CONTRIBUTION TO THE 15th CCTF

M. Granveaud and N. Dimarcq

BNM-LPTF / LHA
61 avenue de l'Observatoire, 75014 PARIS, FRANCE

GENERALITIES

In 2000, the Laboratoire de l'Horloge Atomique (LHA) team moved from Orsay to the Paris Observatory. Since 2001 January 1, the two laboratories BNM-LPTF and LHA belong to the same Department of the Paris Observatory and to the same unit of the National Research Centre CNRS. The creation of a unique structure is being investigated. All the scientific themes mentioned in the document presented at the 14th CCTF (April 1999) by BNM-LPTF and LHA have been developed; special efforts have been devoted to four of them: the double fountain caesium/rubidium, the space atomic clock PHARAO and the program ACES, the inertial sensors using atomic cooling facilities and the development of simple compact caesium frequency standards. New topics have been recently integrated in the scientific program of the two laboratories: it has been decided to study and to realize an atomic frequency standard working with the Sr transitions; the frequency multiplication chain which links optical and microwave regions is being completely renewed, taking advantage of the femtosecond laser technology; introduction of the Quality rules and standards in the operational time section has been scheduled; finally, the laboratory BNM-LPTF has been strongly involved in the experimental testing of the European GPS Complement EGNOS.

OPERATIONAL ACTIVITIES

Two time references have been obtained and disseminated. The time scale UTC(OP) has been issued from a caesium commercial standard; it has been maintained at less than 100 nanoseconds to the UTC since 1996. The time scale TA(F) has been obtained from an ensemble of about 20 caesium commercial standards running in various laboratories linked through GPS signals. An algorithm based upon ARIMA model of the caesium clocks signals has been used for a couple of years. Stability down to 2-3 parts in 10^{-15} have been measured.

REALIZATION OF THE SECOND

The BNM-LPTF has got three laboratory primary frequency standards: LPTF-JPO (optical pumping) and the two fountain type standards LPTF-FO1 and PHARAO; this one is derived from the first zero g cooled caesium atoms standard which was tested in 1997.

LPTF-JPO

Its accuracy capability was estimated to be 6.3 x 10^{-15} in 1999. Investigations have been carried out, in 2000, with respect to the uncertainties of the cavity pulling and the atoms collisions effects; correlations between the various contributions to the uncertainties budget

have been estimated. Practical values from these investigations lead to an estimate of the accuracy of 6.4×10^{-15}.
Three calibrations (durations of 20, 10 and 20 days) have been carried out with LPTF-JPO in 1999; two other calibrations have been obtained beginning 2001.

LPTF-FO1

Its accuracy capability was claimed at 1.4×10^{-15} at the last CCTF. Since that date, uncertainties of the accuracy budget have been revisited. A new bias has been added to the list: the recoil effect and its value has been measured at 3×10^{-16}. The current global uncertainties budget of LPTF-FO1 has been estimated to be 1.1×10^{-15}. Experimental efforts have been carried out upon the black body radiation bias; uncertainty down to 5×10^{-16} has been obtained for the measurement of this bias. It is thought that this uncertainty could be reduced to 10^{-16} with appropriate experimental equipment (H maser, two fountains)
During the year 2000, the LPTF-FO1 standard has been used as a reference for testing quartz oscillators and, more recently, microwave cavities for the space caesium clock of ACES. Several technical improvements of the fountain LPTF-FO1 have been designed and experienced: cold atoms source and optical detection have been refurbished; the running of the standard has been revisited in order to be simplified and made automatic. Frequency calibrations have been operated in 1999 and 2000 over 12 hours periods; reported uncertainties were strongly degraded (about 10 times with respect to the nominal accuracy), due to the fluctuations of the H maser used as flywheel.

