Bias Corrections in Primary Frequency Standards

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***Abstract*—Primary frequency standards serve the function of calibrating the rate of International Atomic Time, TAI, and therefore play a critical role in the accuracy of the world's time. The Working Group on Primary and Secondary Frequency Standards, WGPSFS, is an advisory body to the Time Department of the Bureau International des Poids et Mesures and to the Consultative Committee for Time and Frequency on matters related to primary and secondary frequency standards that are used to determine the rate of TAI. A current issue being considered by the WGPSFS is establishing guidelines for deciding when and how to make corrections for newly discovered frequency biases in primary frequency standards. This paper is intended to generate discussions on this topic in an audience wider than just the WGPSFS.**

Keywords—primary frequency standards; bias corrections; TAI

I. INTRODUCTION

Primary frequency standards, PFS, and secondary frequency standards, SFS, serve the function of calibrating the rate (frequency) of International Atomic Time, TAI, and therefore play a critical role in the accuracy of the world's time. In a PFS all known frequency biases must be evaluated and, if necessary, corrected. The Working Group on Primary and Secondary Frequency Standards, WGPSFS, is an advisory body to the Time Department of the Bureau International des Poids et Mesures, BIPM, and to the Consultative Committee for Time and Frequency, CCTF, on matters related to primary and secondary frequency standards that are used to determine the rate of TAI. As the uncertainties of PFS decrease with improved technology, frequency biases that were previously insignificant may become more important. A current issue being considered by the WGPSFS is establishing guidelines for deciding when and how to make corrections for newly discovered, or newly relevant, frequency biases in primary frequency standards. This paper is intended to generate a discussion on this topic in an audience wider than just the WGPSFS.

II. SOME HISTORY

A brief historical retrospective is presented here using a few biases that have been included as corrections to PFS that report to BIPM. These include biases that were once corrected but no longer are, biases that were unrecognized until long after the definition of the second and have now been included in all PFS bias tables, as well as corrections that are outside of the definition of the SI (International System of Units) second but are applied for the generation of TAI.

The Millman effect is an example of a physical phenomenon that was once used to explain observed frequency biases in some PFS, but was later shown not to be true. The correction was a generalization of an effect that had long been recognized in atomic beam physics. The generalization was initially accepted and a "correction" applied in spite of the fact that no experimental evidence of the effect existed. Wineland and Hellwig [1] later showed that, in fact, the physics of the effect was incorrectly described and that the frequency shift was not allowed on the clock transitions in Cs. Consequently, the frequency bias is no longer considered in PFS.

On the other hand, the blackbody correction is a good example where a previously unknown frequency bias of significant magnitude was proposed theoretically [2], measurements were made to confirm it, and it was formally recommended by the CCTF in 1996. This bias is unusual in that it actually required a clarification to the formal definition of the second [3]. More details of the blackbody correction are given in Section IV.

When the accuracy of clocks and frequency standards improved to the level where shifts due to relativity needed to be included, there was no consensus on how this was to be accomplished. For example, for some period TAI was incorrectly considered a form of *proper time* rather than *coordinate time*. While the gravitational redshift was experimentally verified in the late 1950s, it was not until 1991 that the IAU adopted the specific metric for use in comparing frequency standards which is in use today [4]. The gravitational red shift correction is, in fact, not part of the definition of the second, but is part of the implementation of TAI. It does not depend on the design or operation of the clock, but instead on where it is located.

III. CURRENT SITUATION

The first cesium fountain PFS to report regularly to the BIPM started operation in 1999. Since early 2008, fifteen fountains have reported to the BIPM, of which about eleven report on a fairly regular basis. The situation currently exists where a significant bias correction is being applied to some

PFS based on a theoretical calculation that is still under debate and for which there is no experimental confirmation. It is this issue that has prompted the more general discussion presented here pertaining to when and how "new" biases should be applied to PFS.

A list of typical biases from recent PFS reports is presented in Table 1. These biases are divided into three categories. Category 1 includes four biases for which frequency corrections, along with appropriate uncertainties, are currently applied to all fountain PFS. Category 2 includes bias corrections and uncertainties that are applied to some fountain PFS but not others. Finally, category 3 includes small biases that are handled by simply adding an additional uncertainty without any corrections being made. These are all very small biases that have negligible impact on the total uncertainty and that do vary among the fountains.

The physics of the biases in Category 1 is well understood and everyone agrees that these biases should be evaluated in each PFS and that appropriate frequency corrections and uncertainties should be applied.

In Category 2 the situation is different. The magnitudes of some biases in Category 2, such as microwave leakage for example, are unique to individual standards and the decisions whether to make corrections or not are made by the operators of the individual standards. The microwave lensing shift [5] in Category 2 is the bias that triggered the current discussion. As PFS have improved, the fractional frequency total uncertainty of TAI in any given month can now be as low as about 2×10^{-16}. The magnitude of the proposed bias is about 0.7 to 0.9×10^{-16} in some PFS, and therefore could potentially pull the rate of TAI by more than 30% of its uncertainty. There is no experimental verification of the microwave lensing bias and the theoretical analysis is not universally accepted [6, 7]. Thus, not all laboratories agree that the correction should be made. The details of the microwave lensing shift are not the issue in this paper, but it is the more general topic of how and when any significant new bias should be uniformly evaluated in, and applied to (if necessary), all PFS.

