



## BOOK OF ABSTRACTS

20th European Frequency and Time Forum

27-30 March 2006  
Braunschweig, Germany

## LOCAL ORGANIZING COMMITTEE

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## ACKNOWLEDGMENTS

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- Helmholtz-Fonds e.V.
- Deutsche Forschungsgemeinschaft
- The City of Braunschweig

# Conference Program

## Sunday, March 26

16:00 - 21:00 Registration, Setting up the exhibition  
18:00 - 21:00 Icebreaker

## Monday, March 27

09:00 - 10:45 Mo Plen: Plenary Session I  
10:45 Coffee Break  
11:15 - 12:35 Mo A1: ACES Mo B1: Simulation and Characterization of Oscillators  
12:35 Lunch Break  
14:00 - 15:20 Mo A2: Optical Frequency Measurement Mo B2: Time and Frequency Transfer Techniques  
15:20 Coffee Break  
15:50 - 17:10 Mo A3: Novel Concepts for Atomic Clocks  
18:00 Guided City Tour

## Tuesday, March 28

08:45 - 10:15 Tu Plen: Plenary Session II  
10:15 Coffee Break  
10:45 - 12:05 Tu A1: Atomic Fountain Clocks Tu B1: Piezoelectric and Microwave Resonators  
12:05 Lunch Break  
13:30 - 15:30 Tu P: Poster Session  
15:30 Coffee Break  
16:00 - 17:40 Tu A2: Optical Lattice Clocks Tu B2: TAI Time Links  
19:30 - 20:00 Reception (Dornse Entrance Hall)  
20:00 Banquet and EFTF Awards (Dornse)

## Wednesday, March 29

08:45 - 10:05 We A1: Timing in Galileo and Space Operations We B1: Trapped Ion Clocks  
10:05 Coffee Break  
10:35 - 12:15 We A2: Fundamental Tests We B2: Piezoelectric Materials and Acoustical Effects  
12:15 Lunch Break  
13:30 - 15:30 We P: Poster Session  
15:30 Coffee Break  
16:00 - 17:20 We A3: Clocks for Space Applications We B3: Oscillators and Phase Noise  
17:20 - 18:00 Farewell Address / Presentation of EFTF 2007  
18:00 End of Conference

## Thursday, March 30

09:00 - 14:00 Visit to PTB

# Laboratory Tours at PTB

Thursday, March 30, 2006, 9:00h - 14:00h

Tours through the following laboratories will be offered:

1	Cs fountain clocks
2	Satellite time comparisons
3	Optical clocks based on a single Yb ion
4	Optical frequency divider (comb generator)
5	Optical frequency standards based on Ca and Sr atom clouds
6	X-ray interferometry
7	Josephson voltage standards
8	Single electron tunneling
9	Single electron transport
10	Calibration of fast oscilloscopes using femtosecond lasers

GAUSS AND GEODESY

WOLFGANG NIEMEIER

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Carl Friedrich Gauss can be considered as one of the most famous scientists worldwide, with special emphasis on developments in Mathematics, Physics, Astronomy and Geodesy. Gauss was born in Braunschweig in 1777 and passed away in 1855 in Göttingen.

In this presentation at first the relation of Gauss to Braunschweig will be outlined and some significant findings out of his early years will be presented.

In the main part the research and developments of Gauss within the scientific discipline of Geodesy will be explained and their importance for solutions in Geodesy and related fields today will be evaluated. The principal examples are :

- Studies of the figure of the earth
- Coordinate and reference systems
- Projection of spherical surfaces to the plane
- Adjustment according to the method of least squares

For all concepts the basic ideas and practical examples will be given.

TIME WITH GALILEO

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Galileo, the Global Navigation Satellite System (GNSS) currently developed and built by Europe, will provide an additional and independent source of time. Galileo will use Hydrogen Masers and Rubidium clocks as well as additional frequency bands from the start. This provides a potential for higher accuracies. Galileo services will furthermore undergo certification, i.e. reliability and its assessment will play a crucial role. This requires that failure mechanisms and stability issues are studied and understood thoroughly. Future GNSS services shall take advantage of Galileo and GPS signals jointly, i.e. of signals that are synchronized independently. The joint use of signals substantially improves the availability of a base service and has the potential of contributing to the reliability of time. Different strategies have been developed and analyzed to handle the different synchronizations of the two systems. GNSS is currently used in an increasingly broad spectrum of applications. Accuracy, the critical concern in navigation, turns out to play a role in telecommunications and science as well, but is rather unimportant otherwise. Integrity - including authenticity - and reliability are important and even critical in most applications. In the talk, I will describe various aspects of our current understanding at DLR of the issues mentioned above.

DEVELOPMENT OF THE ACTIVE SPACE HYDROGEN MASER  
FOR THE ACES SPACE EXPERIMENT OF ESA

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The two frequency standards that will be part of the Atomic Clock Ensemble in Space payload (ACES) are firstly a cold Cesium clock (PHARAO) required for its outstanding long-term frequency stability ( $\tau \geq 3000$  s) and accuracy, and secondly an active Space Hydrogen Maser (SHM) mandatory for its ultimate frequency stability performance in the mid-term range ( $3 \text{ s} \leq \tau \leq 3000 \text{ s}$ ). With a double servo loop configuration (short-term and long-term), ACES output signal will take benefit of the best frequency stability for each integration time (PHARAO locked on SHM for short and mid-term, and SHM steered to PHARAO for long-term). The ultimate frequency stability of SHM is essential for ground users, because of the limited time availability of the clock signal (typically 400 s) due to the International Space Station fast rotation.

