Resource Letter: TFM-1: Time and frequency measurement

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(Received 26 August 1994; accepted 5 December 1994)

This Resource Letter is a guide to the literature on time and frequency measurement. Journal articles and books are cited for the following topics: frequency standards; methods of characterizing performance of clocks and oscillators; time scales, clock ensembles, and algorithms; international time scales; frequency and time distribution; and applications. [The letter E after an item indicates elementary level or material of general interest. The letter I, for intermediate level, indicates material of somewhat more specialized nature, and the letter A indicates rather specialized or advanced material. The designations E/I and I/A are used to indicate that the article contains material at both levels, so that at least part of the article is written at the lower of the two levels.]

I. INTRODUCTION

Archeological evidence indicates that since prehistoric times man has been devising progressively better means of keeping track of the passage of time. In the earliest stages this involved observation of the apparent motion of the sun, but finer subdivision of the day later involved devices such as water clocks, hourglasses, and calibrated candles. After long development with many variations, mechanical methods for keeping time, in the form of pendulum clocks, achieved excellent precision (a fraction of a second per day). However, with the invention of the two-pendulum clock in 1921 by William Hamilton Shortt, the practical performance limit of such mechanical clocks was reached. The distinction between frequency standard and clock (between frequency and time) is easily recognized in the pendulum clock. The constant frequency of oscillation of the pendulum constitutes a frequency standard. The mechanism used to count the ticks and display their accumulation as seconds, minutes, hours, days, and years converts this frequency standard into a clock.

The modern era of timekeeping began with the development of the quartz crystal oscillator. In a 1918 patent application, Alexander M. Nicholson disclosed a piezoelectric crystal as the control element in a vacuum tube oscillator. The first clock controlled by a quartz crystal was subsequently developed in 1927 by Joseph W. Horton and Warren A. Marrison. Since the introduction of the quartz oscillator, the performance of frequency standards has advanced by many orders of magnitude, and industry and science have come to rely on the timing made possible by them.

Many modern technological applications require that geographically distributed systems have the same time (synchronization) or run at the same rate (syntonization). Thus, an important consideration in time and frequency measurement has been the precise transfer of timing between separated stations. This has led to an interplay between the development of the two key technologies, (1) frequency standards and clocks and (2) methods of time and frequency transfer. Comparisons between early quartz timepieces were accomplished with adequate precision using signals transmitted by terrestrial radio waves.

Quartz crystal oscillators remained at the performance forefront for only a short time. In 1949, the atomic-timekeeping era began with the construction of the first atomic clock. This standard, based on a resonance in the ammonia molecule, was constructed at the National Bureau of Standards in a project led by Harold Lyons. The ammonia standard was quickly superseded by the cesium-beam frequency standard that forms the current basis for defining the second.

Atomic standards progressed rapidly in accuracy and stability through the 1950s and 1960s. By the mid-1970s the best atomic standards were realizing the definition of the second with an uncertainty of 10^{-13}, allowing timekeeping uncertainty of 10 ns over the period of one day. But the existing methods of time transfer could not easily support comparison of performance between geographically separated devices. At the time, the most convenient method for comparing standards over long distances involved LORAN-C navigation signals. Separated stations could simultaneously monitor the same highly stable LORAN-C broadcast to achieve comparison of the standards, but time comparison errors as large as 500 ns were observed. Clocks could be compared more precisely using portable atomic clocks, but since this involved flying a fully operational clock from one laboratory to another, it was expensive and impractical to do more often than a few times per year.

The most recent thrust forward was fostered by two developments. More precise time transfer using GPS satellites in a "common-view" mode was developed in the early 1980s. This provided the means for precise comparisons of standards constructed in different laboratories. During this same period, physicists were developing methods for using lasers to control the atomic states and the motions of atoms and ions. These new methods offer promise of dramatic advances in accuracy of atomic standards, and evidence of such advances is just beginning to appear. With these new concepts for improved standards and the technology required to compare the performance of separated standards, physicists have gained new motivation to build better atomic clocks, and work is progressing rapidly in many laboratories.

Significant improvements have been made in cesium-beam standards by replacing magnetic state selection and state detection with optical selection and detection. But still greater advances will come with the practical realization of entirely new concepts that have been demonstrated in the laboratory. Radiatively cooled ions stored in electromagnetic traps provide the ultimate answer to Doppler-shift problems, but the atomic-fountain standard that uses laser-cooled neutral atoms offers substantial promise as well.

The pace of improvement in atomic standards, an increase in accuracy by a factor of nearly 10 every 7 years, is expected to continue. The most advanced concepts promise accuracy improvement of three to four orders of magnitude. Frequency is already the most accurately realized unit of measure, so it is surprising to find such great potential for improvement. Since even modest frequency accuracy is often well beyond the accuracy with which other measurements are made, other quantities are often converted (transduced) to frequency to achieve better precision, resolution, and ease of measurement. Length and voltage are examples of units now based on frequency measurements.

The atomic definition of the second has provided the means to improve frequency accuracy, but in many applications the only requirement is for frequency stability. In this case, what matters is that two or more oscillators stay at the same, although not necessarily accurate, frequency. While high accuracy ensures good relative stability, it is not essential for it. Thus, in responding to application requirements, developers of atomic and quartz devices have often emphasized frequency stability rather than frequency accuracy.

Time plays a major role in physical theory, and better clocks have provided physicists with improved means for testing their theories. Over the last 45 years, progress in atomic clock technology has been driven more by scientific than by industrial requirements, but clever engineers have taken good advantage of the advancing technology. A good example is the exceptional navigational accuracy provided by the Global Positioning System (GPS). This accuracy is critically dependent on atomic-clock technology. Other areas benefitting from this technology include telecommunications and electrical-power distribution.

In this resource letter we address time and frequency standards and measurement methods, the special statistical methods used for handling noise in clocks and oscillators, and the distribution of time and frequency signals. Signal distribution is included because a large fraction of measurements made in this field rely on timing signals transmitted from central sources to the points of measurement. Articles in many of the areas covered by this resource letter are published in well-known journals, but in some instances we are forced to refer to papers presented at conferences, the proceedings of which are not widely available in libraries. In these instances, we provide an address where the proceedings can be obtained. In our selection of articles we recognize that biases will be evident, and we apologize for these biases. There are a great number of papers that could have been cited, but are not because of space limitations.

II. JOURNALS

The majority of papers on time and frequency topics are found in the following journals:

IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control
IEEE Transactions on Instrumentation and Measurement
Journal of Applied Physics
Metrologia
Physical Review
Physical Review Letters
Physics Today
Proceedings of the IEEE
Radio Science
Science
Scientific American

Four special issues of IEEE journals (the first four references below) have been devoted exclusively to time and frequency topics. Many of the invited articles in these issues were written as reviews of specialized subtopics and are therefore very readable. Two other special issues on the broader subject of radio measurement methods and standards are also included because they contain a number of useful and easy-to-read articles on time and frequency.

1. **Time and Frequency**, Special Issue of Proc. IEEE **79**(7) (1991).
2. **Frequency Control**, Special Issue of IEEE Trans. UFFC **UFFC-34**(6) (1987).
3. **Time and Frequency**, Special Issue of Proc. IEEE **60**(5) (1972).
4. **Frequency Stability**, Special Issue of Proc. IEEE **54**(2) (1966).

5. **Radio Measurement Methods and Standards**, Special Issue of Proc. IEEE **74**(1) (1986).
6. **Radio Measurement Methods and Standards**, Special Issue of Proc. IEEE **55**(6) (1967).

