

Navigating More Precisely with Laser Clocks



*Artist's impression of two of the satellites in
the Galileo navigation constellation
(Credit: J. Huart)*

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Space-borne atomic frequency standards are the backbone of today's advanced satellite navigation and positioning systems. Rubidium* gas-cell clocks constitute the ideal frequency standard for this kind of space application, since they combine excellent short- and medium-term stability with small size, as well as low weight and power consumption. The development of the key technologies, particularly in terms of reliable diode lasers and atomic vapour cells, will pave the way towards low-power and miniature – ultimately chip-scale – atomic clocks for industrial and domestic use.

Introduction

With today's satellite navigation and positioning systems like Galileo, GPS and Glonass, the position of the receiver unit is determined by measuring and evaluating tiny differences in the arrival times of signals originating from several different satellites. The positioning accuracy of these systems therefore critically relies on the precision of each satellite's timing signal. With the growing demand for satellite navigation providing positioning accuracies of just one or two metres, satellite onboard clocks with superior stability are a key system component, needing to be accurate to within a few nanoseconds per day.

* A silvery-white, highly reactive chemical element found in just a few minerals

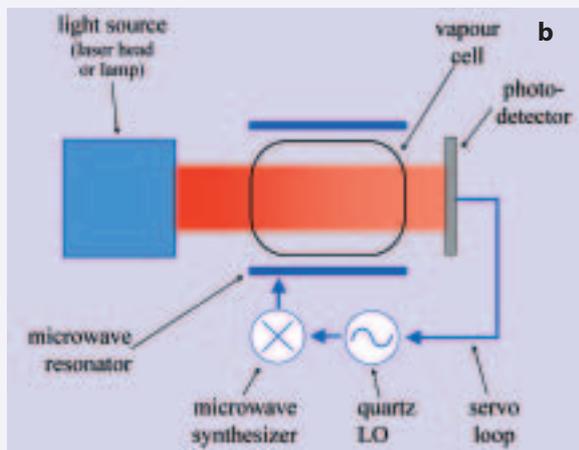
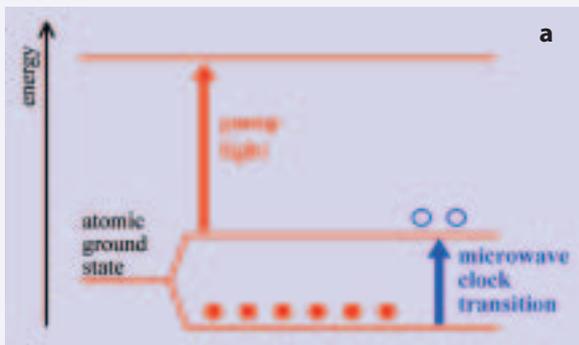
How a Rubidium Gas-Cell Clock Works

In a rubidium gas-cell clock, a signal obtained by interrogating atoms contained in a small vapour-cell is used to adjust the frequency of a local oscillator (LO) in such way that a fixed multiple of this frequency coincides with the atomic reference transition frequency. This results in the local oscillator frequency being effectively stabilized to the atomic reference, and profits from its superior stability over long time periods. The clock thus consists of two main parts:

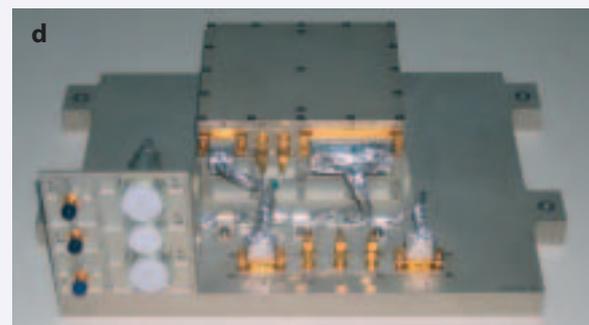
- a physics package, in which the atomic transition is probed using the optical-microwave double-resonance technique, and
- an electronics package, which controls the frequency of the local oscillator (typically 10 MHz), which constitutes the instrument's output signal.

