Progress in Portable Instrumentation for Time Source Verification and Analysis

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***Abstract*— The calibration of the internal GPS-slaved reference clock of a portable time measuring instrument has been carried out using GPS Common View and we report on the subsequent direct measurement of the reference accuracy and stability over different time periods. The measurement architecture has been extended to include Grand Master time sources that conform to IEEE Std 1588 PTP (Precision Time Protocol). Time-code interpretation, network packet capture and time-stamping are performed by a programmable logic array (FPGA) and network transceiver (PHY) combination. This approach eliminates sources of imprecision which are found in traditional software based network package capture systems. Once captured, packets are interpreted by a specialized PTP protocol stack capable of automatically classifying PTPv1 and PTPv2 without the involvement of the operator.**

I. Introduction

In a previous paper [1] we described how our instrument is designed to enable verification of many different kinds of time sources and their time synchronisation outputs. Such sources are themselves often GPS synchronised clocks. These instruments often supply a very accurate one pulse per second (1pps) output; it was our intention to make a reference clock in the portable package that could quantify their performance. In addition, time values are often output in the form of amplitude modulated sine wave carrier codes designed by the Inter-range Instrumentation Group (IRIG) developed for range testing and easy recording onto magnetic tape. Because these codes have been described in standards with a history of some fifty years they have widespread use in energy supply utilities and in public time display of railways and airports far removed from ranges and missile testing facilities. The most common of these codes IRIG B uses a 1kHz carrier and has been extended as described in an IEEE standard [2] related to its use in electricity generating substations but is now widely used in unrelated applications. Besides precise measurement of the time value and simple data-logging, a subsidiary function of our instrument has been to identify modulated time-codes automatically and report their contents.

II. Review of Instrument Architecture

We showed previously [1] that the reference and measurement part of the instrument was designed in three main blocks, namely time reference acquisition with precision measurement, signal acquisition and analysis and network time measurement. They all connect to the main CPU which provides the user interface to an LCD touch-screen and USB port for data-logging; the whole package is portable with an internal rechargeable battery supply.

The reference system uses a GPS receiver to provide a 1pps reference that is compared with 1pps derived from the instrument's internal rubidium oscillator. After validation each time difference measurement provides an error signal for the controller which calculates and implements a correction of the rubidium frequency by means of a DAC.

III. Testing at the National Physical Laboratory (NPL)

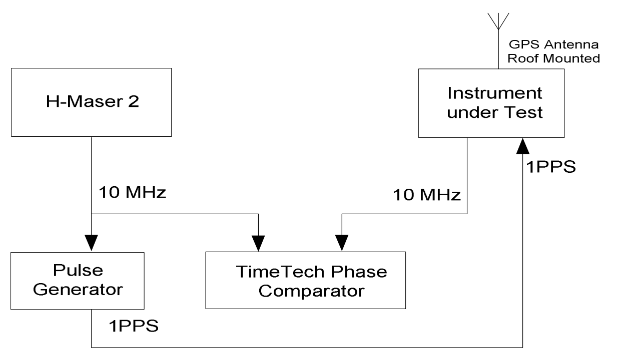

Figure 1. Test System

A production instrument was installed at NPL in Teddington in the configuration shown in figure 1. This instrument received GPS from a roof-mounted antenna during the tests. Prior to commencement we measured and entered the antenna cable delay as 320ns which corresponds to a length of about 64 metres. Cable delay measurement can be

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carried out by our instrument because we provide an output of our internal 1pps reference; it is simply necessary to connect this output to the measurement input through the cable under test. To study the 10MHz output stability, data were collected from a TimeTech phase comparator at 10s intervals. This instrument can measure 10MHz frequency stability to parts in 10^{14} over ten seconds. The raw phase time measurements were used in calculations of frequency and time stability using the classic Allan Variance (AVAR) and time variance (TVAR) statistical methods. The results are shown below in figures 2 and 3. At 10s we show that the frequency stability is about $2\text{x}10^{-12}$ and from 60s onwards it is better than $1\text{x}10^{-12}$, in spite of the broad hump over 1000s to 5000s due to the frequency steering to follow GPS.