In order to reduce the size and the mass of the SHM down to 35 kg, its Physics Package (PP) is based on a sapphire-loaded microwave cavity [1]. Moreover, no vacuum bell jar is surrounding the atomic resonator: the thermal insulation of the RF cavity will only rely on the space vacuum in which the SHM must be placed. The mechanical fixation structure of the SHM is also designed to reduce the overall mass while withstanding the vibration level of a space launch. With these mechanical design constraints, the microwave cavity temperature can only be regulated at the milliKelvin level, which leaves unacceptable residual cavity frequency variation. In order to achieve its ultimate performances, the SHM requires a frequency stability of its microwave cavity at the 0.1 Hz level (1000 improvement factor). Therefore, Observatoire de Neuchâtel has developed an Automatic Cavity Tuning (ACT) using an active control of the cavity frequency through a varactor diode. The novelty of this key electronic function lies in the fact that this ACT already corrects cavity frequency instabilities in the mid-term integration time (typically  $100 \text{ s} \leq \tau \leq 10000 \text{ s}$ ). Moreover, it does not degrade the performance of the SHM for shorter integration time ( $\tau \leq 100 \text{ s}$ ). The ACT functioning and performances have been successfully demonstrated using a representative SHM 50 kg Proto Engineering Model.

The main objective of the current phase is to perform an end-to-end performance demonstration with representative hardware, to be used as a stepping stone for pursuing the development of the SHM and aiming at the delivery of the SHM Proto Flight Model (PFM) in 2008. This development will lead to the lightest ever build active hydrogen maser for space applications.

- [1] A. Jornod, G. Goujon, D. Gritti, and L.G. Bernier, *The 35kg space active hydrogen maser (SHM-35) for ACES*. in *Proc. of the 17th EFTF*. 2003. Tampa, FL, USA.

**EXPERIMENTAL MEASUREMENTS ON THE ENGINEERING MODEL  
OF THE SPACE CLOCK PHARAO**

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Since 2001, CNES has funded the CD phase of the PHARAO<sup>1</sup> space program. The first step is the construction and the performances evaluation of an engineering model of a space clock using cold cesium atoms. The clock is comprised of four main sub-systems: the laser source, the cesium tube, the microwave synthesizer and the computer. CNES has subcontracted their construction to several industrial companies. These subsystems will be finally assembled at CNES, Toulouse, for tests and validations. A second clock, the flight model, will then be constructed to be assembled on the ACES<sup>2</sup> payload. The ACES mission, managed by the European Space Agency, has two main objectives. The first one deals with the study of the cold atom clock to reach a frequency accuracy of  $10^{-16}$ . The second one is to perform fundamental metrology by comparing the clock signal with ground based clocks via a two way link. The expected time resolution is 10 ps per day. A H-maser developed by Observatoire Cantonal de Neuchâtel is the second ACES clock and will be used as a stable frequency reference for mid term duration.

The engineering model of the cold atom space clock PHARAO is being assembled at CEST, CNES Toulouse. Each sub-system has undergone the acceptance tests. Once assembled the last test concerns all the atomic cooling process from capture to detection before performing a full clock performances evaluation.

In this paper, we review the performances of the sub-systems and present the first results of the whole clock operation.

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<sup>1</sup> Projet d'Horloge Atomique à Refroidissement d'Atomes en Orbite

<sup>2</sup> Atomic Clock Ensemble in Space

## CLOCK COMPARISONS IN THE ACES PROJECT

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Time and Frequency comparison techniques are key for the success of the ACES mission onboard the International Space Station (ISS). The main goal is to compare PHARAO onboard to ground-based high performance clocks. This is performed in a 2-step approach. First, within the ACES payload itself, the Active Space Maser (SHM) is synchronised to PHARAO by the Frequency Comparison and Distribution Package (FCDP). The SHM signal then drives the ACES Microwave Link (MWL) for time and frequency comparison to ground-based systems, which are equipped with matching Ground Terminals (GT).

The FCDP provides frequency and phase comparison between PHARAO and SHM, it performs a phase noise measurement on the two clock signals and it phase locks PHARAO to SHM for short to medium term durations, i.e. for  $3 \text{ s} < \tau < 3000 \text{ s}$ . On the long term, SHM is steered towards PHARAO. As result, SHM closely follows PHARAO while providing a clean reference with superior short term stability, which is distributed to MWL again by the FCDP.

The driving design requirement for the FCDP is it's phase stability, which is specified as to not degrade the Allan Variance of the best on-board clock by more than 10%.

To perform space-ground clock comparisons at the level required for the ACES mission, the MWL must exhibit time stability compatible with a clock performance at the  $10^{-16}$  level for time intervals from 1 day and longer.

Using the excellent stability of the on-board clock ensemble, a world-wide time and frequency transfer is achieved at the level of 100ps.

The main functions and the mission objectives of MWL and FCDP as part of the ACES payload will be presented including the system design, development status and recent test results.

This work is performed under ESA contract 16242/02/NL/JS

CLOCK COMPARISON BASED ON THE PHASE GPS SATELLITE CLOCKS  
AND SYNERGY WITH THE FUTURE ACES MISSION

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A method is developed, based solely on phase GPS measurements, to inter-compare ground clocks. The advantage of this method is that all ground clocks connected to a GPS receiver are compared at the same time and together with the clocks of the GPS satellites. Since only carrier-phase measurements are used, an overall clock ambiguity over all ground stations has to be estimated using smoothed P-code measurements from only one ground or space clock taken as a reference. The method using "phase clocks" has originally been developed and tested for precise orbit determination of the CHAMP and GRACE satellites in an low Earth orbit (LEO) for a period of two years, employing about 30-40 ground IGS stations. Since kinematic or dynamic orbit determination of LEO satellites or point positioning of any ground station is performed using solely carrier-phase GPS measurements, the effect of the overall clock ambiguity cancels out completely and use of the noisy code measurements is avoided. The method of "phase clocks" is very appropriate for the study of the spectral characteristics or performance of any ground clock or a clock in space. The required high short term stability ( $< 1$  min.) for the clocks of the GPS satellites on the precise point positioning will be presented. The similar analysis will be performed for the clock on board the first Galileo satellite to be launched end of December 2005.

