for a selection of links used in NPL's common-view service as well as international GPS common-view links. The DFM standard deviation of the benchmark GPS common-clock common view measurements and the GPS common-view links to the NML, Quartzlock, and Time and Frequency Solutions all have very similar values. We conclude that physical processes that affect individual satellite GPS common-view measurements differently, do not increase the DFM significantly over the baselines used for links in NPL's GPS common-view service. The DFM standard deviation of the common-view link to USNO is significantly larger due to the very much longer baseline. The DFM standard deviation was also significantly larger in the case where signal reception problems were experienced; this may have been due to increased receiver noise.

Difference from Mean (DFM) Measurements obtained from GPS common-view links	DFM Standard Deviation
NPL benchmark common-view common-clock measurements	0.96 ns
NML Dublin and NPL	1.0 ns
Quartzlock Totnes, Devon and NPL with signal reception problem	1.5 ns
Quartzlock, Totnes, Devon and NPL without signal reception problem	0.92 ns
Time and Frequency Solutions, Witham, Essex, and NPL	0.85 ns
Transatlantic GPS Common-view measurements (USNO – NPL)	2.4 ns

ANTENNA COORDINATES

Erroneous antenna coordinates may very significantly degrade both the time transfer and frequency transfer capabilities of the GPS common-view method. NPL has developed a method both to optimize and then validate the antenna coordinates used on NPL's GPS common-view service links. It is important to remember that by postprocessing *stand-alone* GPS measurements, it is possible to optimize the GPS antenna *coordinates;* however, for GPS common-view measurements it is only possible to optimize the *coordinate differences.*

Figures 10 and 11 show the dependence of GPS common-clock common-view DFM values on both the satellite azimuth and satellite elevation angle. The increase in scatter with decreasing elevation may easily be explained in terms of reduced antenna gain and increased atmospheric effects. The observed increase in the scatter at azimuth angles close to 360 degrees is harder to explain. However, there is a relatively large number of low elevation angle satellites, and no high elevation angle satellites (because of the GPS constellation "hole") at these azimuth angles. Figures 10 and 11 would have been very similar if UK baseline common-view links had been used rather than the common-clock common-view measurements. The plots shown are constructed from measurements made with receivers using near optimum antenna coordinates. Erroneous antenna coordinates will have the following two effects on the DFM values:

i) The standard deviation of the DFM values will increase significantly.
ii) The plots of DFM values against satellite azimuth and elevation angles shown in Figures 10 and 11 will no longer be symmetrical about the x axis.

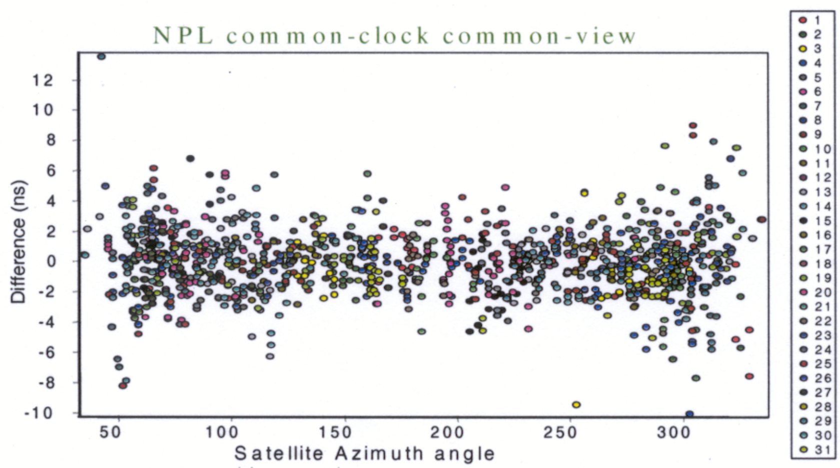

Figure 10 shows the dependence of NPL's common-clock common-view DFM measurements on satellite azimuth angle.

To optimize the *coordinate difference* on a GPS common-view link, the customer's antenna coordinates are adjusted until the scatter of the DFM values reaches a minimum. The coordinate corrections are then entered into the common-view receiver for future use. To validate the *coordinate difference* of the customer's GPS link, the DFM measurements are plotted against satellite azimuth and elevation. We then confirm that the plots appear symmetrical about the x-axis.

