WEB EXCLUSIVE:
THE INNER WORKINGS OF THE WORLD'S MOST ACCURATE CLOCK

See an animation of the F1 cesium clock, courtesy of the NIST, at www.ednmag.com/ednmag/reg/2001/03152001/06hiw.htm.

NO MATTER HOW YOU SLICE IT, FROM MILLENNIA TO MICROSECONDS, TIME MARCHES ON. BUT WAIT A MINUTE: WHAT TIME IS IT...*REALLY?*

How it works: time

By Joshua Israelsohn, Technical Editor

DATELINE Newton, MA, JANUARY 1, 2001, 0:00:00.000000 EST. Happy New Year! Happy New Century! Happy New Millennium! What an auspicious moment! Did you feel it? A jarring bump in the time-space continuum? No? Why not? One second flows smoothly into another. Look closer, and you find that the milliseconds, microseconds, nanoseconds pour like fluid rather than tick by like discrete bits of sand. If time has a quantum limit, we and it have yet to meet.

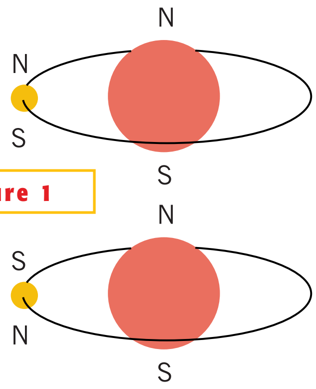
Funny thing about time: We're all aware of it from early childhood, try to make the best of the little we have, catch up with it, waste it, recall it. But beyond recognizing its uncanny ability to keep everything from happening at once, try to get your brain wrapped around it. Even that simplest of questions, "What time is it?" tries to defy answering. But we can't just let time slip away. More and more, our world demands that we keep careful track of time. Research, transportation, manufacturing, communications, and trade all depend on knowing the time and in *our* time, knowing it quite precisely.

WE'VE GOT TIME TO CHILL

People have practiced clock-making in one form or another for at least 5500 years. The earliest known clocks come from northern Africa and the Middle East (**Reference 1**). Indeed, the minute and second owe their origins to the Babylonians who used a base-60 number system in their astronomical calculations. Definitions of time intervals based on astronomical observations served well right up to the modern era. But by the middle of the 20th century, fluctuations in planetary motion—several milliseconds per day—were no longer small compared with the accuracy of manmade clocks. In the 1930s, the late Columbia University Physics Professor and Nobel Laureate Isidor Rabi, PhD, developed atomic-beam magnetic resonance, which in 1945 he suggested could be used to make a clock. Four years later, the NBS (National Bureau of Standards), now NIST (National Institute of Standards and Technology), announced the world's first atomic clock, based on the ammonia molecule. In 1952, the NBS announced NBS-1, the first atomic clock to use cesium atoms as a vibration source. In 1967, the 13th General Conference on Weights and Measures defined the SI (Système International) unit of time, the second, not in astronomical terms but as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom" (**Reference 2**, **Figure 1**).

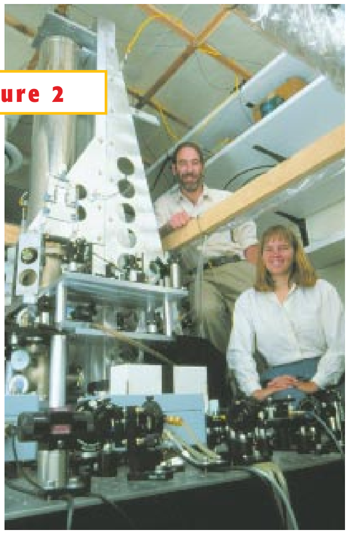
The BIPM (International Bureau of Weights and Measures) in Paris keeps the global official time, called UTC (Universal Coordinated Time). The BIPM derives UTC from some 250 cesium clocks maintained by more than 50 national laboratories around the world. One of these, the NIST-F1 cesium-fountain atomic clock developed by Steve Jefferts and Dawn Meekhof of the NIST Physics Laboratory, serves as the primary

Figure 1



The cesium atom, with one electron in its outer shell, displays two discrete ground states.

Figure 2



Not your grandfather's clock: The NIST-F1 cesium-fountain clock, one of the two most accurate in the world, with its developers, Steve Jefferts and Dawn Meekhof (photo courtesy NIST).

time and frequency standard for the United States (**Figure 2**). The NIST-F1 is one of the two most precise timepieces in the world with an uncertainty less than 2×10^{-15}—less than a second in 20 million years and a five-orders-of-magnitude improvement over the original NBS-1 (**Figure 3**). The NIST maintains this primary standard to within a few nanoseconds of the global standard (**Reference 3**).

