SYSTEMATIC ERRORS IN NIST-7

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Abstract

We describe a continuing, in-depth evaluation of NIST's new optically pumped frequency standard, in which all known sources of systematic error are investigated; most by two or more independent techniques. Additionally, we have used both analog (fast sine-wave modulation) and digital (slow, square-wave modulation) servo systems during the evaluation.

Summary

The US primary frequency standard, NIST-7, was designed to achieve an overall accuracy of 1 part in 10^{14}. To verify this accuracy, we try to evaluate all sources of systematic error with an equivalent frequency uncertainty of no more than 3 parts in 10^{15}. To reach this level of confidence, we attempt to use at least two, totally independent techniques to evaluate each error. In implementing this philosophy, we have used several different frequency control servo systems, one purely analog and two digital with very different microwave synthesis schemes. The digital systems with their great frequency agility allow us to interrogate many facets of the information-rich hyperfine transition spectrum. The systematic errors we have investigated and the techniques we have used to study them, in descending order of the frequency bias they cause, are given below.

Second-Order Zeeman Shift: The frequency shift caused by the second-order Zeeman effect is calculated from a magnetic field value determined through a measured first-order Zeeman splitting. The precision of the measurement is more than adequate, but the magnetic field uniformity must be verified. We have measured the magnetic field inhomogeneity with a flux gate magnetometer during assembly. We have also used a new technique [1] that measures the frequency difference between the center of each Ramsey fringe and its associated Rabi pedestal. The parametric dependence of these shifts on Zeeman state, C-field, and microwave power allow the measurement of field homogeneity, Rabi pulling, and cavity pulling, respectively.

The results of these two techniques are in agreement. The field inhomogeneity in NIST-7 is the order of 5×10^{-4}. This leads to a frequency error of no more than a part in 10^{15}.

End-to-End Cavity Phase Shift: The fractional frequency shift caused by end-to-end phase difference in NIST-7 is about 7.5×10^{-13}. At present we measure this in the conventional way with beam reversal. We are also looking into a cavity mode analysis to add another quantitative measure to this effect.

Second-Order Doppler Shift: The fractional frequency shift due to second-order Doppler effect is of the order of 3×10^{-13}. This means that the mean velocity must be known to the order of 1%. We have used both a Ramsey inversion technique [2] and pulsed optical pumping to measure the velocity profile in the atomic beam [3]. The two techniques agree to an equivalent frequency uncertainty of less than 3×10^{-15}.

AC Stark Shift: The shift caused by blackbody radiation can be calculated with sufficient accuracy with a simple measure of the clock's temperature. The only source of radiation other than blackbody at the tube temperature is from the optical pumping process. We have varied a number of parameters relating to the optical pumping (laser power, beam size, angle, polarization, scattered light, etc.) and have seen no effect at the present level of study.

Cavity Pulling: A mistuning of the microwave cavity causes a well known frequency pulling effect. We documented the cavity tuning very well during assembly. We have subsequently probed it in two ways with the atomic beam. By looking at the symmetry of the entire spectrum both at low magnetic field and at high, we can get an idea of the cavity tuning. We have achieved better results, however, by studying the centering of the Ramsey fringes on their Rabi pedestals [1].

Distributed Cavity Phase Shift: Analysis of the design of the cavity ends predicts this to be a negligible effect [4]. Use of beam masks to shift the center of the beam around within the beam window has confirmed the analysis.

Line overlap shifts: The spectral symmetry produced with optical pumping should lead to no line overlap shifts. The asymmetry observed in NIST-7 is less than 1 %. We have further reduced line overlap shifts by using an H-plane cavity geometry which subjects the atoms to a half sine wave pulse of microwave radiation and very much reduces the Rabi line wings. We confirm the low line pulling by fitting the frequency vs C-field plot to a pure second-order Zeeman curve and also by analyzing the Ramsey/Rabi offsets [1].

Majorana Transitions: The extremely uniform magnetic field in NIST-7 with no variation from optical state preparation region all the way through the detection region should eliminate Majorana transitions. Still, the C-field variation studies performed to search for line overlap shifts should have shown any unexpected Majorana effects.

Microwave radiation in the drift region: Microwave radiation in the drift region can cause transition amplitude that is not phase related to that in the Ramsey cavity. This radiation can come from leakage from the cavity itself or from radiation leaking in from outside the standard. This external radiation may come either from the clock servo or from other cesium clock units in the vicinity. Frequency vs microwave power and stability of end-to-end phase shift measurements are the indicators for this problem.

Effects related to the electronics: Microwave spectral purity is checked by a number of RF spectral analysis techniques, by fitting the clock frequency vs RF power to model predictions and by the Ramsey/Rabi shift technique [1]. Second-harmonic distortion in the analog modulator is investigated both electronically and by measuring the clock frequency as a function of modulation depth. Integrator offsets in the analog servo are measured both electrically and by varying the servo AC/DC gain settings. All manner of potential or hidden problems are investigated by the comparative use of both analog and digital servo systems.

References

[1] Jon H. Shirley, W. D. Lee, G. D. Rovera, and R. E. Drullinger, "Rabi Pedestal Shifts as a Diagnostic Tool for Primary Frequency Standards," these proceedings.

[2] J. H. Shirley, "Velocity Distributions from the Fourier Transforms of Ramsey Line Shapes", Proc. 43rd Annual Symposium on Frequency Control, IEEE Cat. no. 89CH2690-6, pp. 162-167, 1989.

[3] W. D. Lee, J. H. Shirley, and R. E. Drullinger, "Determining the Velocity Distribution of Atomic Beams be Gated Optical Pumping," to be published in Proc. 1994 IEEE Int. Symp. Freq. Control.

[4] Andrea DeMarchi, Jon Shirley, David J. Glaze and Robert Drullingerm "A new cavity configuration for cesium beam primary frequency standards", IEEE Trans. Instrum. Meas. vol. IM-37, pp 185-190, 1988