III. CONFERENCE PROCEEDINGS

Conference proceedings in this field contain a good mix of specialized articles and an occasional review article. The following series of conferences contain the largest concentration of time-and-frequency papers.

A. IEEE International Frequency Control Symposium

The IEEE International Frequency Control Symposium is the best-known conference in the field. It was previously known as the Annual Symposium on Frequency Control. Through 1994, there have been 48 conferences in this series. The proceedings of the last 12 of these conferences are available from IEEE, 445 Hoes Lane, Piscataway, NJ 08854. The most recent eight and three others cited later are listed here.

7. **1994 IEEE Int. Freq. Control Symp.**, IEEE Catalogue No. 94CH3446-2 (1994).
8. **1993 IEEE Int. Freq. Control Symp.**, IEEE Catalogue No. 93CH3244-1 (1993).
9. **1992 IEEE Int. Freq. Control Symp.**, IEEE Catalogue No. 92CH3083-3 (1992).
10. **45th Annu. Symp. Freq. Control**, IEEE Catalogue No. 91CH2965-2 (1991).
11. **44th Annu. Symp. Freq. Control**, IEEE Catalogue No. 90CH2818-3 (1990).
12. **43rd Annu. Symp. Freq. Control**, IEEE Catalogue No. 89CH2690-6 (1989).
13. **42nd Annu. Symp. Freq. Control**, IEEE Catalogue No. 88CH2588-2 (1988).
14. **41st Annu. Symp. Freq. Control**, IEEE Catalogue No. 87CH2427-3 (1987).
15. **38th Annu. Symp. Freq. Control**, IEEE Catalogue No. 84CH2062-8 (1984).
16. **36th Annu. Symp. Freq. Control**, Document No. AD-A130811, available from National Technical Information Service, 5285 Port Royal Road, Sills Building, Springfield, VA 22161 (1982).
17. **35th Annu. Symp. Freq. Control**, Document No. AD-A110870, available from same source as Ref. 16 (1981).

B. European Frequency and Time Forum (EFTF)

This is the major European conference in the field. Through 1994 there have been eight meetings in this series. Printed proceedings are not readily available in libraries, but can be obtained from the EFTF Secretariat at: FSRM, Rue de l'Orangerie 8, CH-2000, Neuchâtel, Switzerland. Three volumes cited later are:

18. **Proc. 7th European Freq. and Time Forum** (1993).
19. **Proc. 5th European Freq. and Time Forum** (1991).
20. **Proc. 4th European Freq. and Time Forum** (1990).

C. Conference on Precision Electromagnetic Measurements (CPEM)

This biennial international conference covers a wide range of measurement topics, but includes a substantial number of useful articles on time and frequency topics. The conference focus on measurements makes this a particularly important reference. Since 1962 the proceedings of this biennial conference have been published in the *IEEE Transactions on Instrumentation and Measurement*. References to the last seven conferences are given below.

21. **Proceedings of CPEM'92**, IEEE Trans. Instrum. Meas. **42**(2) (1993).
22. **Proceedings of CPEM'90**, IEEE Trans. Instrum. Meas. **40**(2) (1991).
23. **Proceedings of CPEM'88**, IEEE Trans. Instrum. Meas. **38**(2) (1989).
24. **Proceedings of CPEM'86**, IEEE Trans. Instrum. Meas. **IM-36**(2) (1987).
25. **Proceedings of CPEM'84**, IEEE Trans. Instrum. Meas. **IM-34**(2) (1985).
26. **Proceedings of CPEM'82**, IEEE Trans. Instrum. Meas. **IM-32**(1) (1983).
27. **Proceedings of CPEM'80**, IEEE Trans. Instrum. Meas. **IM-29**(4) (1980).

D. Symposium on Frequency Standards and Metrology

Although a few other subjects have been covered, this symposium is devoted primarily to the physics of frequency standards. The four conferences in the series have been separated by 5 to 7 years, reflecting the symposium philosophy that very significant progress in the field should occur before each meeting is held. The proceedings of the first and second of these are not widely available, but the 1988 and 1981 proceedings are available in book form.

28. **Frequency Standards and Metrology: Proceedings of the Fourth Symposium**, edited by A. De Marchi (Springer-Verlag, New York, 1989).
29. **Third Symposium on Frequency Standards and Metrology**, J. Phys. **42**, Colloque C-8, Supplement no. 12 (1981).

E. Annual Precise Time and Time Interval Applications and Planning Meeting

The proceedings of these military/NASA planning meetings have been published by NASA in recent years. Through 1993 there have been 25 meetings in the series. Copies of the proceedings are available from the U.S. Naval Observatory, Time Service, 3450 Massachusetts Ave., N.W., Washington, D.C. 20392-5420. The most recent five and three others cited later are noted here. Three of these do not have publication numbers.

30. **25th Annual PTTI Meeting**, NASA Conf. Publ. 3267 (1993).
31. **24th Annual PTTI Meeting**, NASA Conf. Publ. 3218 (1992).
32. **23rd Annual PTTI Meeting**, NASA Conf. Publ. 3159 (1991).
33. **22nd Annual PTTI Meeting**, NASA Conf. Publ. 3116 (1990).
34. **21st Annual PTTI Meeting**, (1989).
35. **18th Annual PTTI Meeting**, (1986).
36. **15th Annual PTTI Meeting**, (1983).
37. **13th Annual PTTI Meeting**, NASA Conf. Publ. 2220 (1981).

F. Other special conferences

Two special conferences, one held in Finland and the other in India, should also be noted.

38. **First Open Symposium on Time and Frequency of URSI Commission A**, Radio Science **14**(4) (1979).
39. **International Symposium on Time and Frequency**, J. Inst. Elec. Telecomm. Eng. **27**(10) (1981).

IV. BOOKS

40. **The Quantum Physics of Atomic Frequency Standards, 2 Vols.**, J. Vanier and C. Audoin (Adam Hilger, Bristol, England, 1989). The most comprehensive resource available on atomic standards. (A)
41. **Precision Frequency Control, 2 Vols.**, edited by E. A. Gerber and A. Ballato (Academic, New York, 1985). Very comprehensive coverage of the entire field. (A)
42. **From Sundials to Atomic Clocks**, J. Jespersen and J. Fitz-Randolph (Dover, New York, 1982). Comprehensive coverage with an easily readable style. Laced with sketches that effectively convey concepts. (E)
43. **Frequency and Time**, P. Kartaschoff (Academic, New York, 1978). Comprehensive coverage of the entire field. (A)
44. **Quartz Crystals for Electrical Circuits**, edited by R. A. Heising (Van Nostrand Co., New York, 1946). An old, yet useful, book covering many fundamental concepts. (I)
45. **Molecular Beams**, N. F. Ramsey (Clarendon, Oxford, 1956). Important background for atomic-beam frequency standards. (A)
46. **Systems with Small Dissipation**, V. B. Braginsky, V. P. Mitrofanov, and V. I. Panov (University of Chicago, Chicago, 1985). Treats high-Q resonators that are important in several different frequency standards. (I/A)

V. CURRENT RESEARCH TOPICS

A. General review articles

There is no single review paper that covers the field comprehensively. A full review of the field can be found in several of the books cited above. The articles listed below provide good reviews of limited segments of the field. Two of these papers review the history of development of atomic standards and in the process give good introductions to their principles of operation.

