Application of ultra-high stability cryogenic sapphire oscillators to Very Long Baseline Interferometry

J.G. Hartnett[1], S.J. Tingay[2], J.H. Searls[3], E.N. Ivanov[1], M.E. Tobar[1], G.I. Moore[3], A. Tzioumis[4]

[1]University of Western Australia, 35 Stirling Hwy, Crawley 6009 WA
[2]Curtin University of technology, Kent Rd, Bentley, 6102 WA
[3]Poseidon Scientific Instruments Pty Ltd, 17 Queen Victoria St, Fremantle, 6160 WA
[4]CSIRO - Australia Telescope National Facility, P.O. Box 76, Epping, 1710 NSW

This project aims to develop a compact transportable commercial version of the state-of-the-art liquid-helium-cooled cryogenic sapphire oscillator (CSO) and adapt it for use as a reference oscillator for current and future radio-astronomy, particular very long baseline interferometry (VLBI) where signal timing is crucial. The CSO has a fractional frequency instability about 2 orders of magnitude smaller than a hydrogen maser at 1 s of integration. Currently hydrogen masers are used as the local oscillator of choice for most installation for the purpose of VLBI. The implementation of the CSO with a state-of-the-art synthesizer to produce the required 5 or 10 MHz signal with the same stability as the microwave signal from the CSO will provide the signals needed for signal timing as well as an ultra-stable reference for all on-site equipment. This has the potential to improve the image quality derived from these deep space observations, in cases where extremely high dynamic range imaging is required, for example for the SKA. Success of the project will also be important for other precision metrology applications such as deep space tracking, atomic clock technology and high precision frequency metrology.

Accurate and frequency stable clocks are of fundamental importance in radio astronomy, in particular, to radio interferometry. Connected Interferometric arrays rely on the distribution of an accurate clock signal to each element of the array, in order to synchronize critical electronic systems such as the generators that produce mixing signals that down-convert the high frequency radiowaves close to DC and the samplers that sample the radio frequency waveform and produce a digital output for further processing.

These electronic elements need to be phase stable and must be able to operate at high frequencies. For example, the 5 MHz output signal from an accurate clock needs to be multiplied up to a frequency of close to 100 GHz in order to down-convert radio signals to DC. In this process, any instabilities in the 5 MHz signal are also multiplied, causing a degradation of the down-converted signal, most usually seen as a decorrelation of the amplitude of the signal of interest, due to a fluctuating phase, over the required averaging times (typically 0.1 to 1 seconds).

With highly accurate and frequency stable clocks, such as hydrogen masers, interferometric arrays produce data that allow detailed images of the radio emission from celestial objects, such as stars and galaxies. In connected element interferometry, a single clock (acting as a local oscillator (LO)) signal is distributed to all antennas in the array. In this way, coherence is maintained more easily, since all antennas experience the same fluctuations in the clock output.

However, in VLBI, antennas can be hundreds or thousands of kilometers apart, not physically connected, thus each requires the operation of an independent clock. In this case, the properties of the clocks have to be very well known, as any fluctuations in the clock outputs will significantly affect the data.

VLBI techniques result in the highest angular resolution of any technique in all of astronomy, producing angular resolutions of ~1 milliarcsecond (4.8×10^{-9} degrees). Not only is VLBI important for astronomy, but the high resolution of the technique allows precision geodesy and provides a realization of the fundamental frame of reference for geodesy, tied to the inertial frame of reference of the most distant objects in the Universe.

In Australia, 6 telescopes are operated for VLBI, for astronomy and geodesy. A further three are being built, specifically for geodesy and funded by the NCRIS 5.13 capability. Different options for accurate and highly stable clocks are being examined for these new telescopes. Hydrogen masers are expensive, often difficult and time consuming to source from overseas suppliers (Russia and China for example) and difficult to maintain. Also hydrogen masers, though accurate over the longer integration times of sampling, the output frequency is not as stable over the shorter integration times compared to other technology (discussed below) already developed in Australia. Developing a local supplier of affordable, yet highly stable clocks to act as local oscillators for radio astronomy, and a source of local maintenance, would therefore be an important development.

