Progress and Feasibility for a Unified Standard for Frequency, Time, and Length

Abstract—The recent successful extension of frequency synthesis upward in the infrared to the 88-THz frequency of the very stable methane frequency standard has implications for expanded uses of frequency/time metrology and hence of frequency/time dissemination systems. After further refinements of the infrared frequency synthesis techniques, metrologists will have the opportunity to define a value for the speed of light and to use a particular frequency standard—the most accurate one—as a unified standard for frequency, time, and length.

INTRODUCTION

The inherently high precision and accuracy available today in frequency standards and in frequency/time metrology (see Figs. 1 and 2) stimulate our technology to devise transducers that convert other measurement tasks to frequency/time measurement tasks [1]. Instruments for measuring length, velocity, temperature, magnetic field, electromotive force, and other quantities are involving frequency/time metrology to a greater and greater extent. These involvements span the range from basic concepts, such as using the Josephson effect to maintain the working volt in national standards laboratories [2]-[4], to applied operations such as radar speed measurement in law enforcement.

Many systems exist which are able to disseminate standard frequencies and time signals, as is extensively discussed elsewhere in this issue [5]. With the help of appropriate transducers, such as the Josephson junction, these same systems may be used to disseminate some other standard units of measurement, including those for electromotive force (volt), length (meter), velocity (meter per second), electrical current (ampere), and magnetic field (tesla), among others. Even attenuation, a dimensionless quantity, can be disseminated by amplitude-modulated radio broadcasts [6].

For most of today's practical measurements, precalibrated commercially available secondary standards for these various units are usually relatively inexpensive and are of adequate accuracy. The marketing of these secondary standards suffices for much of the necessary dissemination of these units of measurement. However, some important present and future technological advances—such as the utilization of the Josephson effect for frequency/voltage metrology [2]-[4], [7] and of infrared (and visible radiation) frequency synthesis for frequency/length metrology [8]—create capabilities that perhaps are best exploited by involvement of the various frequency/time dissemination systems.

Possibility of a Unified Standard

There is an additional, and more fundamental, change in metrology which these technological advances are creating. One of these advances is leading to the ability in the future to do highly accurate frequency synthesis among the microwave, infrared, and visible radiation (MR, IR, and VR) portions of the frequency spectrum [8]. This future ability, coupled with the existing ability to transduce between frequency and wavelength in the IR and VR [9], [10], will give metrologists some new options for highly accurate measurements. Not only will they be able to refer highly accurate measurements of frequency and time to the most accurate standard available, as is possible now, but they will be able also to refer even the most accurate measurements of length to the same standard [10]. The ability to transduce between electromotive force (EMF) and frequency already permits the most accurate and precise measurements of EMF to be referred to this same standard [2]-[4] and with greater accuracy than is attainable via any other technique in EMF standardization.

Today we require and use four independent base standards to realize the primary units of measurement (see Fig. 2). By progressing to a unified base standard for two of these units (time and length) we would be able to reduce the number of required independent base standards to only three. If this could be done today, one part of the unification procedure would be to use an accurate frequency standard [1] as the physical realization of the unified base standard. With an accuracy performance of about five parts in $10^9$ as evaluated in three national standards laboratories [11]-[13], the well-documented atomic cesium beam frequency standard is currently the most accurate type of standard known, and is likely to remain so for at least several more years. There are some other very
promising devices [14] to consider, however, including the methane saturated absorption cell at 88 THz (present accuracy: \( \approx 10^{-11} \) [15]) and the atomic hydrogen storage beam at 1.4 GHz (present accuracy: \( \approx 10^{-12} \) [16]). One of these techniques would become feasible and worthwhile, and the choice should be made on the basis of superior utilizable accuracy.

A second part of the procedure to create the standard for frequency, time, and length would involve a determination of a conventional numerical value to represent the speed of light \( c \). This defined value for \( c \) would be chosen to be in agreement with the measured value of \( c \) obtained by a comparison of the standard for time with the recent standard for length. As of February 1972, the value of \( c \) is not yet determined to a full seven digits, and the krypton lamp length standard is used in many laboratories to at least eight digits [17], [18]. For the unification to be fully desirable, it would be necessary that the value of \( c \) be determined to as many digits as the usable quality of the recent length standard would allow. Hopefully, the gap will be closed soon by experiments at the Bureau International des Poids et Mesures [18] and at laboratories in Canada (National Research Council), England (National Physical Laboratory), France (work is coordinated by the Bureau National de Métrologie), and the United States (Massachusetts Institute of Technology, National Bureau of Standards).

For convenience of the use, the value assigned to \( c \) would convert to a terminating decimal fraction containing a minimal number of digits, consistent with the previous requirement of faithfully rendering the quality of the recent length standard and also consistent with the possibility that the set of digits, taken as an integer, might be chosen to be factorable into a product of several smaller integers. An illustration of a somewhat analogous situation was the formal adoption in 1964 of the earlier choice of 919 263 177 as the digits (ignoring leading and following zeros) involving cesium at the modern base standard for the unit of time of a second.

Finally, a third part of the unification procedure would be to eliminate the length standard as one of the four independent base standards. Thereafter, length would be a derived quantity, and, assuming no other improvements, there would be four independent base standards in the resultant system of measurement: water for temperature (kelvin), prototype kilogram for mass (kilogram), and atomic cesium for time (second).

There are some possible arguments against adoption of a unified standard for frequency, time, and length. We mention three that involve details in the choice of a defined value for \( c \): additional arguments are given by McVinish [19], Towns [20], Smin [21] (and others).