47. "Accurate Measurement of Time," W. M. Itano and N. F. Ramsey, Sci. Am. **269**(1), 56–65 (1993). A popular review article. (E)
48. "Time Generation and Distribution," D. B. Sullivan and J. Levine, Proc. IEEE **79**(7), 906–914 (1991). Reviews current trends in the field. (E)
49. "Standard Time and Frequency Generation," P. Kartaschoff and J. A. Barnes, Proc. IEEE **60**(5), 493–501 (1972). An older but concise review. (I)
50. "History of Atomic and Molecular Standards of Frequency and Time," N. F. Ramsey, IEEE Trans. Instrum. Meas. **IM-21**(2), 90–99 (1972). The early history of atomic standards from one of the key contributors to the development of the concepts. (E/I)
51. "A Historical Review of Atomic Frequency Standards," R. E. Beehler, Proc. IEEE **55**(6), 792–805 (1967). Another early history of atomic standards. (E/I)
52. "Time, Frequency and Physical Measurement," H. Hellwig, K. M. Evenson, and D. J. Wineland, Phys. Today **31**(12), 23–30 (1978). A popular review article. (E/I)
53. "Frequency and Time Standards," R. F. C. Vessot, Chap. 5.4 in **Methods of Experimental Physics**, Vol. 12, **Astrophysics**, Part C: *Radio Observations* (Academic, New York, 1976), pp. 198–227. An older, but useful review. (I/A)
54. "Timekeeping and Its Applications," G. M. R. Winkler, in **Advances in Electronics and Electron Physics**, Vol. 44 (Academic, New York, 1977), pp. 33–97. An older, but useful review. (I/A)
55. "Communications Frequency Standards," S. R. Stein and J. R. Vig, **The Froehlich/Kent Encyclopedia of Telecommunications**, Vol. 3, edited by F. E. Froehlich and A. Kent (Marcel Dekker, New York, 1992), pp. 445–500. A good review with emphasis on quartz-oscillator technology. (E)

B. Frequency standards

The different frequency standards (oscillators) are organized into seven categories. These are arranged roughly in ascending order of complexity and cost.

1. Quartz oscillators

Quartz oscillator development has been characterized by slow, steady improvement for many years and this pace of improvement is likely to continue into the future. Their small size, low power consumption, and excellent short-term performance make quartz oscillators suitable for a large number of applications: more than 2×10^9 units are produced annually. However, quartz oscillators exhibit long-term aging and are sensitive to environmental changes, so they are not suitable for some applications.

With special attention to packaging and environmental control (at some expense) quartz oscillators can provide a frequency stability of 10^{-11} to 10^{-12} for averaging times of one day. The most comprehensive collection of articles on this subject are found in the two-volume set edited by Gerber and Ballato (Ref. 41). Reference 55 includes a more concise review of the topic.

56. "Introduction to Quartz Frequency Standards," J. Vig, in Tutorials from the 23rd Annual PTTI Applications and Planning Meeting, pp. 1–49 (1991). (This specific section of the publication is available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, VA 22161.) A very useful introduction. (E/I)
57. "Quartz Crystal Oscillators from Their Design to Their Performances," J.-J. Gagnepain, in Ref. 20, pp. 121–129. A general review paper. (I)
58. "Environmental Sensitivities of Quartz Oscillators," F. L. Walls and J.-J. Gagnepain, IEEE Trans. UFFC **39**(2), 241–249 (1992). A good review including the basic model of quartz oscillators. Contains a good reference list. (I)
59. "Fundamental Limits on the Frequency Instabilities of Quartz Crystal Oscillators," J. R. Vig and F. L. Walls, in Ref. 7, pp. 506–523. A good review including the basic model of quartz oscillators. Contains a good reference list. (I)

60. "Spectral Purity of Acoustic Resonator Oscillators," T. E. Parker and G. K. Montress, in Ref. 9, pp. 340–348. A survey of state-of-the-art oscillators. (I)

61. "Quartz Crystal Resonators and Oscillators, Recent Developments and Future Trends," R. J. Besson, J. M. Groslambert, and F. L. Walls, Ferroelectrics **43**, 57–65 (1982). A review of development trends. (I)

62. "Filters and Resonators—A Review: I. Crystal Resonators," E. Hafner, IEEE Trans. Son. Ultrason. **SU-21**(4), 220–237 (1974). A review of quartz resonators. (I/A)

63. "The Evolution of the Quartz Crystal Clock," W. A. Marrison, Bell Sys. Tech. J. **27**(3), 510–588 (1948). An excellent early history of quartz oscillator development. (E)

2. Rubidium standards

Rubidium frequency standards are the least costly of the atomic standards. In terms of long-term noise and drift, rubidium standards are generally better than quartz, but not nearly as good as other atomic standards. The traditional rubidium standard relies on optical pumping of atomic states by a discharge lamp. Recent research suggests that substantial improvement in performance can be achieved by pumping the states with a spectrally pure source such as a laser. Rubidium standards are typically passive devices, but they can also be operated in an active (masing) mode.

64. "The Optically Pumped Rubidium Vapor Frequency Standard," M. E. Packard and B. E. Swartz, IRE Trans. Instrum. **I-11**(3&4), 215–223 (1962). A useful description of an early rubidium standard. (E/I)

65. "Rubidium Frequency Standards," J. Vanier and C. Audoin, Chap. 7 in Ref. 40, Vol. 2, pp. 1257–1409. Comprehensive review with extensive reference list. (A)

66. "Fundamental Stability Limits for the Diode-Laser-Pumped Rubidium Atomic Frequency Standard," J. C. Camparo and R. P. Frueholz, J. Appl. Phys. **59**(10), 3313–3317 (1986). Basic model of the rubidium standard including projected performance when pumped by a narrow-line source. (A)

67. "Experimental Study of the Laser Diode Pumped Rubidium Maser," A. Michaud, P. Tremblay, and M. Têtu, IEEE Trans. Instrum. Meas. **40**(2), 170–173 (1991). Operation as a maser. (I)

3. Cesium standards

Since 1967, the second has been defined as "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom." Thus it is not surprising to find a large body of literature on cesium frequency standards.

Cesium standards are passive devices, that is, the atoms play a passive role wherein an external oscillator scans through a range of frequencies and some detection scheme then indicates when the oscillator is on the atomic resonance. Cesium standards typically use the method of separated oscillatory fields, a special mode of interaction of the atoms with the external oscillating field, to produce an especially narrow resonance. This reduces sensitivity to dc and oscillating field inhomogeneities. Elementary introductions to the principles of operation of cesium-beam frequency standards can be found in many of the general review articles cited above in Sec. V A.

The best traditional cesium frequency standards (based on atomic-beam methods) now realize the definition of the second with a relative uncertainty of about 1×10^{-14}. The primary source of this uncertainty is associated with the motions of the atoms. Substantial improvements in cesium standards will require slowing of the atoms. The most promising avenue for such improvement involves the cesium-fountain standard. In this device atoms are laser cooled and then lofted vertically. The resonance is detected as the atoms first rise and then fall under the influence of gravity. Such an approach increases observation time by two orders of magnitude compared to traditional atomic-beam devices, and also dramatically reduces the Doppler shift. A number of laboratories are working on this concept.