Cryogenic sapphire oscillators have been developed at the University of Western Australia since the mid-1980s. The key to the quality of the sapphire oscillator, termed the “sapphire clock”, is the anomalously low dissipation of microwaves in cryogenically cooled sapphire dielectric, particularly around 4.2 K the temperature, reached with liquid helium. This resulted in the creation of microwave signal sources with short-term frequency instability unmatched by any other types of electromagnetic oscillators including laser-cooled atomic fountain clocks.

By the year 2000 state-of-the-art performance was achieved in lab experiments. The measured stability was close to a few parts in 10^{16} over integration times of about 10 seconds and one part in 10^{15} at 1 second. Since then it has been the task of the project to achieve high stability, reproducibility of stability better than one part in 10^{15} at short integration times and portability. As a result two liquid-helium-cooled sapphire clocks were transported to France. One is currently used by SYRTE at the Observatoire de Paris for their atomic fountain clocks, which enabled the first experimental observation of the quantum projection noise in atomic fountain clocks. Another was taken to Toulouse, France for the European Space Agency to use as an earth-based local oscillator to prove the performance of the PHARAO cold atom space clock developed for the Atomic Clock Ensemble in Space mission on board the International Space Station.

Then over the course of 2003 -2006 two high-performance improved-second-generation liquid-helium-cooled clocks were built at the labs of the National Metrology Institute of Japan (NMIJ) in Tsukuba, Japan, to run their atomic fountain clocks as well to achieve new limits in laser spectroscopy based on CSO signals conditioning a fiber-based frequency comb. Finally in 2006 two new CSOs were developed, one for the National Institute of Information Communication Technology (NICT) in Tokyo, Japan, and one for the UWA laboratory reference. The measured fractional frequency fluctuations are state of the art at 1.2×10^{-15} at 1 s and 5.6×10^{-16} at integration times around 20 s and exhibit repeatability. The one that was transported to Japan was running within 48 hours of being unpacked.

The research also looked at techniques to deliver this type of performance at much higher temperatures, where the use of liquid helium could be avoided but it was found that stabilities of the order of one part in 10^{15}, at 1 s of averaging, could not be achieved by novel resonator designs. Cryocooler technology for sapphire clocks also failed to provide the required performance. Therefore, not withstanding future developments with such closed-cycle systems, liquid helium cooled sapphire oscillators, are robust and have proven they can deliver the best short-to-medium-term fractional-frequency stability of any oscillator currently on the planet.

Therefore liquid-helium-cooled CSO technology is the only reasonable approach to provide new technology for future radio astronomy, which delivers the required frequency stability. This project aims to reduce the size of the oscillator, improve the compactness of the control electronics, improve the liquid helium hold time in a purpose built dewar, make the CSO robust and reliable to field testing in Australia, and maintain the state-of-the-art frequency stability.

Looking to the future, Australia is one of the two remaining bidders to host the Square Kilometre Array (SKA), an array that will consist of ~10,000 small antennas over a continent-sized area. If the SKA comes to Australia, a large number of accurate and highly stable clocks will be required to run the array (in the range 100 - 1000), and constant maintenance of the clocks will be required.

The SKA is being planned as a high precision instrument, orders of magnitude beyond the sensitivity and dynamic range specification of current instruments, and the performance of the clocks used will significantly affect the output of the instrument. Time standards of a *higher quality* than hydrogen masers may need to be examined. The CSO offers this. No other technology has yet been developed that could achieve this type of performance, and potentially be commercialized.

As well as the potential market for the SKA, hundreds of accurate and highly frequency stable clocks are currently deployed in the field around the world for astronomy, representing a significant current market for a good quality and affordable alternative to hydrogen masers.

So this project is to provide a replacement to the hydrogen maser as the LO of choice for VLBI where the integration times are less than a thousand seconds. Of course the critical part of the research is to pass the stability of the CSO to the 5 or 10 MHz signal that is used to the signal timing in the VLBI imaging data reduction process. Nevertheless this project has the potential to revolutionize the quality of VLBI imaging by allowing shorter integration of the signal with significant improvement of the image quality.

If the development of the CSO, as proposed here, can lead to a cost-effective and locally produced frequency standard that can operate robustly in the field, then the performance benefit of running this device relative to a hydrogen-maser is clear. The cost-benefit trade-off will need to be examined at the end of this project, when we can determine the price for a mass-produced version of the CSO resulting from this developmental work.

An additional advantage of our project is that we will test the clock in the field at one of the two proposed international SKA sites, in Western Australia, allowing us to get early data in the proposed location for the SKA.