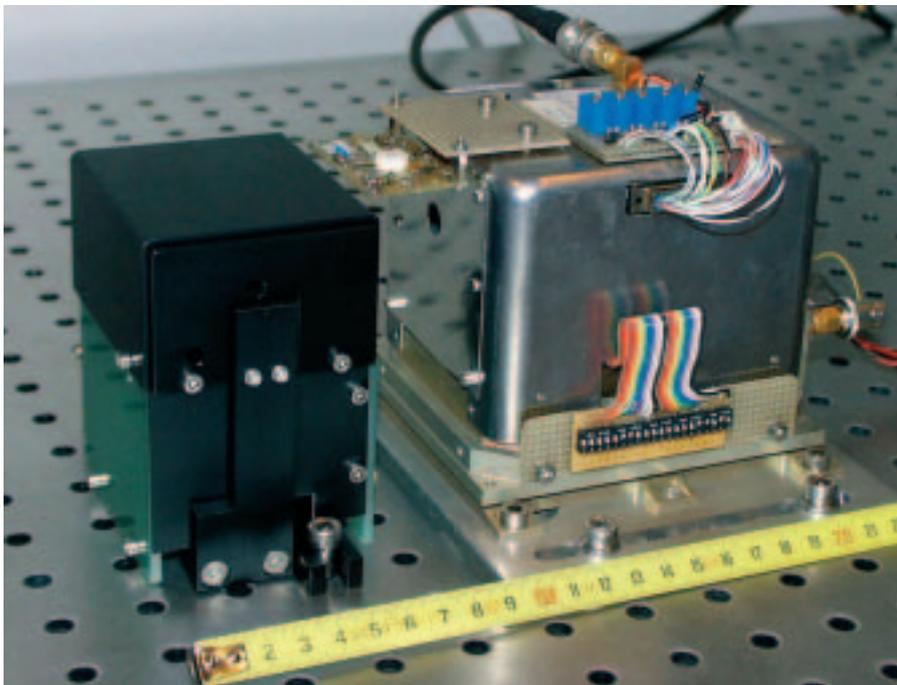
The optical-microwave double-resonance technique represents a powerful, well-established, and still simple way to probe the atomic transition, which allows one to make very compact clocks with high frequency stabilities. Its basic scheme (see Fig. a) relies on indirect detection of the microwave transition: resonant light from a discharge lamp selectively prepares all atoms in the lowest atomic energy ground-state by an optical pumping process and makes them transparent for the pump light. If the applied microwave frequency exactly coincides with the atomic reference 'clock' transition, part of the atoms are transferred back into the de-populated, second ground-state level, where they can undergo optical pumping again and absorb part of the pump light's intensity. The microwave transition thus manifests itself as a decrease in pump-light power transmitted through the atomic vapour cell. In a rubidium clock, this transmitted light power is detected with a photodiode and this signal is used to stabilise the clock's quartz local oscillator.

The gas-cell double-resonance technique has the advantage that the main components can be small. Typical devices can occupy a volume of less than half a litre and still have frequency stabilities of a few parts in 10^{11} over one month. Optically-pumped rubidium clocks are therefore widely applied today in industry, telecommunications and other fields.



- a. Optical/microwave double-resonance scheme for probing atomic reference transitions
- b. Elements of a rubidium gas-cell atomic clock
- c. Key components of a rubidium gas-cell atomic clock: from left to right, the microwave resonator, atomic vapour cell and discharge-lamp light source
- d. Flight model of the ESA space rubidium atomic clock for the Russian Radioastron-1 mission (ESA In-Orbit Technology Demonstration Programme, TDP-II)





Laser-pumped rubidium clock breadboard demonstrator, developed within the ESA ARTES-5 Programme. Left: stabilised laser source. Right: clock resonator module

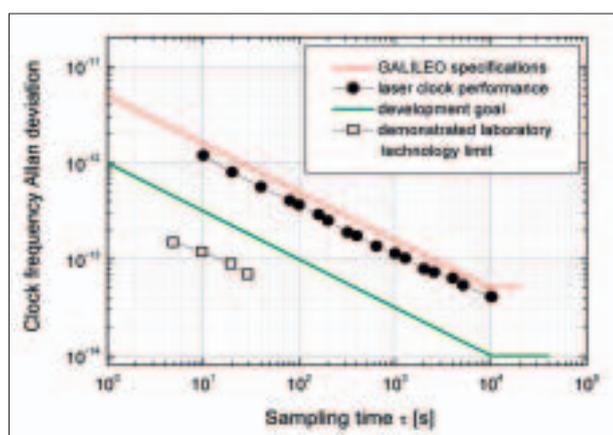
Today, atomic clocks are the most stable and accurate timepieces available and they have become an integral part of modern life in such diverse fields as public time keeping, modern high-speed communication links, and local frequency references for industrial and scientific applications. In these atomic clocks, the 'length' of a second is determined by counting a certain number of oscillations of an atomic transition in the microwave frequency range (see accompanying panel, left). This exploits the superior frequency stability of the atomic transition compared with the last century's timing methods, which relied, for example, on counting the oscillations of a quartz crystal, on a

mechanical pendulum, or on measuring the rotation of the Earth.