68. "The Method of Successive Oscillatory Fields," N. F. Ramsey, Phys. Today **33**(7), 25–30 (1980). Good description of the state-interrogation concept used in cesium frequency standards. (E/I)

69. "The Caesium Atomic Beam Frequency Standard," J. Vanier and C. Audoin, Chap. 5 in Ref. 40, Vol. 2, pp. 603–947. Comprehensive review with extensive reference list. (A)

70. "Atomic Beam Frequency Standards," R. C. Mockler in **Advances in Electronics and Electron Physics**, Vol. 15 (Academic, New York, 1961), pp. 1–71. Deals primarily with the theory of the cesium-beam frequency standard. (A)

71. "CS2: The PTB's New Primary Clock," A. Bauch, K. Dorenwendt, B. Fischer, T. Heindorff, E. K. Müller, and R. Schröder, IEEE Trans. Instrum. Meas. **IM-36**(2), 613–616 (1987). Description of an excellent primary standard of traditional design. (I)

72. "The NIST Optically Pumped Cesium Frequency Standard," R. E. Drullinger, D. J. Glaze, J. P. Lowe, and J. H. Shirley, IEEE Trans. Instrum. Meas. **40**(2), 162–164 (1991). An optically pumped version of the cesium-beam frequency standard. (I)

73. "Design of an Optically Pumped Cs Laboratory Frequency Standard," E. de Clercq, A. Clairon, B. Dahmani, A. Gérard, and P. Aynié, in Ref. 28, pp. 120–125. Provides good detail on design. (I)

74. "Ramsey Resonance in a Zacharias Fountain," A. Clairon, C. Salomon, S. Guellati, and W. D. Phillips, Europhys. Lett. **16**(2), 165–170 (1991). Description of a fountain frequency standard with potential for use as a primary frequency standard. (I)

75. "Laser-Cooled Neutral Atom Frequency Standards," S. L. Rolston and W. D. Phillips, Proc. IEEE **79**(7), 943–51 (1991). Includes a review of the fountain concept. (I)

76. "Laser-Cooled Cs Frequency Standard and a Measurement of the Frequency Shift Due to Ultracold Collisions," K. Gibble and S. Chu, Phys. Rev. Lett. **70**(12), 1771–1774 (1993). Identifies atomic-collision limit to the accuracy of fountain standards. (I)

77. "Observation of the Cesium Clock Transition Using Laser-Cooled Atoms in a Vapor Cell," C. Monroe, H. Robinson, and C. Wieman, Opt. Lett. **16**(1), 50–52 (1991). Suggests a simple cell concept for a cooled-cesium frequency standard. (I)

4. Hydrogen masers

The most common type of hydrogen-maser frequency standard differs from other atomic standards in that it oscillates spontaneously and therefore exhibits very high signal-to-noise ratio. This results in excellent short-term stability. With proper servo control of the resonance of the microwave cavity, the hydrogen maser can also provide exceptional long-term stability. Hydrogen masers can also be operated in a passive mode wherein a local oscillator is tuned to the peak of the transition.

Hydrogen atoms in the maser cavity are contained within a bulb. The atoms interact numerous times with the walls of the bulb, resulting in a very long interrogation time. Since interaction with the walls produces a small frequency shift, the wall coating of the bulb limits the frequency accuracy of the maser. Much work on masers has focused on polymer (PTFE, Teflon) wall coatings. Recent studies indicate that large performance improvements might be achieved through use of a superfluid liquid-helium wall coating.

78. "The Atomic Hydrogen Maser," N. F. Ramsey, IRE Trans. Instrum. **I-11**(3&4), 177–182 (1962). A short review of early work on hydrogen masers. (I)

79. "The Hydrogen Maser," J. Vanier and C. Audoin, Chap. 6 in Ref. 40, Vol. 2, pp. 949–1256. Comprehensive review with an extensive reference list. (A)

80. "Theory of the Hydrogen Maser," D. Kleppner, H. M. Goldenberg, and N. F. Ramsey, Phys. Rev. **126**(2), 603–615 (1962). A classic paper on hydrogen maser theory. (A)

81. "Hydrogen-Maser Principles and Techniques," D. Kleppner, H. C. Berg, S. B. Crampton, N. F. Ramsey, R. F. C. Vessot, H. E. Peters, and J. Vanier, Phys. Rev. A **138**(4A), 972–983 (1965). A good overview of early design principles. (I/A)

82. "The Active Hydrogen Maser: State of the Art and Forecast," J. Vanier, Metrologia **18**(4), 173–186 (1982). A good general review with an extensive reference list. (I/A)

83. "Frequency Standards Based on Atomic Hydrogen," F. L. Walls, Proc. IEEE **74**(1), 142–146 (1986). A brief review covering both active and passive masers. (I)

84. "Experimental Frequency Stability and Phase Stability of the Hydrogen Maser Standard Output as Affected by Cavity Auto-Tuning," H. B. Owings, P. A. Koppang, C. C. MacMillan, and H. E. Peters, in Ref. 9, pp. 92–103. Demonstrates enhanced long-term stability through servo control of the cavity resonance. (I)

85. "Spin-Polarized Hydrogen Maser," H. F. Hess, G. P. Kochanski, J. M. Doyle, T. J. Greytak, and D. Kleppner, Phys. Rev. A **34**(2), 1602–1604 (1986). One of three pioneering efforts on the development of a cryogenic hydrogen maser. (I)

86. "The Cold Hydrogen Maser," R. F. C. Vessot, E. M. Mattison, R. L. Walsworth, and I. F. Silvera, in Ref. 28, pp. 88–94. One of three pioneering efforts on the development of a cryogenic hydrogen maser. (I)

87. "Performance of the UBC Cryogenic Hydrogen Maser," M. C. Hürlimann, W. N. Hardy, M. E. Hayden, and R. W. Cline, in Ref. 28, pp. 95–101. One of three pioneering efforts on the development of a cryogenic hydrogen maser. (I)

5. Stored-ion standards

A particularly promising approach to the problem of Doppler-shift and interrogation-time limitations encountered in cesium-beam standards involves the use of trapped ions. Positive ions can be trapped indefinitely in electromagnetic traps thus eliminating the first-order Doppler shift. They can then be cooled through collisions with a buffer gas to modest temperatures or laser cooled to extremely low temperatures; even the second-order Doppler shift is thus reduced substantially. Using these methods, the systematic energy shifts in transitions in certain ions can be understood with an uncertainty of 1×10^{-18} implying the potential for a frequency standard with this uncertainty.

The construction of such a stored-ion standard poses a very difficult engineering challenge. A key problem to overcome is the lower signal strength associated with the smaller number of particles (ions) involved in most of these standards. Improvement in signal-to-noise ratio can be achieved by increasing the signal and decreasing the noise. Traps of linear geometry readily provide increased signal strength since they store more ions. A proposal has been made to reduce noise using squeezed-state methods.

