IEM KVARZ AND QUARTZLOCK'S GPS-DISCIPLINED RUBIDIUM FREQUENCY AND TIME STANDARD

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Abstract

IEM Kvarz and Quartzlock have devised a GPS-disciplined rubidium frequency and time standard to 10^{-14} level accuracy. As a result of employing unique carrier phase tracking techniques with algorithmic weighting of "all-in-view" software clock techniques with an excellent OCXO or rubidium oscillator built in, both short-term stability (STS) at 10^{-13} level and long-term stability (LTS) to 10^{-14} is realized. Now IEM Kvarz and Quartzlock have reduced the overall size and most importantly introduced temperature control for both the antenna and the downconverter, receiver, and processor. The original quad helix antenna eliminates multipath errors and the need for a choke plate, while the downconverter at the antenna means that the coax carries only 90 MHz, so it can be very long and thin (not short and fat for 1.5 GHz). Time output accuracy meets GPS time transfer atomic clock comparisons at < 5 ns, while LTS can be little improved, and STS has wander, noise floor, and holdover built to the 10^{-14} level. IEM Kvarz and Quartzlock have now exceeded even high performance commercial cesium stability at only 20% of its cost and the need to employ a hydrogen maser test to maintain 10:1 integrity margin above GPS (and cesium) performance.

INTRODUCTION

IEM Kvarz and Ouartzlock have devised a GPS-disciplined rubidium frequency standard with 10^{-14} and time to 5ns uncertainty.

As a result of employing unique carrier phase tracking techniques with algorithmetic weighting of 'all-in-view' software clock techniques with an OCXO or Rubidium Oscillator built in, both short-term stability (STS) at 10^{-13} level and long-term stability(LTS) to 10^{-14} isrealized.

Now it is planned to reduce the overall size and most importantly to temperature control the down converter, receiver, and processor. The original quad helix antenna eliminates multipath errors and the need for a choke plate, while the downconverter at the antenna means that the coax carries only 90 MHz,so it can be very long and thin (not short and fat for 1.5 GHz). Time output accuracy meets GPS time transfer atomic clock comparisons at <5ns, while LTS can be little improved.

IEM Kvarz and Quartzlock have now exceeded even high performance commercial cesium stability at only 20% of its cost and the need to employ hydrogen masers in test to maintain 10:1 integrity margin above GPS (& cesium) performance.

A special measurement system had to be developed to meet the requirements of precision GPS frequency & time standards. A reference source with stability of parts in E-15, distribution amplifier with only <10ps/°C phase stability, and very low phase noise of -165 dBc/Hz at 100 Hz offset; extraordinary high isolation of 130dB and internal stability of 10^{-15} complement the phase comparator system with 1.5 10^{-15} resolution in a short measurement time 100 seconds.

The complete measurement system and results are described below.

Carrier phase tracking GPS enables this level to be maintained as tests at 5 & 33 days have demonstrated (5 x 10^{14})

Two demonstrations show identical results at locations 2,500 km apart using the best available national references in Germany (PTB) and Russia (IEM) for the carrier phase tracking GPS.

Certification of the 'starting point' passive hydrogen maser in the UK by NPL confirmed that performance to 10^{-14} levels in a stand alone portable unit with required retrace is realised . Measurement capability in a 100 second measurement time was realized at 1.5 10^{-15}

Using a GPS-disciplined MTI oscillator (the 250 oven version at 1000s control time constant), time (!) error data relative to the PTB standard time were recorded in the PTB once an hour for several weeks. Over a time interval of 33 days, the linear regression of one-day-values (which in turn were derived from the one-hour-values) yielded a slope of (1.008 +/- .007)ns/d.

Now the slope of the time error data is the (averaged) frequency. Thus, from these measurements the frequency error was determined to be a systematic component of 1ns/d or 1 10^{-14}, which corresponds to the frequency difference between UTC (PTB) and UTC (UNSO) to which GPS time is linked. This result could (within 33 days) be determined with an uncertainty of only 8* 10^{-16} !

Another result from the data was that the one-day-values for the time error (each calculated from 24 one-hour values) has a noise of only 3 or 4 ns. If you use these to estimate the frequency stability as 4 ns/86400s you get 5* 10^{-14} ! Even if you add a square root of 2 for beginning and end of the day, each having their own uncertainty, you are still clearly better than 10^{-13} for the one-day-average frequency stability.