The cesium-fountain clock gets its name from the path cesium atoms follow. At the beginning of the cycle, a quantity of cesium gas enters the clock's vacuum chamber. Six mutually orthogonal lasers slow the atoms' movement, cooling them in the process to just a few millionths of a degree higher than absolute zero. The lasers push the individual cesium atoms together into a spherical cloud at the intersection of the six beams (**Figure 4**). After forming this cloud, the vertically oriented lasers gently "toss" the small cesium ball upward about a meter like drops of water in a fountain. At this point, the clock's control system shuts off all of the lasers while the cesium sample passes through a microwave cavity and past a probe laser and detector. When the microwave energy excites the cesium atoms to their natural resonant frequency, they fluoresce when the system's seventh laser strikes them. A light detector measures the fluorescence and feeds the information back to the microwave tuner. The fluorescence peaks when the microwave tuner converges on, you guessed it, 9,192,631,770 Hz. (See the online version of this article at www.ednmag.com/ednmag/reg/2001/03152001/06hiw.htm for an animation of the F1's mechanism, courtesy of the NIST.)

A key advantage of NIST-F1 over traditional cesium clocks derives from the fact that cesium atoms have a thermal velocity of centimeters per second at a few microdegrees Kelvin compared with several hundred meters per second at room temperature. The result is a roughly one-second-long measurement window, allowing for much greater resolution than the few milliseconds that more conventional cesium clocks afford.

TIME IS ON MY SIDE (YES IT IS)

So now we know the official time. Well, actually *they* know the official time. Like manufacturing and distribution, making time solves only half the problem. Delivering the product in a timely fashion is another matter; NIST provides time services through a number of channels. Users without Internet service or with Internet connections through a firewall can synchronize systems equipped with analog modems through the ACTS (Automated Computer Time Service) dial-up servers located in Colorado and Hawaii (**Reference 4**). Of course, it takes time to get the message from the time server to the client system, so ACTS provides for two levels of time correction to account for the delivery delay. The time code corresponds to the arrival time of the last character that ACTS transmits in the code pattern, called the OTM (on-time marker). For uncalibrated transmissions, ACTS sends the OTM 45 msec early. The nominal correction constant assumes the 8 msec required to send the OTM at 1200-baud, 7-msec propagation delay to the average location in the United States, and 30 msec for the modem-processing delay. To reduce the residual uncertainty, the ACTS uses a loop-back signal. If the client software returns the OTM, ACTS measures the round-trip time, divides the value by two, and uses that value instead of the 45 msec as the correction constant. The system acknowledges the correction by changing the OTM character for subsequent transmissions during the session. The loop-back calibration reduces residual synchronization uncertainty for calibrated paths to less than 10 msec.

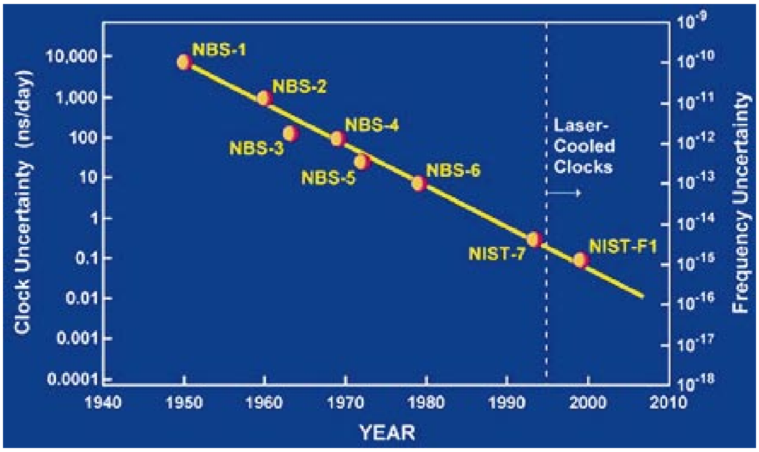
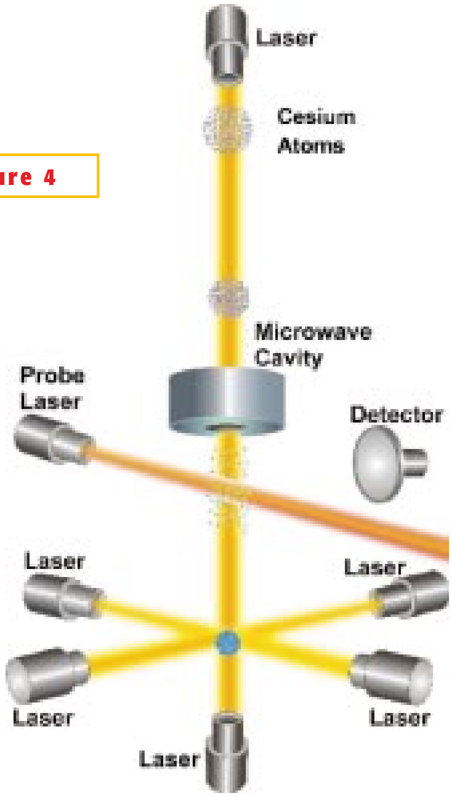