88. "Atomic Ion Frequency Standards," W. M. Itano, Proc. IEEE **79**(7), 936–42 (1991). A brief review. (I)

89. "Trapped Ions, Laser Cooling, and Better Clocks," D. J. Wineland, Science **226**(4673), 395–400 (1984). A brief review. (E/I)

90. "A Trapped Mercury 199 Ion Frequency Standard," L. S. Cutler, R. P. Giffard, and M. D. McGuirre, in Ref. 37, pp. 563–578. Description of the first buffer-gas-cooled ion standard. (E/I)

91. "Initial Operational Experience with a Mercury Ion Storage Frequency Standard," L. S. Cutler, R. P. Giffard, P. J. Wheeler, and G. M. R. Winkler, in Ref. 14, pp. 12–19. Performance of a buffer-gas-cooled ion standard. (E/I)

92. "Linear Ion Trap Based Atomic Frequency Standard," J. D. Prestage, G. J. Dick, and L. Maleki, IEEE Trans. Instrum. Meas. **40**(2), 132–136 (1991). Improved signal-to-noise performance through use of linear trap geometry. (I)

93. "A 303-MHz Frequency Standard Based on Trapped Be^+ Ions," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, IEEE Trans. Instrum. Meas. **40**(2), 126–128 (1991). Description of the first laser-cooled ion standard. (I)

94. "Hg^+ Single Ion Spectroscopy," J. C. Bergquist, F. Diedrich, W. M. Itano, and D. J. Wineland, in Ref. 28, pp. 287–291. Concepts for ultra-high-accuracy standards. (I)

95. "Squeezed Atomic States and Projection Noise in Spectroscopy," D. J. Wineland, J. J. Bollinger, W. M. Itano, and D. J. Heinzen, Phys. Rev. A **50**(1), 67–88 (1994). Suggests a fundamental noise-reduction method that could have impact on atomic clocks. (A)

6. Other oscillators

The superconducting-cavity-stabilized oscillator and the cooled-sapphire oscillator do not fit neatly into previous categories and they are not yet widely used. However, the potential for extremely good short-term stability has been demonstrated for both, and they could play a role in the future, so they are mentioned here.

96. "Development of the Superconducting Cavity Maser as a Stable Frequency Source," G. J. Dick and D. M. Strayer, in Ref. 15, pp. 435–446. Provides design details. (I)
97. "Ultra-Stable Performance of the Superconducting Cavity Maser," G. J. Dick and R. T. Wang, IEEE Trans. Instrum. Meas. **40**(2), 174–177 (1991). Description of performance. (I)
98. "Ultra-Stable Cryogenic Sapphire Dielectric Microwave Resonators," A. G. Mann, A. N. Luiten, D. G. Blair, and M. J. Buckingham, in Ref. 9, pp. 167–71. Design and performance description. (I)
99. "Low-Noise, Microwave Signal Generation Using Cryogenic, Sapphire Dielectric Resonators: an Update," M. M. Driscoll and R. W. Weinert, in Ref. 9, pp. 157–162. Design and performance description. (I)

7. Optical-frequency standards and optical-frequency measurement

Many of the techniques described above can be used with optical (rather than microwave) transitions to produce optical-frequency standards. We include a section on this topic because optical-frequency standards have a special niche within the field: their development burgeoned after researchers first measured the speed of light c by measuring the frequency and wavelength of a visible laser. After the accuracy of measurement of c was improved through many measurements, an international agreement defined the speed of light as a constant and redefined the meter in terms of c and the second.

But the interest in optical-frequency standards goes well beyond the redefinition of the meter. Because of their higher Q (or narrower relative linewidth $\Delta f/f$), frequency standards based on optical transitions have the potential for achieving higher performance than those based on microwave transitions. The key disadvantage in using optical transitions is that most applications require access to a frequency in the microwave or lower range. An optical-frequency standard thus requires an auxiliary frequency-synthesis system to accurately relate the optical frequency to some convenient lower frequency. With current technology this is very difficult. Nonetheless, work on optical-frequency standards proceeds with the assumption that the frequency-synthesis methods will be simplified or that optical-frequency standards can be directly useful in the optical region. In fact, good optical-frequency measurements already contribute to more accurate spectral measurements that support a wide range of important applications.

100. "Resource Letter RMSL-1: Recent Measurements of the Speed of Light and the Redefinition of the Meter," H. E. Bates, Am. J. Phys. **56**(8), 682–687 (1988). A good review of the subject with an excellent reference list. (E)
101. "Speed of Light from Direct Frequency and Wavelength Measurements of the Methane-Stabilized Laser," K. M. Evenson, J. S. Wells, F. R. Petersen, B. L. Danielson, G. W. Day, R. L. Barger, and J. L. Hall, Phys. Rev. Lett. **29**(19), 1346–1349 (1972). First measurement of c using this technique. (I)
102. "Laser Frequency Measurements and the Redefinition of the Meter," P. Giacomo, IEEE Trans. Instrum. Meas. **IM-32**(1), 244–246 (1983). A good brief review. (E)
103. "Documents Concerning the New Definition of the Metre," Metrologia **19**(4), 163–178 (1984). Report of the international agreement redefining the meter. (E)
104. "Microwave to Visible Frequency Synthesis," J. J. Jimenez, Radio Science **14**(4), 541–560 (1979). A good review. (I)
105. "Optical Frequency Measurements," D. A. Jennings, K. M. Evenson, and D. J. E. Knight, Proc. IEEE **74**(1), 168–179 (1986). A comprehensive review. (I)
106. "Infrared and Optical Frequency Standards," V. P. Chebotayev, Radio Science **14**(4), 573–584 (1979). A good description of high-stability lasers. (I)
107. "Optical Frequency Standards," J. Helmcke, A. Morinaga, J. Ishikawa, and F. Riehle, IEEE Trans. Instrum. Meas. **38**(2), 524–532 (1989). A good review focusing on more recent work. (I)
108. "Resolution of Photon-Recoil Structure of the 6573-Å Calcium Line in an Atomic Beam with Optical Ramsey Fringes," R. L. Barger, J. C. Bergquist, T. C. English, and D. J. Glaze, Appl. Phys. Lett. **34**(12), 850–852 (1979). Describes application of optical Ramsey fringes (three standing waves) in resolving a calcium line that is currently considered to be an ideal reference for optical-frequency standards. (I)
109. "Optical Ramsey Fringes with Traveling Waves," C. J. Bordé, C. Salomon, S. Avrillier, A. Van Leberghe, C. Breant, D. Bassi, and G. Scoles, Phys. Rev. A **30**(4), 1836–1848 (1984). Theory for optical Ramsey fringes with four traveling waves. (A)

C. Methods of characterizing performance of clocks and oscillators

1. Estimation of systematic effects and random noise

Oscillators and clocks are subject to both systematic effects and random noise. In evaluating the performance of a particular device, we commonly first estimate and remove systematic effects, and then examine the residuals to assess the magnitude of random noise. For most physical systems, the standard variance is used to characterize the random noise and in such systems we usually find that a longer averaging time leads to a lower uncertainty. Unfortunately, the standard variance cannot be applied to clocks and oscillators because this variance is appropriate only if the noise in the system is white, that is, if the noise power is constant over the Fourier frequency interval to which the system is sensitive. Clocks and oscillators exhibit white noise over some frequency range, but for lower frequencies (or longer averaging times) noise components more often depend on negative powers (f^{-1}, f^{-2}, etc.) of the Fourier frequency. In such cases continued averaging of the data can result in progressively poorer results. While the source of the f^{-1} behavior is partially understood for some devices, there is only speculation that the higher-order, nonwhite noise terms are the result of environmental changes affecting systematic terms.

To handle this nonwhite noise, special statistical-characterization techniques have been developed. In the time domain the two-sample (Allan) variance is used to characterize this type of noise. Modifications of this variance have been developed to deal with special situations, but the different variances now in use are all closely related. In the frequency domain, noise in oscillators is characterized by computing the spectral density of either the phase or frequency fluctuations. Spectral density remains a well-behaved quantity in the face of nonwhite noise processes. The choice of approach (time domain *versus* frequency domain) depends on the physical measuring system (as discussed below) and the application. The time-domain specification is most useful for discussing performance in the long term while the frequency-domain measures are most useful for describing short-term behavior. These measures have been the subject of considerable confusion, so the field has adopted standards for terminology and characterization.

