DEVELOPMENT OF A NEW REFERENCE CLOCK FOR TELECOMMUNICATIONS

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ABSTRACT

Quartzlock (UK) Ltd has recently been awarded a European Commission 'CRAFT' award to design a new reference clock for telecommunications; the ALPHA 1. The clock will find application within the fields of metrology, telecommunications and radio transmitter referencing.

In addition to the standard passive hydrogen maser and GPS elements, the ALPHA 1 will thus incorporate GLONASS, Rubidium, BVA crystal oscillator and VLF tracking receiver technology. A unique software clock will drive all elements in a modular high redundancy ring or grid. This allows existing user clocks to be joined at any time. A very high resolution and low noise floor frequency and phase measurement system will also be included.

The ALPHA 1 is intended to be a modular, flexible system featuring high-level redundancy. The objective is to combine and reduce a considerable number of diverse frequency standards to a single output. This will have improved performance (short, medium and long term frequency stability of the source), and high reliability in that the output should not show any sudden phase glitches if the output of one or more of the sources should fail. In space, for example, the ability of the clock to survive - and maintain stable timing in - extreme environmental conditions is at least as important as the actual frequency stability of the device. The vibrations encountered by such a clock during launch far exceed anything experienced in the laboratory.

To monitor the varying environmental conditions the ALPHA 1 may face, an in-built environmental monitor is being developed to continuously display parameters such as humidity, atmospheric pressure, magnetic field, vibration, radiation levels, static and lightning risk. In addition, it is not feasible to repair failed components and so normally satellite systems would carry several clocks in case one failed. The multiple redundancy of the ALPHA 1 renders this unnecessary.

This paper will include a full description of the projects 10 elements, with the improvement expected/already made outlined. The latest test results in tabular and graphical formats will be presented, along with a progress report for each element. A short discussion on anticipated applications for the Alpha 1 will conclude the paper

1. INTRODUCTION

Quartzlock (UK) Ltd has recently been granted €400k of European Commission money to design a new 'primary reference clock', the ALPHA 1. It hoped that such a clock would find applications within the fields of telecommunications, metrology and radio transmitter referencing. The clock will not be a primary frequency standard like NIST F1, the newly developed Caesium Fountain Frequency Standard, but will be a commercially available 'top-level' clock ensembling system for multiple applications. Quartzlock (UK) Ltd has proven to be the leading British company in the American dominated Time and Frequency field. The expertise gained during the previous 20 years in developing and producing highly accurate, stable and affordable Time and Frequency generation, distribution and measurement instrumentation will be used in this project.

This project will bring together the expertise of several European companies. Quartzlock (UK) Ltd is to be project leader and co-ordinator of the project. K&K Messtecknik Gmbh, a small German company will develop innovative software for the GPS elements of the ALPHA 1. A consortium of small companies comprising Simek, Cathodeon, Eltek, Menvier Hybrids and Farran technologies will provide expertise in thick/thin film technology, scientific glass blowing, crystal oscillators and ceramic substrate hybrids. The Physikalische-Technische Bundesantalt (PTB) Germany's national metrology institute will do the primary research into each individual element of the proposed 'Primary Reference Clock'. RF solutions and Mark Rainer will give expert advice in the fields of Hydrogen Maser and Rubidium electronics, GPS and LF Tracking receivers. **[1] [2]**

The ALPHA 1 is intended to be a modular, flexible system featuring high levels of redundancy and implementing "state of the art" electronics whilst taking care to allow for future developments to be incorporated in an evolutionary way rather than requiring replacement with consequent disruptions. This in effect means that should one element of the system fail, other components will ensure continuous high-level performance of the overall system. To monitor the varying environmental conditions the ALPHA 1 may face, an optional, in-built environmental monitor will continuously display parameters such as temperature, humidity, atmospheric pressure, magnetic field, vibration, radiation levels and incident EMP. In addition, failed components will be automatically isolated without unnecessary disruption of the primary time-scale. The multiple redundancy of the ALPHA 1 will enable effective "hot-swapping to be accomplished with ease. In addition to the new passive hydrogen maser and GPS elements, the ALPHA 1 could easily incorporate GLONASS, Galileo, Rubidium, BVA crystal oscillator and LF tracking receiver technology. A unique ensembling algorithm will enable all such elements to be combined in a modular high redundancy ring or grid structure. This allows existing user clocks to be joined or removed at any time. The failure or late delivery of any element within the system will not preclude the optimum performance of the overall system.