The second part of the paper deals with a proposal submitted to the ESA in response to an Announcement of Opportunity in 2004 in support of the orbit determination for the ACES mission on the Space Station and the time transfer using GPS/Galileo receivers. The idea is to install on board the Space Station a GPS/Galileo receiver driven by the external frequency of the ACES clock and perform time transfer to the ground clocks. The novelty is the combination of the ACES MW-link measurements with the GPS/Galileo phase measurements stemming from the 30 to 40 ground IGS stations and a GPS/Galileo receiver on-board of the Space Station. An important advantage of the carrier-phase GPS/Galileo measurements is that they are continuous and a very long uninterrupted time series can be obtained, as compared to the ACES MW-link measurements limited to the very short tracking passes of the Space Station in the LEO orbit. Time transfer using GPS is limited by the accuracy of the code GPS measurements, but combination of carrier-phase GPS/Galileo measurements with the MW-link measurements may solve this problem. Using simulated GPS/Galileo carrier-phase measurements from the 30 to 40 IGS stations and MW-link measurements from about 10 ground stations, highly accurate, calibrated "phase clocks" will be estimated for the GPS and Galileo satellites simultaneously with all ground clocks. This second part will show the benefits of a combined processing of GPS/Galileo phase measurements and MW-link measurements for definition of the time scale for the Galileo and GPS navigation systems and demonstrate the possibility of highly accurate time transfer using calibrated "phase clocks".

FREQUENCY COMBS AND PRECISION SPECTROSCOPY OF HYDROGEN

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A femtosecond frequency comb is a simple and compact tool that allows the phase coherent connection of the radio frequency domain (below 10 GHz) with the optical domain (above 200 THz). It greatly simplified high precision optical frequency measurements and provides the long awaited clockwork mechanism for an all-optical atomic clock. In addition it allows to shape the electric field transients of femtosecond pulses including the phase between the carrier wave and the pulse envelope.

We have used such a frequency comb to measure the absolute frequency of the 1S-2S two-photon transition in atomic hydrogen, i.e. comparing it with the Cs ground state hyperfine splitting. By comparing data taken in 2003 with earlier measurements in 1999 we can set an upper limit on the variation of the 1S-2S transition frequency of  $(-29 \pm 57)$  Hz within 44 months [1]. To derive limits on the drift rates of fundamental constant such as the fine structure constant, we combine these measurements with the results obtained by S. Bize *et al.* at NIST [2] and E. Peik *et al.* at PTB [3] with different optical transitions. This gives precise and separate restrictions for the fractional time variation of the fine structure constant and the Cs nuclear magnetic moment measured in Bohr magnetons. The latter is a measure of the drift rate of the strong interaction.

Furthermore we report a frequency comb at much shorter wavelength. Based on intra cavity high harmonic generation an XUV (up to 60 nm) frequency comb is generated with a repetition rate of 110 MHz useful for high resolution laser spectroscopy in this region [4].

[1] M. Fischer *et al.* Phys. Rev. Lett. **92**, 230802 (2004).

[2] S. Bize *et al.* Phys. Rev. Lett. **90**, 150802 (2003).

[3] E. Peik *et al.* Phys. Rev. Lett. **93**, 170801 (2004).

[4] Ch. Gohle *et al.* Nature **436**, 234 (2005).

VUV QUANTUM INTERFERENCE SPECTROSCOPY WITH UP-CONVERTED  
FREQUENCY COMB LASER PULSES

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Previously we have demonstrated with an experiment in krypton at 212 nm [1] that the remarkable precision of frequency comb lasers can also be utilized at deep UV wavelengths, by direct excitation with multiple amplified and subsequently frequency up-converted comb laser pulses. We have taken this a step further now by performing quantum interference spectroscopy in xenon at 125 nm, demonstrating that sub-MHz precision is feasible with phase-coherent ultrafast VUV pulses obtained by third-harmonic generation in a gas.

In the experiment 2 to 6 pulses from a repetition rate and phase stabilized frequency comb laser are amplified and up-converted to 125 nm. Excitation of xenon with the resulting multiple phase-coherent VUV pulses leads to interference effects in the excitation probability from which the transition frequency can be deduced, much like Ramsey spectroscopy. The excited state population is probed by a 532 nm ionization laser. Figure 1 shows the measured interference pattern as a function of the time delay between 2 VUV pulses. This delay is scanned on an attosecond time scale by varying the repetition rate of the laser. The high stability of the interference patterns indicates that this method is very promising for sub-MHz precision spectroscopy at VUV and XUV wavelengths.