Oscillators and clocks respond to changes in environment, so this aspect of characterization is also important. Performance in the face of temperature change is probably of broadest concern, but some applications demand relative insensitivity to, for example, magnetic field, acceleration, and humidity.

110. "Time and Frequency (Time-Domain) Characterization, Estimation, and Prediction of Precision Clocks and Oscillators," D. W. Allan, IEEE Trans. UFFC **UFFC-34**(6), 647–654 (1987). A review of clock/oscillator models and time-domain methods for characterization. (I)

111. "A Frequency-Domain View of Time-Domain Characterization of Clocks and Time and Frequency Distribution Systems," D. W. Allan, M. A. Weiss, and J. L. Jespersen, in Ref. 10, pp. 667–678. Provides a very useful frequency-domain interpretation of the two-sample variances. Introduces a variance useful for characterizing time-transfer systems. (I)

112. "Characterization of Frequency Stability in Precision Frequency Sources," J. Rutman and F. L. Walls, Proc. IEEE **79**(6), 952–960 (1991). Review of time-domain and frequency-domain techniques and their relationships. (I)

113. "The Measurement of Linear Frequency Drift in Oscillators," J. A. Barnes, in Ref. 36, pp. 551–582. Demonstrates difficulty in estimating linear drift. (I)

114. "Confidence on the Second Difference Estimation of Frequency Drift," M. A. Weiss, D. W. Allan, and D. A. Howe, in Ref. 9, pp. 300–305. Improved method for estimating drift. (I/A)

115. "Characterization of Clocks and Oscillators," NIST Technical Note 1337, edited by D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls (1990). (Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D. C. 20402-9325.) A collection of reprints with an introductory guide and errata for all of the reprints. (E/I/A)

116. "Characterization of Frequency Stability," J. A. Barnes, A. R. Chi, L. S. Cutler, D. J. Healey, D. B. Leeson, T. E. McGunigal, J. A. Mullen, Jr., W. L. Smith, R. L. Sydnor, R. F. C. Vessot, and G. M. R. Winkler, IEEE Trans. Instrum. Meas. **IM-20**(2), 105–120 (1971). Until the late 1980s, this served as the *de facto* standard for defining measures of performance for clocks and oscillators. Some nomenclature has since changed. (A)

117. "Standard Terminology for Fundamental Frequency and Time Metrology," D. W. Allan, H. Hellwig, P. Kartaschoff, J. Vanier, J. Vig, G. M. R. Winkler, and N. F. Yannoni, in Ref. 13, pp. 419–425. This paper is identical to IEEE Standard 1139-1988. (I)

118. "IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators," IEEE Standard 1193. (Available from IEEE, 445 Hoes Lane, Piscataway, NJ 08854.) Describes standard methods for characterizing response to changes in environment. (E)

2. *Measurement systems*

Measurement systems used to characterize clocks and oscillators can be classified into three general categories. These are (1) direct measurements where no signal mixers are used, (2) heterodyne measurements where two unequal frequencies are mixed, and (3) homodyne measurements where two equal frequencies are mixed. The first are by far the simplest, but lack the resolution of the other methods. Measurement methods can also be categorized as being in the time domain or the frequency domain. The time-domain-measurement systems, on the one hand, usually acquire time-series data through repeated time-interval-counter measurements. Proper analysis of these data yields the performance as a function of data-averaging time τ. Such time-domain analysis is most useful for looking at medium-term to long-term noise processes. Frequency-domain measures, on the other hand, use fast Fourier transforms (FFTs) and spectrum analyzers, and are effective for looking at higher-frequency noise processes. Caution must be used when quantitative results are derived from spectrum analyzers, since the type of measurement window used by each instrument affects the results.

119. "Properties of Signal Sources and Measurement Methods," D. A. Howe, D. W. Allan, and J. A. Barnes, in Ref. 17, pp. A1–A47. A very good tutorial. (E/I)

120. "Frequency and Time—Their Measurement and Characterization," S. R. Stein, Chap. 12 in Ref. 41, Vol. 2, pp. 191–232. A comprehensive review of measurement concepts. (I/A)

121. "Phase Noise and AM Noise Measurements in the Frequency Domain," A. L. Lance, W. D. Seal, and F. Labaar, Chap. 7 in **Infrared and Millimeter Waves**, Vol. 11, edited by K. J. Button (Academic, New York, 1984), pp. 239–289. A comprehensive review. (I)

122. "Performance of an Automated High Accuracy Phase Measurement System," S. Stein, D. Glaze, J. Levine, J. Gray, D. Hilliard, D. Howe, and L. Erb, in Ref. 16, pp. 314–320 A method for high-accuracy phase measurement. (I)

123. "Biases and Variances of Several FFT Spectral Estimators as a Function of Noise Type and Number of Samples," F. L. Walls, D. B. Percival, and W. R. Irelan, in Ref. 12, pp. 336–341. Demonstrates the effect of window shape on FFT spectral measurements. (A)

D. Time scales, clock ensembles, and algorithms

Since all clocks exhibit random walk of time at some level, any two independent clocks will gradually diverge in time. Thus, the operation of several clocks at a single site poses a major question: Which clock should be trusted? Timekeeping, furthermore, requires extreme reliability. When a timekeeping system fails, the time must be reacquired from another source. This can be very difficult for high-accuracy timekeeping. Thus, methods for increasing reliability have great appeal to those charged with maintaining national time scales. To improve reliability and timekeeping performance, a number of national laboratories combine the data from many standards to form something referred to as a clock ensemble. The problem is how to integrate the data from different clocks so as to produce the best possible ensemble time scale.

Combining data from several clocks requires an algorithm that assigns an appropriate weight to each clock and combines the data from all of the clocks in a statistically sound manner. Such algorithms have evolved over the past two decades, and systems based on these algorithms deliver an ensemble performance that is statistically better and much more reliable than that of any single clock in the ensemble.

124. "A Study of the NBS Time Scale Algorithm," M. A. Weiss, D. W. Allan, and T. K. Peppler, IEEE Trans. Instrum. Meas. **38**(2), 631–635 (1989). A study of one of the earliest time-scale algorithms. (I/A)

125. "Comparative Study of Time Scale Algorithms," P. Tavella and C. Thomas, Metrologia **28**(2), 57–63 (1991). Comparisons of the international algorithm (ALGOS) and the NIST algorithm (AT1). (I/A)

126. "Report on the Time Scale Algorithm Test Bed at USNO," S. R. Stein, G. A. Gifford, and L. A. Breakiron, in Ref. 34, pp. 269–288. Comparison of the performance of two algorithms including description of one of the algorithms. (A)

127. "Sifting Through Nine Years of NIST Clock Data with TA2," M. A. Weiss and T. P. Weissert, Metrologia **31**(1), 9–19 (1994). Study of an improved algorithm. (I/A)

128. "An Accuracy Algorithm for an Atomic Time Scale," D. W. Allan, H. Hellwig, and D. J. Glaze, Metrologia **11**, 133–138 (1975). The addition of frequency-accuracy considerations to a time-scale ensemble. (A)

E. International time scales

Until 1967 the world's timekeeping system was based on the motions of the earth (see Chap. 7 of Ref. 42 for details on the history of this period). After the stability of atomic timekeeping was recognized to be far superior to that defined by the earth's motions, the world redefined the second in terms of the cesium atom as noted in Sec. V B 3. Subsequent decisions then gave the world the atomic-time scales denoted as International Atomic Time (TAI) and Coordinated Universal Time (UTC). TAI is a purely atomic scale derived from data from the best atomic clocks in the world. UTC is similarly derived, but incorporates a provision for addition or deletion of "leap seconds" that are needed to keep the world's atomic-timekeeping system in synchronization with the motions of the earth. UTC has the stability of atomic time with a simple means for adjusting to the erratic motions of our planet. This world time scale replaces the familiar Greenwich Mean Time. The Bureau International des Poids et Mesures (BIPM) in Paris serves as the central agent for this international timekeeping activity.

