Time and Frequency Technology at NIST

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Abstract

The state of development of advanced timing systems at NIST is described. The paper presents work on cesium and rubidium frequency standards, stored–ion frequency standards, diode lasers used to pump such standards, time transfer, and methods for characterizing clocks, oscillators and time distribution systems. The emphasis is on NIST–developed technology rather than the general state of the art in this field.

1. Introduction

At an earlier meeting in this series I presented a paper which provides a concise outline of the activities of the NIST Time and Frequency Division[1]. See that paper for details of these programs. This paper focusses on subsequent developments and special issues which, in my judgement, might be of interest to this meeting. I divide the paper into sections on frequency standards (atomic clocks), time transfer, and characterization of components and systems.

2. Frequency Standards

2.1 Cesium Frequency Standards

The most substantial advance made by NIST in this area is the development of NIST–7, an optically pumped, cesium–beam frequency standard[2]. The design goal for this standard was an accuracy of 1×10^{-14}. At this date it has been evaluated to an accuracy of 2×10^{-14}, and all indications are that the full design accuracy will be achieved shortly. With very low beam flux (low oven temperature) the short–term stability has been demonstrated to be 6×10^{-13} at 1 second, a short–term stability better than that of any previous cesium–beam standard. The standard achieves its short–term stability through the more–efficient use of beam atoms afforded by the process of optical state preparation. The excellent short–term performance simplifies the evaluation of systematic uncertainties, since the standard's output averages down to well below 1×10^{-14} in a few hours. This standard will contribute significantly to the rate of coordinated Universal Time (UTC) as maintained by the Bureau International des Poids et Mesures.

2.2 Stored–Ion Frequency Standards

Looking further to the future, NIST is developing a mercury–ion frequency standard using a linear trap design[3]. The trap design is related to that used by the Jet Propulsion Laboratory (JPL) in their successful development of a standard with exceptional short–term stability[4]. However, the NIST work differs from the JPL work in that NIST uses a smaller number of ions (50 to 100) located along the axis of the trap. With laser cooling to the millikelvin region, these ions experience exceedingly small perturbations, so that systematic errors should be controllable at a level well less than 1×10^{-16}. Trapping, cooling, and optical detection of the 40.5 GHz clock transition have been demonstrated, and we are now initiating study of the accuracy of the prototype standard. Earlier studies on a beryllium–ion standard indicated an unexpected shift arising from collisions between the stored ions and background gases in the trap[5]. To minimize such effects, the linear–trap experiments will use cryogenic cooling to reduce the background pressure to much lower levels.

2.3 Rubidium Frequency Standards

NIST[6] and others have been studying methods for improving the performance of rubidium frequency standards. Theory suggests[7] that replacing the spectrally broad, discharge lamp with a line–narrowed diode laser should substantially improve rubidium performance.

2.4 Quartz Oscillators

NIST does not have a major program on quartz oscillators but, in a small cooperative project, is looking at the question of flicker–floor noise limits in quartz devices[8]. This involves modelling and experiments designed to test the models. Environmental sensitivities of quartz oscillators have also been studied[9].

2.5 Diode Lasers for Advanced Frequency Standards

Emerging methods for laser–controlling the motions and quantum states of atoms and ions will have a dramatic impact on future frequency standards. Cesium–beam standards are reaching accuracy limits imposed by the Doppler effect and short observation times. These fundamental limits are removed when atoms and ions are cooled to very low temperatures. Recognizing the importance of lasers to future standards, NIST has initiated a program[10] to develop lasers that are suitable for use in frequency standards. Fortunately, during the last decade, simple, reliable diode lasers have emerged to play a role in a variety of commercial products. These diodes fit most of the requirements for application to future frequency standards, except that the spectral purity of their output radiation is poor. Key aspects of the NIST program include line–narrowing of the output of the diode lasers, accurate control of their frequency tuning, and extension of their frequency coverage to spectral regions of importance to specific standards. The hope is that this program will produce lasers that are both simple and reliable and thus useful in the construction of both primary frequency standards and practical field standards.

3. Time Transfer

3.1 Two–Way Time Transfer

Two–way, time–transfer experiments between the U.S. and Europe will be performed during the next year. NIST, USNO, and a number of laboratories in Europe are collaborating to demonstrate this concept which uses telecommunication satellites. Two–way time–transfer experiments are described in greater detail in a number of other papers at this meeting. The potential accuracy of this technique is substantially higher than that of GPS common–view time transfer, but this is obtained at the price of broadcasting a signal from each of the comparison sites. Such broadcasting requires additional equipment and special licensing. NIST is also completing development of a new spread–spectrum modem for use in two–way time transfer. The NIST modem differs from existing two–way modems in that bandwidth and chipping rate are adjustable over broad ranges. The objective is to vary operating conditions so as to achieve high performance at minimum cost (for use of the communication channel).