MEASUREMENT SYSTEM - QUARTZLOCK MODEL A7 FREQUENCY AND PHASE COMPARATOR

The two measurement inputs are called A and B. An input from the reference source at 5 or 10MHz is connected to A and an input from the device under test (DUT) is connected to B. The inputs A and B are actually interchangeable.

Both inputs are multiplied to 100MHz and then mixed down to 1MHz using an internal LO at 99 MHz. As the LO is common to both channels, any phase jitter or drift will eventually be removed when the channels are compared. The LO is actually phase-locked to one of the inputs. The 1MHz signals are multiplied to 10MHz. The 10 MHz from channel B is converted to 9MHz by mixing with 1MHz signal derived from the LO. The 10MHz from channel A is mixed with the 9MHz from channel B to give the 1MHz difference.

The basic 1MHz difference signal is made available at the front panel and is then processed further as follows:
It is filtered by a crystal filter and then multiplied by 5 to give 5MHz. This 5MHz is available at the front panel. The filtered 1MHz difference signal is then mixed down to 100MHz by means of a 900kHz LO-obtained division from the 99MHz LO. This 100kHz signal is then divided by 100000 to give 1Hz pulses, which are output to the front panel. The frequency difference multiplier may be operated in two modes, frequency mode and time difference mode.

THE PASSIVE HYDROGEN MASER FREQUENCY SOURCE

The 5 MHz frequency output of a CH1-76 passive hydrogen maser was measured at the National Physical Laboratory relative to two active hydrogen masers that form part of the UK national time standard. A brief description of the measurements and the results are provided below.

The Phase Measurements

A 5/10 MHz phase comparator (TimetechModel P/Comp 10-001/96) was used to measure the phase differences between the 5 MHz signals from two Sigma Tau active hydrogen masers (one Model MHM-2010, and one Model VLBA-112) and a CH1-76 passive hydrogen maser (serial no. 84065). The phase differences were recorded every second over a seven-day period from 1997 August 26 (MJD 50686) to 1997 September 2 (MJD 50693). The performance of the phase comparator was monitored by recording common signal inputs. Comparisons of the three hydrogen masers relative to each other showed that the CH1-76 was the dominant source of instabilities for averaging times of 10 seconds or greater.

THE RESULTS - FREQUENCY OFFSET FOR PASSIVE MASER CH1-76

Figure 1 shows the phase differences between the CH1-76 passive hydrogen maser and the Sigma Tau active hydrogen maser (Model VLBA-112) from MJD 50686.5 to MJD 50693.3. The change in rate on MJD 50692 is a result of steering correction applied manually to the CH1-76 passive hydrogen maser. The mean frequency offsets of the CH1-76 maser relative to UTC (NPL), before and after the steer, are listed below.

MJD 50686.5 to MJD 50692.6 (CH1-76 after a cold start) mean relative fractional frequency offset = -44 x 10^{-14}

MJD 50692.7 to MJD 50693.3 (CH1-76 after manual steer) mean relative fractional frequency offset = 3 x 10^{-14}

THE RESULTS - FREQUENCY INSTABILITY FOR CH1-76

Figure 2 shows the phase differences between the CH1 - 76 passive hydrogen maser and the Sigma Tau active hydrogen maser (Model VLBA -112) From MJD 50686.5 to MJD 50692.6, with a frequency offset of 38 ns/day subtracted from the data. Note that data after the manual steer are not included. The instability in the frequency output of the CH1-76 passive hydrogen maser for averaging times from 10 to 10^5 seconds was calculated from the phase measurement data using the standard formula for the Allan variance ($\sigma^2_y(\tau)$):

$$\sigma^2_y(\tau) = (2(N-2)\,\tau^2)^{-1} \sum_{t=1}^{t=N-2} (x_{i+2} - 2x_{i+1} + x_i)^2$$

where the formula is applied to a data set of N evenly spaced points $x_1 \ldots x_N$ spaced an interval τ apart. The results of the calculations are shown in Figure 3. The values for the root Allan variances at averaging times increasing at decade intervals are listed in Table 1, and were determined by interpolating between the calculated results shown in Figure 3.

