IMPROVED TECHNIQUES FOR MONITORING THE PHASE OF L.F. STANDARD-FREQUENCY TRANSMISSIONS

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The prime means of disseminating time and frequency in the UK is the 60 kHz transmitter at Rugby, known by its call-sign MSF. This signal serves the entire UK and much of north-western Europe. The carrier frequency is held within a tolerance of ± 2 parts in 10^{12} and daily readings of the carrier phase measured against the Coordinated Universal Time scale maintained by the National Physical Laboratory, UTC(NPL), are published monthly by the NPL. The BBC Radio 4 UK transmissions on 198 kHz from Droitwich are also used as a frequency reference, and daily measurements of this too are published by the NPL.

Whenever phase measurements are made on a sinewave signal there is an ambiguity of one carrier period, $16.\underline{6}$ µs in the case of MSF and $5.\underline{05}$ µs in the case of Droitwich. This places a limit on the period of time during which the reference frequency can be absent and yet still allow the correct cycle to be recognised afterwards to provide continuity of readings when monitoring the performance. This period is directly dependent on the worst-case fractional frequency difference between the device being measured and the reference. Table 1 lists the time intervals over which the phase at 60 kHz would drift by one complete cycle with different fractional frequency differences, also listed are the figures for one centicycle (one hundredth of a cycle), which is a very conservative figure to avoid 'gaining or losing a cycle' during a break.

Table 1

Time intervals corresponding to one cycle, or one centicycle, at 60 kHz for various fractional frequency differences (δf/f).

δf/f	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}
one cycle	16.6s	2.8 min	28 min	4.6 hr	1.9 day	19 day	193 day	5.3 yr
centicycle	0.166 s	1.66 s	16.6 s	2.8 min	28 min	4.6 hr	1.9 day	19 day

The MSF transmission has a regular monthly break of four hours on the first Tuesday of each month, and an annual break of 14 days during the summer (when the transmission is restored overnight whenever possible). Table 1 indicates that, given suitable equipment, measurements of a rubidium oscillator can safely be continued across the monthly break and measurements of a high-quality caesium oscillator can safely be continued across the annual break, even without the overnight transmissions.

Over many years measurements of the phase of MSF and Droitwich have been made using commercial locked oscillators which produce, typically, 1 MHz and 100 kHz signals locked to the received standard frequency. These signals are then compared with locally-generated 1 MHz or 100 kHz signals using an analogue phase recorder coupled to a chart recorder (Figure 1). For example, comparison at 100 kHz allows a conventional chart to show 10 µs full scale with major divisions of 1 µs. This approach requires calibration of the phase comparator and chart recorder in combination.

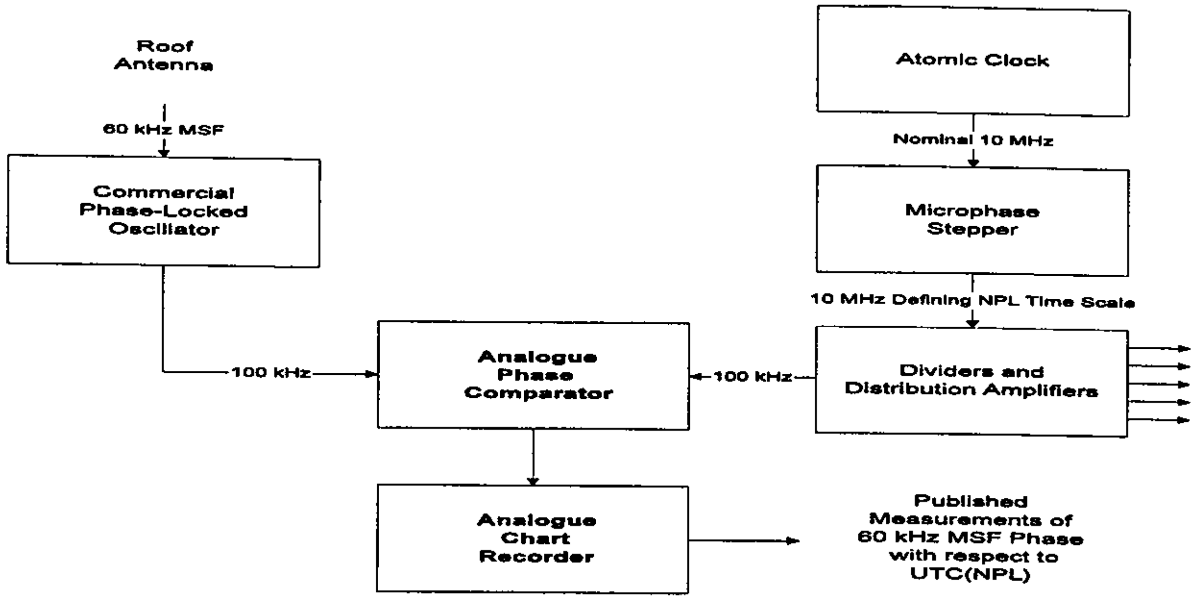


Figure 1. Equipment at the NPL to measure the phase of the 60 kHz MSF transmissions.

