Operation of a Primary Frequency Standard in the Real World

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***Abstract* — Optical frequency standards offer the potential for a substantial improvement in the uncertainty of primary frequency standards if the SI second is redefined in terms of an optical transition. However, a primary frequency standard operates as part of a system, and the whole system has to be considered when calculating the uncertainty of the standard as seen by the user. The contributions to the total uncertainty from the various components of the system are examined.**

***Index Terms* — Atomic frequency standards, optical frequency standards, primary frequency standards, time and frequency transfer.**

I. Introduction

It is very likely that a redefinition of the second based on an optical transition will occur at some time in the not too distant future. At this point one, or preferably several, optical frequency standards will become the world's Primary Frequency Standards (PFS's). However, beyond a decision on what specific transition, or transitions, to use, it is important to consider how a primary frequency standard actually operates in a practical sense. A major function of a primary frequency standard is to provide the Bureau International des Poids et Mesures (BIPM) with periodic frequency calibrations of International Atomic Time (TAI). TAI is made up of an ensemble of some 400 commercial atomic frequency standards located around the world. The stability of this ensemble determines how fast a calibration of TAI degrades over time, and therefore how often TAI must be recalibrated by a PFS to maintain a specified accuracy. The total fractional frequency uncertainty of this calibration process is determined by three major components. The first, and most important, is the primary standard itself. Its uncertainty in terms of type A and B uncertainties must be carefully determined and regularly checked to make sure nothing has changed. Also, the standard must be operated periodically to provide formal calibrations for the BIPM. If the standard does not operate 100 % of the time, a local flywheel frequency reference must be used, and its stability will play an important role in how well the uncertainty of the primary frequency standard can be transferred to other standards. In the case of TAI, its own frequency stability will be important to how well it can be calibrated in the presence of dead time. Finally, the technology for making long distant frequency comparisons must be considered since instabilities in this process will contribute to the overall uncertainty of the frequency comparison. In the present situation, with cesium fountain primary frequency standards, the three components are all reasonably well balanced with each contributing roughly equally to the overall uncertainty of a typical calibration of TAI. A significant improvement in one component must be matched by similar improvements in the other two for the full potential to be realized.

II. Primary Frequency Standard

The role of the primary frequency standard in the calibration of TAI is central, with the uncertainties and stability of the standard directly impacting the time required to incorporate the information from the standard into TAI. As the accuracy of the standard improves, the standard must operate more often and more continuously in order that the information derived from the standard is not corrupted by uncertainties introduced by the flywheel and time transfer processes. At the current state-of-the-art in time transfer, the fractional frequency uncertainty associated with the transfer process after 30 days of continuous operation is about $\delta f/f = 2\times10^{-16}$ (see Section IV). This level of inaccuracy is well above that claimed for the best optical standards and requires that the optical standard operate essentially continuously for at least a year for the transfer uncertainty to approach $1\text{x}10^{-17}$. Current PFS's, based on cesium fountain technology, required many years of refinement to reach continuous operation, insofar as they have reached it at all. For example a recent report by the NIST-F1 PFS states that the standard was operational 83% of the time over 30 days, and the lack of 100% operational time contributed a dead time uncertainty (see Section III) equal to the time-transfer uncertainty of $\delta f/f = 2\times10^{-16}$. The combined type A and B uncertainty of the fountain itself was $\delta f/f = 4\text{x}10^{-16}$. This situation may be tolerable in current PFS's where the additional uncertainty contributed by a lack of 100% operational time is small compared to the uncertainty of the PFS, but in the situation where the PFS uncertainty is much smaller, the standard must operate essentially continuously over long time intervals.

If the PFS is operated continuously for long periods of time (e.g. 30 days), then the systematic frequency biases must be stable and/or measured continuously over that time. If measured continuously, then, for the reasons outlined above, the measurement must take only a very small time or the dead time uncertainty becomes significant relative to the PFS uncertainty. This presents challenges which must be confronted in a continuously operated PFS.

In light of the operational challenges certain features of an optical standard to be used as a PFS can be deduced irrespective of the actual optical transition in question. The standard must have relatively small and stable systematic biases and these biases should ideally be able to be measured very quickly. The standard must be simple enough that continuous unattended operation is feasible and finally, at the current state-of-the-art in the rest of the troika (PFS, time transfer and local oscillator), it is likely that sacrificing the ultimate attainable accuracy in the standard for robust long-term operation will be an acceptable tradeoff for purposes of calibration of TAI.

III. Flywheel (Dead Time)

If the operation of the PFS is interrupted, a local oscillator with adequate frequency stability must maintain the accuracy at a reasonable level until the standard can come back online. In the case of TAI, an ensemble of some 400 commercial atomic frequency standards (cesium thermal beam standards and active hydrogen masers) serves this purpose. Currently the best commercially available flywheel frequency standard for time intervals longer than 1 day is a hydrogen maser ensemble with a flicker floor in the mid to low 10^{-16} range. TAI also has a similar flicker floor, but at longer times. In order to maintain an uncertainty of 10^{-17}, the amount of dead time that can be tolerated over a several day run with such a flywheel standard is less than 0.3 %. As another example, if TAI were calibrated by an optical standard over a ten day run to an uncertainty of 10^{-17}, the uncertainty of this calibration of TAI will degrade by about two orders of magnitude in the next ten days to about 10^{-15}. Thus, the present day flywheel technology would require that a PFS with an uncertainty of 10^{-17} operate virtually continuously to fully realize its capabilities.

IV. Long Distance Transfer Process

The calibration of TAI inherently involves long distance frequency comparisons since TAI is created from an ensemble of atomic frequency standards scattered around the world. Currently, the best techniques for long distance frequency transfer use variations of GPS common view (code and/or carrier phase), and Two-Way Satellite Time and Frequency Transfer (TWSTFT) using commercial Ku-band geostationary communication satellites. GPS carrier phase and TWSTFT have similar performance at time intervals longer than a day and require comparison times of more than 30 days to approach an uncertainty of 1×10^{-16}. This can be achieved only under ideal conditions and if both are available for use.

V. What's Needed For An Optical PFS

The present system using Cs fountain primary frequency standards, maser based ensembles for flywheels, and TWSTFT or carrier-phase GPS for frequency transfer is reasonably well balanced between the three components. With the second defined in terms of an optical standard, the primary frequency standard will have a much smaller uncertainty than either the flywheel or the time transfer. As far as the flywheel is concerned, the optical primary frequency standard will either have to run 100 % of the time (and therefore serve the role of the flywheel), or better flywheel standards will be needed. For TAI this means improved commercial atomic frequency standards. A possible solution to this problem would be commercial optical frequency standards designed for frequency stability and reliability (including reliable optical frequency combs). The frequency transfer problem may be solved by two-way time and frequency transfer over optical fibers, but this is a formidable problem for long distances. In any case, to realize the full potential of optical frequency standards as primary frequency standards, other parts of the time and frequency infrastructure must also be improved.

Beyond the practical problems discussed here, there are other issues not discussed that will need to be addressed with a redefinition of the second. At a level of 1×10^{-17} or lower, there are difficult to handle relativistic effects that begin to become important (for example: How well is the geoid defined? How well is the local gravitational potential at the PFS known?). The redefinition of the second may need to go well beyond simply the choice of a new optical transition.

VI. Conclusion

The redefinition of the second in terms of an optical transition brings with it an obligation to operate, on a regular basis, one or more primary frequency standards based on this transition. For the purposes of calibrating TAI, the PFS does not operate independently, but as part of a system. Improvements in all parts of this system are necessary for the full potential of the optical standard to be realized.

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