NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Report to the 16th Meeting of the CCTF
Activities of the NIST Time and Frequency Division
April 2004

This brief summary is not intended as a comprehensive report of all the activities of the NIST Time and Frequency Division, but serves to highlight some of the Division's accomplishments and some changes in Division activities over the past three years.

1. Cesium primary frequency standards

1.1 NIST-F1 frequency evaluations

The NIST-F1 cesium fountain primary frequency standard [1] has been in operation since November 1998 with the first formal report to BIPM made in November 1999. NIST-F1 has reported 12 formal evaluations to BIPM, with uncertainties generally decreasing as improvements are made to the standard and its operational reliability improved. Four formal evaluations were reported in 2003. A NIST-F1 formal evaluation consists of measuring the frequency of one of the five hydrogen masers at NIST compared to NIST-F1 and reporting the results and uncertainties to BIPM. The NIST ensemble of five active, cavity-tuned hydrogen masers provides a very stable frequency reference to characterize the performance of the reference maser. The NIST-F1 frequency at zero atom density is determined by performing frequency measurements over a range of atom densities and conducting a linear least squares fit extrapolation to zero atom density.

Some recent improvements in NIST-F1 include extensive cleaning and improvements to the vacuum system, improved temperature control and instrumentation, improved magnetic field control, improvements to the shutter and fiber optics systems, and improvements in the molasses optics. These improvements helped reduce the light shift uncertainty, improved general reliability reducing dead time during evaluations, and a larger molasses with about twice the number of atoms but only a small increase in atom density.

As of the time of this report, the most recent NIST-F1 evaluation demonstrated a combined in-house uncertainty of 6.7×10^{-16} (statistical uncertainty, $u_A = 5.0\times10^{-16}$, and systematic uncertainty, $u_B = 4.4\times10^{-16}$), the lowest uncertainty ever reported for NIST-F1. The overall reported uncertainty to BIPM was 1.22×10^{-15}, including a dead time uncertainty of 2.0×10^{-16} and a transfer uncertainty of 1.0×10^{-15}.

For this most recent report, the most significant components of the systematic uncertainty were the spin exchange at 2.7×10^{-16}, blackbody shift at 2.6×10^{-16}, microwave leakage at 1.8×10^{-16}, and Zeeman and gravitation shift at 1×10^{-16}. Design for the second generation NIST fountain, NIST-F2, is well underway with the principal goal of introducing a cryogenic drift tube to substantially reduce the blackbody shift uncertainty, as well as permit more sensitive tests of the magnitude of the blackbody shift by measuring the fountain frequency at drift tube temperatures between about 50 K to about 320 K.

NIST-F2 is also being designed to permit upgrades to a multiple launch velocity fountain system that will permit the launching of some 10 balls of atoms to different heights that return simultaneously to the detection region. This approach, first proposed and investigated by Levi et al. [2], will permit the reduction of atom densities by about an order of magnitude with a comparable reduction in the frequency shift uncertainty. Very preliminary tests of a multi-toss approach were demonstrated in NIST-F1 [3]. Separately, a very recent successful demonstration of rapid filling of an optical molasses using a low-velocity intense source of atoms indicates that it should be possible to capture and launch 10^7 atoms in about 25 ms, an important step for the eventual development of a multi-toss system with about 10 atom balls. [4]

1.2 Primary Atomic Reference Clock in Space (PARCS)

NIST is collaborating with the Jet Propulsion Laboratory, the University of Colorado, the Havard-Smithsonian Center for Astrophysics, and the Politecnico di Torino to develop the Primary Atomic Reference Clock in Space (PARCS), a NASA-sponsored program to operate a laser-cooled cesium atomic clock on the International Space Station (ISS) [5]. The PARCS mission objectives include (1) sensitive tests of general and special relativity by measuring the frequency shift of PARCS; (2) measure local position invariance by comparing the PARCS frequency to that of a hydrogen maser assumed to be part of the PARCS package; (3) improve the realization of the second through the reduced frequency uncertainty of PARCS afforded by the long atom drift time; (4) use PARCS to study the performance of GPS timing and time transfer. NIST and University of Colorado staff serve as co-principal investigators for the experiment, with the Jet Propulsion Laboratory providing the Project Scientist, Project Manager, and construction of the flight hardware. Other partners provide key input to the design of the systems.

