ATOMIC FREQUENCY STANDARDS AND TIME MEASUREMENT

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"What is the time?"
"If no one asks me, I know. If I wish to explain it to one that asketh I know not."
St. Augustine of Hippo

1. INTRODUCTION

In the history of mankind, in his explorations and quest for knowledge, time has always played a crucial role. Without a precise measurement of time, many human activities, in particular space exploration, would hardly be feasible at the level of precision we know.

Time is a concept most difficult to comprehend. It has generated a multitude of essays of either philosophical or physical nature. However, for essentially all practical requirements, the notion of time has been reduced to one of measurement, without reference to its philosophical aspect.

To count the time that passes, or almanac (in Arabic, "almanac" means "to count"), is very simple for a child. He sees the Sun rising every morning and lying down every evening. The child is right on a short term scale. To evaluate time over millions of years is more complex and beyond our terrestrial concept of the length of a day. However, can we measure time well?

A first obvious thing to note is that the Moon turns around the Earth in a little less than 30 sunrises. One second obvious thing, discovered at least 3000 years ago, but accepted universally only 400 years ago is that the earth turns around the Sun. Celestial bodies - the Sun, the Moon, the planets, and the stars - have provided us with a reference frame for measuring the passage of time throughout our existence as human beings. Ancient civilizations relied upon the apparent motion of these celestial bodies to determine seasons, months, and years.

2. PEOPLE, CIVILIZATIONS AND TIME

Ice-age hunters in Europe over 20,000 years ago scratched lines and made holes in sticks and bones, possibly counting the days between phases of the moon. The earliest Egyptian calendar was based on the moon's cycles. Before 2000 BC, the Babylonians used a year of 12 alternating

29 day and 30 day lunar months, giving a year of 354 days. In contrast, the Mayas of Central America relied not only on the Sun and the Moon, but also on the planet Venus, to establish 365 day calendars.

As far as we know, great civilizations in the Middle East and North Africa began making clocks to improve their calendars about 5000 to 6000 years ago. Obelisks (slender, tapered, four-sided monuments) were built as early as 3500 BC. Their moving shadows formed a kind of sundial, enabling people to partition the day into morning and afternoon. Another Egyptian shadow clock or sundial, possibly the first transportable timepiece, came into use around 1500 BC. *The merkhet*, the oldest known astronomical tool, was an Egyptian invention developed around 600 BC. A pair of merkhets was used to establish a north-south line (or meridian) by aligning them with the Pole Star.

The history of time keeping is the story of the search for ever more consistent actions or processes to regulate the rate of a clock. Water clocks were among the earliest timekeepers that didn't depend on the observation of celestial bodies. The "water thief" later named by the Greeks *clepsydra*, one of the oldest clock, was found in the tomb of the Egyptian pharaoh Amenhotep I, and began to be used about 325 BC. More elaborate and impressive mechanized water clocks were developed between 100 BC and 500 AD by Greek and Roman clock-makers and astronomers. In the first half of the first century BC, a Macedonian astronomer, Andronikos, supervised the construction of his *Horologion*, known today as the Tower of the Winds, in Athens market place. In the first half of the 14th century, large mechanical clocks began to appear in the towers of several large Italian cities. In 1656, Christian Huygens, a Dutch scientist, made the first pendulum clock, regulated by a mechanism with a "natural" period of oscillation. Around 1675, Huygens developed the balance wheel and spring assembly, still found in some of today's wristwatches. Those improvements allowed portable 17th century watches to keep time with an accuracy of 10 minutes per day. In 1721, George Graham improved the pendulum clock's accuracy to 1 second per day by compensating for changes in the pendulum's length due to temperature variations. John Harrison, a carpenter and self-taught clock-maker, refined Graham's temperature compensation techniques and developed new methods for reducing friction. The performance of those clocks was overtaken by that of quartz crystal oscillators and clocks developed in the 1920s. Nowadays, the timekeeping performance of quartz clocks has been substantially surpassed by atomic clocks. Fig.1 shows in a dramatic way the evolution of time keeping.

Figure 1: Dramatic representation of time keeping evolution

The evolution of the quality of clocks during the century is illustrated in the Fig.2. There