Many laboratories throughout the world contribute raw clock data to the BIPM for the computation of UTC. Most of these in turn steer their own output time signals to UTC, assuring that their broadcast time signals are in very close agreement with this international scale. Each laboratory designates its output signal as UTC(XXXX) where XXXX designates the laboratory. Thus, UTC(NIST) is NIST's best representation of UTC.

129. "Standards of Measurement," A. V. Astin, Sci. Am. **218**(6), 2–14 (1968). Contains a brief discussion of the atomic definition of the second. (E)

130. "The BIPM and the Accurate Measurement of Time," T. J. Quinn, Proc. IEEE **79**(7), 894–905 (1991). A good review of international timekeeping. (E/I)

131. "Establishment of International Atomic Time," BIPM Annu. Rep., D1–D22 (1988). (Available upon request from the Director, BIPM, Pavillon de Breteuil, F-92312 Sèvres Cedex, France.) Description of how TAI is generated. Other parts of this report give a good description of the process of international timekeeping. Includes extensive data for the year. (I/A)

F. Frequency and time distribution

Once a national laboratory generates its estimate of UTC, any of a number of methods can be employed to deliver it to the user. The complexity of the method selected is determined by the accuracy and precision required by the user. At the highest accuracy, the synchronization of widely separated clocks involves consideration of relativistic effects.

132. "Characterization and Concepts of Time-Frequency Dissemination," J. L. Jespersen, B. E. Blair, and L. E. Gatterer, Proc. IEEE **60**(5), 502–521 (1972). An older, but very useful review of the topic. (E/I)

133. "Synchronization and Relativity," G. M. R. Winkler, Proc. IEEE **79**(7), 1029–1039 (1991). A good review. (I)

134. "Practical Implications of Relativity for a Global Coordinate Time Scale," N. Ashby and D. W. Allan, Radio Science **14**(4), 649–669 (1979). A good review. (I/A)

1. One-way time transfer

In "one-way" time transfer, the user receives a broadcast signal that corresponds to a given time scale and then compares the clock to be set with the received time signal. To obtain higher accuracy, some estimate of the time delay associated with transmission is often factored into the setting of the clock. Short-wave broadcasts of timing signals are but one example of this type of time transfer. Such broadcasts usually include a digital time code so that the clock-setting process is readily automated. Several types of one-way broadcasts are described below.

a. Shortwave and low-frequency broadcasts. In the United States, WWV, WWVH, and WWVB, stations operated by NIST, provide broadcasts in the short-wave and low-frequency (LF) regions. The best achievable uncertainty for such broadcasts is about 10^{-11} for frequency and about 100 μs for time. Similar stations are operated by many other countries, and the broadcasts from these stations are regulated by the International Telecommunications Union (ITU).

135. NIST Time and Frequency Services, NIST Special Publication 432 revised (1990), R. E. Beehler and M. A. Lombardi (1991). (Available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402-9325.) Outlines all NIST time-and-frequency dissemination services. (E/I)

136. "The Role of the Consultative Committee on International Radio (CCIR) in Time and Frequency," R. E. Beehler, in Ref. 32, pp. 321–330. Describes the international coordination of timing-signal broadcasts. (E)

b. Broadcasts from geostationary satellites. Geostationary satellites have been used effectively for broadcasts of timing signals of moderate accuracy. Such broadcasts generally include regularly updated information on the location of the satellite so that the receiver, knowing its location and that of the satellite, can correct for the propagation delay. The timing uncertainty (typically 100 μs) of such systems is limited by the accuracy of the satellite position broadcast with the time signal.

137. "NBS Time to the Western Hemisphere by Satellite," D. W. Hanson, D. D. Davis, and J. V. Cateora, Radio Sci. **14**(4), 731–740 (1979). Describes dissemination of timing signals through weather satellites. (E)

138. "Satellite Time Broadcasting of Time and Frequency Signals," A. Sen Gupta, A. K. Hanjura, and B. S. Mathur, Proc. IEEE **79**(7), 973–981 (1991). Describes a service operated by India. (E/I)

c. Digital time codes by telephone. Clocks in computers can be conveniently set using a digital code transmitted by telephone. The first service of this type was developed in Canada. One U.S. version of this service is the Automated Computer Time Service (ACTS). We include this under one-way methods because such services can be operated in that mode. However, a number of these services include provision for operation in the more-accurate two-way mode as described in the next section. More recently, time services of this type have been added to the INTERNET. For information on one such service see the directory /pub/daytime at the INTERNET address time.nist.gov.

139. "A Telephone-Based Time Dissemination System," D. Jackson and R. J. Douglas, in Ref. 35, pp. 541–553. Description of a Canadian system. (E)

140. "The NIST Automated Computer Time Service," J. Levine, M. Weiss, D. D. Davis, D. W. Allan, and D. B. Sullivan, J. Res. NIST **94**(5), 311–321 (1989). Description of a U.S. service. (E)

141. "Keeping Time on Your PC," M. A. Lombardi, Byte **18**(11), 57–62 (1993). A popular review article that describes telephone and other timing delivery methods. (E)

d. LORAN-C. LORAN-C is a U.S. Coast Guard radionavigation system consisting of many stations located throughout the Northern Hemisphere. Special LORAN-C receivers allow a user to precisely determine frequency relative to that of a specific LORAN-C frequency. Since the LORAN-C frequencies are themselves regulated by atomic clocks and carefully steered in frequency to each other, this represents a very useful and readily available frequency reference. With an averaging period of 1 day, frequency uncertainty approaching 1×10^{-12} can be achieved.

142. "Precise Time and Frequency Dissemination via the LORAN-C System," C. E. Potts and B. Wieder, Proc. IEEE **60**(5), 530–539 (1972). A review of LORAN-C timing. (E)

143. **Traceable Frequency Calibrations: How to Use the NBS Frequency Measurement System in the Calibration Lab**, NBS Special Publication 250-29, G. Kamas and M. A. Lombardi, (U. S. Department of Commerce, Washington, D. C., 1988). (Available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402-9325.) Description of a service based on LORAN-C. (E)

e. Global Positioning System (GPS). The Global Positioning System (GPS) is a system of satellites operated by the U. S. Department of Defense. These satellites are used for navigation and timing purposes. With a GPS receiver, one can determine local time relative to that of the GPS system clock. The GPS system clock is traceable to a time scale maintained by the U. S. Naval Observatory.

The GPS signal is subject to Selective Availability, an intentional degradation aimed at reducing the real-time accuracy available to civilian users of the system. With the current level of Selective Availability, timing uncertainty may approach 100 to 200 ns under favorable conditions. With the character of degradation (noise) now used, local averaging can improve the accuracy, but there is no guarantee that the character of the degradation will remain the same.