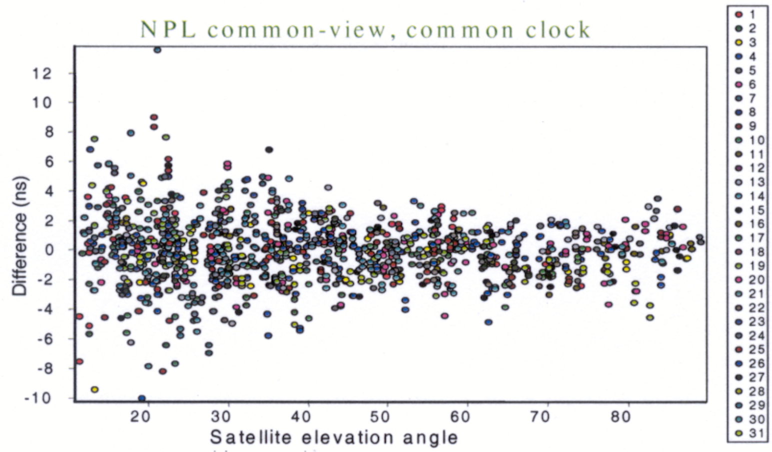

Figure 11 shows the dependence of NPL's common-clock common-view DFM values on satellite elevation angle.

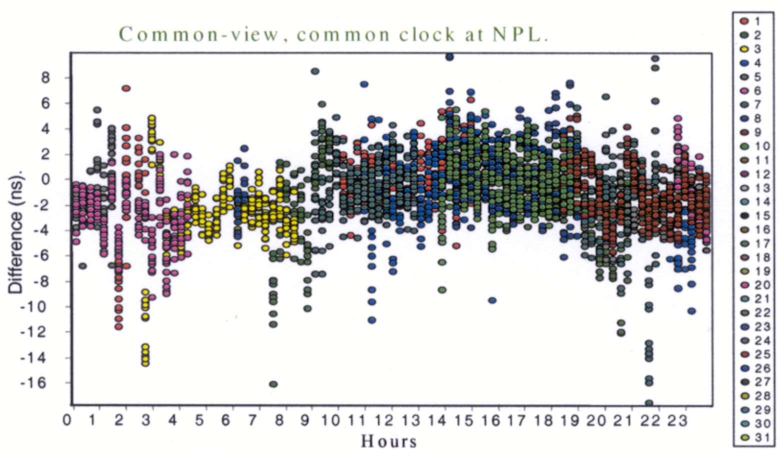

Figure 12 showing the dependence of NPL's common-clock common-view values (prn 1-10) on time of the sidereal day.

MULTIPATH

Code multi-path is a major limitation to the short-term performance of a GPS common-view receiver, and the multi-path may be strongly dependent upon the receiver antenna's coordinates. Multipath is due to unwanted signal reflections in the receiver's antenna; the magnitude of the multipath will change rapidly as the location in the sky of the GPS satellites change. Because the GPS constellation's position repeats each sidereal day, so a repeating pattern of multipath may be observed.

Figure 12 shows the plots of common-clock common-view DFM values (prn 1-10) over 10 days. The time within the sidereal day is plotted on the x-axis, so that tracks having the same time on successive sidereal days are plotted with the same x values. Consider the DFM values obtained from a single satellite. The scatter within the DFM values obtained at the same time on successive days (same x axis value) is relatively small. In contrast, there is a far greater scatter in the DFM values obtained on successive epochs of the same day. This repeating daily pattern is a clear indicator of code multipath.

CONCLUSIONS

NPL and Time and Frequency Solutions have jointly developed a new GPS common-view receiver. NPL has launched a new GPS common–view frequency and time transfer service that will provide both lower uncertainties and higher integrity than is possible from time and frequency transfer methods previously available within the UK. NPL has developed techniques for optimizing validating the performance of the GPS common-view links using only the regularly recorded GPS common-view measurements.

ACKNOWLEDGMENTS

The authors thank Nigel Helsby and Simon Eavery at Time and Frequency Solutions, Clive Green and Lucy Martin at Quartzlock, and John Murray at the National Metrology Laboratory, Dublin, for their contributions to the work. This work has been funded by the National Measurement System Directorate of the Department of Trade and Industry under contract GBBK/C/017/000.

REFERENCES

[1] W. Lewandowski and C. Thomas, 1991, *"GPS Time transfer,"* **Proceedings of the IEEE, 79,** 991-1000.

[2] J. A. Davis and J. M. Furlong, 1997, *"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),"* NPL Report no. CTM1, October 1997.

[3] D. W. Allan and C. Thomas, 1994, *"Technical directive for the standardization of GPS time receiver software,"* **Metrologia 31,** 67-79.