PHARAO fountain

The first prototype of frequency standard for space working with cold caesium atoms was tested in 1997 in zero g Airbus flights. This prototype, called PHARAO, has been modified to be a transportable fountain frequency standard. Its accuracy capability has been investigated and estimated at $1\text{-}2 \times 10^{-15}$. Comparisons with LPTF-FO1 over the two months period 27 February to 27 April 2000 have shown an agreement at the level of 1.5×10^{-15} ($1\ \sigma$) in agreement with the claimed accuracies.
Investigations upon the accuracy of the PHARAO fountain are continuing; it has been decided to change its microwave cavity and to develop a running procedure more automatic than now. The PHARAO fountain was moved from BNM-LPTF to the Max Planck Institüt in Munich, in May/June1999, and was used as a frequency reference to hydrogen experiments. Its transportation to PTB Braunschweig has been scheduled. Numerous frequency calibrations of a H maser have been performed but their attached uncertainties have been strongly degraded as mentioned above for the LPTF-FO1 standard. The PHARAO fountain has also been used as an experimental device for the design and the test of the space caesium clock on the International Station.

RESEARCH AND DEVELOPMENT

As mentioned at the 14th CCTF a fountain working with caesium atoms and/or rubidium ones has been designed. In a first step, the prototype has run with rubidium atoms. Two specific effects have been particularly studied: cavity pulling and atoms collisions. Results obtained on the collision effect are very promising: rubidium atoms lead to collision effects which are quite smaller than caesium ones (a factor 300 has been measured).

The frequency of the rubidium fountain has been measured with respect to the LPTF-FO1 standard during two years. The uncertainty of the measurement reaches 2.5 x 10^{-15}. From the two years comparison an upper limit of the possible variation of the α fine structure constant has been deduced (5 x 10^{-15}/year).
End 2000, the fountain, called LPTF-FO2, has been dismantled and rebuilt in a new environment with integration of numerous improvements with respect to the preliminary device: in particular, the optical parts, the cooled atoms sources, the two microwave cavities finely tuned to the caesium and rubidium transitions. Running of the LPTF-FO2 has been scheduled in 2001, first with caesium atoms.

COMPACT CESIUM CLOCKS

High frequency performance compact atomic clocks are required in specific systems such as inertial navigation or positioning with satellite systems. An important effort is currently done in this field in Europe within the development of the GALILEO positioning system.

OPTICALLY PUMPED CESIUM BEAM STANDARDS

Compact optically pumped caesium beam frequency standards are developed by French industry under the scientific and technological expertise of LHA. The clock prototype built in LHA, whose physics package has an overall volume of 2 dm^3, leads to a short term frequency stability of 4. 10^{-12} for 1 second integration time, a long term stability of 2.5 x 10^{-14} over 1 day and an accuracy at the level of 5. 10^{-13}.

Further studies are currently carried out on these clocks to improve either their frequency stability (two-laser optical pumping, clock signal detection with a cycling transition) or their volume (use of a cylindrical microwave cavity rather than a Ramsey cavity).

MINIATURIZED COLD ATOM CLOCKS

A miniaturized cold atom clock, called HORACE (HOrloge à Refroidissement d'Atomes en CEllule) is currently developed at LHA. It relies on a specific operation mode since all the interactions (cooling, atomic preparation, microwave interrogation and clock signal detection) take place inside the microwave cavity. The cooling, performed with isotropic light, has been studied in different cavity geometries (spherical, cylindrical). New "capsule" cavities have been tested to optimised both the cooling and the microwave interrogation processes. A clock prototype has been built and preliminary results should be obtained in mid-2001. The objective is to reach frequency performance (stability, accuracy) below 10^{-14}.

ULTRA STABLE CLOCKS IN SPACE : THE ACES PROJECT

ACES is a european space mission which aims at operating ultrastable clocks on board the International Space Station (ISS). The ACES payload is scheduled to be launched in june 2005 in the UF6 shuttle flight and attached to an external pallet located on the COLOMBUS module of ISS.

The ACES payload includes two clocks :

- **PHARAO**
  PHARAO is a cold caesium atom clock designed by BNM-LPTF, ENS-LKB, LHA with the technical and financial support of the french space agency CNES. PHARAO frequency stability is expected to be better than $\sigma_y(\tau) = 10^{-13}.\tau^{-1/2}$ for an integration time τ. It corresponds to a frequency stability below 3.10^{-16} for a one-day integration time and below $1.\ 10^{-16}$ for ten days. PHARAO frequency accuracy target is at 10^{-16} level.