Several successful development studies have been completed [6], and PARCS has successfully passed several NASA program reviews. However, at the time of this report, the longer-term plans for PARCS are uncertain. PARCS flight on the ISS was originally planned for approximately 2005, but that schedule was significantly delayed in the aftermath of the 2003 Columbia Space Shuttle tragedy. In addition, in early 2004, U.S. President Bush announced a new long-term strategic vision for NASA emphasizing manned missions to the moon, establishment of a permanent manned lunar base, and preparation for a manned mission to Mars. The detailed future of Space Shuttle missions and the ISS, and thus PARC's future, are currently uncertain in light of NASA's possible reprioritization of its programs in response to this new strategic direction.

2. Optical frequency standards

2.1 Single mercury ion optical frequency standard

NIST has continued development and systematic evaluation of an optical frequency standard based on the 1.06×10^{15} Hz (282 nm) electric quadrupole transition in a single trapped ^{199}Hg+ ion. The mercury ion standard demonstrates measured fractional frequency instabilities of about 7×10^{-15} at 1 second, and a theoretical quantum-limited fractional frequency uncertainty approaching 10^{-18}. The standard uses a cryogenic spherical Paul electromagnetic traps to enable storage of a single trapped ion for as long as 100 days, and uses a laser locked to a high-finesse Fabry-Perot cavity with stringent temperature control and vibration isolation, providing laser linewidths below 0.2 Hz for averaging periods of about 1 second to 10 seconds. Over a period of more than three years, several intercomparisons have been conducted between the mercury ion standard and the NIST-F1 cesium primary frequency standard, using the NIST optical frequency comb. These intercomparisons demonstrate stability of the mercury ion clock transition to better than $1x10^{-14}$ over three years. [7]

A second mercury ion optical frequency standard has been constructed using most of the same designs and principles as the first standard, but with an improved and independent laser system. The second standard is being tested, and will provide another independent means of studying the systematics of mercury ion frequency standards. [8]

The long-term intercomparisons of the mercury ion frequency standard and the NIST-F1 cesium frequency standard have also permitted sensitive testing of possible time variation in the fine structure constant, α. Some measurements of the spectra of distant quasars have suggested possible variations in α on the order of 10^{-5} over 10^{10} years, which suggest the possibility of violations of Einstein's Equivalence Principle. Possible temporal variations in quantities related to α can be studied in the laboratory over a period of a few years by measuring the ratio of the cesium transition frequency to the mercury ion transition frequency, which measures the product of the fundamental constants $g_{Cs}(m_e/m_p)\alpha^{6.0}$. Such measurements conducted at NIST over a period of more than two years placed an upper limit on any time variation in α (assuming only α changes in the product) of about $1.2x10^{-15}$ per year, the most sensitive laboratory measurement by far, but a result that cannot rule out possible temporal variations on the order of those suggested by the quasar spectra. [9] Future intercomparisons over time between optical frequencies in mercury ions and neutral calcium or other optical standards could significantly improve the measurement of temporal variations in fundamental constants.

2.2 Neutral calcium optical frequency standard

Significant progress continues in the neutral ^{40}Ca optical frequency standard. Among recent developments are the demonstration of quenched narrow-line second and third stage laser cooling of ^{40}Ca to reach atom to about 10 μK, an improvement of more than 2 orders of magnitude, with the potential to reduce systematic frequency uncertainties in the calcium standard to better than 1 Hz (about $3x10^{-15}$). [10] The calcium optical frequency standard continues to be an invaluable reference for extensive work using optical frequency combs, described below.