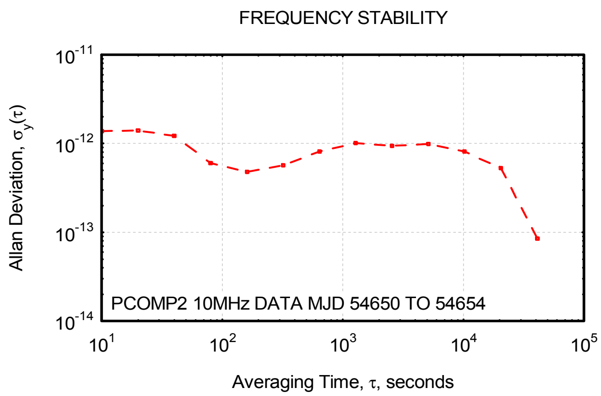

Figure 2. Frequency Stability of the Instrument Reference Clock

The TVAR graph illustrates the best possible time measurement stability that will be achievable using the instrument; in practice for time intervals less than 100s the time measurement stability is limited by the resolution of the time measurement interpolator, rather than by the reference clock, to about 3 parts in 10^{11} over 10s.

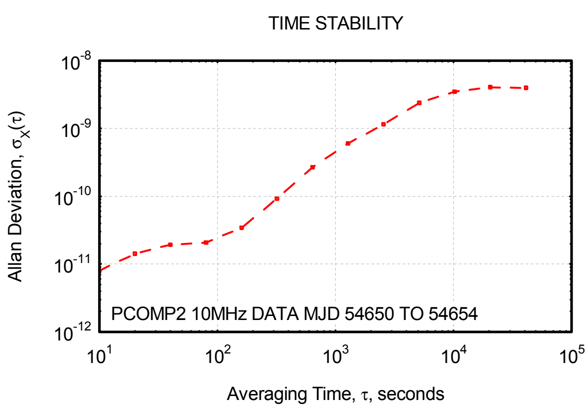

Figure 3. Time Stability of the Instrument Reference Clock

IV. Time Measurement Calibration

In addition to stability, our design goal was to achieve high accuracy. For this reason the reference clock in each production unit is calibrated by GPS Common View to our national standard UTC(NPL) at NPL, Teddington. However, our instrument can only make comparisons with GPS_Time; for this reason we take care to relate the calibration to GPS, rather than UTC or UTC(NPL), by using NPL measurements of GPS_Time. To investigate the effectiveness of this procedure we carried out the normal calibration procedure at our Witham site, comparing our laboratory clock time by Common View with NPL, then installed the instrument at NPL Teddington where we used it to measure 1pps from H-Maser2 for 42 days continuously. This 1pps had a known delay from UTC(NPL) which we have subtracted from our time interval readings and plotted. On the same graph, data taken from measurement of UTC(NPL)-GPS_Time is shown. The daily means of these results are shown in figure 4 below.

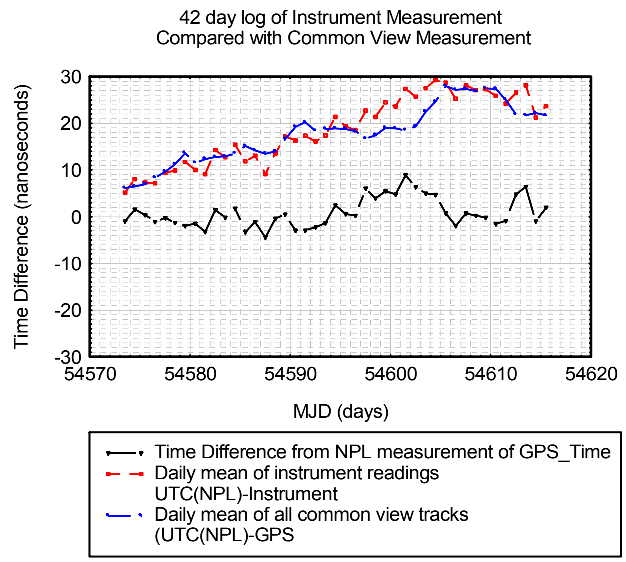

Figure 4. Assessment of Calibration

The slope of the blue and red points is due to the frequency difference between UTC (NPL) and GPS_Time. The instrument time error from GPS_Time, the black line, as evaluated by this method had a mean value of less than 1ns over the 42 day measurement period. Standard deviation is 3ns and the maximum of the daily average error is 9ns. When a calibration adjustment from BIPM is taken into account the calibration error was measured as 11.9ns by NPL and the 1σ uncertainty is estimated to be 11.2ns

V. Precision Time Protocol (PTP) Measurement

Our instrument is designed to meet the requirement for time tagging and datalogging repetitive pulses and common time-codes and includes our own precision network packet capture logic for measurement of Network Time Protocol (NTP) transactions over Ethernet. This has enabled us to estimate the precision of synchronisation over a network to much higher precision than is available from standard NTP servers. In 2002 IEEE published IEEE 1588™ describing a Precision clock synchronisation protocol which is referred to as PTPv1; in 2008 a revision was published as IEEE 1588™ which we refer to as version 2.