- **SHM**
  SHM is an active hydrogen maser designed by Neuchâtel Observatory with a financial support of the european space agency ESA. SHM will exhibit a medium term frequency stability better than PHARAO's one ; it will be used for the evaluation of some frequency shifts affecting PHARAO accuracy and as a high spectral purity local oscillator for PHARAO.

These two clocks will be either intercompared on board or compared to Earth based clocks using a dedicated microwave link MWL. Such a microwave link must exhibit a very low phase noise compatible with the clock stability of 10^{-16}. Time fluctuations below 0.3 ps over 300 s and 6 ps over 1 day are required for the link. No existing microwave link (GPS, TWSTFT) can reach today the required performance for ACES. A specific microwave link technique will be developed for ACES. Different promising concepts, which are upgraded versions of the Vessot Two-Way technique used for the GP-A experiment in 1976, have been already studied.

ACES user groups have been formed to identify experiments in various domains (physics of cold atoms, relativistic effects, precise orbit determination, laser time transfer, microwave link, T&F metrology, geodesy, earth observation). ACES primary scientific objectives concern T&F metrology (primary standards, clock comparisons, time scales, …) and Fundamental Physics (tests of special and general relativity).

PHARAO project will enter phase C/D in june 2001 and ACES project will enter phase C/D at the end of 2001.

TIME AND FREQUENCY INTERCOMPARISONS

The GPS phase method has been investigated in close cooperation with the BIPM Time Section. A simplified software has been developed and applied to various data. Stability down to 6.4×10^{-15} over 1 day has been measured between the H masers of Wettzell and BNM-LPTF. Periodic effects have been identified. Time calibrations of the BNM-LPTF and BIPM GPS phase receivers have been carried out.

The BNM-LPTF has been involved into the time/frequency link of the ACES program of ESA. The microwave link as proposed by industrial companies has been studied. Processing of the ACES time data has been investigated with respect to the very low International Space Station orbit.

GALILEO and the program EGNOS have also been considered by the BNM-LPTF. It has been scheduled to get an EGNOS station in the laboratory.

OPTICAL FREQUENCIES METROLOGY

Activities in the field of optical frequencies have been oriented towards 3 main directions. First of all, the laboratory has improved secondary frequency sources such as CO2/OSO4 lasers and transportable devices based upon laser diode/rubidium. Stabilities down to 6 x 10-16 have been obtained in the first case. A frequency synthesis set-up has been developed from CO2/OSO4 laser up to the Nd:YAG/I2 laser; it will allow new measurements of iodine transitions near 563 THz, as recommended by CIPM to realize the definition of the meter.

Second, end 1999, it has been decided to realize an optical frequency standard using strontium cold atoms. Various parts of the device have been designed and tested: a laser source working in the region of 461 nm, a robust source of strontium atoms, the cooling of the atoms. Third, in connection with the Sr project, a completely new frequency chain is being developed; it will take advantage of the Ti:Sa femtosecond laser. OPO frequency divider by 3 are being intensively studied as well as new non-linear crystals in cooperation with European laboratories.

COLD ATOM INERTIAL SENSORS

LHA/LPTF has been working for 3 years on a new kind of inertial sensors relying on interferomety techniques applied to atomic waves.

The device is very similar to an atomic clock and take benefit from the use of cold atoms. The cold atoms, which are first prepared by optical pumping in a given atomic state, cross the central interaction region where the atomic waves are splitted and recombined in a so-called Mach-Zender interferometer. The probability for the atoms to perform the transition between the two level in the fundamental state is a function of the phase shift induced between the two arms of the interferometer : this phase shift depends on the acceleration or on the rotation (Sagnac effect).

The expected sensitivity of the prototype built in LHA/LPTF is 10 $nrad.s^{-1}.Hz^{-1/2}$ in rotation and 10^{-9} $g.Hz^{-1/2}$ in acceleration.

Like atomic clocks, the performance of such cold atom inertial sensors are improved with an operation in microgravity. It is the aim of the european project HYPER to operate a cold atom gyroscope and accelerometer in space to carry out experiments in fundamental physics. On Earth, such inertial sensors can also be used as gravimeters or gradiometers and should find applications in metrological domains such as the Watt balance.

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