2.3 Frequency combs

Substantial progress continues in the development and applications of high-repetition-rate mode-locked lasers to develop optical frequency combs. A recent intercomparison of four optical frequency combs – two from NIST and one each from BIPM and East China Normal University – demonstrated the generation and control of optical frequencies over 100 THz of bandwidth with fractional frequency uncertainties approaching $1x10^{-19}$. [11] NIST optical frequency combs have been crucial in enabling direct intercomparison of cesium microwave frequency standards with optical standards in mercury ions and neutral calcium, as described above, including experiments placing limits on the temporal variations of fundamental constants. Research involving the NIST Time and Frequency Division and other NIST organizational units led to highly accurate new measurements of frequency standards in the optical telecommunications region (approximately 1300 nm to 1600 nm) which are being developed into new NIST standards the telecommunications industry will use for dense wavelength division multiplexing and other applications. [12]

NIST and JILA, a joint research institute between NIST and the University of Colorado, also used optical frequency combs to demonstrate transfer of optical frequency standards through approximately 3.5 km of optical fiber with instabilities on the order of $3x10^{-15}$ (one second averaging). The two laboratories exchanged optical frequency standards based on Nd:YAG (1064 nm, in-house instability of about $4x10^{-14}$ at one second) and radio-frequency standards based on synthesized signals from a maser (in-house instability of about $2.4x10^{-13}$ at one second) with approximately $3x10^{-15}$ transfer instability. [13] This work not only enables NIST and JILA to share their complementary standards for various research and metrology projects, but opens up further investigations into the highest accuracy dissemination of frequency standards over fiber networks, which will be needed for future dissemination of optical frequency standards.

2.4 Chip-scale atomic clocks

Significant progress continues in the project to develop atomic clocks with the physics package on the order of 1 cm^3, with sufficiently low power consumption to enable battery operation, and with frequency uncertainty on the order of 10^{-11} at one second. Such a "chip-scale" atomic clock could potentially be assembled at the wafer level, enabling production of thousands of identical units at sufficiently low cost to become local oscillators in applications such as GPS, communications, and surveillance, significantly improving performance over current quartz oscillators. NIST has been continually decreasing the size and improving the performance of vapor-cell devices using coherent population trapping, vertical-cavity surface-emitting lasers, and MEMS fabrication technologies to meet these challenging goals. The most recent NIST devices occupy a volume of less than 10 mm^3 (physics package) and dissipate less than 75 mW of power while providing fractional frequency instability of about $3x10^{-10}$ at one second. [14, 15] NIST is working closely with several U.S. companies and universities in the development of chip-scale atomic clocks in a major research program sponsored by the U.S. government.

2.5 Logic clocks: Applications of quantum computing research to frequency standards

The NIST Time and Frequency Division has a highly productive program in quantum computing using laser-cooled, trapped ions. Developing quantum computing and quantum communications is an area of intense research across the world, including a large effort at NIST involving the Time and Frequency Division and several other NIST laboratories. The primary goal of the Time and Frequency Division's world-class program is to conduct the fundamental research needed to demonstrate a small-scale working quantum computer with about 10 quantum bits (qubits). Such research is being intensively pursued across the world using a wide variety of schemes including ions, neutral atoms, and various solid state technologies. The Time and Frequency Division's program using laser-cooled trapped ions is demonstrably a world-leader, with several significant research breakthroughs reported in recent years, and with the trapped ion approach being the only one to have successfully demonstrated all five of the so-called DiVincenzo criteria necessary to the development of a working, scalable quantum computer.

Because most of the extensive quantum computing achievements in the Time and Frequency Division are not directly related to time and frequency metrology, they will not be detailed here. Interested persons can find extensive references to quantum information activities in the Time and Frequency Division and at NIST overall at http://qubit.nist.gov/ and at the Time and Frequency Division's publications database at .
http://tf.nist.gov/general/publications.htm

This report briefly notes one important application of quantum information technologies to time and frequency metrology: the possibility of developing a "logic clock," which is in the early stages of exploration at NIST.