Figure 3 Continuous improvement: Atomic clocks' residual uncertainty has decreased by an order of magnitude per decade for five decades.

Figure 4



A laser tosses cesium atoms in the air like drops in a fountain. When excited to their natural resonant frequency in a microwave cavity, they fluoresce when a laser probe strikes them.

Other time synchronization channels do not accommodate two-way signaling like ACTS does, yet every channel has an associated delay time that varies according to client location and, in some cases, routing. Each channel has its own correction technique that the client-side system must use. In this fashion, the time information maintains its traceability to the NIST, with the calculable levels of uncertainty needed to conform to the common practices that most national and international standards organizations require.

In addition to the ACTS dial-up service, NIST provides ITS (Internet Time Service). The service supports four protocols using three time-stamp codings available through ITS online-service requests. The protocol definitions appear in an RFC (Request for Comment) document for each protocol. Time Protocol (RFC-868) returns a 32-bit binary number corresponding to the number of UTC seconds since Jan 1, 1900 (philosophically an interesting measure considering that UTC seconds did not exist until more than a half-century later). Daytime Protocol (RFC-867) returns a time code in ASCII format. RFC-867 does not specify the specific message format, but the NIST has adopted one similar to that used by ACTS. NTP (Network Time Protocol, RFC-1305) returns a packet containing a 64-bit time stamp representing the time in UTC seconds since Jan 1, 1900, with a resolution of 200 psec and accuracy of 50 msec or better. NTP client software can continuously run in the background and receive periodic updates from the NIST time server. Last, the Simple Network Time Protocol (RFC-1769) also uses the NTP data packet but performs less processing and results in less accuracy.

Perhaps best known of the NIST time services, radio stations WWV and WWVB transmit from Colorado, and WWVH from Hawaii. WWV and WWVH broadcast standard frequency tones, BCD time stamps, and voice announcements on several frequencies (**Table 1**). WWVB transmits only BCD-coded time signals on a 50-kW carrier at 60 kHz (**Figure 5**). The modulation scheme allows uninterrupted use of the carrier itself as a traceable frequency standard good to 1 in 10^{12}. At the start of each second, the carrier power drops 10 dB, signaling a bit. Measuring the time until the modulator restores full carrier power reveals the bit value: 200 msec for a zero, 500 msec for a one, and 800 msec for a position marker. The entire BCD message includes the year, day of the year, hour, minute, second, and flags indicating daylight savings time status, leap years, and leap seconds. The entire code sequence fills a one-minute frame aligned to the UTC minute and contains position markers every 10 seconds. Receiving clocks that compensate for the transmission-path delay can provide UTC time with an uncertainty of less than 100 µsec.

Figure 5

WWVB, which broadcasts at 60 kHz, requires multiple towers to support the large wire antenna.

TABLE 1—WWV AND WWVH BROADCAST CHANNELS

Frequency (MHz)	Power (kW)	
	WWV	WWWH
2.5	2.5	5
5	10	10
10	10	10
15	10	10
20	2.5	—

HOW TIME FLIES

Each of the channels discussed so far has one common weakness: Single point failures along the delivery path can interrupt the availability of time-synchronization data. A failure of this type can cripple certain time-sensitive activities. For example, the National Association of Securities Dealers, which operates a modest $11 trillion stock exchange, requires its member companies to synchronize their computer clocks at the start of each business day and resynchronize them during the day as necessary to traceably maintain them within three seconds of the NIST. Other applications, such as high-speed or secure communications that operate on time slices, cannot tolerate the synchronization uncertainty associated with ACTS, ITS, or WWVx services. Companies that require one enterprisewide method of maintaining UTC time synchronization across sites worldwide may find these services impractical.

