CCTF Working Group on coordination of the development of advanced time and frequency transfer techniques (WG ATFT)

Report to the19th meeting of the Consultative Committee for Time and Frequency, 13-14 September 2012

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1 Working group activities

Membership and Terms of Reference

The terms of reference and list of current members of the Working Group are available on the WG page on the BIPM web site.

The terms of reference state that the group members include (among others) "experts from laboratories members of the CCTF". In early 2011 an invitation was sent to all CCTF member laboratories inviting them to nominate such representatives and several laboratories responded. It should be considered that this possibility remains open; additional laboratories are welcome to designate a representative to the WG by informing the WG Chair.

For reasons of efficiency, laboratories were requested to designate only one person as their official representative. However it was decided that additional persons are welcome to participate in the WG with the status of "Expert". Laboratory representatives should inform the Chair of the names of such additional participants.

Working group meetings

Two working group meetings were held in the period since CCTF 18 in 2009. The first was on 28 June 2011 at BIPM, during the Workshop on Development of advanced time and frequency transfer techniques (see below). This meeting was open to workshop participants as well as WG members and thirty people attended. The second meeting was held on 25 April 2012 at Chalmers University, Göteborg, during the EFTF conference and had fourteen participants. The minutes of these meetings are available on the WG page on the BIPM site.

BIPM Workshop on Development of advanced time and frequency transfer techniques

This workshop was organized by the WG with the support of BIPM. It was held on 28-29 June 2011 and attracted about 40 participants. The programme and the presentations may be downloaded from the workshop web page: http://www.bipm.org/en/events/advanced_time_frequency.

2 Short summary of the status and perspectives for time and frequency transfer

This chapter summarises very briefly the current needs for and performances of long-distance frequency comparisons of the best current clocks, and the perspectives for the evolution of these comparisons. For simplicity we consider only the noise or instability of frequency comparisons, taking 1 day as a representative measurement duration. Time transfer accuracy and stability are not addressed.

2.1 Status

2.1.1 Needs and applications for time and frequency transfer

Several caesium fountains have estimated accuracies better than 10^{-15}, reaching down as far as 2-$3x10^{-16}$. One rubidium fountain also has an estimated systematic uncertainty with respect to the rubidium transition frequency in the low 10^{-16} range. The smallest observed fountain instability is in the low 10^{-14} range at 1 s, and local comparisons between fountains can achieve statistical uncertainties on the order of 10^{-16} after one day.

Optical clocks have now overtaken microwave standards in terms of systematic uncertainty with respect to their respective atomic transitions of reference, with the lowest uncertainties being in the low 10^{-17} – high 10^{-18} range, for two single trapped ion clocks. Optical clock instabilities are reaching the low 10^{-15} range at 1 s, with local comparisons between optical clocks achieving statistical uncertainties in the low 10^{-17} range after a few hours. Many optical clocks are in development around the world and their systematic uncertainties and stabilities are continually improving. Fundamental limits on their performances are thought to be an order of magnitude lower than the figures just mentioned. The list of recommended secondary representations of the second illustrates the vitality of this field of work, and there is of course a great deal of interest in a possible redefinition of the second based on optical clocks.

It must be noted that for several reasons it is very important to have the possibility to carry out long-distance comparisons between optical clocks such that the comparison noise becomes negligible after a few hours to 1 day, as for the local comparisons mentioned above. This is essential for example for:

- the development of optical clocks themselves, such as in exploring systematic effects;
- building up confidence in optical clock uncertainties, which is necessary for moving toward a redefinition of the second;
- applications of optical clocks such as timescales (flywheel problem), basic science, etc.

2.1.2 Current GNSS and TWSTFT time and frequency transfer

TWSTFT and GNSS-based methods are of course the current, widely used techniques for long-distance time and frequency transfer. For frequency comparisons, both methods have link noise which averages down to the order of 10^{-15} at 1 day and which continues to decrease thereafter, at least into the low 10^{-16} region.

Thus of the order of 10 days of measurement is currently required for long-distance comparisons of the best fountain clocks. A trivial extrapolation suggests that hundreds of days would be necessary for comparisons of the best optical clocks, although such comparisons are likely be infeasible for a variety of reasons.

In order to maximize the possibilities for exploiting the best clocks it is highly desirable to reduce the needed durations for long-distance comparisons to less than one day. This would require a reduction of 2 to 3 orders of magnitude in the noise of comparison methods compared with the methods routinely used today.

2.2 Perspectives

2.2.1 GNSS

The field of GNSS is currently being developed intensively around the world, for example concerning:

- new regional and global constellations;
- the introduction of new codes and signals;
- the adaptation and development of signal analysis methods.

These developments will certainly benefit time and frequency metrology in a variety of ways such as increases in the quality, reliability and quantity of measurements, etc. However they do not currently appear to bring possibilities for orders of magnitude improvements in long-distance comparison noise.

2.2.2 Two-way microwave methods

TWSTFT code and carrier phase

Current TWSTFT comparisons, based on code, could certainly be significantly improved by using significantly larger bandwidths. Leaving aside questions of new hardware development, an obvious disadvantage of this approach is that the cost of satellite usage would likely be proportional to bandwidth, in the current procurement situation.