Table 1
Frequency instability of passive maser CH1-76 expressed as root Allan variances for averaging times from 10 s to 10^5 s

τ (s)	σ_y
10	$3x10^{-13}$
10^2	9×10^{-14}
10^3	4×10^{-14}
10^4	2×10^{-14}
10^5	6×10^{-15}

Typical Results

Figure A: Frequency and time transfer stability characteristics of GPSDO at τ = 1,000s averaging time calculated from phase data

σ_y	**MODσ_y**	σ_X	**Mean Fractional Frequency Offset**
$5.0x10^{-13}$	$3.5x10^{-13}$	$2.1x10^{-10}$	$6.3x10^{-13}$

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

σ_y	**MODσ_y**	σ_X	**Mean Fractional Frequency Offset**
$1.0 x10^{-12}$	$5.7x10^{-13}$	$3.6x10^{-10}$	$1.3x10^{-12}$

Fig C: Performance Characteristics of GPSDO H (Quartzlock 8A-Rb)

Characteristics	**GPSDO H**
Mean Frequency Offset (τ=1,000s)	$5.0\mathrm{x}10^{-13}$
Free Running Oscillator σ_y (τ=1,000s)	$6.0\mathrm{x}10^{-13}$
Free Running Oscillator σ_y (τ=100,000s)	$6.0\mathrm{x}10^{-14}$

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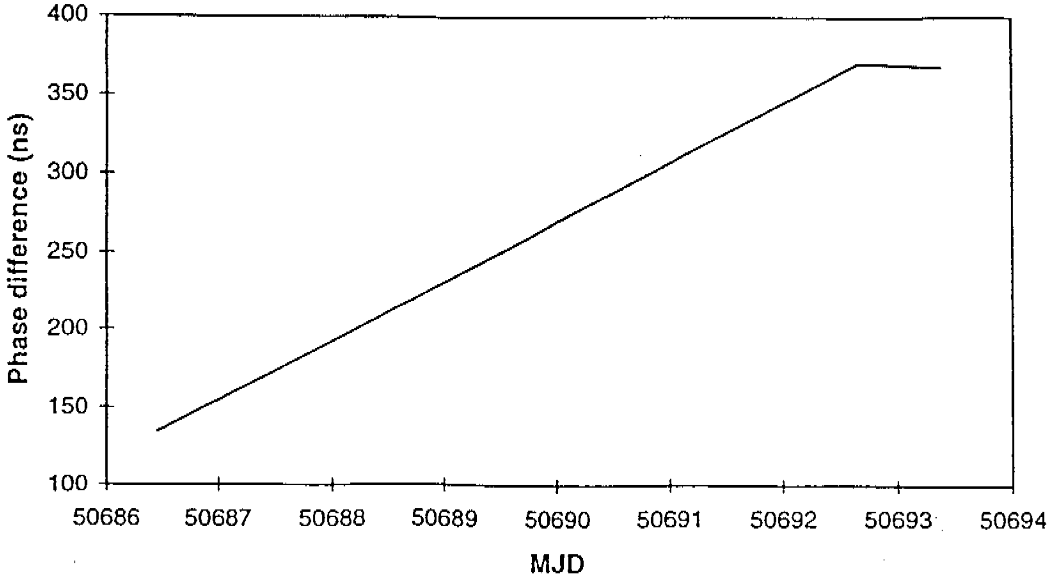

FIGURE 1 : phase difference between 5 MHz outputs of NPL active hydrogen maser and CH1-76 passive hydrogen maser (serial no. 84065)

