

Time & Frequency Dissemination in the UK

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Abstract

This paper provides a qualitative review of those standard-frequency and time signals available in the UK which can be used to trace time and frequency measurements to national standards. Particular emphasis is given to use of the Global Positioning System, as well as the more traditional terrestrial radio broadcasts from Rugby on 60 kHz and Droitwich on 198 kHz. A brief mention is given to telephone and inter-net time services, where similar traceability principles apply but where they are likely to be in demand from a new and wider community because of the growth in electronic commerce.

1. Comparing Time and Frequency Measurement Standards

The base unit of time, the second, is the most accessible of all the SI units. A signal generated by a time and/or frequency standard can be directly broadcast over a wide geographical area, making that standard directly available to users with the appropriate receiving equipment. The fact that the same standard-frequency and/or time signal can be received by many users allows for the indirect comparison of remote standards, a mechanism used at the international level for comparing the time held by national laboratories and at the national level for establishing a traceable measurement chain to one of those national standards. In contrast, measurement standards for other physical quantities have to be disseminated through the transfer of artefacts - either by transfer standards or by the direct calibration or inter-comparison of measurement instruments - a much slower and more cumbersome process.

2. Co-ordinated Universal Time (UTC)

Co-ordinated Universal Time (UTC) is the foundation of the international time system, and is both a measurement system and a time scale. The fact that UTC is generated by national time laboratories, and that the seconds of UTC are based on the SI definition of the second, means that UTC is the mechanism for establishing quantitative agreement on the performance of the various national time standards around the world. As a time scale, it provides the internationally agreed *time of day* and *date* for science, technology, commerce as well as for everyday communications. Thus the time used for the most mundane and for the most technologically demanding tasks are locked to the same reference. The value in this approach is that time and frequency measurements are transparent across national boundaries and across different science and technology sectors.

The UTC time scale is determined using some 260 atomic clocks in some forty national time laboratories around the world, including the National Physical Laboratory (NPL) in the UK. The time difference between the laboratories is compared using the Global Positioning System (GPS) satellites as transfer standards, via the "classical GPS common-view" method. The Bureau International des Poids et Mesures (BIPM) in Paris collates time data from each laboratory, along with time transfer data, and computes UTC. The medium term stability of UTC (up to 40 days or so) is set by the stability of the contributing clocks, and the statistics associated with the algorithm used to compute the time scale. The accuracy and long term stability of UTC is established with

measurements from a small number of primary frequency standards. Over the last year, measurements have been made using six primary frequency standards at the PTB in Germany, NIST in the United States and NRLM and CRL in Japan. While the primary standards ensure that UTC keeps time in a highly accurate and regular manner, additional procedures are needed to keep UTC in approximate agreement with the time based on the rotation of the Earth (i.e. UT1, the more scientifically precise version of Greenwich Mean Time). The agreement is maintained by inserting leap seconds into UTC, effectively setting the UTC "clock" either backwards or forwards by one second when required, typically every 18 months.

One key point to note is that UTC is a post-processed time scale, with the latest results published each month by the BIPM in their Circular T. If access to UTC is required in real-time, one must establish a link to a national time laboratory either directly or indirectly through a broadcast system referenced back to a national time laboratory (e.g. the MSF 60 kHz transmission which is under the control of NPL, or GPS which obtains UTC from the US Naval Observatory). The uncertainty in the comparison will be dependent on the quality of the link, and the ability of the national time laboratory to predict its own departure from the UTC ahead of the publication of next BIPM Circular T.

3. Standard-Frequency and Time Signals for Traceability in the UK

Three standard-frequency and/or time signals are listed below which can be used to establish a traceable measurement link to NPL in the UK. The two terrestrial VLF radio broadcasts (i.e. MSF 60 kHz broadcast transmitted from Rugby and the BBC Radio 4 long wave transmission from Droitwich on 198 kHz) have been the mainstay of time and frequency calibrations in the UK in recent years. While GPS has dominated the time and frequency market in recent years, particularly for telecommunications applications, it has only just been accepted as a method for achieving NAMAS accreditation for time and frequency measurements. The GPS common-view method is a differential time transfer method rather than a broadcast service: it is not currently used for disseminating national standards at present, but new services are planned in the very near future.

SFTS	Geographical Coverage	Nominal Time dissemination accuracy	Nominal Frequency dissemination accuracy
Droitwich on 198 kHz	Southern England	n/a	10^{-11}
MSF on 60 kHz	UK	2 ms	10^{-12}
GPS (one-way)	Global	340 ns	10^{-12}
GPS (common-view)	Global to NMI's (UK only to NPL)	10 ns	10^{-13}

3.1 MSF and Droitwich

In the case of the MSF 60 kHz transmission from Rugby, the time signal is broadcast by the BT but under contract from NPL. Hence NPL has direct control of the signal. In the case of the Droitwich transmissions, the signals is not under active control from a

national time laboratory. One may choose to use these signals in receive only mode, using the operator's stated signal specifications and taking account of signal distortions from atmospheric propagation effects. However, there is always a risk in that the signal may go out of specification using such an approach. For measurement traceability, and for some critical applications, the risks associated with blindly accepting the SFTS as "truth" are considered too great. Additional checks are then required either on site, or at a third party laboratory with an independent time reference. It is here that the National Metrology Laboratories have a role to play, in monitoring the received signals and reporting on their performance. The information gathered in this way can either be used to confirm that the signal is operating within specification or to improve on the raw broadcast signal by applying corrections relative to the national time standard. Interestingly, the MSF signal is clearly more stable than that from Droitwich, but because of the different atmospheric propagation effects at 198 kHz compared to 60 kHz, the Droitwich transmissions can in principle be used to achieve a lower uncertainty for frequency traceability when used in differential mode.