An alternative possibility is the use of carrier phase. This has been attempted in the past and is currently being explored by some groups. It remains to be demonstrated whether this method can function well over comparisons times as long as a day, however preliminary results suggest it offers the possibility of a significant reduction in comparison noise, of 1 to 2 orders of magnitude.

The PHARAO/ACES mission and its microwave link MWL

The ACES mission is now expected to be launched in 2016. It will carry a new generation of two-way microwave link called MWL, which is a multiple-frequency, high-bandwidth, code and carrier phase link. In common view comparisons, this link is expected to achieve stability better than 10^{-17} at 1 day. In the context of the ACES mission, which will be installed on the ISS and thus in a low orbit, this stability will be available for comparisons over distances up to several hundreds of km. This will demonstrate the possibilities of microwave links which include modern, time and frequency-dedicated hardware in the space segment. The ACES mission will also allow for inter-continental, non-common view comparisons with stability better than 10^{-16} at 1 day, by exploiting the stability of the on-board clock PHARAO.

2.2.3 Optical links

Fibre optical links

Fibre optical links have been in use for some time within laboratories and in some “local” networks over tens of km, with extremely good stabilities. However in the 3 years since the previous CCTF meeting an extremely important milestone has been passed: the demonstration that it is possible to realize these exceptional performances with links of up to the order of 1000 km in length. For example, as is well-known, a 900 km link is now operating routinely in Germany, which achieves a stability significantly lower than 10^{-18} at 1 day. Thus we can now state that optical fibre links have a proven capacity to realise frequency comparisons over distances up to continental scales, with the performance levels necessary to cater for the best current optical clocks and for the improved clocks which are anticipated in the foreseeable future. The main cost implication of this method concerns access to optical fibre networks, and efforts are under way in various places around the world to create partnerships, operating methods, applications, which will facilitate and limit the cost of this access.

For basic technical reasons such as the need to install amplifiers or other equipment along the fibres, there does not currently appear to be an obvious path for extending this method to intercontinental links.

Pulsed free-space optical links

T2L2, “Time transfer by laser link”, is a time transfer system based on pulsed laser technology similar to that used for satellite laser ranging, with the addition of precise time stamping on the ground and on the satellite. This system was launched on the Jason-2 mission in late 2008. In common view, it is designed to achieve a frequency stability of the order of 10^{-16} or better at 1 day. Another pulsed laser link, the European Laser Timing experiment (ELT), will be carried on the ACES mission.

Coherent free-space optical links

R&D work is being carried out on a phase coherent laser link for time and frequency transfer in space experiments. A laser communication link using such an approach is already commercially available. Such a link can be expected to achieve frequency transfer stabilities better than 10^{-18} at 1 day.

2.2.4 Transportable standards

Transportable standards may be another possibility for realizing long-distance clock comparisons. For this application a transportable standard should have excellent reproducibility and stability, but accuracy is not necessary. For comparison, one transportable, high-precision frequency standard is currently in use, the mobile caesium fountain, having performances in the mid 10^{-16} range, although this is of course also a primary standard. There is currently quite a lot of interest in developing compact, transportable optical frequency standards, such as in space-oriented R&D, which may also be useful for long-distance clock comparisons. Another very interesting potential application for such clocks is in geodesy, using techniques closely related to clock comparison methods.

2.2.5 VLBI for time and frequency transfer

Various groups are exploring the possibility of using VLBI (Very long baseline interferometry) observations as a tool for time and frequency transfer. Preliminary experiments have been carried out using current VLBI observations. Studies and simulations suggest that new VLBI equipment, in development or currently being deployed, may achieve better stabilities than the current routinely used frequency comparison methods.

2.2.6 Future space missions

Space-oriented R&D and future scientific missions may provide further opportunities for developing and demonstrating new time and frequency transfer equipment. An example is the STE-QUEST fundamental physics project, which is a candidate for an ESA launch in the period 2022-24 and which could carry both a post-ACES microwave link and a coherent laser link in a high Earth orbit.

Another possibility is to include such new links as “passengers” in other kinds of projects, such as new or experimental telecommunications or GNSS satellites, which may have the advantage of providing longer-term availability. This may be justifiable via alternative applications of time and frequency transfer, for example in communications or space geodesy.

It is important to continue to explore such possibilities, which may provide the metrology community with access to new and improved space-based links, with different cost structures from the current TWSTFT satellite arrangement.

3 Conclusion and proposed recommendation

As stated above, there is a crucial need for time and frequency transfer methods which allow long-distance comparisons of the best optical clocks to be made with measurement times of a few hours. Fibre optical links now have a demonstrated capacity to realize such comparisons, at least for distances up to continental scales. It is therefore useful and appropriate at this time to make a strong recommendation in favour of the development of such links and of networks of links.

On the other hand, there is currently no single preferred possibility for very significantly improving the performance of intercontinental clock comparisons, although several possibilities exist. This is also an important subject for work in the coming years. (One possible overall scenario is that fibre networks will be developed in various continental regions, with only a small number of intercontinental links being needed to tie them together, however the nature of these intercontinental links is unknown.)

Most, if not all, of the possible new comparison methods have significant cost implications for access to the necessary infrastructures (optical fibres, satellites, etc). It is therefore important to explore different possible justifications and scenarios for this access, such as “public service”; passenger equipment providing added value or new applications for the infrastructure; science/research; etc.

These different elements motivate the proposed recommendation for the CCTF which has been submitted separately from this report.