One limitation to atomic frequency standards is that the same atom or ion is used to incorporate the functions of laser cooling, laser fluorescence detection, and a low uncertainty clock transition. However, some atoms or ions have very promising clock transitions (narrow linewidths, relative insensitivity to environmental effects, etc.) but impractical laser cooling and detection transitions. But using concepts of quantum entanglement of two or more atoms or ions from quantum computing research has the potential to exploit the advantages of two different species: Convenient laser cooling and detection for one species and good clock transitions for the other species. [16]

In this scheme, ions of two different species are prepared in an entangled state. The "logic" ion has relatively convenient transitions for laser cooling and fluorescence state detection, and is used to sympathetically cool the "clock" ion. The quantum state of the clock ion, a superposition of the two clock transition states when properly prepared, is entangled with the logic ion, and the state of the clock ion can be inferred from fluorescence measurements on the logic ion. One specific example might be using Be^+ ions for cooling and fluorescence state detection and a Group IIIA ion such as B^+ or Al^+ for the clock ion (1.2 Hz and 320 Hz linewidths, respectively). The magnetic quadrupole transitions in these clock ions are insensitive to the electric quadrupole affects that limit uncertainties in Hg^+ ions, and thus may prove better frequency standards in the future. NIST has demonstrated sympathetic cooling of different ion species (Be^+ and Mg^+) as part of the early investigation of logic clocks and quantum computing. [17]

3. Time and Frequency Dissemination

3.1 Internet Time Service

Use of the NIST Internet Time Service (ITS) [18] to automatically synchronize computer clocks continues to expand at the rate of about 7% per month (doubling time of about 10 months) with well over one billion requests for service per day on average at the time of this report. Part of the growth in use results from ITS being one of the default sources of network time built into newer popular computer operating systems such as Microsoft Windows XP and Apple Mac OS X. To meet this demand, the Division is conducting upgrades to its system of 14 servers distributed across the United States. NIST has also been exploring with different companies the possibility of providing secure, authenticated NIST time for auditable time-stamping of electronic transactions and electronic documents. Some companies already use NIST time for such timestamping, including the U.S. Postal Service's

"Electronic Postmark" program in collaboration with the company Authentidate, which allows customers to timestamp electronic documents for a fee. [19]

3.2 Web clock

NIST and USNO jointly operate a Java web clock, www.time.gov, which provides users with a ticking display of the current official U.S. time, usually accurate to a few tenths of a second. (The current accuracy is displayed with the clock.) This service receives about 300,000 hits per day on average.

3.3 Automated Computer Time Service (ACTS)

This modem-based time-of-day service continues to receive an average of about 10,000 requests for service per day, although its historically high usage has dropped with the increasing popularity of the Internet Time Service. While NIST does not track individual users of ACTS, anecdotal evidence suggests a significant portion of the users are in the U.S. financial markets. U.S. regulations require the traceability of some electronic transactions, such as those on the NASDAQ stock exchange, to NIST time, and ACTS is one convenient method of establishing such traceability.

3.4 Radio stations

NIST broadcasts low frequency (60 kHz) time code signals from station WWVB near Ft. Collins, Colorado (about 100 km from the main NIST laboratories in Boulder, Colorado), to automatically set radio-controlled timepieces. A major upgrade of WWVB was completed in 1999, boosting effective radiated power to approximately 50 kW from the previous approximately 12 kW. At this power level, nearly all parts of the 48 contiguous United States receive sufficiently strong radio signals to permit synchronization of commercial timepieces (at least at night), and U.S. sales of radio-controlled timepieces are accelerating. NIST continues to implement a number of improvements in WWVB to increase reliability, improve broadcast efficiency, and ensure the greatest possible synchronization of the on-time marker to UTC(NIST). NIST has also in the earliest stages of implementing a nation-wide system of field strength monitors that will provide real-time measures of received WWVB signals. The data will eventually be available on the public NIST web site so users can check WWVB field strength as measured relatively near them. Such information will be helpful to NIST, radio-controlled clock manufacturers, and users.

NIST also broadcasts high frequency (2.5 MHz to 20 MHz) time and frequency information from radio stations WWV near Ft. Collins, Colorado and WWVH on the Hawaiian island of Kauai. NIST also continues to upgrade the infrastructure for stations WWV and WWVH to improve reliability of broadcasts, including a major antenna replacement program at WWVH and significant automation improvements at WWV to enable ensure backup transmitters appropriately take over upon loss of primary transmitters.

