**PROJECT PERIODIC REPORT**

**Grant Agreement number:** 255000
**Project acronym:** Mobile Optical Clock
**Project title:** Mobile Optical Clock with Neutral Atoms in a Blue Magical Optical Lattice
**Funding Scheme:** FP7-MC-IEF
**Period covered - start date:** 01/09/2010
**Period covered - end date:** 31/08/2012
**Name, title and organisation of the scientist in charge of the project's coordinator:**

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# 1. PUBLISHABLE SUMMARY

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It shall be of suitable quality to enable direct publication by the REA or the Commission. You may extract this wholly or partially from the website of the project, if suitable, but please ensure that this is set out and formatted so that it can be printed as a stand-alone paper document.
Please include:
- a summary description of the project objectives,
- a description of the work performed since the beginning of the project,
- a description of the main results achieved so far,
- the expected final results and their potential impact and use (including the socio-economic impact and the wider societal implications of the project so far).

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**Publishable Summary:**

In today's world, clocks play a very fundamental role in science and technology ranging from the Global Positioning System (GPS), international time standards to the test of the fundamental laws of physics at an unprecedented level of precision. In particular, millions of ultra cold neutral atoms confined in periodic light potentials can be used for precision metrology and quantum measurements. By carefully choosing the wavelength and polarization of the lattice laser, one can arrive at a situation where the two probed electronic states of an atom experience the same light shifts. In such a magical lattice, perturbations on the two electronic states due to light field cancel out and the spectroscopy becomes independent of the motion of the centre-of-mass of the atom.

The main aim of this project is to create a novel mobile optical clock using Sr atoms in a "magic" blue detuned 3D optical lattice. The ultra narrow, 698 nm transition from $5s^2\ {}^1S_0$ to $5s5p\ {}^3P_0$ is used as a clock transition. In the first stage the project aims at a device to demonstrate relativistic geodesy and explore first applications. Furthermore this project delivers enabling technology for various cold atom applications, such as force sensors for oil and mineral exploration or quantum simulation as a first step to full scale quantum information. These applications are now becoming mature with many fascinating laboratory demonstrations but suffer from a critical lack of readiness in terms of robust device-ready technology. This project benefits from an intra-European transfer of such technology from the German QUANTUS BEC in microgravity project to the UK

and at the same time widen the application of the technology developed. It also links to ESA-programmes related to quantum sensors and space applications.

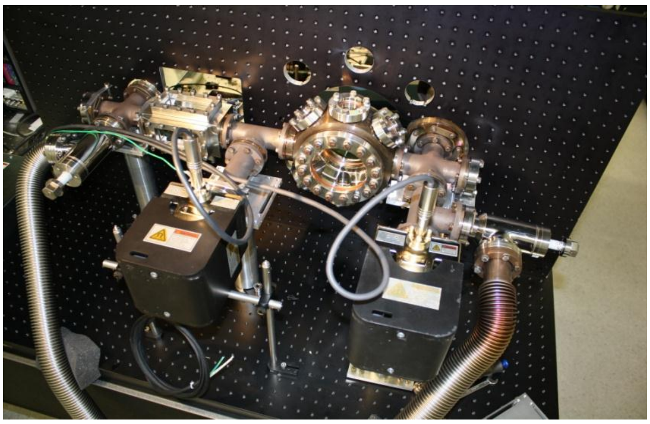
As this is an individual fellowship, providing an appropriate research training to the researcher so that he reaches professional maturity on a way to becoming an independent scientist, is an essential goal of it. This project has provided a unique and close to ideal environment for Dr. Singh to enrich his training to acquire new professional skills, in the form of research techniques, scientific oral & written communications, supervision and project management, specifically:

1. To offer him the opportunity to acquire intellectual knowledge and expertise in precision metrology, quantum measurements, relativity and related areas. In particular, he has had the opportunity to set up a robust, portable, ultra precise and ultra accurate lattice clock.
2. To enable him to learn new techniques such as stabilizing a clock laser with a Febry-Perot cavity or frequency comb.
3. To train and enrich him as an expert in the state-of-the art technology that can pave the way for the space endeavors on atomic sensors and other applications.
4. To offer him further interdisciplinary research abilities through the use of core facilities and close collaboration with a number of internationally leading scientists.
5. To provide him with further transferable skills such as communication skills (written and oral) and working as part of a team.
6. To provide him with leadership qualities by participating in the supervision of and advice to undergraduate project students and graduate students.

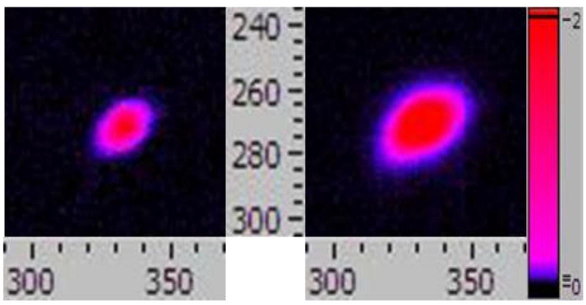
In order to achieve the above, the project has been carefully divided into a set of technical objectives which are: 1) Laser system for cooling & computer control; 2) Precooling and DMOT; 3) Lasers for interrogation (FP locking etc); 4) Lattice Instalation; 5) State preparation; 6) Investigation into blue detuned lattice; 7) Frequency standard optimisation and investigation of systematic errors; 8) Paper writing and finishing backlog.