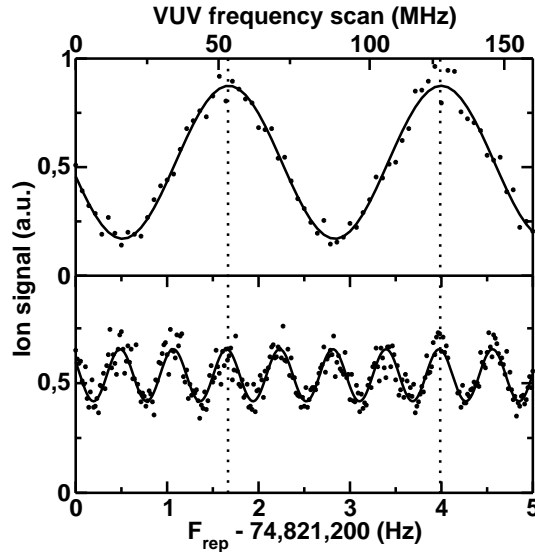


Figure 1: Quantum interference fringes measured on the  $5p^6 \ ^1S_0 \rightarrow 5p^5 \ (^2P_{3/2}) \ 5d \ [1/2]_1$  transition in  $^{132}\text{Xe}$  at 125 nm, pulse delay 13.36 ns (upper) and 53.46 ns (lower trace).

[1] S. Witte *et al.*, Science **307**, 400 (2005)

Phase noise issues in fiber laser based frequency combs

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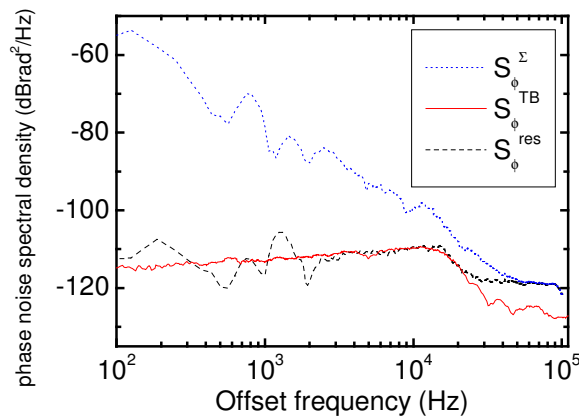
In this work, we conduct a thorough study on the phase noise properties of a fiber laser based frequency comb. The fluctuations of the free-running carrier-envelope offset (CEO) phase, the repetition phase, and the phase of an optical comb line are simultaneously detected. We show that these fluctuations can be effectively eliminated by exploiting the known correlation among this quantities and that a fractional frequency instability better than  $2 \times 10^{-14}$  can be achieved within 1 sec of integration time.

This study is motivated by the fact that by applying the so called transfer oscillator concept, any technical and quantum noise of an optical frequency comb can be eliminated from a measurement, provided that all fluctuations are sufficiently correlated [1]. We express the frequency of a line within the comb as

$$\nu_m(t) = m \cdot f_{\text{rep}}(t) + \nu_{\text{CEO}}(t) + \delta\nu_{\text{res}}(t) \quad (1)$$

where  $m$  is an integer,  $f_{\text{rep}}$  the laser repetition rate,  $\nu_{\text{CEO}}$  the offset frequency, and  $\delta\nu_{\text{res}}$  a residual term accounting for potential uncorrelated contributions.

We use an advanced experimental scheme involving two optical frequency comb generators to record electronic signals for  $\nu_m$ ,  $f_{\text{rep}}$  and  $\nu_{\text{CEO}}$  with a digital storage oscilloscope [2]. When all noise contributions are treated as uncorrelated, the spectral noise density of the residual phase would be given by the sum of the noise densities of its constituents  $\nu_m$ ,  $f_{\text{rep}}$ , and  $\nu_{\text{CEO}}$ . This scenario is represented by the blue dotted line in the figure. In contrast to a picture of uncorrelated phase fluctuations, we find a strong phase noise suppression when  $\delta\nu_{\text{res}}$  is calculated according to Eq. (1) (black dashed line).



Our results are limited by the instability of the oscilloscope time base (red solid line). From our experimental findings, we infer an upper limit of the frequency instability of the comb corresponding to an Allan standard deviation of  $1.4 \cdot 10^{-14} [\tau \text{ Hz}]^{-1/2}$ , where  $\tau$  is the integration time. To the best of our knowledge, this is the lowest reported value for a fiber laser based frequency comb.

[1] H. R. Telle et al., Appl. Phys. **B 74**, 1-6 (2002)

[2] E. Benkler et al., Opt. Express **13**, 5662-5668 (2005)

HIGH STABILITY AND HIGH ACCURACY MEASUREMENTS OF A CA OPTICAL CLOCKC. W. OATES<sup>1</sup>, G. WILPERS<sup>2</sup>, Y. LECOQ<sup>1</sup>, L. HOLLBERG<sup>1</sup><sup>1</sup> National Institute of Standards and Technology, Boulder, CO 80305<sup>2</sup> National Physical Laboratory, Teddington, Middlesex, TW11 0LW, United Kingdom

The 657 nm intercombination line in neutral calcium has been much studied through the years with particular emphasis on optical clock applications. The highest performing calcium clocks use laser-cooled atoms, which are released from magneto-optic traps and freely expand during the clock spectroscopy [1]. Since Doppler shifts present serious potential limitations, groups at PTB and NIST have developed new versions of calcium-based clocks that use two stages of laser cooling to reduce the temperature of the atomic sample to  $\sim 10 \mu\text{K}$  [1]. Here we report a measurement of the absolute frequency of the clock transition that attains a fractional uncertainty of  $7.5 \times 10^{-15}$ , the lowest value to date achieved with a neutral atom optical transition. Additionally we have minimized the duration of the measurement cycle (total cooling and measurement time  $\sim 25$  ms) in order to reduce the clock instability to  $4 \times 10^{-15}$  @ 1 s, which averages to below  $2 \times 10^{-16}$  @ 2000 s [2].

