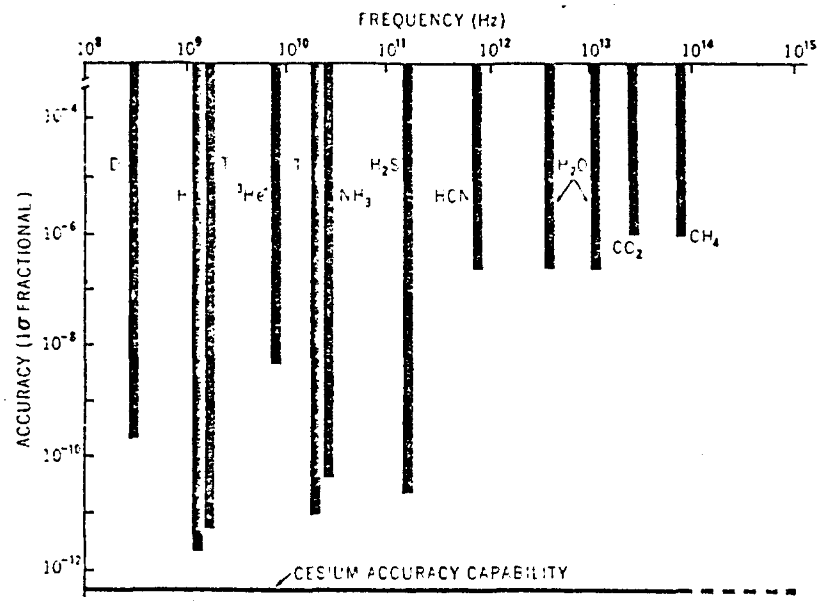

Fig. 1. Survey of selected accurate frequency measurements throughout the electromagnetic spectrum (adapted from [1]). The accuracies reflect the state of the art as of the end of 1971. The accuracy capability of the methane (CH_4) device is at present about five orders of magnitude greater than the accuracy to which its frequency has been measured (see text). Consult [1] for literature references for these measurements, except for H_2O [28] and CH_4 [25].

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 measurements 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),[1] 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].

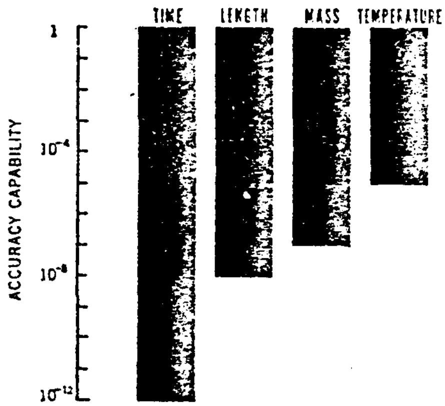

Fig. 2. Accuracy capability of the four independent base standards as of the end of 1971. They use atomic cesium for time, atomic krypton for length, the prototype kilogram for mass, and water for temperature [29], [30]. The primary units of measurement of the International System of Units currently are based on these standards [17], [31].

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^{13} 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

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[1] As a historical note, we point out that in the early years of radio broadcasts the wavelength aspect of the broadcast signal was considered to be of even greater significance than its frequency aspect.

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 other devices might become the superior device by the time the unification becomes 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 unified standard for frequency, time, and length would involve assignment 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 would 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 Mètrologie), and the United States (Massachusetts Institute of Technology, National Bureau of Standards).

For convenience of use, the value assigned to c would be 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) involved in using cesium as the modern base standard for the base unit of time interval.

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 only three 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 pro and con by McNish [19], Townes [10], Simkin [20], Bay [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 10^9." 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 krypton-86 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 inaccuracy of the most accurate frequency 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-average ("there and back") speed of light is impressive [23], but there is a paucity of direct experimental evidence relative to the spatial isotropy of 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 frequency of a laser occurred in 1967 [24]. 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 (1964) at 0.89 THz [27].

There seems little doubt that scientists and technologists do use and will use *de facto* both primary and secondary unified standards as soon as such a procedure is the technically superior one. The determination of range and range rate by radar in ships and airplanes is a practical example 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^{11} level or better, then the 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^{12} 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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ime Transfer Using Near-Synchronous eception of Optical Pulsar Signals

Abstract—The concept of time transfer between two geographically separated locations using nearly simultaneous reception times from a common transmission has been used fruitfully, e.g., the TV line-10 time transfer system and Loran-C. Some germane aspects of the concept are discussed and use of a signal from the optical pulsar NP0532 as the common transmitter is considered.

Theoretical considerations suggest that time could be transferred using this mode to an accuracy of about 2 μs and with global coverage. The data were made available from Lawrence Radiation Laboratory giving the dates of pulsar arrivals received at their observatory and also the Harvard Observatory. A precision of about 13 μs was inferred from the data analysis.

This optical pulsar time transfer system seems to be feasible and worthy of further consideration because of the high accuracy and precision (a few microseconds for both) potentially achievable. For this potential, the development costs appear to be favorably competitive.