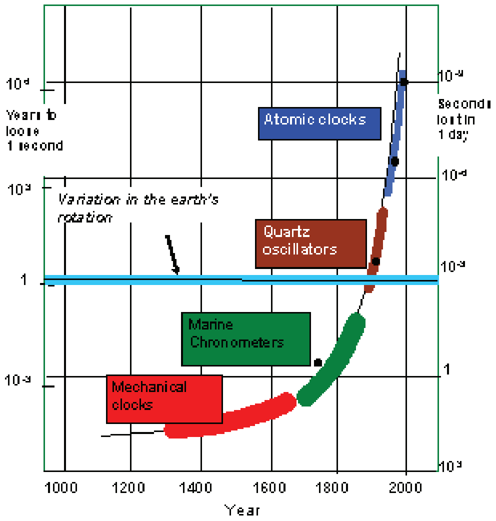

Figure 2: Evolution of the quality of clocks with time

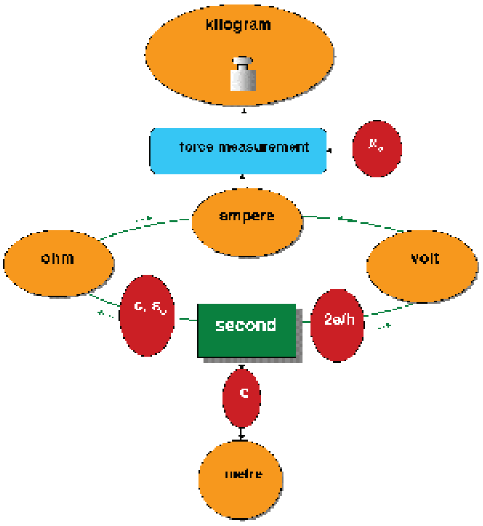

Figure 3: The unit of time - the second- as a central unit in the SI

has been a continuous improvement in quality and there is no end in sight.

3. THE UNIT OF TIME: THE SECOND

Time is the basic quantity in the International System of units (SI), whose representative unit, the second, was the first to be defined in terms of an atomic property: the hyperfine frequency of the cesium atom in its ground state. It is also the quantity that can be measured with the greatest accuracy due to the extraordinary development that has taken place in the field of atomic and laser physics. In present times, an accuracy of one part in 10^{15} in the implementation of the second is obtained routinely in the laboratory. Furthermore, the second plays a central role in the international system of units. Fig. 3 illustrates this concept by showing how all four independent basic quantities, length, current, mass and time are interconnected by means of fundamental constants. First the meter is directly connected to the second by means of the speed of light, c. The volt is connected directly to the second by means of h/2e (Josephson effect), where h is Plankc's constant and e is the charge of the electron. The ohm is related to the second by means of ϵ_0 and c (via the calculable capacitor) where ϵ_0 is the vacuum dielectric constant. Finally, the ampere is obtained by means of ohm's law. In principle, it is then possible to measure or monitor the kilogram by means of an ampere balance, a measurement that relies on the constant μ_0, the permeability of free space. All base units are then connected to fundamental constants. In this scheme, the kg could be lost and it would be possible to reconstitute it to an accuracy somewhat better than 10^{-7}.

4. Cs AND Rb FOUNTAINS AT SYRTE

At SYRTE, in Paris, one ^{87}Rb and two Cs fountains have been already constructed. A dual Cs and Rb fountain has been implemented in a (1,1,1) configuration (fig.4). Two optical benches, one for Rb and one for Cs, provide all the radiation fields required. They are completely separated and independent of each other and of the fountain mechanical structure. The benches are coupled to the vacuum chamber by means of polarizing optical fibres and through prealigned collimators. In the same trapping region Rb and Cs molasses are loaded by two atomic beams, pre-cooled by means of a chirping laser technique. The atomic beam flux at the exit of the oven is about 10^{12} atoms/s for an oven temperature of 383 K. We collect up to 10^9 Cs atoms and detect up to 10^7 atoms for a 0.3 s loading time. A typical Ramsey fringes pattern is shown in Fig. 5, for a launching height is typically 0.865 m above the trapping region. This corresponding for a 0.53 s period between the two microwave interaction times, producing a 0.94 Hz FWHM for the central Ramsey fringe.

