Statement from CCTF President to CCU on the role of relativity in time & frequency metrology

The role of relativity in time and frequency (T/F) metrology enters naturally in the scope of CCTF activities. As a matter of fact, this subject has been deeply studied both for atomic frequency standards and for T/F transfer techniques, including special and general relativistic effects. An important bibliography already exist on the subject; see for example ref. [1] to [3].

In atomic clocks, the 1st Doppler effect is generally cancelled by the use of adequate techniques: interactions with a stationary waves instead of running waves, operation in the "Lamb-Dicke" regime where the movement of the atoms or ions is confined within a region whose size is much smaller than the interrogating signal wavelength. The main remaining relativistic effect is the 2nd order Doppler effect which is equivalent to time dilation in special relativity. The associated relative frequency shift is proportional to v^2/c^2, where v is the atom or ion velocity inside the device and c is the light velocity. The order of magnitude of the 2nd order Doppler shift is 10^{-16} for an object moving at a few meters per second. The impact of this effect has been dramatically reduced those two last decades by the use of laser cooling techniques. This allows unambiguous realization of the proper time of the clock.

T/F comparisons between remote clocks involve a relativistic treatment in two ways: To compute the relation between the proper time of the clock and coordinate time; and to determine the coordinate time of propagation of the signal between the two clocks. The latter has been developed in several references covering the needs of all T/F transfer techniques, see a list in ref. [2]. The former relates to the so-called "relativistic frequency shift" of the clock, composed of the 2nd order Doppler shift and the gravitational shift. The 2nd order Doppler shift is particularly significant for clocks installed in a satellite moving at high velocity (few $km.s^{-1}$). When comparing two clocks, the gravitational frequency shift is equal to $\Delta U/c^2$ where ΔU is the difference between the two gravitational potentials at the clock locations and c is the light velocity. On ground, the two shifts are merged in the so-called gravity frequency shift. The frequency shift is typically 10^{-16} between two clocks whose altitudes differ of 1 m.

Relativity is already taken into account not only for basic metrology purposes but also for operational industrial systems, for instance to properly correct the time and frequency information from space clocks used in global navigation satellite systems. The algorithms and procedures to be used in comparing clocks on the surface of the Earth and space clocks have been validated and widely disseminated to various communities (see for example the ITU Recommendation in [4]). Such relativistic corrections are also well managed for international frequency comparisons and for the construction of international atomic time scales (TAI, UTC), assuming a sufficient knowledge of the gravitation potentials.

Today, it is recognized that general relativity is a correct framework for T/F Metrology. The present implementations are designed to provide uncertainty of 1×10^{-18} in frequency (for clocks) and 1 ps in time (for time transfer). The validity beyond this level has still to be studied and the improvements on the theoretical sides will be of course linked to the improvements of clocks and transfer techniques.

[1] Guinot B., Initial report of the WG on relativity and metrology, Metrologia, 34, 261-290 (1997)

[2] Petit G., Wolf P., Delva P., Atomic time, clocks and clock comparisons in relativistic space-time: a review, in Frontiers of Relativistic Celestial Mechanics, Volume 2, Applications and Experiments, Sergei M. Kopeikin Ed., De Gruyter (2014)

[3] Denker H., Timmen L., Voigt C., Weyers S., Peik E., Delva P., Wolf P., Petit G., Geodetic methods to determine the relativistic redshift at the level of 10^{-18} in the context of international timescales – A review and practical results; J Geod, doi:10.1007/s00190-017-1075-1 (2017)

[4] Recommendation ITU-R TF.2118-0 on Relativistic time transfer (2018)

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