How Accurately Can We Tell the Time?

Since 1967, the SI second has been defined as equal to 9,192,630,700 periods of the ground-state microwave transition oscillation in an unperturbed caesium atom. So-called 'primary' atomic clocks match this definition by probing thermal atomic beams or laser-cooled atomic fountains of caesium atoms flying freely in well-shielded vacuum chambers, and form the basis for public timekeeping. The most accurate primary clocks occupy the space of a large wardrobe and are accurate to one part in 10^{15} . So-called 'secondary' atomic

clocks use different technologies, for instance to probe caesium or rubidium atoms contained in small gas-filled cells, or to probe atomic transitions in materials other than caesium. With these technologies, the



Stability performance of the laser-pumped rubidium clock

atomic reference transition frequency is shifted from its value in primary standards, and thus the clock frequency always needs to be calibrated. However, such secondary atomic clocks can be very compact and still offer competitive stabilities over one to several days, which makes them the instruments of choice for navigation and telecommunications satellites. More generally, compact secondary clocks can be implemented as upgrades to conventional quartz technology for stable time and frequency references in basically all satellite applications where superior performances are required.

Today's state-of-the-art lamp-pumped rubidium clocks for space applications occupy a volume of 2 litres, weight around 3.5 kg, and dissipate only 35 W of power. They are stable to within just a few nanoseconds per day. They are already being used by a number of ESA projects, including the Cassini-Huygens mission to Saturn and Titan, and have also been successfully developed for the future Galileo system by Temex Neuchâtel Time (CH).

The limitations arising from the discharge-lamp light source currently represent one of the main obstacles in terms of further improving on the frequency-stability limits of these types of clocks whilst still maintaining their compactness. Here the implementation of advanced diode lasers as pump light sources, together with refined gas-cell production technologies, can lead to improved clock performances to meet future, even more demanding requirements in navigation and telecommunications applications.

Laser Optical Pumping and Detection

Compared with discharge lamps, diode lasers offer an extremely narrow spectrum of the light emission, which in rubidium

ARTES-5 Project Results

From 2001 to 2004, a development project funded within the ESA's ARTES-5 Programme was conducted by Temex Neuchâtel Time and Observatoire de Neuchâtel (CH) to demonstrate and evaluate the potential arising from the implementation of laser optical pumping in compact and high-performance Rubidium clocks for space telecommunications and satellite navigation. A laser-pumped Rubidium clock demonstrator was breadboarded using a modular design, consisting of a modified, lamp-removed Rubidium space clock, and a frequency-stabilised laser head as pump light source (see accompanying figure). With this approach, the laser head can be easily modified to incorporate new laser diodes becoming available for evaluation in the actual clock application.

The laser-head physics package occupies 200 cm³ and includes a small Rubidium reference cell for frequency stabilisation to saturated absorption spectroscopy reference lines. As no European intrinsically single-mode laser diodes were available at the start of the project, the laser design is based on a compact (54 cm³) extended-cavity diode laser (ECDL) with feedback from an external diffraction grating. The complete laser head represents, to our knowledge, the most compact realisation of an ECDL including frequency stabilisation. The laser frequency stability is $\leq 2 \times 10^{-12}$ from 1 to 10⁵ s. The laser head emits 2 mW of optical power within a 500 kHz line width at 780 nm, with frequency noise of order 3 kHz/ $\sqrt{\text{Hz}}$ and an amplitude noise of order 1×10^{-13} (Relative Intensity Noise at 300 Hz) and thus fulfils the requirements for a high-performance Rubidium clock.

