Making the Case for a New Portable Atomic Clock

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Global Positioning Systems (GPS) allow location and movement tracking across the world by simultaneous communications between satellites. Besides the many applications of GPS, it is the primary means of long range aircraft tracking and coordinating flights. Operation is achieved by sending microwave signal transmissions between them. Ground receivers for GPS are vulnerable to jammers designed to obscure the signal in a background of equivalent microwaves. GPS functions by timing the microwave signals between satellites using atomic clocks, instruments capable of accuracy down to 1 s in millions of years. Each satellite carries an atomic clock synchronised with each other. In an equivalent fashion to GPS, a mechanism for triangulating the location of an active jamming source is an understood procedure, one that Forsberg Ltd. is working to implement. This is achieved through a local mobile network of receivers which precisely measure the jamming signal. Accuracy to 10 m requires a timing synchronisation less then 30×10^{-9} s. Such precision still requires the standards of atomic clocks. The clock must be very small for portability, and low in power consumption for operation on a battery supply. No atomic clock exists that meets these criteria.

Atomic clock accuracy comes from a reference atom which keeps the frequency fixed. This make use of atomic energy transitions for their very narrow and well defined resonances, and introduces resistance to temperature, friction, and other sources of error. Fig. 1 illustrates this process of locking to a particular frequency. The smallest rubidium clocks (the most common atomic reference) are about 200 cm^3 and demand 10 W of power. There exist small quartz crystal clocks, however they lack precision. A small chip-scale caesium atomic clock (20 cm^3, 100 mW) is commercially available, however it suffers from drifts in the stability over long timescales, and uses gas in a vapour cell which is vulnerable to mechanical vibrations from the gaseous state. Vibrations are inevitable for a portable clock carried on a drone making sudden movements.

A potential atomic clock could use N@C_{60} as a reference material, a nitrogen atom in a cage of 60 carbon atoms. Measurements of the splitting in energy levels by magnetic fields can be made by placing the sample in a static magnetic field B_0 and driving electron transitions with an input frequency. Known as electron spin resonance (ESR), a sweep of B_0 will find a transition which matches the frequency based on the energy gap, and resonates. A suitable transition for an atomic clock has been found, located at the base of the arc in Fig. 2. Here changes in B_0 have minimal effects on the frequency. This transition is measurable at room temperature and while dissolved in a solution. This removes the power demands of the vapour cell and heating to 85 ^{o}C in the caesium clock. A high concentration of material can be achieved with the solution, leading to a larger reference signal. The solution state also offers potential mechanical resistance through the

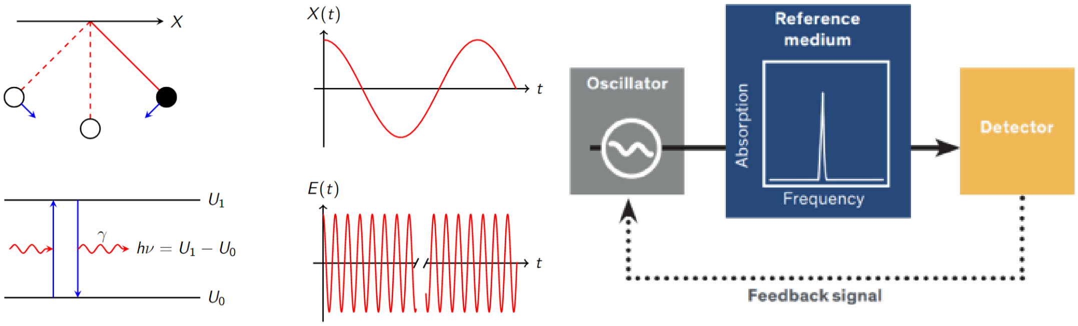


Figure 1: The basic operation of a clock. Any oscillator provides a counting basis of time through oscillations, mechanically or atomically. Generally a higher frequency gives more precision, comparing the pendulum swings of 1 Hz to atomic transitions of over 1 MHz (10^6 Hz). Making a reference a clock requires linking it to an external oscillator through a feedback loop.

higher density compared to the vapour and the shielding in the carbon cage. The technology to miniaturise this is readily available but the investigation is not yet complete.

Intuitively, a narrower reference transition will provide a superior clock. The ESR method inherently broadens the width δf. The true width at 38.6 MHz is unknown, but at least below 100 kHz. This detail will indicate how close to the 30×10^{-9} s synchronisation this reference can achieve. Further development with this limitation considered can then be pushed to reach the required clock standard, one of these being the concentration of material as mentioned. The development of the clock design as a chip will wait until the clock behaviour has been demonstrated on a larger scale with optimised parameter choices.