Given the ambitious and technological nature of the project, it has been a very successful project. Apart from the technological readiness, the following results could be described as two of the main results.

**Sr 2D MOT:** The technique of 2D MOT loading is well established for alkali atoms like Rb and Cs, but is new for Sr, which has a much lower vapour pressure at room temperature, which might be expected to reduce the effectiveness of the concept. We have obtained some preliminary results where a 3D MOT is loaded from the 2D MOT system (see fig 1). We have observed clear enhancement (~10 times) in the atom number in the 3D MOT when a cold atomic beam generated by the 2D MOT is transported through a differential pumping stage and captured in a 3D MOT (Blue MOT) using the $^1S_0$-$^1P_1$ transition for laser cooling.



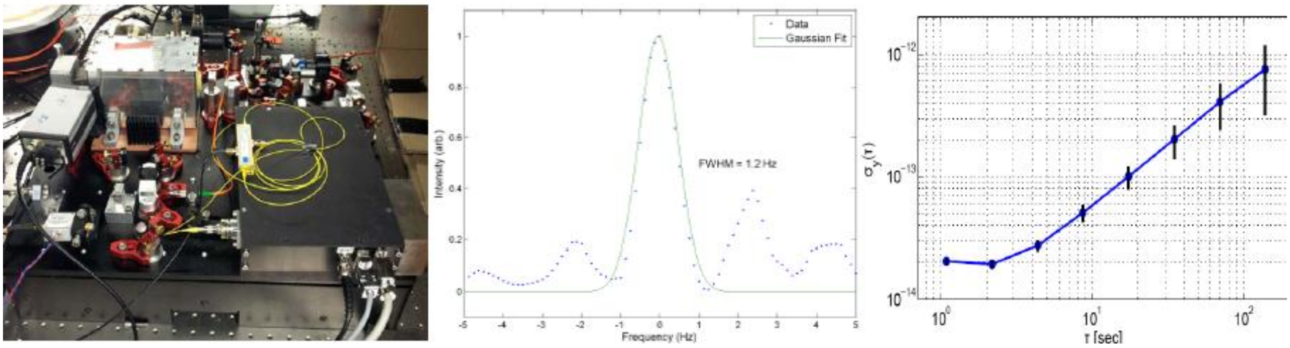
**(a)**




**(b)**

**Fig 1. (a). 2D & 3D MOT assembly. (left)** 2D MOT chamber shown with rectangular windows. **(right)** 3D MOT chamber shown with circular windows. The two chambers are connected to each other via a CF-35 T which also serves the purpose of differential pumping. Two ions pumps maintain ultra high vacuum (UHV) environment with vacuum in 3D chamber in range of $10^{-11}$ -$10^{-12}$ mbar. Here only vacuum assembly has been shown for the sake of clarity. **(b) Enhancement due to 2D MOT. (left)** 3D MOT cloud with 2D MOT OFF. **(right)** 3D MOT cloud with 2D MOT ON. Though the units in both panels are arbitrary (a.u.), the enhancement in the atom number of the 3D MOT, due to 2D MOT, can easily be seen.

**Hertz beat measurement:** we have realised two compact and mechanically stable external cavity diode lasers (ECDL) at 698nm for Sr based optical metrology. In our preliminary investigation we have achieved a ~1.2 Hz optical beat note linewidth between the lasers independently stablized to two Fabry-P´erot (FP) reference cavities with a finesse of 400000 each (see fig 2). The cavities are mounted such that the effect of acceleration and vibrations is significantly suppressed. Moreover, in order to further suppress thermal drifts, the FP spacers are made from ultra low expansion (ULE) glass which has a zero linear expansion coefficient. We have also calculated the Allan deviation which is the measurement of the stability of an oscillator over a range of comparison times. We compare the change in frequency from one reading to another separated by a specific time period.




(a) (b) (c)

**Fig 2. (a). Cavitysetup.** Horizontal cavity together with clock laser and optical elements has been shown here. The cavity setup is mounted on a vibration isolation table and housed in special wooden box in order to minimise the external noise such as accoustic vibrations. **(b) Beat signal.** We have built two clock lasers stabilised to two independent cavities (horizontal and vertical; only horizontal shown in **(a)**). The graph here shows a beat measurement between these two clock lasers. **(c) Allan Deviation.** Allan deviation calculated from the frequency data. The thermal floor appears at $2x10^{-14}$Hz/√Hz, however with lasers remaining stable for more than 2 seconds

As we have already mentioned that these are preliminary results and once the results are thoroughly refined as well as properly checked, they are expected to be published in internationally renowned journals. In terms of scientific progress the project has been a great success, highlighting the importance of a mobile optical clock not only to the wider scientific community but also to the society at large.