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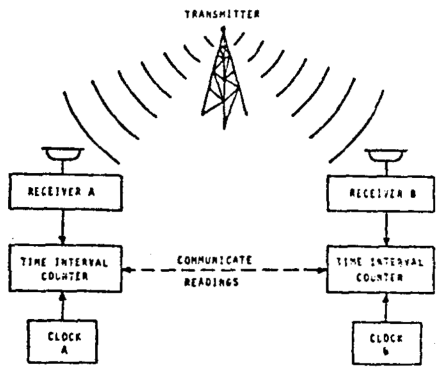

Fig. 1. Concept of precise time transfer using nearly simultaneous reception time of signals from a common transmitter.

Time synchronization or comparison of remote clocks is a common but often difficult to achieve need among the users of precise time signals. For example, the clocks at a satellite tracking station may need to be synchronized with respect to all other similar tracking stations around the globe to within a few microseconds. Many techniques have been developed and/or employed to satisfy the above needs, e.g., portable clocks, a multiplicity of satellite timing approaches, and the multimillion-dollar moon-bounce technique [1]–[10]. Though the cost for a single portable clock trip is not prohibitive, the accumulated investment for any of the above has been very large. This letter is an effort to present what may be a less expensive operational system for accurate time synchronization (or comparison) to within a few microseconds and with essentially global coverage.

From among the many methods that have been developed for time transfer or remote clock synchronization, one method will be discussed which has yielded some fruitful results during the past few years using TV signals [11]–[16]. Then the same method will be discussed with reference to its applicability to pulsar signals.

Fig. 1 illustrates this method in which time transfer or synchronization is accomplished by receiving signals at A and B at nearly the same time from a transmitter common to both receivers. In many cases, clocks A and B are much more stable and accurate than the transmitter clock; nevertheless, the transmitted signal as received can be used as a time transfer device. Under certain assumptions the instabilities of the transmitter and the propagation medium to first order contribute neither to the imprecision nor to the inaccuracy of the time transfer system.

As a more detailed analysis, suppose that at a time t_X an identifiable signal, e.g., a pulse or a zero crossing of a sinusoid, is emitted from the transmitter shown in Fig. 1. Let τ_{XA} and τ_{XB} be the propagation and equipment delay times from the transmitter to the time interval counters at A and B, respectively. If the readings of clocks A and B are t_A and t_B, respectively, then the difference in the readings of the time interval counters will be

$$[t_A - (t_X - \tau_{XA})] - [t_B - (t_X - \tau_{XB})] = t_A - t_B + \tau_D \quad (1)$$

where τ_D is the differential propagation delay $\tau_{XA} - \tau_{XB}$. If τ_D is calculable, then obviously the time difference between clock A and clock B can be accurately determined within the uncertainty of the calculated differential delay. If τ_D is not calculable, then it needs to be measured, e.g., with a portable clock. The stability of τ_D in either case will determine a limit for the precision with which the time difference $t_A - t_B$ can be measured by this system. If the propagation and equipment delay paths are similar, the differential delay τ_D may be extremely stable, e.g., for TV timing several nanosecond stabilities over several seconds have been achieved within a given transmitter locale [17].

Note that in this simple case the time of emission of the identifiable signal cancels in (1). However, in general, the identifiable signal will be repetitive, and A and B can receive events with different transmission times. All that needs to be added to (1) is the transmitter emission time difference Δt_X of the different events received, which can often be inferred from the repetitive nature of the signal, assuming the ambiguity can be resolved. In some cases ambiguity resolution may be difficult [15]. Measuring different events usually places very minimal constraints on the transmitter's stability and accuracy. That is, if δt represents the precision or accuracy desired of the time transfer system, then the stability or accuracy, respectively, of the transmitter need only be better than $\delta t/\Delta t_X$. For example, if time transfer is desired to a precision or accuracy of 1 μs, then Δt_X can be several hundred seconds and still require only 1 part in 10^9 stability or accuracy, respectively, of the transmitted signal.

There are several important time transfer users employing this near-synchronous reception mode. The International Atomic Time Scale maintained at the Bureau International de l'Heure, IAT (BIH), employs Loran-C and TV signals in this time transfer mode, and achieves precisions of a few tenths of a microsecond between seven international laboratories utilized in the scale [18]. The standard time and frequency radio station WWV is synchronized with respect to the Atomic Time Scale UTC (NBS) to a precision of about 30 ns using the TV line-10 time transfer system developed by the National Bureau of Standards [19]. Some satellite systems employ this mode for time transfer, and long baseline interferometry indirectly employs this mode as data are cross-correlated with impressive precisions in the picosecond region [20]. Though this letter is an effort to explore some of the capabilities of pulsar signals when used in the above time transfer mode, there are other interesting unexploited systems where this mode of time transfer is possible and perhaps useful. For example, the TV color subcarrier signal (3.58 MHz) appears to have stabilities in the nanosecond region over thousands of miles with, however, some difficulty in removing the ambiguity [15]; and even though the 60-Hz power-line system has very poor stability, the stability of the differential delay of this coherent power-line grid appears to be in the submillisecond region.