1. Perhaps the Speed of Light Is Changing with Time: If there are secular changes in the speed of light, then such changes are too tiny to have permitted observation, even at the part per million level, up to the present date. Null-type measurements can place even harsher upper limits on possible secular changes. Bay [21] interprets an experiment of Kennedy and Thorndike to show that the speed of light "is constant throughout the year to within 2 parts in \( 10^8 \)." To date, the hypothesis that the value of \( c \) is independent of time is reasonable and tenable. We note that the proposed unified standard is neither more nor less dependent upon this hypothesis than is the present atomic hydrogen lamp standard for length. Both methods rely upon the spatial extension of radiation (wavelength).

2. Perhaps the Speed of Light Has Different Values at Different Frequencies: There exists experimental evidence from observations of the radiation from binary stars and from pulsars which indicates that the dispersion (if any) of the speed of light is negligible compared to the accuracy of the most significant base standards [20], [22]. But even if the speed of light were found to be dispersive, the problem could be nullified by stipulating that the defined value for \( c \) is for a specified frequency.

3. Perhaps the Speed of Light Has Different Values in Different Directions: The experimental evidence for spatial isotropy of the round-trip-averaged ("there and back") speed of light "is constant throughout the one-way speed of light. We offer two suggestions. First, for the purposes of a unified standard, it is sufficient and desirable to assign a value only to the round-trip-average speed of light. Second, it would be interesting and relevant to perform an accurate direct test for spatial isotropy of the one-way speed of light.

Discussion

The concept of a unified base standard for frequency, time, and length is not new [10], [19], [20], nor is the concept of one fully unified base standard for all quantities—The Standard [1], [19]. At least one metrologist has explicitly pointed out that systems of measurement are possible—but not necessarily desirable—in which there are no independent base standards [19].

The new aspect is the recent extension of frequency synthesis into the IR, with an expectation of ultimately allowing a very high accuracy of measurement. The first measurement of the speed of light occurred in 1967 [25]. By late 1971, the upper limit to which frequencies were measured with reference to the base unit of time had been raised by two orders of magnitude to 88 THz [25], the frequency of the very stable methane saturated absorption cell [15]. [26]. The preceding letter in this issue gives a brief survey of progress in IR frequency synthesis [8].

We note that frequency synthesis into the IR, in turn, followed the availability in the 1960's of laser oscillators in the far-IR, especially the HCN laser (1965) at 0.59 THz [27].

There seems little doubt that scientists and technologists do use and will use \( c \) both primary and secondary unified standards as soon as such a procedure is the technically superior one. The determination of range may be a critical test of flight dynamics, for example. The example is a practical one where already a calibrated, secondary unified standard for frequency, time, and length is used by choice. Many measurements of distance in astronomy are referred to the base standard for time. When large distances are to be measured, often the most accurate determinations involve time interval metrology and a time standard.

The present form of the International System of Units (SI) realizes its primary units with four independent base standards. It is a consequence of historical development and experimental expertise that we use such a particular formal system of measurement; no fundamental physical principle is responsible for the creation of the present form of the SI. Hence the SI could be modified if it became desirable to do so. If the accuracy of IR frequency synthesis were to improve to at least the part in \( 10^8 \) level, and preferably to the part in \( 10^9 \) level, we believe there would be opportunity in the SI to adopt a unified standard for frequency, time, and length (based on the atomic cesium beam) would become attractive.

We expect the spectral range and also the accuracy of frequency synthesis to increase. No fundamental obstacles are known which would prevent frequency synthesis upward into the VR region with accuracies of parts in \( 10^8 \) and better. There are practical difficulties to overcome, but several lines of attack are already under way. The outlook is promising.

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References

Time Transfer Using Near-Synchronous Reception of Optical Pulsar Signals

Abstract—The concept of time transfer between two geographically separated locations using nearly simultaneous reception times of a common transmission has been used for satellite tracking. This paper considers how such a method can be used for remote clock synchronization, and the properties of the resulting system are described.

The concept of time transfer using pulsar signals has been proposed and studied by several authors [1]-[10]. The main advantage of using pulsars for this purpose is that they are very stable sources of frequency and time, with typical stabilities in the nanosecond region over periods of months or years. The stability of pulsar signals makes them suitable for time transfer applications, such as remote clock synchronization.

The basic principle of remote clock synchronization using pulsar signals is to establish a common reference time for the clocks at the two locations by measuring the time difference between the arrival of the transmitted signal at each location. This time difference can be measured using various methods, such as measuring the time interval between the arrival of the signal at the two locations, or by comparing the time of arrival of the signal at each location with a reference time.

Time synchronization of remote clocks can be achieved by comparing the signals transmitted by the transmitter with those received by the receiver. The time difference between the transmitted and received signals can be calculated using the known properties of the pulsar signal. This time difference can be used to adjust the time of the remote clock so that it is synchronized with the time of the master clock.

There are several advantages of using pulsar signals for remote clock synchronization. First, pulsar signals are very stable and accurate, with stabilities in the nanosecond region. This makes them suitable for time transfer applications, such as remote clock synchronization, where high accuracy is required. Second, pulsar signals can be transmitted over long distances, making them suitable for remote clock synchronization applications where the two locations are geographically separated.

However, there are also some challenges associated with using pulsar signals for remote clock synchronization. One challenge is the need to establish a common reference time for the clocks at the two locations. This can be achieved by using a master clock, such as the atomic clock maintained by the National Institute of Standards and Technology (NIST). Another challenge is the need to account for propagation delays, which can be significant for long-distance transmissions.

Despite these challenges, the use of pulsar signals for remote clock synchronization has the potential to provide high accuracy time transfer solutions for applications where traditional time transfer methods are not feasible or not practical. Further research is needed to fully explore the capabilities of pulsar signals for remote clock synchronization and to develop practical applications for this technology.