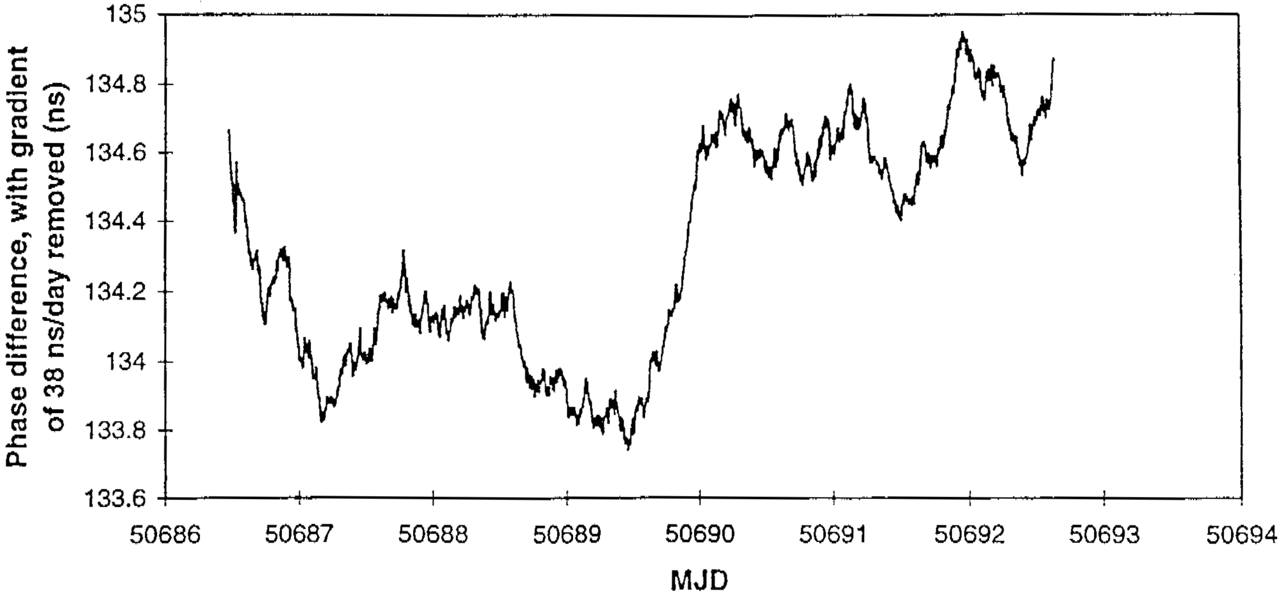

FIGURE 2: phase difference, with 38 ns/day gradient removed, between 5 MHz outputs of NPL active hydrogen maser and CH1-76 passive hydrogen maser (serial no. 84065)

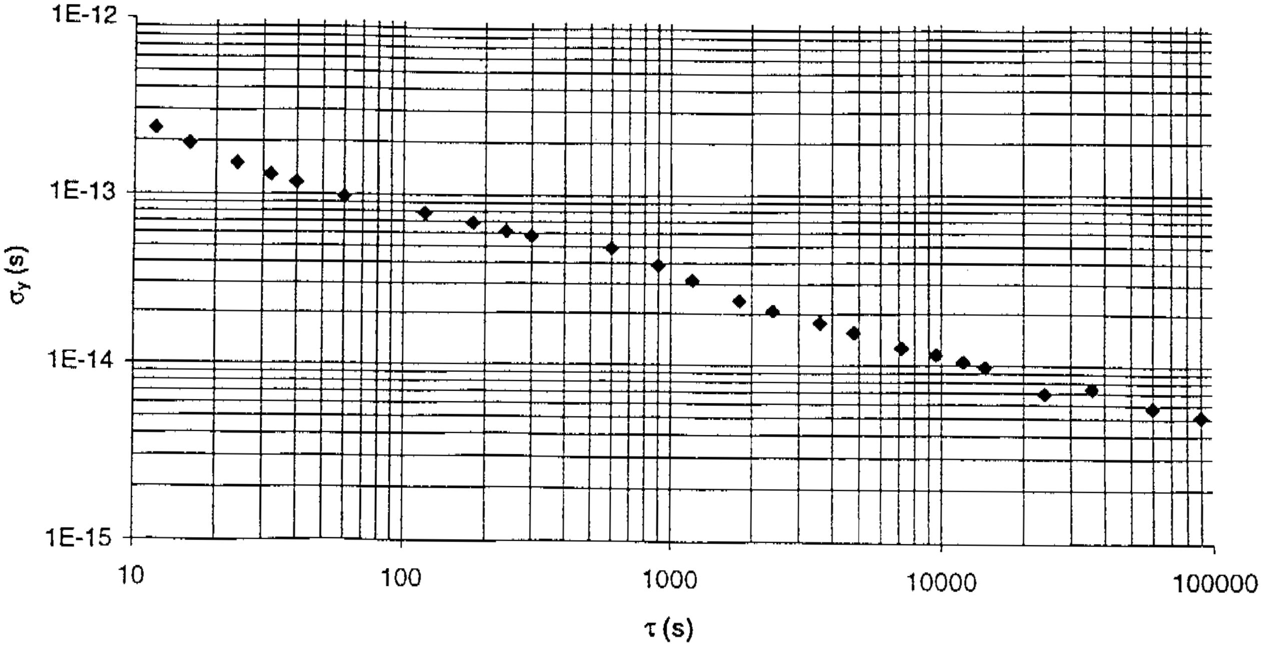

FIGURE 3: frequency stability of CH1-76 passive hydrogen maser (serial no. 84065) expressed in terms of the root Allan variance (σ_y)