

Optical Clocks

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Over the past 50 years, atomic clocks have been based on microwave frequencies and primary standards have demonstrated uncertainties at the level of a few parts in 10^{16} . Optical clocks are a new generation of atomic clock, in which the frequency of *light* is the signal used for timing. They are based on “forbidden” atomic transitions for which light is absorbed over a very narrow range of frequencies. Depending on the particular atomic species and transition used, the ratio of the frequency to the frequency width (Q-factor) ranges from 10^{14} - 10^{23} , thus, these transitions constitute very precise frequency references. They are also insensitive to external electromagnetic fields and can be highly reproducible and it is anticipated that optical clocks will reach uncertainties of a part in 10^{18} . Further, given that the frequency of light is $\sim 100,000$ times higher than that of microwaves, the same level of precision as a microwave atomic clock may be reached in a much shorter time. As optical clocks come of age and prove the stability and reproducibility predicted of them, the prospect will open up for a redefinition of the second in terms of an optical frequency.

The atomic absorber in an optical clock takes one of two forms: it is either a single ion confined in an electrodynamic trap (Paul trap), or an ensemble of neutral atoms held in an electric dipole force trap (optical lattice). The atomic absorbers are laser cooled so that they are nearly at rest and, to first order, do not experience a Doppler shift on interaction with the light used to probe the atomic transition. To make use of the high-Q of the atomic transition, the probe light must also have a very narrow frequency width and this is achieved by stabilising a laser to a secondary reference, a high-finesse Fabry-Pérot etalon. A mode-locked femtosecond-pulsed laser (femtosecond comb) converts the very rapid oscillations of the light from some 100's of THz down to a radio frequency so that output of the optical clock can be counted by commercial electronics and compared to the SI second and the outputs of other optical clocks.

This tutorial will give an overview of the essential elements of an optical clock: the atomic reference, the ultra-stable laser and the femtosecond comb. It will describe how each of these elements is realised in practice and the experimental challenges involved in operating such an apparatus. The methods by which the performance of optical clocks are measured and how one makes comparisons between clocks will be considered. The current state-of-the-art will be reviewed including the improvements that are likely to occur over the next few years.