Working with atoms at microkelvin temperatures allowed us to develop and employ a new method to measure and optimize spectroscopy beam parameters, which has the potential to reduce residual Doppler effect uncertainties to well below one part in  $10^{16}$ . To evaluate the systematic shifts efficiently we use a multiplexed measurement system that takes advantage of the low instability of the atomic frequency standard. The multiplexed system enables internal measurements of various shifts relative to a stable reference cavity with hertz level accuracy in 100 s averaging time. Among the most critical shifts evaluated for the absolute frequency measurement were frequency chirps in the acousto-optic modulators [3] and locking offsets that result from lineshape asymmetries [4].

Finally, we will discuss modifications to a simplified calcium clock based on millikelvin atoms [5]. This system has great potential for compactness and high stability (albeit with reduced accuracy) and could be used in a range of applications.

[1] U. Sterr, C. Degenhardt, H. Stoehr, C. Lisdat, H. Schnatz, J. Helmcke, F. Riehle, G. Wilpers, C. W. Oates and L. Hollberg, *Com. Rend. Phys.* **5845** (2004).

[2] L. Hollberg, C. W. Oates, G. Wilpers, C. W. Hoyt, Z. W. Barber, S. A. Diddams, W. H. Oskay, and J. C. Bergquist, *J. of Phys. B* **38**, 469 (2005).

[3] C. Degenhardt, T. Nazarova, C. Lisdat, H. Stoehr, U. Sterr, and F. Riehle, *IEEE Trans. Instr. Meas.* **54**, 771 (2005).

[4] C. W. Oates, G. Wilpers, and L. Hollberg, *Phys. Rev. A* **71**, 023404 (2005).

[5] C. W. Oates, E. A. Curtis, and L. Hollberg, *Opt. Lett.* **25**, 1603 (2000).

ATOM-BASED STABILIZATION FOR LASER-PUMPED ATOMIC CLOCKS

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We present a novel technique for controlling the light source frequency and cell temperature for a laser-pumped atomic clock [1]. The frequency stability of such clocks is degraded by the sensitivity of the parameters of the laser and vapor cell to ambient temperature. To reduce such sensitivity, the temperature of these components is usually controlled using sensors. In chip-scale atomic clocks (CSACs) [2], large temperature gradients exist between the sensor and the controlled component because of the presence of highly localized heat sources. These gradients depend on the ambient temperature. They affect the actual temperatures of both laser and vapor cell, and lead to clock frequency instabilities. To address the problem, we present a novel technique which results in a simpler setup and an improved long-term stability of the clock.

We implement several novel control schemes simultaneously. The temperature of the cell is controlled by measuring the laser light absorption. This eliminates the cell temperature instabilities caused by changing temperature gradients between the cell and the sensor with ambient temperature fluctuations. The laser frequency is stabilized to the atomic absorption line using a feedback to the laser substrate heater. Injection current feedback is used to stabilize the laser output intensity. Finally, the RF modulation index of the laser is controlled by maximizing the first-order sidebands present in the laser spectrum. The active control of the laser frequency, intensity and modulation index is shown to reduce the drift of the clock frequency of laser-pumped clocks caused by ambient temperature fluctuations and is expected to reduce clock frequency drifts due to laser aging.

Different feedback schemes for laser intensity and frequency stabilization, as well as cell temperature control are experimentally compared, and their relevance to future design of chip-scale devices is discussed.

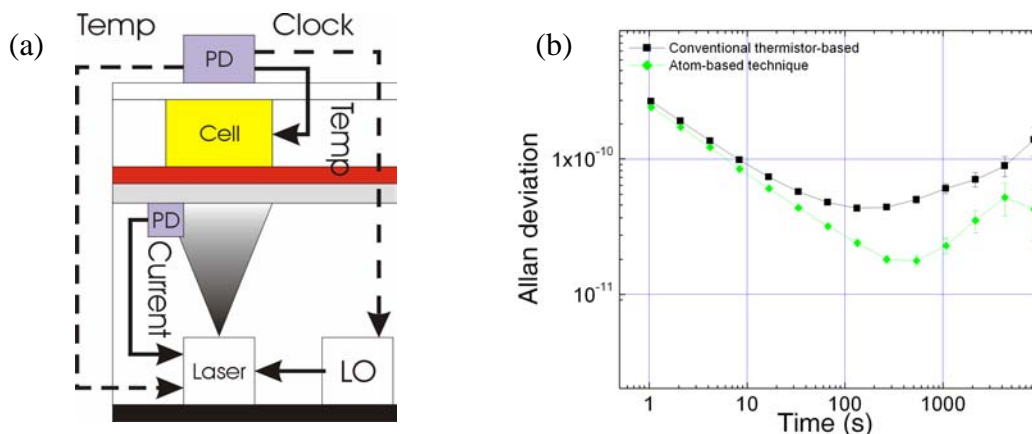


Fig. 1. (a) CSAC structure. (b) Improved long-term stability of the CSAC.

[1] J. C. Camparo and R. P. Frueholz, *J. Appl. Phys.* **59**, 3313, 1986.

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OPTO-ELECTRONIC OSCILLATOR AS AN ATOMIC CLOCK

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We use electromagnetically induced transparency (EIT) in rubidium vapor as a photonic filter in an opto-electronic oscillator (OEO). The EIT “ $\Lambda$ -system” is formed by the ground state hyperfine  $F=1$  and  $F=2$  levels of the D1 transition of  $^{87}\text{Rb}$  coupled to the blue and red optical sidebands, respectively. Using the optical carrier as a local oscillator for photodetection, we make our system oscillate at exactly half of the hyperfine frequency, hence realizing an atomic clock. The oscillation frequency is to the first order insensitive to Zeeman and (at least in theory) AC Stark shift variations. Furthermore, by virtue of Townes relation, the oscillation linewidth is much narrower than the EIT resonance. This is an important advantage of an active loop that distinguishes it from the passive loops, e.g. such where the EIT or CPT resonance is used to stabilize an external reference oscillator.