The use of a derived frequency for comparison, however, worsens the ambiguity of the measurement by an integer factor. This is because a phase-locked loop generating a comparison frequency f_c m/n times a reference frequency f_r necessarily produces m cycles of f_c for every n cycles of f_r before the pattern repeats. Any of the possible relative phasings is equally likely to arise by chance following any significant break in transmission (or a break in the power supply at the measuring station). In the case of 100 kHz comparison for 60 kHz this factor is five, and in the case of 100 kHz comparison for 198 kHz the factor is fifty. In each case these figures are the lowest multiple of the reference frequency which corresponds to a multiple of 100 kHz or, equivalently, the lowest multiple of the 100 kHz period which corresponds to a multiple of the reference period. Note that a locked oscillator producing, for example, both 1 MHz and 100 kHz from 60 kHz could actually lead to a factor of fifty even for the 100 kHz output, but this would only arise if unrelated counter chains were used to lock at 1 MHz and to provide 100 kHz.

So comparison at 100 kHz instead of 60 kHz divides the times given in Table 1 by a factor of five, and comparison at 1 MHz would divide them by a factor of fifty. In the case of 198 kHz as the reference frequency the times in Table 1 will first need to be scaled by a factor 60/198 to account for the shorter carrier period and then further divided by a factor of 50 for comparison at 100 kHz or 500 for comparison at 1 MHz. Clearly the use of derived frequencies for comparison can degrade the performance of the system by a very large factor, even when the reference frequency itself remains coherent across the break. For example, the chart record reproduced in Figure 2 appears to show a shift of 3⅓ μs (one fifth of a cycle) in the phase of MSF during the monthly break earlier this year, whereas the carrier actually resumed in its correct phase.

It could happen that there is a discontinuity in the phase, perhaps even a complete phase reversal, between the loss and the resumption of a standard frequency transmission. If this is to be detected there must clearly be no ambiguity whatsoever in the method of measuring the carrier cycle phase. This can only be achieved when the derived frequency is 1/n times the reference frequency, and the best resolution in the final result is obtained when this factor is unity. So phase measurements of the 60 kHz MSF transmissions are now being made using a 60 kHz oscillator phase-locked to the transmission. It is important to provide adequate screening and isolation inside this unit and in the associated cabling to avoid any breakthrough from the local 60 kHz into the antenna and receiver. A similar unit to provide 198 kHz locked to the Droitwich transmissions will also be put into use.