The network packet capture subsystem is described in [1]. As in [1], packet capture and timestamping are carried-out entirely in hardware, and so are not subject to software-related sources of inaccuracy. The capture filtering mechanism is sufficiently generic that no hardware or logic modifications were required when adding PTP support. When placed in 'PTP Mode', the instrument commences the capture and timestamping of all UDP/IP packets addressed to the PTP multicast address (by default, this is 224.0.1.129, although the instrument may be configured to use other addresses).

A measurement cycle is initiated by the receipt of a 'Sync' packet from any PTP Master Clock operating on the same subnet as the instrument. PTPv1 Sync packets contain complete information about the master clock, whereas PTPv2 Sync packets are much more compact, and cannot be fully processed unless an 'Announce' message has already been received. The instrument determines the protocol version automatically from the content of the Sync packet.

An important feature of PTP is the 'follow-up' or 'two-step' synchronisation. This, optional, feature allows a master to transmit a second packet after a Sync. This packet contains more precise information about the transmission time of the preceding Sync packet, typically based on hardware timestamping of the Sync packet as it is transmitted from the master. The instrument can work with or without follow-up packets.

After receiving a Sync (and any associated follow-up) packet, the instrument always responds by sending a 'Delay Request' to the master. The 'Delay Request' and its response allow the instrument to measure the round-trip delay in the transmission network between the instrument and the master. To send a delay request for every received Sync packet does not adhere to the PTP specification (Delay Requests would normally be sent less frequently), but is consistent with the requirements of a test instrument. It is not likely that such a large number of instruments would be in operation on a single subnet that Delay Request traffic would represent a significant burden to a master clock.

The instrument adopts the conventions of IEEE1588 to calculate the following results from the packet timestamps:

Master-to-Slave delay

Slave-to-Master delay

One-way-delay (mean of M-to-S and S-to-M)

Offset from Master (sync offset – one-way-delay)

These results are logged within the instrument for external analysis and charting.

The instrument's network capture system uses a 50MHz core clock, phase-locked to the reference clock 10MHz signal. This gives rise to up to an underlying resolution of 20ns on network packet timestamps. Network timestamps are generated at the MAC level of the network interface, and the presence of a 4-bit, 25MHz interface between the MAC and the PHY (physical layer transceiver) places a limit on overall timing resolution of network timestamps of 40ns. In our next revision of the instrument this will be reduced to 8ns.

VI. PTP GRANDMASTER DATALOG

Figure 6 shows 24 hours of once per second measurement of another manufacturer's Grandmaster clock (blue) and a caesium reference clock (green) from which first order frequency error has been removed. The Grandmaster used GPS as a reference to steer its timing derived from an ovened quartz oscillator.

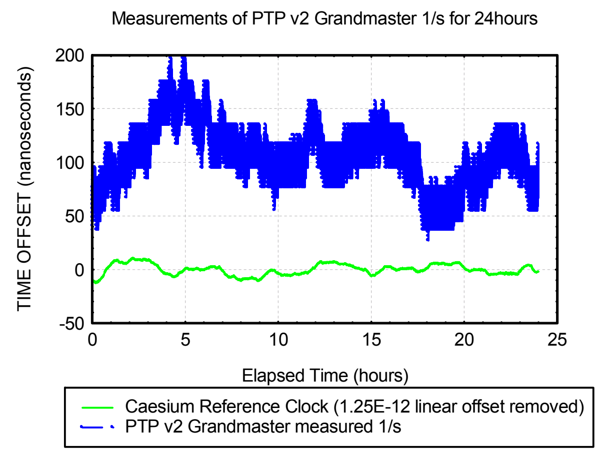

Figure 5. Time Stability of a Grand Master compared to Caesium Standard

VII. CONCLUSIONS

We have shown that our GPS referenced instrument is capable of measurement accuracy that is comparable with the order of magnitude of Common View comparison errors over a day of measurement. The measurement of PTP disseminated time has been added and has been shown to be capable of quantifying Grandmaster clock performance.

ACKNOWLEDGMENT

Thanks are due to Dr Peter Whibberley and his colleagues at NPL for their assistance with characterizing the performance of our measuring instrument reference clock.

REFERENCES

[1] N. C Helsby and W. Dean, "Portable Instrument for Time Source Verification and Analysis" Proceedings of the IEEE 2007 Frequency Control Symposium pp 854-857

[2] IEEE Standard for Synchrophasors for Power Systems IEEE Std 1344-1995