However, there are other factors to be considered as well when judging whether to use MSF or Droitwich. Both systems are prone to occasion outages, and MSF has regular maintenance periods when the signal is taken off-air. Droitwich only covers a portion of Southern England, while MSF covers the whole of the UK and a good part of Western Europe. In contrast, GPS is being used more widely because of its global coverage, its greater time dissemination accuracy, and the falling price of GPS receivers.

3.2 Global Positioning System (GPS)

The other main route for tracing time and frequency measurements is to use the Global Positioning System (GPS). GPS is a satellite navigation system operated jointly by the US Departments of Defence and Transport. Its underpinning principle of operation is the measurement of the time-of-flight of GPS radio signals from the GPS satellites to GPS receivers in order to calculate the distance between them. If the satellite orbits are well known, and the distances from the GPS receiver to enough satellites are known, then the GPS receiver position can be calculated. As GPS seeks to provide position information with accuracies of a few tens of metres (and because light only travels 30 cm in 1 nanosecond), atomic clocks are required to provide the timing facilities for the GPS system. The by-product of all this is that GPS provides time information with sub-microsecond accuracy.

Typically, GPS based time and frequency standards do not provide raw time information from the GPS receiver. The short-term jitter of the signal makes raw GPS much worse than a simple free-running ovenised quartz or rubidium frequency standard. However, the long term performance of GPS, which is steered to stay in close agreement with UTC, is much better than any commercial oscillator operating in isolation. The typical package will be a GPS Disciplined Oscillator (GPSDO), where a local oscillator is steered to stay in agreement with time derived from GPS. The short term performance of the GPSDO is set by the local oscillator, the long term performance is set by the GPS receiver, and the intermediate performance (typically for averaging time from 500 to 5000 seconds) is set by the steering of the local oscillator.

In principle, the same traceability methodologies used for MSF and Droitwich can be employed using GPS:

- calibrating the SFTS receiver
(to confirm that the unit is operating satisfactorily)

- validating the SFTS via measurements at a national standards laboratory
(to confirm that the reference signal is within specification for receive only operation, or to apply corrections to the reference signal in differential mode)
- validating that the local measurement system is fit for purpose
(i.e. monitoring environmental effects, confirming sub-component calibrations where required, self-consistency checks, comparisons with an independent oscillator, etc.)

However, because of the way the GPS receiver computes the time, and the way the GPSDO applies the corrections, two additional points need to be considered: the GPS antenna co-ordinates and the disciplining algorithm.

In the majority of circumstances, the GPS receiver will compute its own position. Any errors in position, will translate into an error in the time calculated from each GPS satellite (because the time calculation is dependent on assumptions about the distance the GPS signal has travelled). The GPS receiver's position determination is dependent on the averaging time used, the number of satellites in view, and multipath, with these latter two parameters being site dependent. Hence a simple calibration of a GPSDO at one site is no guarantee that it will perform at the same level at another site, and so care is needed when selecting a location for the GPS receiver's antenna. The initial site survey, and data sets generated from it, are vital to the validation procedure. The issue is of fundamental importance for time measurement traceability, but less critical for frequency measurement traceability where a constant phase offset does not matter so much.

The value in a GPSDO is based largely on its disciplining algorithm, and hence the details of the algorithm are rarely available for assessment. For this reason, a "black-box" approach has to be taken and the outputs of the GPSDO compared continuously with an independent oscillator. The stability of the reference oscillator needs to be considered when establishing uncertainty budgets, as it will set the threshold at which anomalies can be detected. It should be possible to use the GPSDO oscillator itself, provided that quantitative data on the steering corrections are available. The premise here is that for an oscillator of known stability, and a GPS signal of known accuracy, the steering corrections should always be less than a given threshold if the GPSDO is functioning normally.

4. Telephone and Internet Time

A number of time laboratories provide telephone time services which allow computer based systems to receive accurate time information via a modem and telephone line directly from the national time laboratory. The method is traceable because the time delays over the telephone line can be calibrated during each call. There may be more demand for this method in the near future, with new interest in active audits of time servers used in electronic commerce applications.

5. Conclusions

The paper has outlined some of the background to traceable time and frequency measurements, and made some general qualitative comments on the main methods of achieving traceability for time and frequency measurements in the UK. The Poster presentation itself will explore these ideas further and in a more quantitative way.

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