The priorities in the performance domain are excellent short, medium and long-term stability. The overall performance will be that of the best clock or clocks, which it includes. This may vary depending on the measurement interval such that, for instance, where a Caesium and a Rubidium clock are combined, the short-term stability of the Rubidium may be enhanced with the longer-term accuracy of the Caesium. The ALPHA 1 system may have international traceability to the highest authorities when appropriately referenced, as offered by the BIPM in France and NIST in the USA. A significant advantage of this system is its strategic independence from any one country's military (e.g. GPS in the US, Glonass in Russia and Galileo in Europe).

2. PASSIVE HYDROGEN MASER

One of the aims of the Hydrogen Maser element of this project is to substantially modernise and globalise the electronics within the existing Passive Hydrogen Maser, currently being produced by IEM Kvarz, Russia. To date a significant amount of work has already been undertaken to analyse the areas where work may be necessary. Quartzlock (UK) Ltd have been working with IEM Kvarz for many years now and the expertise demonstrated by Quartzlock (UK) Ltd in developing new electronics for Rubidium oscillators, in distribution amplifiers and GPS disciplined oscillators will be put to good use in this project. One of the current worries for potential users of Passive Hydrogen Masers is the availability of components upon failure of even minor elements of the Maser, say a capacitor. Quartzlock understand this concern, and as Passive Masers become more widely accepted as a viable alternative to high performance Cesium, this issue comes to the fore. It is anticipated that this new maser will be substantially smaller sized, improving its appeal to Telecoms and other non-metrology industries.

The target specification has already been laid down, with a core 5 MHz and 1pps being the main physical output of this new maser. Unlike the current maser, a frequency converter will be incorporated, enabling the user to obtain maser quality outputs at 0.1, 1.0 and 10MHz. To date this has only been possible using an external frequency converter. In addition to these output frequencies, a 1pps GPS/Glonass synchronised timing output is envisaged. An IRIG-B module will appeal to timing users. In unsteered mode (i.e. with no GPS disciplining) an output accuracy of 1E-12 over a period of 5 years is anticipated**.** When GPS/Glonass disciplining is incorporated, the accuracy should improve to 5E-14, determined by the accuracy of the on-board Navstar clocks. Performance for many users is the short-medium term stability (1s to 1 day). Short-term stability specification is currently ~1.5E-12/$\tau^{1/2}$, and the improved specification is hoped to be 6E-13/$\tau^{1/2}$ up to about 10000s. Due to the nature of the whole system, the GPS-Glonass disciplining will control the long-term stability of the system. A definite figure for this has yet to be finalized. Phase Noise at 10 kHz from the carrier will be reduced to below -155dBc at least with -160dBc the objective. In addition to the metrological improvements anticipated, it is also intended to make the controls and interfaces substantially user-friendlier. To that end RS232 control will be implemented.

Quartzlock will continue to work closely with Kvarz on fundamental advances, to simplify the use of Hydrogen Masers as stable and accurate frequency standards. The wall shift problem will be further investigated. It is hoped to make some further advances in understanding this problematic phenomenon.

3. LF TRACKING RECEIVER

Quartzlock are currently manufacturers of medium stability LF tracking receivers (formerly called off-air frequency standards), which use the 198 kHz signal from Droitwich in the UK or the 162 kHz France Inter signal to discipline either a VCXO or an OCXO. However, it has been difficult in the past to make this receiver work on other LF signals, such as DCF77 on 77.5 kHz in Germany and WWVB on 60 kHz in the US. In order to increase the export appeal of the unit and to provide a lost cost alternative to the use of GPS as a method for disciplining an oscillator, Quartzlock have started work on developing multiple input frequency instruments. This opens up a worldwide market for low cost frequency standards.