Owing to the crucial importance of the laser frequency stability for the clock performance, different spectroscopic schemes were studied in order to evaluate the stability obtainable from a compact reference setup. Among the possibilities evaluated, a saturated absorption scheme was identified as the optimal solution. It provides a narrow and inverted atomic reference line that simultaneously allows simple and unambiguous line identification together with excellent frequency stability. Other, simpler spectroscopic schemes did not show sufficient frequency stability for the high-performance space Rubidium clock envisaged. Such schemes can, however, be of advantage for less-demanding clock applications, where compactness and robustness of the stabilisation are crucial.

The clock module is based on a Temex Neuchâtel Time RAFS type clock for Galileo, where the discharge lamp was removed and the electronics modified in order to adapt it to laser pumping. By introducing a buffer-gas mixture to the reference vapour cell, the cell's temperature sensitivity could be reduced by a factor of order 30, allowing clock stabilities of a few 10^{-14} . Limitations on the long-term stability arising from light shift effects were reduced by adjusting the total buffer-gas pressure in the resonance cell such that the point of zero light shift closely coincides with the reference line used for the laser frequency stabilisation. These techniques show the potential for optimised suppression of the long-term stability limitations arising from both the light shift and the cell's temperature sensitivity towards the level of 10^{-14} or below. To reach this goal, full optimisation and control of the vapour-cell technology will be needed. This includes the development of refined cell-filling processes, predictability and reproducibility issues, as well as more general studies on, for example, possibilities for cells using novel wall coatings, or other methods.

The Elegant Breadboard (EBB) that was realised shows a short-term stability of about $3 \times 10^{-12} \tau^{-1/2}$, which meets the specifications for the Galileo Rubidium clocks. The signal-to-noise ratio of the double-resonance signal allows a stability corresponding to the project goal of $1 \times 10^{-12} \tau^{-1/2}$, and thus is not the limiting factor here. Full optimisation of several components will allow further reduction of the short-term stability to the signal-to-noise limit, and eventually towards its demonstrated technology limit of around $3 \times 10^{-13} \tau^{-1/2}$. The long-term stability of 4×10^{-14} at 10⁴ s is limited by both temperature and light-shift effects and consistent with the determined cell parameters. Measured long-term drifts of around $3 - 5 \times 10^{-13}$ /day measured during operation under normal atmospheric pressure are already comparable to or lower than those for conventional lamp-pumped clocks under the same conditions.

The EBB's overall mass of some 3 kg and volume of approximately 2 litres are already much lower than those of other atomic clocks. Future miniaturisation of the laser head and its complete integration into the clock-module envelope can be expected now that the advanced single-mode laser diodes are available. This will result in a further reduction in the mass and volume and improved robustness of the clock.

A final optimisation of the resonance cell's buffer-gas content and adaptation of the clock electronics will provide improved medium-term and short-term stability, respectively. Pushing these two aspects to their limits will result in a compact laser-pumped Rubidium clock for space applications like telecommunications or satellite navigation, delivering performance figures of $1 \times 10^{-12} \tau^{-1/2}$ or better and 1×10^{-14} at 10⁴-10⁵ s.

Specifications for Different Rubidium-Atomic-Clock Applications

	High performance (space)	Compact telecommunication	Miniature/chip-scale
Short-term stability	$< 10^{-12} \tau^{-1/2}$	$< 10^{-11} \tau^{-1/2}$	$< 3 \times 10^{-10} \tau^{-1/2}$
Long-term stability	$< 10^{-13} / \text{day}$	$< 5 \times 10^{-11} / \text{month}$	$< 10^{-11} / \text{hour}$
Volume	< 4 litres	< 0.3 litres	$< 1 \text{ cm}^3$
Mass	< 4 kg	< 0.3 kg	–
Power consumption	< 25 W	< 10 W	< 50 mW

where τ is the sampling time

clocks results in improved short-term frequency stability. The smallness of diode lasers offers the opportunity to realise more compact light sources, and their excellent quantum efficiency also holds potential for reduced power consumption compared with discharge-lamp optical pumping. Laboratory experiments have confirmed that the introduction of laser optical pumping improves the signal contrast and detection signal-to-noise ratio, resulting in improved short-term rubidium clock stabilities down to $3 \times 10^{-13} \tau^{-1/2}$, which is superior to those obtained with discharge lamps.