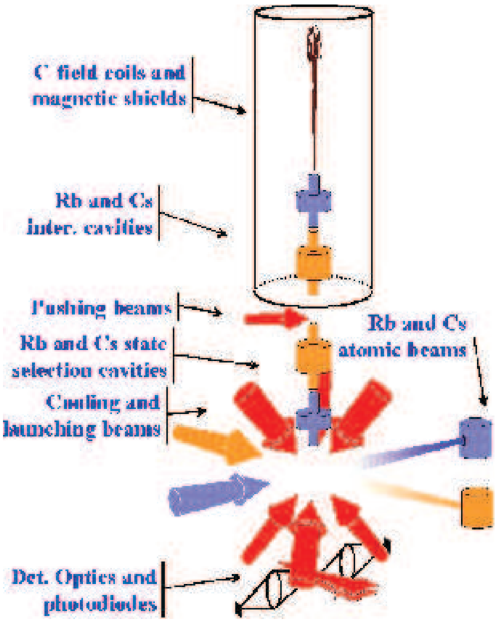

Figure 4: Dual atomic fountain FO2

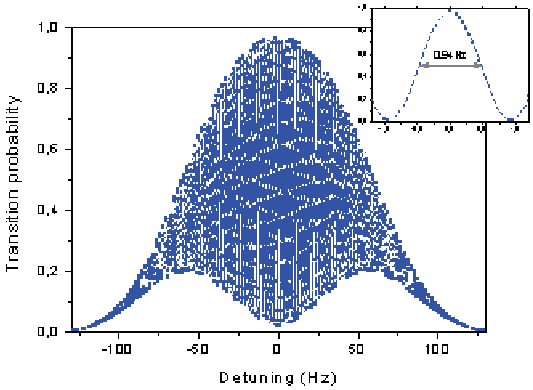

Figure 5: Ramsey fringes observed in fountain FO2

An atomic frequency standard is characterized by its stability and its accuracy. With an ultra-stable cryogenic sapphire oscillator as flywheel oscillator, a cesium fountain operates at the quantum projection noise limit. With 10^6 detected atoms, the relative frequency stability is $4.10^{-14}\tau^{-1/2}$. At t = 2.10^4 s the measured stability reaches 6 10-16. The accuracy of our fountain FO2 is presently slightly better than 10^{-15}. The error budget of the atomic fountain is given in Table 1

Effect	Rb	Cs
2nd order Zeeman	(320,7 ± 0,47).10^{-15}	(177,3 ± 0,52).10^{-15}
Blackbody Radiation	(-12,7 ± 0,21).10^{-15}	(-17,3 ± 0,23).10^{-15}
Cold collision and cavity pulling	(0 ± 0,1).10^{-15}	(-9,5 ± 0,46).10^{-15}
First order Doppler	(0 ± 0,2).10^{-15}	(0 ± 0,2).10^{-15}
Other	(0 ± 0,4).10^{-15}	(0 ± 0,4).10^{-15}
Quadratic Somme	$\mathbf{0,7.10^{-15}}$	$\mathbf{0,8.10^{-15}}$
Gravitational correction	$(6,5 \pm 0,1).10^{-15}$	$(6,5 \pm 0,1).10^{-15}$

Table 1: Error budget of the FO2 fountain

5. NEW METHOD FOR THE MEASUREMENT OF THE COLLISION SHIFT

To obtain a good frequency stability it is necessary to implement a fountain clock operating with as great a number of atoms as possible. In that case the collision displacement becomes very significant (a few 10^{-14} for Cs). Methods traditionally used to measure this displacement result in a precision of the order of 15-20 %, which is insufficient. A new method using the adiabatic passage was developed and makes possible the preparation of an atomic clouds having a stable density ratio. The difference of atomic frequency between high and low density should allow the determination of the collision displacement to one part in 10^{-16}.

6. TESTING THE EQUIVALENCE PRINCIPLE USING COLD ATOM FOUNTAINS

Due to their high accuracy, atomic fountains can be used to perform very stringent tests of the fundamental physical laws. We have made an experiment to perform a new test of the variation of with time at the laboratory scale. The principle of the method is to compare at various times the hyperfine frequency (hyperfine separation energy) of ^{87}Rb and ^{133}Cs. We have compared a Rb fountain and two Cs fountains during a period of 5 years, and we have shown that $\frac{\dot{\alpha}}{\alpha}$ is less than $(-0.4 \pm 16)10^{-16}$ per year.

7. ATOMIC CLOCKS ON EARTH AND IN SPACE

Because micro-gravity allows long interaction times between the atoms and the microwave field and because the velocity is constant and smaller than in the earth fountains, we expect an excellent accuracy for a cold atom space clock. The space mission, ACES (Atomic Clocks Ensemble in Space), carries ultra-stable clocks. ACES have been selected by the European Space Agency to fly on the International Space Station in 2006. It consists of two clocks, a cold atom clock (PHARAO-SYRTE) and a hydrogen maser (Observatory of Neuchtel) together with microwave and optical links for time and frequency transfer to ground users . The scientific objectives of ACES include a measurement of the gravitational red-shift with a 25-fold improvement over the relativity experiment carried by Vessot and Levine in 1976, a better test of the isotropy of the speed of light and a search for a possible variation of the fine structure constant a with time. Finally, with appropriate time transfer equipment, ACES will allow synchronization of time scale of distant ground laboratories with 30 ps accuracy and frequency comparisons at the 10^{-16} accuracy level.

8. CONCLUSION

Microwave frequency standards using atomic fountains have now reached a high level of maturity. Their frequency stability of $3.10^{-14}\tau^{-1/2}$ makes possible the maintenance of time scales to an unsurpassed precision. They presently allow the determination of the unit second to an accuracy of few 10^{-16}. They also make possible the study of physical phenomena such as relativity and time variation of fundamental constants with unprecedented accuracy.

9. REFERENCES

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