One of the problems with using the 198 kHz signal from Droitwich is that it suffers from severe phase shifting due to sky-wave propagation at night, which significantly reduces its short-term accuracy. This makes operation even a few tens of kilometres from the transmitter at night almost impossible due to ionospheric reflections. However, this was preferable to using the other LF and VLF signals because of their time code modulation, which caused discontinuities and made frequency lock difficult with simple PLL technology. They also have periods of outage due to maintenance, which is inconvenient. Existing receiver technology suffers from indeterminate temperature coefficients, particularly where ferrites are used, which may be the prime cause of medium term frequency error. Also receivers are constrained to the use of only one frequency by the use of costly RF crystals. Analogue filtering techniques as currently employed restrict the use of long time constants causing medium-term stability degradation.

It is proposed to employ a microprocessor in the new receiver, which will enable the use of a synthesizer in the unit. This will have the advantage of removing the restriction on input carrier frequency, a significant advance. This use of a novel form of direct conversion will enable a reduction in the bandwidth of the receiver to <1 Hz, removing the need for narrow band tuned circuits and consequently improving the thermal stability of the unit. The narrow bandwidth of the receiver also improves the range of the unit and the microprocessor permits the use of significantly longer time constants. This should improve the short-term stability by several orders of magnitude, with the limiting factor being local oscillator quality. The long-term accuracy will be determined by the frequency reference employed at the originating transmitter. A Kalman Filter may be implemented at an early stage.

The design of the new unit will initially allow the use of any carrier signal whose frequency is a multiple of 100 Hz. Also the receiver architecture enables the receiver to remain unaffected by all forms of pulse modulation currently employed. This includes the A1 pulse modulation of MSF rugby. This is the factor, which has hitherto made the use of these carrier signals for oscillator frequency disciplining extremely difficult.

It is early days in the design of this unique LF tracking receiver, but potential applications include calibration and referencing of RF test equipment. The current UK market alone is anticipated to be significant (Quartzlock currently sell LF tracking receivers in the UK). A much larger potential market exists in the rest of Europe, the USA and the Far East where LF transmitters exist. The customers will be found in and amongst utilities, standards laboratories, Telecoms and RF engineering. Future papers dedicated to the explanation of the new design will be given within the next year, when preliminary test results become available. **[3]**

4. RUBIDIUM

Quartzlock are a manufacturer of Rubidium Frequency Standards. A major research element of this project is to evaluate through detailed technical and scientific analysis the following: Rubidium Isotope specification, Buffer gas specification, pressure in Rb lamp and cell, volume of Rb lamp and cell, environmental specification of lamp and cell, MTBF calculation, definition of Rb lamp and cell operation, isotope placement, inert gas filling, pressure testing, plasma evaluation and cell tuning. The overall aim of this element is to investigate the reason for Rubidium lamp failure and make progress towards extending the lamp lifetime. The aim is to increase the reliability and environmental stability of the units. This is generally measured in the Mean Time Before Failure (MTBF) and the temperature stability. Temperature stability is increasing in importance due to the placement of Rubidium in areas of extreme environmental conditions. The aim is to increase the range (ambient) over which the unit may perform to -65 deg C to +65 deg C, with a potential base plate temperature of over 85 deg C. The stability over this range should be in the range of 1E-10 to 1E-11 giving a temperature coefficient of ~ 1.... 5E-13/ deg C, a significant advance over units currently in operation. The size of the unit will also be of importance if several are to be integrated into the final PRC. An enclosure of ~220cc has been proposed with potential for 150cc version with OCXO footprint. This competes favourably with many of the miniature rubidium currently being developed and produced in the US. The rubidium oscillator will also be sold separately (as will hopefully every other element of the system).

Unfortunately the full specification for this element is currently subject to a NDA due to the sensitive nature of the work and the high level of competition that currently exists in producing rubidium oscillators.

5. MICROWAVE SATELLITE RECEIVERS

Quartzlock have been looking at integrating a Glonass/Galileo module into their current high performance GPS disciplined Rubidium Time and Frequency standard for some time now. In context of the Craft project the aim is to do several things. The purpose of the GPS/Glonass/Galileo element of the PRC will be to improve the long-term stability, removing the (small) drift element associated with Passive Hydrogen Masers (typically of the order of 1E-15 per day) cf Cesium. As part of this element an extensive improvement will be made in the software packages to algorithmically weight the satellite information. This potential re-design of the algorithms is to achieve the following goals: high level redundancy (unlimited) by modular arrangement, limitless generator connection, cellular division ability in the event of a crisis, hot swap capability with zero transients, nodal connection arrangement, inter-node communication ensuring robust operation and improved system integrity and security. Kalman filtering may be employed.