144. "Using a New GPS Frequency Reference in Frequency Calibration Operations," T. N. Osterdock and J. A. Kusters, in Ref. 8, pp. 33–39. GPS for frequency measurement. (E)

145. "A Precise GPS-Based Time and Frequency System," J. McNabb and E. Fossler, in Ref. 18, pp. 387–389. GPS for time and frequency. (E)

146. "Real-Time Restitution of GPS Time Through a Kalman Estimation," C. Thomas, Metrologia **29**(6), 397–414 (1992). Description of a process for improving the accuracy of GPS time signals. (A)

f. Wide Area Augmentation System (WAAS). In the near future, a signal very similar to that used in GPS will be broadcast from a number of commercial geosynchronous communications satellites. Satellites covering the U.S. and adjacent regions will be operated by the U.S. Federal Aviation Administration (FAA). The primary purpose of this satellite system is to provide critical information on the integrity of GPS signals so that GPS can be used for commercial air navigation. Fortunately, among other features of this service, the FAA is including provisions for delivery of highly accurate timing signals. The timing accuracy achievable using these signals, while yet to be demonstrated, should be at least comparable to and perhaps better than that of GPS.

147. "Precise Time Dissemination Using the INMARSAT Geostationary Overlay," A. Brown, D. W. Allan, and R. Walton, in Ref. 8, pp. 55–64. Describes preliminary experiments demonstrating the utility of WAAS for timing applications. (I/A)

2. *Common-view time transfer*

In common-view time transfer, two sites compare their time and frequency by recording the times (according to the clock of each lab) of arrival of signals emanating from a single source that is in view of both sites.

A well-established method of common-view time-and-frequency transfer uses GPS signals. In common-view GPS time transfer, most of the effects of selective availability are canceled out. This comparison method can yield uncertainties in time comparison of 1–10 ns for an averaging time of 1 day and can compare the frequency of the clocks with an uncertainty on the order of 10^{-14}. The Russian counterpart to GPS is known as GLONASS. Common-view time transfer using GLONASS has also been studied, but only more recently. The availability of this second independent satellite system for use in time transfer should prove useful in the future.

148. "GPS Time Transfer," W. Lewandowski and C. Thomas, Proc. IEEE **79**(7), 991–1000 (1991). Discussion of performance of common-view time transfer. (I).

149. "GPS Time Closure Around the World Using Precise Ephemerides, Ionospheric Measurements and Accurate Antenna Coordinates," W. Lewandowski, G. Petit, C. Thomas, and M. A. Weiss, in Ref. 19, pp. 215–220. An exacting test of the accuracy of GPS common-view time transfer. (I)

150. "Precision and Accuracy of GPS Time Transfer," W. Lewandowski, G. Petit, and C. Thomas, IEEE Trans. Instrum. Meas. **42**(2), 474–479 (1993). A good review. (I)

151. "An NBS Calibration Procedure for Providing Time and Frequency at a Remote Site by Weighting and Smoothing of GPS Common View Data," M. A. Weiss and D. W. Allan, IEEE Trans. Instrum. Meas. **IM-36**(2), 572–578 (1987). A report on the earliest work on the subject. (I)

152. "Comparison of GLONASS and GPS Time Transfers," P. Daly, N. B. Koshelyaevsky, W. Lewandowski, G. Petit, and C. Thomas, Metrologia **30**(2), 89–94 (1993). Comparison of time transfer using the Russian and U.S. systems. (I)

3. Two-way time transfer

The two-way method assumes that the path connecting the two participants is reciprocal, that is, that the signal delay through the transmission medium in one direction is the same as that in the reverse direction. In two-way time transfer, each of two sites transmits and receives signals. The timing of the transmitted signal at each site is linked to the site's time scale. If these transmissions occur at nearly the same time, the transmission delay between the sites cancels when the data recorded at the two sites are compared. The result is a time comparison dependent only on imperfections in the transmission hardware along the path and on second-order effects relating to reciprocity.

Several of the telephone time services described in Sec. V F 1 c above include a provision for two-way operation that allows them to achieve an uncertainty approaching 1 ms rather than the 10 to 30 ms normally encountered in the one-way mode. The two-way method produces much higher accuracy when used with satellite or optical-fiber links.

a. Two-way time transfer using satellites. Commercial communication satellites are typically used for this time transfer. Properly implemented, such time transfer should achieve a time-comparison uncertainty of less than 1 ns and stability of a few hundred picoseconds.

153. "Telstar Time Synchronization," J. McA. Steele, W. Markowitz, and C. A. Lidback, IEEE Trans. Instrum. Meas. **IM-13**(4), 164–170 (1964). An early two-way experiment. (E/I)

154. "Two-Way Time Transfer Experiments Using an INTELSAT Satellite in a Inclined Geostationary Orbit," F. Takahashi, K. Imamura, E. Kawai, C. B. Lee, D. D. Lee, N. S. Chung, H. Kunimori, T. Yoshino, T. Otsubo, A. Otsuka, and T. Gotoh, IEEE Trans. Instrum. Meas. **42**(2), 498–504 (1993). A Japanese-Korean experiment. (I)

155. "NIST-USNO Time Comparisons Using Two-Way Satellite Time Transfers," D. A. Howe, D. W. Hanson, J. L. Jespersen, M. A. Lombardi, W. J. Klepczynski, P. J. Wheeler, M. Miranian, W. Powell, J. Jeffries, and A. Meyers, in Ref. 12, pp. 193–198. A U.S. experiment. (I)

156. "Comparison of GPS Common-view and Two-way Satellite Time Transfer Over a Baseline of 800 km," D. Kirchner, H. Ressler, P. Grudler, F. Baumont, C. Veillet, W. Lewandowski, W. Hanson, W. Klepczynski, and P. Uhrich, Metrologia **30**(3), 183–192 (1993). A comparison of the two methods. (I)

b. Two-way time transfer in optical fiber. The two-way method has also been applied to time transfer in optical fiber. The broad bandwidth of optical fiber and its immunity to pickup of electromagnetic noise make it an attractive option for linking sites that must be tightly synchronized. Furthermore, since optical fiber is used so widely in telecommunications, telecommunications synchronization might one day take advantage of this method.

157. "Characteristics of Fiber-Optic Frequency Reference Distribution Systems," R. A. Dragonette and J. J. Suter, in Ref. 18, pp. 379–382. Local-area timing distribution. (I)

158. "Precise Frequency Distribution Using Fiber Optics," R. L. Sydnor and M. Calhoun, in Ref. 18, pp. 399–407, Local-area timing distribution. (I)

159. "Accurate Network Synchronization for Telecommunications Networks Using Paired Paths," M. Kihara and A. Imaoka, in Ref. 18, pp. 83–87. Description of long-line (2000 km) timing experiments. (I)

VI. APPLICATIONS

In a technological society, the need for accurate time and frequency is ubiquitous. The uses of frequency and time range from the commonplace need to know when it is time to go to lunch to scientifically demanding tests of relativity theory. In fact, science has often been the driving force behind many of the major advances in timekeeping, but industry has quickly commercialized much of this technology for applications involving transportation, navigation, power generation and distribution, and telecommunications. The following references discuss some of the more notable commercial and scientific applications. These are offered without comment.

160. "Time, The Great Organizer," J. Jespersen and J. Fitz-Randolph, Chap. 11 in Ref. 42, pp. 99–109. (E)

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