Well-established technologies allow for excellent control of the laser spectrum, making it possible to separate different physical effects connected to the temperature, light intensity or frequency, and to minimise separately the limitations arising from each of these effects. They are also of special importance for improving the clock stability over the long time scales of primary interest for an atomic clock. Here, optimisation of the vapour-cell technology and fine-tuning of the cell's buffer-gas content can reduce limitations due to the cell's temperature coefficient. Important contributions to clock instabilities also stem from so-called 'light-shift effects' due to interactions of the atoms with the pump light, unless the latter is perfectly resonant and its spectrum well-controlled. These effects also occur with discharge lamps, but are more strongly pronounced for the narrow laser spectrum.

Until recently, the availability of suitable laser diodes offering the required intrinsic single-mode emission and spectral quality directly from the laser chip represented the predominant obstacle to reliable laser-pumped rubidium clocks. The existing laser diodes required spectral control by optical feedback from mechanically moving external parts, which is a standard technique in laboratory applications but makes the laser source comparably bulky and susceptible to mechanical shocks and vibrations. The last few years, however, have seen increased activities in industry and ESA-funded projects to provide advanced single-mode laser diodes, such as new Fabry-Perot laser diodes, Distributed Feedback, and Distributed Bragg Reflector lasers. The first diodes operating at a variety of wavelengths and suitable for gas-cell atomic clocks became commercially available in 2004 from several European manufacturers. Early samples of such diode lasers have been spectrally characterised at Observatoire de Neuchâtel, using dedicated test benches specially installed for the purpose. The tests showed encouraging single-mode operation with emission line widths around 6 MHz, both for commercial Distributed Feedback samples and Fabry-Perot diodes from ESA contract developments, making them ideal candidates for making reliable and spectrally well-controlled pump laser modules for rubidium clocks. The use of fibre or volume Bragg gratings for spectral control in diode lasers may also offer interesting alternatives in the near future.

Thanks to the ongoing effort within ESA's ARTES-5 Programme directed towards the development of diode lasers for space atomic clocks, several projects are already pursuing the realisation of suitable diodes of different types and wavelengths. These activities also include the independent characterisation of diode performance both in solitary operation and when integrated into an atomic clock. Naturally, qualification issues connected with the laser's lifetime, reliability and ageing under different radiation and vacuum conditions in space also have to be addressed. The first samples of such diode lasers have been spectrally characterised at Observatoire de Neuchâtel, with respect to, for example, their single-mode operation, line width, continuous tuning range, and frequency and intensity noise, and the tests are showing encouraging results.

The Future

The studies undertaken to date show that there are excellent prospects for the realisation of improved next-generation, laser-pumped, gas-cell atomic clocks. Continued development is needed to fully master the critical key technologies, such as the availability and spectral control of advanced single-mode diode lasers, as well as enhanced vapour-cell technologies such as the use of better wall coatings, and the control and reduction of light-shift effects. Pushing the existing technologies to their physical performance limits should help to bring significant improvements in terms of realising compact and high-performance

rubidium atomic clocks. The miniaturisation of the clock components and dedicated novel clock schemes should allow the production of miniature atomic frequency references for mass-market applications, and which could replace quartz oscillators in a variety of devices. A modular approach to these topics will also open the way for the development of a whole family of gas-cell clocks that can respond to the needs of a variety of space- and ground-based applications.

Two main directions for the future development of laser-driven vapour-cell clocks can be identified. One line aims for the realisation of compact but nevertheless high-performance rubidium frequency standards with improved stability ($< 10^{-12}$ $\tau^{-1/2}$ short-term, $< 10^{-14}$ over one day) for satellite navigation as well as for use as a local oscillator in optical combs and cold-atom frequency standards. A second line concerns miniature, low-power-

consumption and comparably low-performance atomic clocks in the spirit of a chip-scale clock that eventually could compete with quartz oscillator references in a variety of electronics systems or end-user applications, offering reduced sensitivity to shock and environmental parameters. For such developments, the availability and miniaturisation issues in terms of suitable diode lasers, vapour cells and microwave resonator and electronics will have to be addressed, as well as the reliability, lifetime, and ageing behaviour of these clock components.

The progress made during the last years in many of the key technology fields makes it realistic to expect the production within the next few years of compact high-performance vapour-cell atomic clocks that could find application in those fields calling for stability levels of around 10^{-14} /day, which are currently served by far bulkier masers and caesium-beam

clocks. The miniaturisation of the clock components and dedicated novel clock schemes should allow one to produce miniature atomic frequency references for mass-market applications, or to replace quartz oscillators in a variety of systems.

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