Ultimately the long-term performance (offset) of the clock must be better than 5E-14 over 5 days. This is currently the frequency offset displayed by the present engine utilized. This will help improve the overall accuracy of the clock. Temperature controlling of the antenna and downconvertor will naturally improve the timing capabilities of the clock, essential for many users. Features like the Quad Helix antenna will continue to be used in the new design.

6. MEASUREMENT SYSTEM

Quartzlock currently produce a very high resolution Frequency and Phase Comparator measurement system. The system has an integrated distribution amplifier and rubidium oscillator. The system is limited to 1 Hz sampling rate in phase mode, which makes it impossible to look at Allan Variance for t less than 1s. This is inconvenient for many people producing Rubidium Oscillators and high quality OCXO's, where very short term stability is of interest. The very high resolution of the current system is a result of the techniques employed in the phase comparator (frequency different multiplier), which is the heart of the system. Quartzlock are currently developing a new Phase Comparator that will have several advantages. At the moment input frequencies are limited to 5 and 10 MHz, which is inconvenient for Telecoms users using 1544 kHz, 13 MHz, 2048 kHz, 800 kHz. The input range will therefore be broadened. The unit will also be a 1U system dedicated solely to measurement.

7. TIME TRANSFER MODULE

Whilst GPS one way is a very cost-effective and useful system, it cannot compare the world’s best clocks with high enough accuracy. The system that is routinely used throughout the world is the method of common view, whereby users track particular satellites simultaneously and note the differences in readings between their clocks and the satellite clocks. If two or more users do the same then the satellite clock may be subtracted out of the equation and the two users have made an accurate comparison between their accurate clocks. As part of the total package, which the PRC will offer, a time transfer mo dule has been proposed. This is to have 1ns resolution with an accuracy of at least 5ns. The module will be similar to those employed for the creation of TAI/UTC, in that the inputs will be a 1pps of the PRC and a reference 1pps from common view GPS receiver. The software employed in the TT module will enable automatic tracking of the BIPM schedule. This enables autonomous operation of the module, with automatic satellite selection and data collection. Free running atomic clocks and not those steered by GPS can only make contribution to TAI. GPS disciplined oscillators are merely replications of remote timescales (in the case of GPS this will be GPS time). Therefore using one timescale replication to contribute towards another is of no use. If the PRC wishes to follow the BIPM schedule and send readings to the BIPM for the creation of TAI/UTC, then some method must be found of taking the raw unsteered Passive Maser readings and measuring these. Due to the unique modular and nodal structure envisaged for the PRC, this should not be a difficult thing to do. This will enable more laboratories to participate. As more and more countries set up standards laboratories a cost effective way for them to set up a system will find increasing use. The cost for this system is not expected to be high as the individual elements are really only a basic GPS receiver engine, a simple time interval counter and the BIPM software.

8. SOFTWARE CLOCK

Ring/Grid Phase Alignment Combiner

In principle this should have two integrated functions

i) Phase aligning interface modules enabling the coupling of each clock to the interconnecting lines.

ii) A measurement system that enables clock drift to effect weighting in the algorithm that realizes averaging of clocks in a robust system

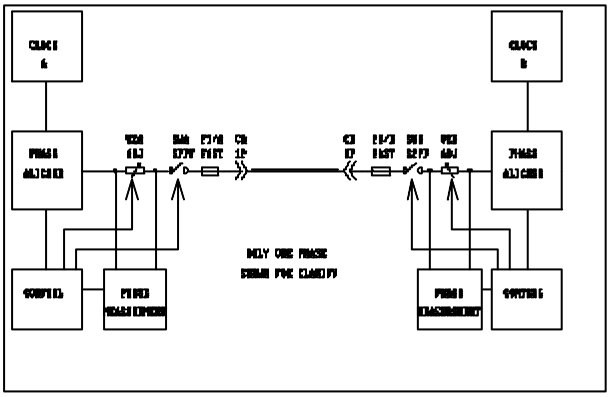

FIGURE 1: SIMPLIFIED PRC DIAGRAM

This will be the innovative element of the clock. Many of the individual elements of the clock will have been improved but the significant advance in resilience will not be possible if this element is not researched and implemented properly.