3.4 NIST Frequency Measurement Service

NIST continues to improve its Frequency Measurement and Analysis Service which provides automated traceability to NIST for measuring any frequency from 1 Hz to 120 MHz in 1 Hz increments, and accommodating up to five different customer devices simultaneously. In addition to the real time data tracing the device under test to NIST standards at an uncertainty of 2×10^{-13} per day, customers receive monthly written calibration reports compliant with ISO Guides 25 and 17025 and the ANSI Z-540 standard. A major revision and update is underway for the primary document describing the service. [20]

4. Noise metrology

4.1 100 GHz AM and PM noise measurement system

NIST is implementing a new system to measure ultra-low amplitude modulation and phase modulation noise at 100 GHz in support of a number of applications, particularly in communications and sensing. The new system employs state-of-the-art dual channel cross-correlation noise metrology, with two amplitude noise and phase noise detectors operating in parallel with cross-correlation spectrum analysis. This new measurement system supports the development of gallium arsenide and indium phosphide amplifiers and oscillators. Data on the measurement system performance are available. [21]

4.2 New statistic for estimating long-term frequency stability

NIST has developed a new statistic, "Theoretical Variance #1" or "Theo1," which is valuable for determining the frequency stability of frequency standards and oscillators for averaging times longer than those addressed by the traditional Allan variance. Theo1 permits determination of the frequency stability at 75% of the data run rather than the 50% from the traditional Allan variance. For example, the three-month stability can be determined with Theo1 from four months of data rather than the six months required by the Allan variance. The new statistic is unbiased relative to the Allan variance for white noise, with only moderate biases for other noises. Theo1 has already been incorporated into some commercial noise analysis programs. As with any new statistic, the experience of the time and frequency metrology community will demonstrate the utility of the measure. [22]

References

Below is the list of publications cited in this report. Reprints (pdf) of all publications of the NIST Time and Frequency Division, including the NIST publications listed below, are publicly and freely available on a searchable database:
http://tf.nist.gov/general/publications.htm

1. S.R. Jefferts, J.H. Shirley, T.E. Parker, T.P. Heavner, D.M. Meekhof, C.W. Nelson, F. Levi, G. Costanzo, A. DeMarchi, R.E. Drullinger, L. Hollberg, W.D. Lee, and F.L. Walls, *Accuracy evaluation of NIST-F1*, Metrologia **39**, 321-336 (2002).

2. F. Levi, A. Godone, L. Lorini, *Reduction of the Cold Collision Frequency Shift in a Multiple Velocity Fountain: A New Proposal*, IEEE Trans. Ultrason. Ferr, **48**, pp 847-853 (2001).

3. S.R. Jefferts, T.P. Heavner, E.A. Donley, J. Shirley, and T.E. Parker, *Second Generation Cesium Fountain Primary Frequency Standards at NIST*, Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 1084-1088 (2003).

4. E. A. Donley, T. P. Heavner, S. R. Jefferts, *An Optical Molasses Loaded from a Low-Velocity Intense Source of Atoms* (in preparation).

5. T.P. Heavner, L. Hollberg, S.R. Jefferts, H.G. Robinson, D.B. Sullivan, F.L. Walls, N. Ashby, W. Klipstein, L. Maleki, D. Seidel, R. Thompson, S. Wu, L. Young, E. Mattison, R. Vessot, and A. DeMarchi, *PARCS: A Laser-Cooled Atomic Clock in Space*, Proc. 2001 Freq. Stand. Metrology Symp., 253-260 (2001).

6. For example, see J.H. Shirley and S.R. Jefferts, *PARCS Magnetic Field Measurement: Low Frequency Majorana Transitions and Magnetic Field Inhomogeneity,* Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 1072-1075 (2003); G.J. Dick, W.M. Klipstein, T.P. Heavner, and S.R. Jefferts, *Design Concept for the Microwave Interrogation Structure in PARCS*, Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 1032-1036(2003).

7. U. Tanaka, J.C. Bergquist, S. Bize, S.A. Diddams, R.E. Drullinger, L. Hollberg, W.M. Itano, C.E. Tanner, D.J. Wineland, *Optical Frequency Standards Based on the ^{199}Hg+ Ion*, IEEE T. Instrum. Meas. **52**, 245-249 (2003).

8. U. Tanaka, S. Bize, C.E. Tanner, R.E. Drullinger, S.A. Diddams, L. Hollberg, W.M. Itano, D.J. Wineland, and J.C. Bergquist, *The ^{199}Hg+ Single Ion Optical Clock: Recent Progress*, J. Phys. B. **36**, 545-551 (2003).