For greater robustness, accuracy, and availability, clock makers use time signals from multiple GPS (Global Positioning System) Navstar (navigation-satellite tracking and ranging) satellites, which the United States Naval Observatory maintains and the NIST monitors to ensure traceability. The Standard Positioning Service, available from all 24 GPS satellites in the Navstar constellation, provides 100m horizontal position and 340-nsec UTC timing accuracy (**Reference 5**). GPS clocks capture data from four satellites to resolve the four unknowns: latitude, longitude, altitude, and time. Unlike GPS navigation receivers, which their makers design to rapidly fix their location while in motion, manufacturers of GPS clock receivers optimize them for time accuracy.

GPS time servers, which receive, decode, and distribute GPS time data, often use extra GPS channels and traceable non-GPS data sources, such as ACTS or ITS in the absence of satellite data. Some offer a freewheeling mode, using a rubidium oscillator or temperature-compensated crystal oscillator to provide a local timebase (**Reference 6**). Depending on the precision of the local oscillators, the length of time the system operates without GPS lock, and the precision the application requires, some client systems may or may not be able to use ITS or locally derived time.

Basic systems, such as the $1995 NTP-SyncClock from Brandywine Communications, keep time to better than 2 μsec of UTC under GPS lock. The $3595 2100LD from Datum features a front panel display and comes with an antenna and cable; receives time data from as many as six satellites; and supports network time requests from NTP, SNTP, Daytime Protocol, Time Protocol, and several others through 10BaseT Ethernet. Like most time servers of its type, the 2100LD comes in a 1U, rack-mountable chassis.

Spectracom's $2000 8183 NetClock tracks eight GPS satellites and reports time that is accurate to UTC within ±1 to ±100 μsec, depending on format via RS-232 or RS-485. Programming options allow the serial ports to report either native UTC or time corrected for any time zone at baud rates of 1200 to 9600. A one-pulse/sec signal available through a BNC connector is UTC-synchronized to within ±500 nsec.

The 8183 illustrates how different applications for time data make different demands on time-server features and how time-server manufacturers differentiate their products. For example, emergency services and other applications that require an audio log cannot use time information in digital form. For these applications, Spectracom can configure Net-Clocks with time annunciators for feeding the logging recorders that are standard equipment in such applications.

For greater GPS-lock reliability, the $4395 TimeVault time server from TrueTime receives signals from 12 satellites and can also receive traceable time data though the NIST's ACTS service. The TimeVault server responds to NTP requests through an autosensing 10/100BaseT Ethernet port.□

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5. "Precision time and frequency using GPS," Application note 24, 1999, TrueTime Inc.

6. "Timing and time code reference," Datum, Inc.

ACKNOWLEDGMENTS

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FOR MORE INFORMATION...

For more information on products such as those discussed in this article, go to our information-request page at www.rscahners.ims.ca/ednmag/. When you contact any of the following manufacturers directly, please let them know you read about their products in *EDN*.

Brandywine Communications
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www.brandywinecomm.com
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Datum
1-781-372-3600
www.datum.com
Enter No. 312

Spectracom
1-716-381-4827
www.spectracomcorp.com
Enter No. 313

TrueTime
www.truetime.com
1-707-528-1230
Enter No. 314

SERVICE AND INFORMATION RESOURCES

NIST ACTS service
Colorado dial-up: 1-303-494-4774; 9600,8,N,1
Hawaii dial-up: 1-808-335-4721; 9600,8,N,1
ACTS time-code format information: www.boulder.nist.gov/timefreq/service/acts.htm

NIST ITS service
Server list, client software: www.boulder.nist.gov/timefreq/service/time-servers.html
Protocol descriptions: www.boulder.nist.gov/timefreq/service/nts.htm

NIST broadcast services–WWV and WWVB Colorado, WWVH Hawaii
WWV and WWVH
Frequencies: www.boulder.nist.gov/timefreq/stations/trans.html
Formats: www.boulder.nist.gov/timefreq/stations/iform.html
WWVB: www.boulder.nist.gov/timefreq/stations/wwvb.htm
WWV audio: 1-303-499-7111
WWVH audio: 1-808-335-4363

SUPER INFO NUMBER
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