The objective of this software clock is to combine a (considerable) number of diverse frequency standards so as to result in a single time-scale, which has improved performance (the measure of performance is the short, medium and long term frequency stability of the source), and hitherto unsurpassed reliability in that the time-scale should vary by any more than a negligible amount if one or more of the frequency sources should fail. In addition, it would be desirable that the random behaviour of the output phase of a source should be detectable by comparison with the phase of the other sources.

The sources may be divided into two classes: The first is the free running oscillator type of source or primary clock, which may show a frequency offset from an internationally defined time scale. The hydrogen maser and the rubidium oscillator are in this class. They may have excellent intrinsic stability, but can still have an unknown, although small, frequency offset.

The second class of source is the type, which provides a reference to a time scale elsewhere. The quality of the link controls the short and medium term stability of the standard. In the long term the stability of this class of source will approach that of the host time scale. **[2]**

The redundancy requirement poses several problems. The outputs of the various standards can only be combined if they are all in phase and operating at the same frequency. If sine waves are added without phase alignment, the output sine wave may have zero amplitude with some combinations of input phase. If we consider a simple system where one source is considered to be the master, then the other sources may be phase aligned to the master, and all the sources may be added together with equal amplitude weighting. If one source should now fail, the amplitude of the output will only drop by the ratio of the number of sources to be combined. This simple system would work quite well if all the sources were of the same class and the same degree of frequency (phase) stability. If we were combining three rubidium oscillators, we would want to give them equal amplitude weighting, as the expected short-term stability's are similar. One will even derive performance benefit as the phase noise (instability) of each will not be correlated, and thus the output noise of the ensemble will be lower than that of the individuals.
If we are combining sources of quite different performance levels, the output should be substantially that of the best standard, for example a hydrogen maser (short to medium term). Any addition of output from the other standards can only degrade the performance.

One could argue that a good method would be to improve the short-term stability of the lesser sources by phase comparison with the hydrogen maser, and then phase adjustment (of these standards). This is certainly true, and one could then use a higher percentage of the improved (phase adjusted) standard in the final output. However, if the hydrogen maser did fail, then the reference source for the phase adjustment would suddenly vanish, and the basic (inferior) noise characteristics of the lesser sources would suddenly reappear. The next best source, for example the rubidium oscillator, could then be designated the master and used for phase alignment. However, it would be difficult to achieve a smooth change over.

A better solution might be to derive a notional time scale based on phase measurement of all the sources and the to phase-align all the sources to the notional time scale. In this way, the need for a master is overcome. Careful consideration of the weighting of each source contribution to the notional time scale would be required, with a different contribution at different averaging times. To clarify this, a source of the second class would have more weight over a long period of time as it is directly referenced to an international time scale.

A major part of this project is in the computer algorithms used to derive the notional time scale, and to control the phase aligners that condition the outputs of each standard before they are added together. It is also important that the phase aligners themselves do not contribute noise and phase drift. The successful implementation of the PRC will combine state of the art electronic design, software analysis and control algorithms **[2]**

9. CONCLUSION

The ALPHA 1 is intended to improve reliability for time standards of all kinds, whether for standard laboratory calibration, telecom network synchronisation at the Stratum 1 level or national standards laboratories. Whilst the advantages of this project are deemed to be high, the risks associated with it are very low. The ALPHA 1 will be a user-friendly system, with the modular structure enabling customer choice and cost flexibility, ease of service and the ability to upgrade when required. The extreme reliability will be derived by virtue of multiple redundancies with all processing being accomplished in a distributed fashion. No single module or component will be vital for the continued operation of the system wherever three or more clocks are used and with greater numbers, it is even possible to imagine that the system could be separated into two or more totally independent systems each of which could continue in operation independently.

10.REFERENCES

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