9. S. Bize, S.A. Diddams, U. Tanaka, C.E. Tanner, W.H. Oskay, R.E. Drullinger, T.E. Parker, T.P. Heavner, S.R. Jefferts, L. Hollberg, W.M. Itano, and J.C. Bergquist, *Testing the Stability of Fundamental Constants with the ^{199}Hg+ Single-Ion Optical Clock*, Phys. Rev. Lett. **90**, 150802 (2003).

10. E.A. Curtis, C.W. Oates, and L. Hollberg, *Quenched narrow-line second- and third-stage laser cooling of ^{40}Ca*, J. Opt. Soc. Am. B. **20**, 977-984 (2003).

11. L-S Ma, Z. Bi, A. Bartels, L. Robertsson, M. Zucco, R.S. Windeler, G. Wilpers, C.W. Oates, L. Hollberg, and S.A. Diddams, *Optical frequency synthesis and comparison at the 10^{-19} level*, Science **303**, 1843-1845 (2004).

12. K.L. Corwin, I. Thomann, A. Bartels, T. Dennis, R.W. Fox, W.C. Swann, E.A. Curtis, C.W. Oates, G. Wilpers, S.L. Gilbert, L. Hollberg, N.R. Newbury, S.A. Diddams, J. Nicholson, and M.F. Yan, *Absolute-Frequency Measurements With a Stabilized Near-Infrared Optical Frequency Comb from a Cr:Forsterite Laser*, Opt. Lett. **29,** 397-399 (2004).

13. J. Ye, J. Peng, R.J. Jones, K.W. Holman, J.J. Hall, D.J. Jones, S.A. Diddams, J. Kitching, S. Bize, J.C. Bergquist, L. Hollberg, L. Robertsson, and L. Ma, *Delivery of High-Stability Optical and Microwave Frequency Standards Over an Optical Fiber Network,* J. Opt. Soc. Am. B. **20**, 1459-1467 (2003).

14. S. Knappe, V. Velichansky, H.G. Robinson, L. Liew, J. Moreland, J. Kitching, and L. Hollberg, *Atomic Vapor Cells for Miniature Frequency References* , Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 31-32 (2003).

15. J. Kitching, S. Knappe, L. Liew, V. Shah, P. Schwindt, J. Moreland, and L. Hollberg, *A Millimeter-Scale, Microfabricated Atomic Clock* (submitted).

16. D.J. Wineland, J.C. Bergquist, T. Rosenband, P.O. Schmidt, W.M. Itano, J.J. Bollinger, D. Leibfried and W.H. Oskay, *Ion Optical Clocks and Quantum Information Processing* , Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 68-71 (2003).

17. M. Barrett, B.L. DeMarco, T. Schaetz, D. Leibfried, J. Britton, J. Chiaverini, W.M. Itano, B.M. Jelenkovic, J.D. Jost, C. Langer, T. Rosenband, and D.J. Wineland, *Sympathetic Cooling of* $^{9}Be+$ *and* $^{24}Mg+$ *for Quantum Logic*, Phys. Rev. A. **68**, 042302 (2003).

18. J. Levine, M.A. Lombardi, and A.N. Novick, *NIST Computer Time Services: Internet Time Service (ITS), Automated Computer Time Service (ACTS), and time.gov Web Sites*, NIST Spec. Publ. 250-59 (2002).

19. http://www.usps.com/electronicpostmark/welcome.htm

20. M. A. Lombardi, *Remote Frequency Calibrations: The NIST Frequency Measurement and Analysis Service (FMAS)*, NIST Special Publication 250-29 (in review).

21. A. Sen Gupta, D.A. Howe, C.W. Nelson, A. Hati, F.L. Walls and J.F. Garcia Nava, *High-Spectral-Purity Microwave Oscillator: Design Using Conventional Air-Dielectric Cavity* , Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 423-429 (2003).

22. D.A. Howe and T.K. Peppler, *Very Long-term Frequency Stability: Estimation Using a Special-purpose Statistic* , Proc. 2003 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf., 233-238 (2003).