The OEO is a gain loop which is partly optical and partly electrical (microwave). The loop is closed by modulating the laser beam by the microwave signal derived from photodetection of this beam. Oscillation frequency of the OEO is determined by the phase cyclic condition in the loop, while the linewidth is determined by the loop finesse, that is by the time of signal propagation around the loop. Long propagation time can be achieved by either making the the loop longer, or by introducing in it a dispersive element. In the former case both phase and group delay increase and the OEO has narrow line at any frequency. In the latter case only group delay is introduced, and the oscillator has high finesse only at a specific frequency. To the benefit of our system, the EIT is known to result in ultra slow group velocity of light, so large group delay can be implemented even with a small atomic vapor cell.

We report the results of our study of various configurations of the OEO atomic clock. We conclude that the greatest promise lies in the configuration where the loop is closed by directly modulating the current of a VCSEL. This approach eliminates all necessarily large and power-hungry elements from the system and allows us to implement a high-stability clock of small volume and conservative power budget. We report the latest performance and size/power budget of our system and discuss the issues of general interest that we have faced in this research.

## **Realization of a Pulsed Optically Pumped Rubidium Frequency Standard**

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We will present the more recent development of the pulsed optically pumped (POP) frequency standard. This frequency standard was first proposed by M. Arditi and T. R. Carver [1], but a recent theoretical investigation has shown interesting metrological features that were not understood at that time [2].

A temporal Ramsey interrogation is implemented in a Rb cell-like device, but the optical detection is replaced with an heterodyne detection of the atoms microwave emission. The observation of the microwave emission allows to double the quality factor of the atomic transition with respect to the optical detection, and furthermore reduces the impact of the laser noise.

The disadvantage of this technique is that the high Q of the microwave cavity introduces a higher sensitivity to some environmental parameters typical of the masers.

We have developed a prototype of a POP frequency standard to investigate some physical features of this new frequency standard and to investigate the short and medium term stability behaviors.

Results of this prototype will be reported at the time of the conference.

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INTENSE RUBIDIUM FOUNTAIN FREQUENCY STANDARD

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The progress in setting up the intense rubidium fountain frequency standard at NPL is reported. To use in full the advantage of a small collision cross section of  $\text{Rb}^{87}$  atoms [1], the fountain (Fig. 1) is designed to use a large number of atoms loaded into the optical molasses directly from a continuous magneto-optical source of cold atoms [2].

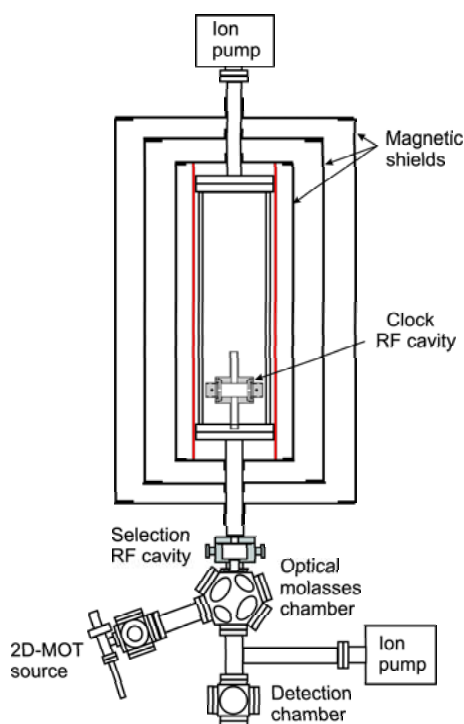


Figure 1: Design of the intense Rb fountain frequency standard.

We are able to load into the bright optical molasses about  $2 \times 10^9$  in just 250 ms time. To improve the frequency stability of the Rb fountain standard an ultra-stable local oscillator based on a cryogenic sapphire ring resonator has been developed with relative frequency stability below  $6 \times 10^{-15}$  for integration times of 1 to 100s [3].

The prospects of using the Rb fountain in a quasi-continuous regime are discussed.

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SIMULATION OF A PARAMETRIC QUARTZ CRYSTAL OSCILLATOR  
BY THE SYMBOLIC HARMONIC METHOD

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In this paper, we present an application of the Symbolic Harmonic Analysis method, a frequency domain approach for computing the steady state of ultra stable quartz crystal oscillators. First, we review the method as a general approach to converting a set of differential equations into a non-linear algebraic system of equations that can be solved for the periodic steady state solution of the original differential equations. Then, we apply this method to simulate the behavior of parametric quartz crystal oscillator. This oscillator is currently developed by S. Galliou at FEMTO-ST/LCEP [1]. It has a 10 MHz quartz and a 20 MHz pump. The second order harmonic signal at 20 MHz is generated by a varactor-diode from the quartz signal. The quartz induces too long simulation converging time for classical integration methods, and the unknown phase of the two frequencies (10MHz current across the quartz and 20MHz from the pump) forbids the use of the ADOQ method [2]. The paper shows that the symbolic harmonic analysis is a good alternative to quickly obtain the steady state of this parametric quartz crystal oscillator. Our simulation results are compared with experimental data.

