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LOCAL OSCILLATOR REQUIREMENTS AND STRATEGIES FOR THE NEXT GENERATION OF HIGH-STABILITY FREQUENCY STANDARDS

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Abstract

This paper provides a brief introduction to the special session on high-stability frequency synthesis from rf to the visible. The special session is motivated by a number of proposals that have been made for developing frequency standards with frequency stabilities in the 10^{-16} to 10^{-18} range. Currently available local oscillators, frequency synthesis techniques, and the measurement methods are not, however, sufficient to support this level of stability. Some general approaches to solve these problems, such as the effect of interrogation type on local oscillator induced white frequency noise, are briefly introduced. The details are to be found in the individual presentations.

Introduction

The purpose of this paper is to set the stage for the special session on high-stability frequency synthesis from the rf to the visible. A number of groups around the world are working on new frequency standards that hold promise of attaining fractional frequency stabilities in the 10^{-16} to 10^{-18} range. Frequency standards based on Ba^+, Be^+, Hg^+, Mg^+, Yb^+, have been proposed in the microwave region. Frequency standards based on Ba^+, Hg^+, Sr^+, Yb^+, and Ca have been proposed in the region from 10^{12} to 10^{15} Hz [1-7]. To achieve the projected frequency stabilities of 10^{-16} to 10^{-18} and to translate this stability to other frequencies will require substantial improvements in local oscillators, frequency synthesis techniques, and measurement procedures. Although the frequencies of the clocks range over 5 orders of magnitude, there are many common elements which must be addressed and that is the focus of this special session.

Projections for Local Oscillators Requirements

The requirements for local oscillators depend on the frequency stability, the line width of the atomic resonance, and the type of modulation. Most of the new ultra-high precision atomic clocks under development use some type of confinement scheme to reduce the linewidth of the resonance. Digital modulation schemes are usually indicated for frequency standards with linewidths under a few hertz. Several common approaches are shown in Fig. 1. In these approaches, the phase accumulation in the clock during portions of the cycle when the atomic reference is not sensitive to the clock frequency contributed to a pseudo white frequency level that limits the short-term frequency stability of the standard. This has been investigated in considerable detail by Dick et al [8]. Their results summarized in Fig. 2 show that for square-wave frequency modulation and a single atomic reference sample, the local oscillator induces white frequency noise at approximately 50% of the open-loop stability of the local oscillator, at the period of the interrogation cycle.

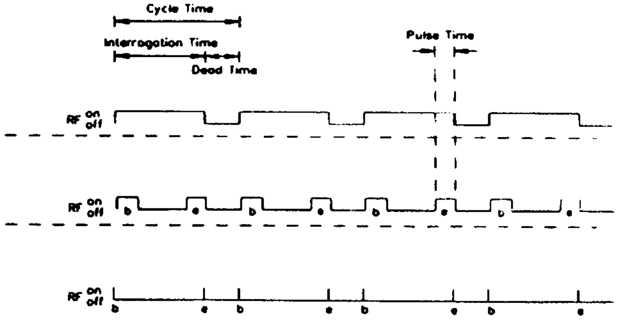

Figure 1. Timing diagram for (a) Rabi type square-wave frequency modulation with dead time, (b) Ramsey type time-domain interrogation with dead time, and (c) Ramsey type time-domain interrogation with very short pulses. Adapted from [8]

If a time-domain Ramsey interrogation cycle is used, the local oscillator induced white frequency can be reduced as much as a factor of 30 for small fractional dead times. If, however, two or more reference samples are available, it is possible to shape the interrogation process such that the white frequency contribution due to noise in the local oscillator is reduced even more. The amount of reduction depends on the details of the interrogation cycle and the type of noise in the local oscillator. Flicker frequency was assumed for the calculations of Fig. 2.

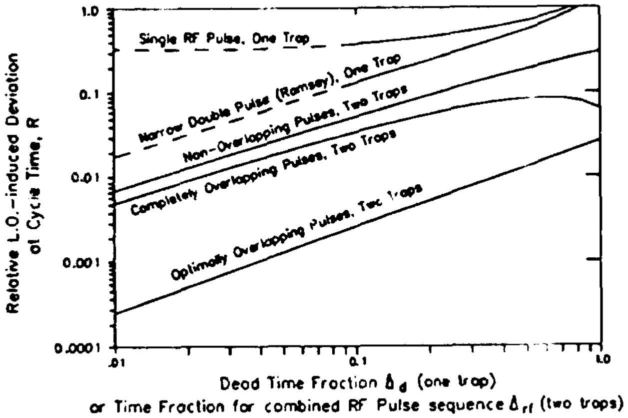

Figure 2a. Relative level of white frequency induced by the local oscillator as a function of dead time for both one and two atomic samples as a function of interrogation type and fractional dead time.