3.2 Digital Time Codes through Telephone

Following the development of a digital telephone time service in Canada[11], NIST developed a related but different service called the Automated Computer Time Service (ACTS)[12]. These telephone services can be used to set time in computers to an accuracy approaching 1 ms. To achieve this accuracy requires a two–way process which calibrates the delay in the telephone link. The NIST service differs from the Canadian service in that the correction is developed at the delivery end rather than at the user's end of the connection. A very large number of applications can be served inexpensively through such services.

3.3 Digital Time Codes through Computer Networks

The telephone connection can be handled in a very predictable fashion, since the delay for a given connection remains very stable over a long period. This is not the situation for package–switched computer networks, but the need for delivering reasonably accurate time through such networks is high. Levine, in a paper in these proceedings, describes a method for handling this problem and a new network time service offered by NIST.

4. Characterization of Components and Systems

4.1 Measurement of Spectral Purity

Specifications of spectral purity (phase and amplitude noise) have been rising in importance during the last decade. While commercial instrumentation has been developed to meet some of these needs, there have been no central standards available to certify the performance of such instrumentation. NIST has thus developed capability for making highly accurate measurements of both phase noise and amplitude noise over a broad dynamic range. Measurements can be made at carrier frequencies from 5 MHz to 75 GHz at Fourier frequencies up to 1 GHz or 10% of the carrier frequency (whichever is smaller) from the carrier. The NIST measurement system supports evaluation of all measurement errors. Transfer standards operating at carrier frequencies of 5, 10, and 100 MHz have also been developed to support round–robin testing among laboratories. Transfer standards for 10, 20, and 40 GHz are nearing completion.

4.2 A Measure for Time Transfer Performance

The Allan variance and the modified Allan variance have been with us for many years but, while they are very useful in characterizing clocks and oscillators, they fail to provide an adequate measure of the performance of time transfer systems. Thus, NIST has developed a third measure, the time variance, which fills this need[13]. This new variance, a simple modification of the Allan variance, has been accepted as a standard by the telecommunications industry and by both the Telecommunication Standardization and Radio–Communication Sectors of the International Telecommunications Union (ITU). The additional development of a digital–filter view of all of these two–sample variances[13] has substantially aided in their acceptance by a broader segment of the technical community.

5. Summary

Over the last decade, advances in time and frequency technology by NIST and a large number of other organizations in the United States and elsewhere have been substantial. This paper has presented only those contributions made by NIST. The reader must integrate these with the much larger body of advances made worldwide to complete the picture of progress made in this field. The work reported here is that performed by many different staff members of the NIST Time and Frequency Division.

6. References

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QUESTIONS AND ANSWERS

Nicholas R. Renzetti, JPL: Based on the physics of the trapped mercury ion, what do you believe is achievable in terms of stability over time periods of several thousand seconds?

Donald Sullivan: Understand that what we are looking for is real long–term stability because of our approach. I think the stability of 1000 seconds will look much better from a device that is developed at the JPL. We are looking at hopefully a part in ten to the fifteen, a part in ten to the sixteen long–term. But I don't believe that we will achieve that at 1000 seconds. I think that is something that you need to look at with devices that have may more ions than the ones we are looking at. So our focus is dramatically different from that of the JPL.

Nicholas Renzetti: Well one reason for the question is that a distinguished member of the faculty of Cambridge University said that the inherent accuracy or stability would be a part in ten to the twentieth. Does that ring any bell with you?

Donald Sullivan: It doesn't ring a bell with me. Actually I don't know of any fundamental physical reason that limits us at all. It is a practical thing. The mercury ion is limited by the fact that we probably have a line with the width of one hertz at 10 to the 15 hertz for the optical transition; and we sort of believe that we can take care of all the systematics at that level. But there is no reason to imagine that the physics at this stage is limiting us. There may be things that I don't know about that he's mentioning, but I haven't heard the part in ten to the twentieth.

Nicholas Renzetti: Well what is driving this question is, we are involved in the search for gravitational waves. And we want to have a fairly long time period for the radio signal to go to the spacecraft and return to earth to capture more of space, through which a gravitational wave will pass. And that is the reason for driving these requirements.

Donald Sullivan: At 1000 seconds, I would be more willing to believe that the cryogenic hydrogen maser has a better chance in the long term than anything I know of. But there are many competitors. I think that the JPL work is pushing the hydrogen maser, but the hydrogen maser has a chance to make a quantum leap forward with the cool devices. That may be, for that type of experiment, the most important standard.