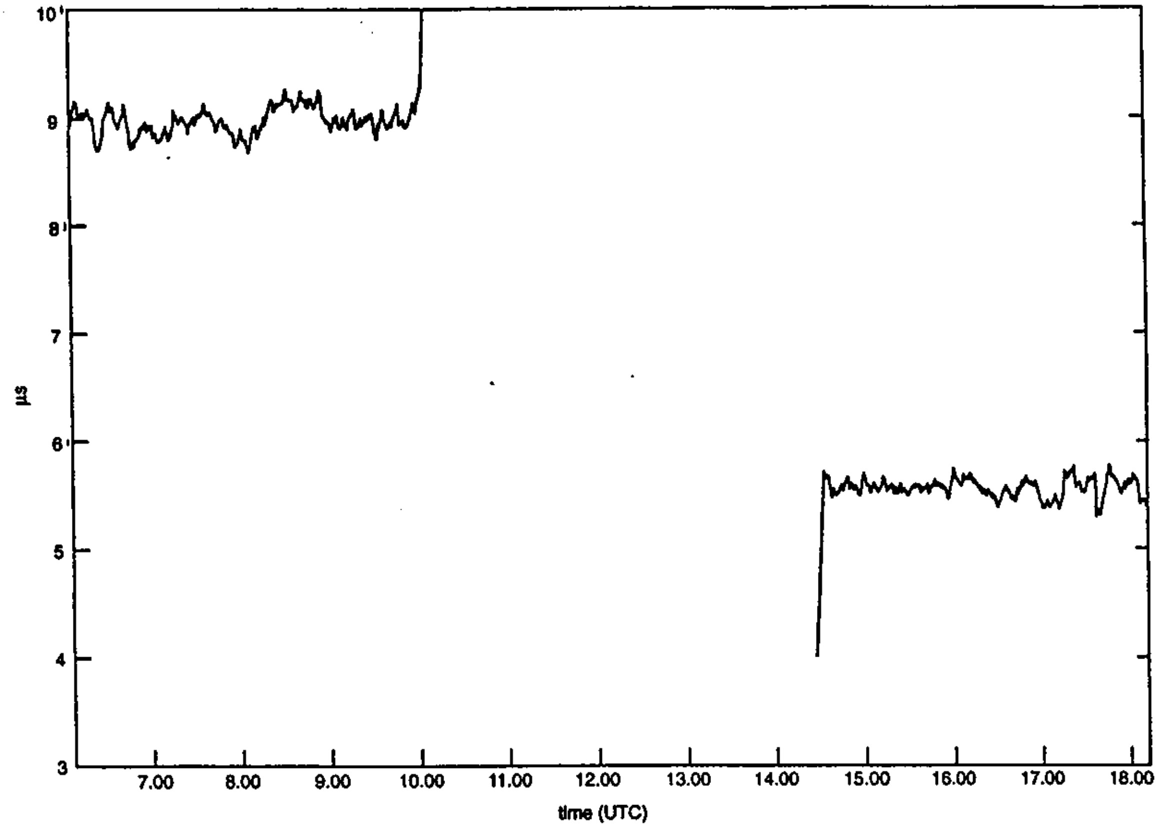


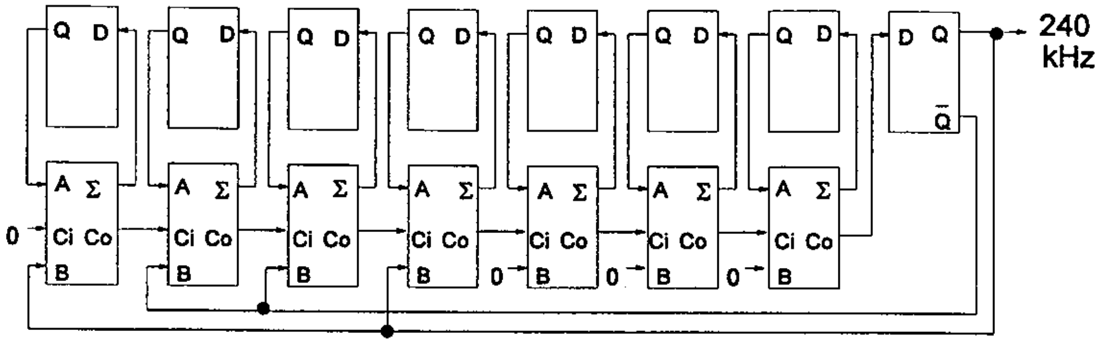
Figure 2. The chart record of MSF phase on 1995 March 07.

In order to make a phase comparison at the reference frequency, a local source of that frequency needs to be provided. Again this needs to be carefully screened and routed to avoid interfering with the received signal. When a conventional analogue phase comparator is used with a chart recorder, it is not necessary to provide a well-shaped or jitter-free local signal, because the low-pass filtering provided in the detector will effectively remove any fast low-amplitude jitter and because almost any repetitive waveform monotonic within each cycle and with adequately fast zero-crossings can be used. In particular, there is no need to synthesise a low-distortion sine wave, a jittery square wave is entirely adequate provided, of course, that its mean frequency is correct.

A suitable local signal at 60 kHz for comparison with the MSF-locked signal can be made directly from a local standard-frequency source by using a combination of binary full-adders and registers [1,2]. For example, Figure 3 shows a configuration which generates a signal at 240 kHz from a 5 MHz source by counting in steps of 6 modulo-125. The resulting signal has a mean frequency of exactly 6/125 times the 5 MHz reference with a peak-to-peak edge jitter of 200 ns (i.e. one period of 5 MHz). This, in turn, can be divided by four using a pair of D-type registers to give all four quadrature phases of 60 kHz, each with mean duty cycle 1:1, one of which can be selected for use as an input to a phase comparator.

This residue counting technique could be used to synthesise a 60 kHz sine wave by using the state of the seven-bit register to address a sine look-up table and using the state of the lowest significance register and one other to select the appropriate quadrant before driving an analogue-to-digital converter. However, in this application, a sine wave is not needed.

eight D-type registers clocked at 5 MHz (and set at 1 p.p.s.)



seven binary full adders

Figure 3. Generation of 240 kHz (with 200 ns p-p jitter) from 5 MHz.

The above method of synthesising 60 kHz from 5 MHz has the added advantage that the phase of the 60 kHz signal can be rigidly locked to a time scale (itself made by counting the same 5 MHz signal) by setting all 10 registers (including the divide-by-four) in an appropriate state using a sufficiently short one pulse-per-second (1 p.p.s.) signal. This means that, even after a counting fault or a power failure, the readings will always be absolutely locked to the local time scale which, in the case of UTC(NPL), is itself usually within 100 ns of UTC.

This counting technique has been presented as an improvement in analogue phase measurement. However, an all-digital approach can be used in which the incoming 60 kHz event is used to sample the state of eight of the registers to give a number representing one of 250 equi-spaced relative phases. In effect, the phase of 60 kHz can be measured in increments of 66⅔ ns. With summation of a set of consecutive readings, and with the possible deliberate addition of systematic timing jitter, even better resolution can be obtained.

Conclusion

The advantages of making phase measurements at the carrier frequency of an l.f. standard frequency transmission, rather than at a derived frequency, have been described. A simple method of synthesising the reference frequency locked to the local time scale has been shown, for use with conventional analogue measurement techniques. An all-digital approach has been indicated. In the case of the MSF signal all these techniques give at least a five-fold improvement in resolution over an earlier method.

References

[1] British Patent 1 455 821
[2] Chambers, J.P. 'The use of digital techniques in television waveform generation' pp 40-46 International Broadcasting Convention, 1974 (IEE Conference Publication)