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EXPERIMENTS WITH A COMMERCIAL MULTIVIBRATOR AS A DETECTOR  
FOR HIGH IMPEDANCE PATTERNS

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Certain industrial detectors call for robust, low-cost varying oscillators in the MHz range. In our application high impedance patterns in the frequency domain are detected by sensing a small capacitance change related to the pattern passing a detection plane. Various commercial building blocks are readily available e.g. in CMOS IC chip form. We have studied the applicability of some typical products such as TC74HC4060, however, in most cases the obtained dynamic range in frequency domain has been inadequate for our purposes.

A compact solution is the HEF4047B type multivibrator from the LOCMOS HE4000B family. A sensitive astable multivibrator circuit with a base frequency of 6.7 MHz has been constructed. By utilizing a simple counter the sensitivity in the range of 500kHz/pF has been achieved. The response time far exceeds the requirements of this application. The sensor function is based on variable capacitance and therefore all stray sources must be carefully controlled. This has been accomplished through a dedicated printed circuit board layout. A buffer circuit is mandatory in the oscillator output not only to reduce the load pulling effects but also to provide convenient output levels. The full paper will include a detailed circuit description, photographs of the actual prototype and selected measurement results in time and frequency domains.

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LOW DRIVE LEVEL SENSITIVITY OF QUARTZ CRYSTAL RESONATORS

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Drive Level Dependency (DLD) or Drive Level Sensitivity (DLS) of quartz resonators, i.e. the increase of the resonator's series resistance at low drive level is known for about fifty years. Very early, that phenomenon has been attributed to surface defects coming from microscopic scraps of various origin often associated with a sticky surface coating or surface scratches. A lot of works and experiments have been done and many models have been described to explain the DLS mechanism and to correlate the resistance increase with the surface defects. Attempts also have been made at relating the DLS with the noise of the resonator with conflicting conclusions. On the other hand, the needs for resonators of higher and higher performance in the domain of telecommunication and/or space localization encourage to further investigate on this phenomenon.

The work presented in this paper is a contribution to a better understanding of the DLS mechanism. The paper will describe an experimental set-up allowing resonator's motional parameter measurements with variable drive level as low as – 113 dBm in a controlled temperature enclosure. As the drive level becomes very low, measurement becomes more and more noisy and difficult to perform. Specific experimental procedures and data processing required to improve the signal-to-noise ratio will be also described. The shape of the resistance vs. drive level curve of several crystals exhibiting DLS reveals different behaviours whose reproducibility and temperature sensitivity have been investigated. Phase noise measurement of resonators exhibiting DLS by using a high performance interferometric instrument developed in our lab are currently being performed at the idea of answering the question of the correlation between the two phenomena. Eventually, by using a submicron resolution scanning electron microscope, a number of surface defects have been observed on the surface of the resonators exhibiting DLS. The responsibility of these defects for the DLS will be discussed.

NOVEL SCANNING PROBE METHOD FOR VISUALIZATION OF STANDING  
ACOUSTIC WAVES IN PIEZORESONATORS

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NEW scanning probe microscopy (SPM) for visualization of standing acoustic waves in piezoresonators based on registration at every pixel the wave inherent electric field (normal to surface) is developed. Up to now, no obstacles are seen for visualizing of propagating waves using synchronous amplitude registration.

SIGNIFICANT is, that acoustic wave amplitude is registered linearly, which will allow its easy comparing with computer models. Moreover, phase difference between the standing acoustic wave and resonator electrode RF voltage is simultaneously registered. This phase information allows coexisting modes to be distinguished and complex structured standing waves to be better analyzed. The method is applicable in both single-crystal and poly-crystal resonators.

Visualization of the acoustic wave patterns for the entire set of interacting vibration modes is efficient instrument for analyzing, understanding and improvement of piezoresonators.

The physical background of the presented method is electric charge induction in a probe by wave electric field. As in any scanning probe microscopy, the probe is the key part and the resolution is the goal. For the case, the long-range nature of electric field rise the main hindrance. In the paper, a complete analysis of basic/fundamental requirements and interdependences (in graphic form) of the method are presented (i.e. precision of positioning, probe to surface distance, sensitivity, noise, resolution, dynamic range, etc.).

Full mathematical analysis of probe functioning focused on effective aperture is also presented (as formulas and in graphic form). It clarifies the significant factors (impedance, noise, etc.), trade-off's and guides for design, fundamental limitations (i.e. physically achievable parameters for broadband or selective system, for room temperature or cooled electronics, etc.).

This SPM technique visualizes acoustic waves over the bare surface of the resonator, in contrast to X-ray topography, in which the presence of electrodes is not an obstacle. However, for resonators with small area of electrodes or perforated electrodes, the images could be completed through amplitude interpolation below the electrodes.

A SPM system, builded in accordance with presented analysis, is described in detail along with its parameters (which are close to physical limits).

Three-dimensional, coloured images of standing waves of different modes (main, anharmonic, third harmonic, etc.) for a number of resonators are presented, as examples of the method possibilities.

RAPID TRANSATLANTIC TIME TRANSFER: SURVEYING THE LINK  
BETWEEN USNO AND IEN WITHIN THE IGS GLOBAL REAL-TIME NETWORK

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Natural Resources Canada (NRCan) computes real-time wide-area differential GPS corrections, known as GPS-C [1]. These corrections allow real-time Canadian users of GPS to reduce the errors in the broadcast satellite position and clock states and achieve improved positioning accuracy. One by-product of the estimation process is receiver clock states for all stations used in the corrections computation.

NRCan is currently testing an improved phase-based corrections algorithm with a global network of stations. These stations include a selection of those from the International GNSS Service (IGS) prototype real-time network (RTIGS), supplemented with stations from the IGS Low Earth Orbiters (LEO) network to maximise satellite visibility. The selected RTIGS stations include that contributed by the Istituto Elettrotecnico Nazionale, IEN (Turin, Italy). Due to the inherent delay in the submission of the LEO data, the estimation process runs in near-real-time, that is every 15 minutes and with a delay of 2 hours, yielding satellite and station parameters at 2 seconds interval.