For now, all of the very small biases in Category 3 are not of any concern.

Table 1

Cesium Fountain Bias List

Category 1

Bias corrections, with uncertainties, made on all fountain PFS.

- Second order Zeeman effect
- Blackbody shift
- Atom density (spin exchange, cold collisions)
- Gravitational red shift

Category 2

Bias corrections, with uncertainties, made on some fountain PFS.

- Microwave lensing
- Distributed cavity phase shift
- Cavity pulling
- Microwave leakage

Category 3

Biases covered by increased uncertainty (no corrections made).

- Rabi, Ramsey pulling
- Microwave spectral purity
- Majorana transitions
- AC Zeeman (heaters)
- Fluorescence light shift (AC Stark shift)
- DC Stark shift
- Background gas collisions
- Bloch-Siegert shift
- Second order Doppler
- Electronics

IV. WHAT SHOULD BE DONE?

To address the issue of new biases several questions need to be asked and answered. If this were a purely academic situation, the issue could be left to resolve itself in the literature. However, this is not simply an academic situation since the accuracy of the rate of TAI is at stake. So the first question is: should the WGPSFS step in and provide some recommended guidelines for uniformly evaluating, and if necessary, introducing significant new biases into the list of biases for which corrections should be applied? Or should the WGPSFS do nothing and let individual laboratories make their own decisions? It is the opinion of the authors that the WGPSFS should be involved.

If it is decided that the WGPSFS should develop recommended guidelines, then there are several more questions to be answered. How large does a bias have to be relative to the total uncertainty of TAI before it becomes a concern? Is it in the range of 10%, 50% or 100%? Does the magnitude of the bias relative to the uncertainty of an individual PFS make any difference as to whether the bias should be corrected for in that standard?

If a new bias is deemed to be of concern, what criteria does it have to meet to be considered valid for evaluation by all PFS? Is experimental confirmation necessary? Can it be of purely theoretical origin? If so, are more than one independent theoretical derivations needed? This may have to be decided on a case by case basis, but some guidelines would be helpful. Clearly, experimental verification is highly desirable, but this can sometimes be very difficult to provide. If the circumstance regarding the bias remains unclear, the best alternative may be to recommend that an additional uncertainty be added to the uncertainty of TAI without making any PFS corrections.

The situation with the blackbody correction is a good example of what can happen. The theory was first presented in 1982 [2] but the correction was not applied to all PFS until mid-1995 and only later was direct experimental verification obtained [8]. The blackbody fractional frequency bias is nominally $2x10^{-14}$ in room temperature standards, yet total uncertainties of some PFS at the time ranged from 1 to $3x10^{-14}$. There was a period of at least a year prior to mid-1995 in which this significant correction was made on some regularly reporting PFS and not others, even though all PFS had about the same bias. During this period, the uncertainty of TAI was increased above that calculated by the standard procedure to $2x10^{-14}$ in order to handle this inconsistency. Clearly, this is the type of situation that the PFS community would like to avoid.

In the blackbody situation there was a period of time in which the scatter in the data was not consistent with the stated PFS uncertainties. This is not a circumstance unique to PFS. It is not uncommon in many areas of science to have inconsistent data in which the scatter in the data is too large to be consistent with the stated uncertainties. Unlike the blackbody case, in which the cause was known, in many circumstances there is no explanation for the discrepancy. In any precision measurement there are almost always unknown things occurring, but fortunately they are generally too small to be of concern. But this is not always true. There is no generally accepted way of handling large inconsistencies and in many cases uncertainties are simply increased so that they are consistent with the observed scatter in the data.

Fortunately this is not a problem with the current fountain PFS data. Using all fountain data reported to the BIPM from early 2008 to the present a Birge ratio ranging from 0.9 to 1.1 over time is obtained indicating that the data is generally consistent with the stated total uncertainties. The relative microwave lensing bias is not large enough at this time to have a significant impact on the Birge ratio. However, if a large enough bias is not uniformly corrected among the PFS, the situation could arise where the PFS community might again have to consider arbitrarily increasing uncertainties to make the scatter consistent with the uncertainties.

V. SUMMARY

The PFS community is facing a situation where a potentially significant frequency bias is not being uniformly applied to all PFS. This paper does not address the validity of the bias, but the more general question of whether the WGPSFS should develop some recommended guidelines for addressing this type of situation. If it is decided that guidelines should be developed, then the WGPFS will have the task to implement them. It will have to determine how large a bias needs be before it is recommended that it be evaluated in all PFS, and also what criteria must be met regarding the validity of the bias. It is hoped that this paper will generate a broad discussion among the frequency standard community that can be used by the WGPSFS to shape its recommendations to the CCTF.

Everything said here also applies to secondary frequency standards (microwave and optical) and eventually to optical PFS when or if there is a redefinition of the second.

ACKNOWLEDGMENT

The authors thank Neil Ashby and Mike Lombardi for useful comments.

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