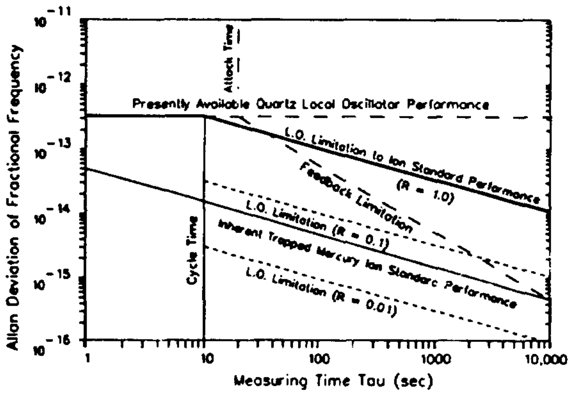

Figure 2b. Limitation on the frequency stability due to local oscillator induced noise as a function of measuring time for selected values of R. Adapted from [8]. Some of the oscillators from Norton exhibit flicker levels a factor of 5 better than assumed in this example [11].

Frequency standards having linewidths larger than a few hertz are potential candidates for sine-wave modulation. Sine-wave modulation also induces a pseudo contribution to the white frequency noise which has been examined in detail by Barillet et al [9]. They show that the phase noise in the local oscillator at the second harmonic and even higher harmonics of the modulation frequency, f_m, limits the frequency stability to

$$\sigma_y(f) = f_m/\nu_o\,[0.723\, S^{1/2}{}_{\phi}(2\,f_m) + CS_{\phi}(4f_m)] \qquad (1)$$

where $S_{\phi}(2f_m)$ and $S_{\phi}(4f_m)$ are the power spectral densities of phase noise in the local oscillator at 2 and 4 times the modulation frequency, and C is typically of order 0.1. For sine-wave modulation the frequency stability of the source at long times is of little concern since the induced white frequency noise level is due primarily to noise at the second harmonic of the modulation. Lowe et al examine the practical limitation and potential improvements that might be obtained by using a notch filter at ± 2 f_m from the carrier [10]. They show that, by careful selection of the configuration, it is possible to realize substantial reductions in the induce white frequency.

Using these results as a guide, we can now estimate the effect of various local oscillators on the overall performance of the proposed frequency standards as a function of modulation type. In general the stability of presently available local oscillators does not meet the needs of the potential super clocks in either the rf or optical regions.

Local Oscillators in the rf, Microwave, and Optical Regions

A large number of the talks in the special session and throughout the conference examine the present stability and prospects for future improvements in oscillators based on quartz acoustic resonators, microwave oscillators at cryogenic and room temperature, composite rf and microwave oscillators, and various optical sources. In most cases the best local oscillator is distributed in nature. The frequency stability at different times (or Fourier frequencies) is derived from a combination of several oscillators or oscillators and filters. The distributed approach of necessity involves high-precision frequency synthesis.

Frequency Synthesis Requirements

There are generally two drivers for improving techniques for frequency synthesis. The first is the need to fabricate the local oscillator from several sources to optimize the frequency stability at a variety of measurement times or Fourier frequencies. The second is the need to translate the precision output frequency to another frequency or to keep time.

In the rf region frequency multiplication, division, and translation are well established techniques. The very high precision and accuracy of the new clocks will, however, require a factor of approximately 100 improvement in the phase stability of these techniques at frequencies of 5 to 10 MHz and a factor of 10 improvement at 100 MHz. At 10 GHz present techniques are sufficient.

In the optical region, frequency multiplication and translation have been used for a long time, but frequency division is still in its infancy. In this region the phase stability requirements are often just that there be no cycle slips. Reliability of the sources and the nonlinear devices are still important issues in this region. We have a number of exciting talks in the special session which focus on improving frequency division, translation, multiplication, and the reliability of sources in the optical region.

Measurements and Distribution Strategies

Measurement strategies for determining the frequency stability of local oscillators in the short term and long term differ greatly from the rf to the optical region.

In the region below 10 GHz, many of the problems of frequency synthesis and metrology are due to environmentally induced phase shifts in signal transmission and detection. The magnitude of the problem at low frequencies can be visualized by noting that at 5 MHz only 3×10^{12} rad accumulate in a day. To achieve a fractional frequency stability of 10^{-17} requires a phase stability of 30 μrad/d! A number of the talks and posters address this problem in frequency synthesis and/or in measurement systems. Several of the talks in the special session focus on developing better phase detectors for both frequency synthesis and time-domain measurements.

Conclusion

The development of new clocks with frequency stabilities in the 10^{-16} to 10^{-18} range will require major improvements in the stability and reliability of reference sources, frequency synthesis, and measurement techniques. Potential solutions to many of these problems appear in the talks of this conference. Although many of these techniques have yet to be fully implemented and refined, we have hope that several types of frequency standards and clocks exhibiting frequency stabilities in this range will be realized within the next few years.

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