Proc. Symp. Ultrason. Electron., Vol. **24**, (2003) pp.341-342
12-14 November, 2003

I-2

Atomic Clocks - Past, Present, and Future

Steven Ryan Jefferts

NIST - Time and Frequency Division, 325 Broadway, Boulder, CO 80305, USA

Atomic Clocks have become ubiquitous in modern electronic systems. Modern navigation systems, such as the global positioning system (GPS), and wide-bandwidth communication systems are examples of two systems that cannot exist without the long-term frequency-stability offered by atomic clocks. Commercially available atomic clocks range from Rubidium based oscillators, which cost around $1,000 with thousands of units per year produced, to Hydrogen masers costing $250,000 with a yearly production of a handful. Finally laboratory based atomic clocks using sophisticated laser-cooling techniques have been built in a few laboratories around the world. These premier atomic clocks offer fractional frequency accuracy at the 10-15 level, equivalent to one second in 31 million years.

Laser-cooled atomic clocks are also being developed for flight aboard the International Space Station (eg. the NIST/NASA/JPL PARCS and the ESA/ACES projects) where they promise to deliver frequency accuracy of $df/f = 5\times10^{-17}$. Even more exotic atomic clocks are being developed in laboratories with potential accuracies at the 10^{-18} level.

The underlying physical principles that govern all of these clocks will be illustrated. The basic structure of many of these atomic oscillators will be presented along with some discussion of the trade-offs inherent in all of these designs.

In particular, the laser-cooled primary frequency standards such as NIST-F1 and PTB CS-F1 will be the subject of detailed examination. An examination of this type of frequency standard will require a short discussion of laser-cooling. The laser-cooling process used in NIST-F1 allows the temperature of the cesium (caesium) atoms used in the clock to be lowered from room temperature (300K) to 1 μK: a reduction of the thermal energy of almost 9 orders of magnitude! These very low energy cesium atoms obtained through laser-cooling are crucial to the operation of a frequency standard with an accuracy equal to or better than the 10^{-15} level. The relatively detailed description of NIST-F1, along with the previous presentation of the more traditional atomic clocks, will allow a discussion of the PARCS and ACES atomic clocks scheduled to be flown aboard the ISS in 2005.

Finally, the current state of the art of new standards based on optical transitions will be presented. These optical standards based on transitions with frequencies on the order of 10^{15} Hz as opposed to the 10^{10} Hz hyperfine transition frequencies typical of existing atomic clocks, are being actively developed in many standards laboratories around the world. They are quickly approaching the accuracy of the very best hyperfine transition atomic clocks and the future promise of the optical clocks is bright.

NIST: National Institute of Standards and Technology

NASA: National Aeronautics and Space Administration

JPL: Jet Propulsion Laboratory

PARCS: Primary Atomic Reference Clock in Space

ESA: European Space Agency

ACES: Atomic Clock Ensemble in Space

NIST-F1: NIST Fountain Clock #1

PTB: Physikalisch Technische Bundestanstalt (in Germany)

CS-F1: Cesium Clock Fountain #1 at PTB

ISS: International Space Station