A preliminary assessment of the near-real-time receiver clock state estimates was performed in early 2005 [2], showing the estimates to be consistent with IGS Final clock products in terms of availability, accuracy (at ns-level) and frequency stability, but with much reduced latency. This is currently a few hours in near-real-time but could potentially be a few minutes or less with sufficient station data available in real-time.

In this paper, we report on the capability of rapid time/frequency transfer, surveying the transatlantic link between timing laboratories of the U.S. Naval Observatory (Washington D.C., USA) and the IEN. Over a 6 month period, the near-real-time estimation of the UTC(USNO) to UTC(IEN) offset is then directly compared with BIPM Circular T data and other independent synchronization techniques, such as TWSTFT, putting this new technique into perspective aiming to support the real-time institutional activities of timing laboratories.

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MULTIPATH MITIGATION IN GPS-BASED TIME AND FREQUENCY  
TRANSFER

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GPS-based time and frequency transfer is presently performed either with a code-only analysis (as done for TAI, using C/A or P codes), or with a combined analysis of code and carrier phase measurements using geodetic analysis techniques (as used for the generation of the IGS time scale).

When neglecting calibration issues, the accuracy of both solutions highly depends on the noise of the GPS codes. An important part of this code noise is caused by multipath. However, when using a linear combination of GPS codes and carrier phases, we are able to characterise the behaviour of multipath in a specific station. Using this information to mitigate the effect of multipath on the code measurements, we evaluate the influence of the code noise reduction on the time transfer results. On one hand, we investigate a possible reduction of the rms of the code-only CGGTTS results. On the other hand we evaluate the influence of the multipath mitigation on the results obtained from the combined code and carrier phase time transfer. Especially in this last case, we will compare the results obtained using Precise Point Positioning (where each GPS station is processed independently) with the zero-difference network approach (where the synchronisation errors between the different GPS receivers are all determined in a common adjustment).

COMBINED MULTI-SYSTEM GNSS ANALYSIS  
FOR TIME AND FREQUENCY TRANSFER

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The Center for Orbit Determination in Europe (CODE) is one of the Analysis Centers (AC) of the International GNSS Service (IGS). It is located at the Astronomical Institute of the University of Bern (AIUB). Since May 2003, CODE provides consistent GPS and GLONASS satellite orbits from a combined analysis using the Bernese GPS Software package. The data of about 30 stations in the IGS network that are equipped with GNSS receivers tracking GPS as well as GLONASS satellites are analysed for that purpose together with numerous stations that only track the GPS satellites.

With the background of the experience in orbit determination for more than one satellite system we discuss the use of both GPS and GLONASS observations in a combined analysis for geodetic time and frequency transfer using code and phase measurements. On one hand the number of satellites that can be used for time transfer is increased when adding the GLONASS observations to the analysis. This may help to improve the redundancy for the receiver clock parameters that are estimated for each station from all satellites in view.

GLONASS satellites emit the signals on individual frequencies. This may lead to frequency dependent biases in the receivers that have been investigated, e.g., in (Foks et al., Latest calibration of GLONASS P-Code time receivers, 36<sup>th</sup> PTTI, 2004). Of course, they have also to be considered in a combined analysis of GPS and GLONASS code data. Corresponding parameters can be estimated for all GNSS receivers even if they are not connected to an external reference clock. This offers the possibility to investigate the frequency-dependent biases for all receiver types that are represented in the IGS network. The estimated biases can be interpreted as a relative “calibration” of each individual frequency used by a GLONASS satellite with respect to the GPS frequency.

The rigorous common analysis of GPS and GLONASS measurements is considered as a good preparation for including the upcoming European GALILEO system into the processing for geodetic time and frequency transfer with a maximum benefit for the solution.

THE T2L2 GROUND EXPERIMENT :  
TIME TRANSFER IN THE PICOSECOND RANGE OVER FEW KILOMETRES

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The new generation of optical time transfer (T2L2: Time Transfer by Laser Link [1]) under development at OCA and CNES shall allow the synchronisation of remote ultra stable clocks and the determination of their performances over intercontinental distances. The principle is based on the propagation of light pulses between clocks to synchronize. T2L2 is the follow-on mission to LASSO (LAsER Synchronisation from Stationary Orbit) [2, 3] with performances in the picosecond range for both stability and accuracy. T2L2 is based on a space instrumentation that includes an event timer linked to the space clock, and some laser ranging stations linked to the ground clocks.

In order to validate the concept and to precisely evaluate the error budget, we realized two global experiments with some prototypes of both the ground and space instrumentations. These prototypes are based on electronic event timers and photo-detection devices we developed these last few years in the framework of T2L2 project. In 1998, we performed a first ground experiment involving two OCA's laser stations and a first prototype of the space instrumentation 2.5 km apart. Results were promising but with some limitations due to the use of a quartz oscillator as the space clock. A second experiment was decided in 2004 with the Lunar laser ranging station and a more finalized space segment installed closed to the station. The experiment was based on a free space propagation of 10 kilometres thanks to a large corner cube placed 2.5 km away. In order to measure the noise of the optical link T2L2 without the noise of the clocks, a third event timer was able to measure the direct phase between signal clocks of both the space and ground prototypes.

This paper reports the results of these experiments. The architecture of the test configuration and of the main subsystems will be given. The performances of each equipment and the performances of the whole time transfer will be presented.

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