Craft Project Alpha 1

This brief technical note is intended to highlight design problems associated with a proposed highly redundant time and frequency standard and to suggest areas where detailed theoretical analysis may be required.

Quartzlock (UK) Ltd has recently been awarded a unique European award 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 Cesium Fountain Frequency Standard, but will be a commercially available ‘top-level’ clock 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, providing expertise in Time and Frequency standards essential to the project. Kramer and Klische, a small German company will develop innovative software for the GPS elements of the ALPHA 1. A consortium of small companies comprising Simek, Cathodean, Eltek and Menvier Hybrids 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, Mark Rainer and Farran will give expert advice in the fields of Hydrogen Maser and Rubidium electronics, GPS and general radio frequency.

The ALPHA 1 is intended to be a modular, flexible system featuring high levels of redundancy and implementing sophisticated year 2000 electronics. This in effect means that should one element of the system fail, other components will ensure continuous high-level performance of the overall system. This seamless switching would be vital in any space-qualified version of the clock, where replacing failed elements is costly and impractical. In addition, the ability of the clock to survive - and maintain stable timing in - extreme environmental conditions is at least as important as the frequency stability of the device. The vibrations encountered by such a clock during launch would far exceed anything experienced in the laboratory. To monitor the varying environmental conditions the ALPHA 1 may face, an in-built environmental monitor will 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 would make this unnecessary. In addition to the standard hydrogen maser and GPS elements, the ALPHA 1 will thus incorporate GLONASS, Rubidium, BVA crystal oscillator and LF 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. The failure or late delivery of any element within the system will not prevent the overall system from optimal performance.

The objective of this software clock is to combine a (considerable) number of diverse frequency standards so as to result in a single output, which has improved performance (the measure of performance is the 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 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, 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 frequency offset (although this offset will not affect the stability)

The second class of source is the type, which supplies a replica of a time scale elsewhere. The GPS standard and the lf tracking receiver are of this type. They provide a link to an ensemble of standards, which is monitored and referred to other internationally maintained time scales. 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.

The local standards of the first class are likely to have much better short and medium term stability than standards of the second class. For example, the hydrogen maser has much better stability than either the GPS standard or the LF tracking receiver to averaging times of weeks. The final outputs of the PRC should have the short-term quality of the hydrogen maser, but the long-term quality of GPS (months to years)

The redundancy requirement poses several problems. The outputs of the various standards can only be combined if they are all in phase. 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 the same. One will even derive performance benefit as the phase noise (instability) of each will be uncorrelated, 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, in this case the hydrogen maser (short to medium term). Any addition of output from the other standards can only degrade the performance. However, if the hydrogen maser should fail, the output may fall to an unacceptably low level. Thus the performance requirement conflicts with the redundancy requirement.

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 alingers 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

One of the aims of the project is for the ALPHA 1 to be significantly smaller and lighter than the current Cesium beam and hydrogen maser atomic clocks, which at present are the most accurate, stable and precise devices on the market. In a world increasingly driven by smaller, yet high performing technology, the ALPHA 1 is almost certain to find many applications, for example in space where weight is at a premium. The priorities in the performance domain are excellent short, medium and long-term stability combined with low offset. The overall performance will approach that of the active hydrogen maser. The ALPHA 1 will have international traceability to the highest accuracy, 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 and Glonass in Russia).

In order that the ALPHA 1 is to be capable of delivering such high performance, intensive research and development will be needed into existing frequency standards, to understand their limitations and enable the ALPHA 1 to incorporate any improvements suggested. Such research and development may be split up into two areas: fundamental and non-fundamental. One of the key fundamental research areas is the deeper understanding, measurement and (possible) solution of the wall shift in the hydrogen maser storage bulb. The wall shift is the frequency shift arising during the collision of the hydrogen atoms with the walls of the storage bulb. Since the accuracy of hydrogen masers are primarily determined by the degree of uncertainty on the wall shift, a more thorough understanding of this parameter will enable their accuracy to compete more favourable with that of (commercial) Cesium beam frequency standards. At the moment hydrogen maser accuracy is of the order of 3×10^{-13}. The reproducibility and repeatability of hydrogen maser measurements also depends directly upon the value of the wall shift. This is work will be carried out in conjunction with Kvarz, developers and manufacturers of Passive and Active Hydrogen Masers for over 30 years. They have produced over 400 to date. Quartzlock continue to work closely with Kvarz on the Physics package of the Masers, whilst developing modern western electronics for the passive maser.

Another fundamental research question is to understand the ageing mechanism plus failure cause and cure in the rubidium plasma lamp. This work is also being done with Kvarz, with whom Quartzlock have been working on developing new low profile and cost rubidium oscillators, whilst continuing to look at fundamental problems associated with the use of rubidium as a stable and accurate frequency oscillator.

Finally, the rubidium and hydrogen maser electronics, where phase stability is of paramount importance, are to be re-designed without temperature sensitive circuits whilst at the same time reducing power consumption.

The ALPHA 1 is intended to improve standard laboratory calibration, telecom network synchronisation at the Stratum 1 level and increase the channel capacity and stability within the radio frequency spectrum by up to 10%. One of the benefits proffered by an increased number of channels is that the radio communications industry is better able to serve its customer base by freeing it from current restraints caused by the problems of precise channel mensuration.

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 device, with the modular structure enabling customer choice and cost flexibility, ease of service and the ability to upgrade when required