The progression of this project towards a working clock began with repeating measurements down to 38.6 MHz on an updated ESR setup, the results in Fig 2. This was used to verify the clock transition results, ensure the ability to measure at such a low frequency, and prepare for operating as a clock by observing a singular resonance at the parabola base. Reductions in frequency come with substantial loses in the size of the signal, which is a major difficulty when conducting these measurements.

The most recent research has taken measurements of δf by running short pulses of the frequency. A sequence of pulses giving what is known as a spin echo can be used to measure δf without the broadening. The sequence is two pulses separated by time τ. The echo appears at 2τ and its amplitude decreases with increases of τ based on δf. Initial results have measured this at 460 MHz. An echo with B_0 and the measurements for δf are presented in Fig. 3. Progression towards 38.6 MHz has faced a number of difficulties. Firstly the signal amplitude falls by a factor of 50 from 460 to 100 MHz. Secondly the pulse must be very short and high power to prevent offsetting from the proper 2τ time.

The issue of echo size can be addressed in two ways. One is obtaining more N@C$_{60}$ material. Making this is currently a relatively slow process. The other is increasing the power of the pulses. This has the added benefit of shortening the pulses. A limitation of this has been obtaining equipment that can handle > 1 W without being damaged.

A secondary line of development has been building a prototype clock to use N@C$_{60}$. This is based on alterations to the ESR experiment. B_0 and the frequency are fixed, while the measurement

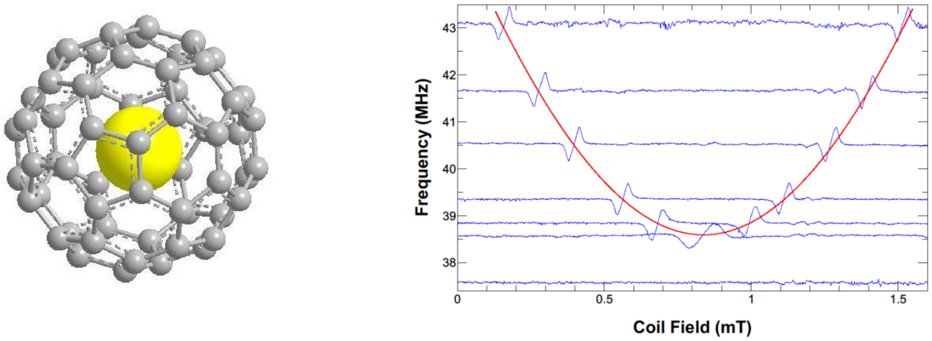
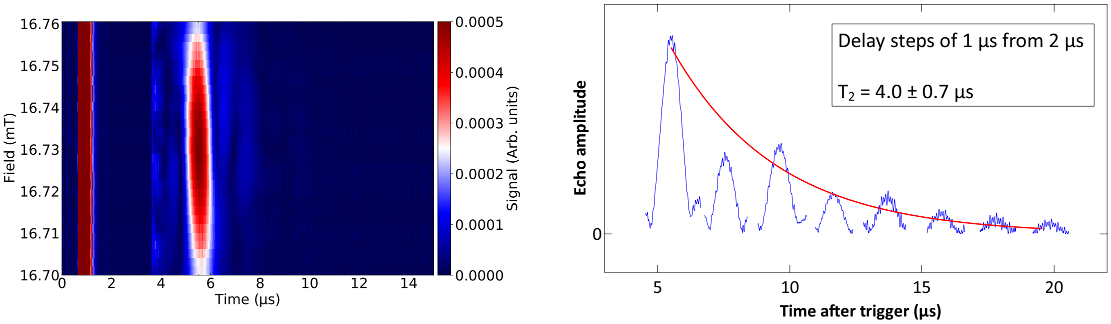


Figure 2: The molecule N@C_{60} and the transition resonances measured at various frequencies with sweeps of field. The clock transition is at the base of the parabola at 38.6 MHz. A small change in the field will have a minimal effect on the frequency.



(a) A spin echo with a $2\,\mu$s separation. The echo appears at twice the separation.

(b) Centres of echos in field. Each echo is from different pulses with a change in separation time.

Figure 3: Pulsed ESR measurements at 460 MHz. The decrease in amplitude is described by T_2 which is $1/\delta f$.

result is fed back to the frequency, which will lock it back to the centre, correcting drifts in frequency.

The current objectives focus on pushing the frequency down with a visible echo to measure. The results of δf will determine a base standard of the clock. This will lead into the work on the clock prototype. Fine tuning of the clock setup can reduce the broadening that follows from the ESR experiment down to δf. Additionally a method for stabilising B_0 is intended to be implemented by carefully monitoring transitions which behave differently with B_0. The result will be a direct measurement of the clock's stability for the target of $30 \times 10^{-9}\,\mathrm{s}$.