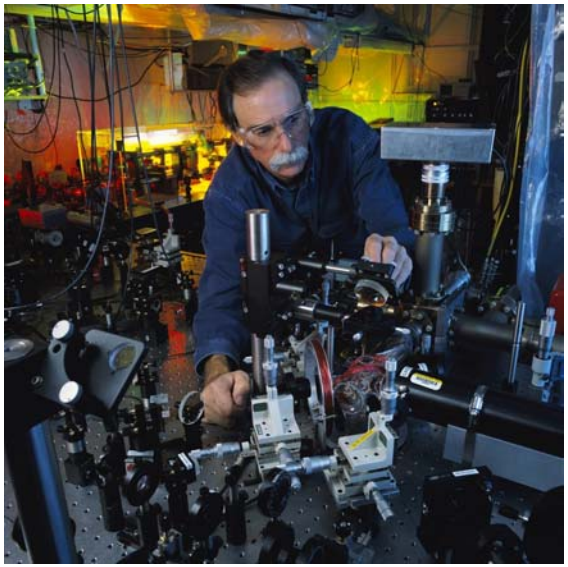
NIST Time and Frequency Division

Physics Laboratory

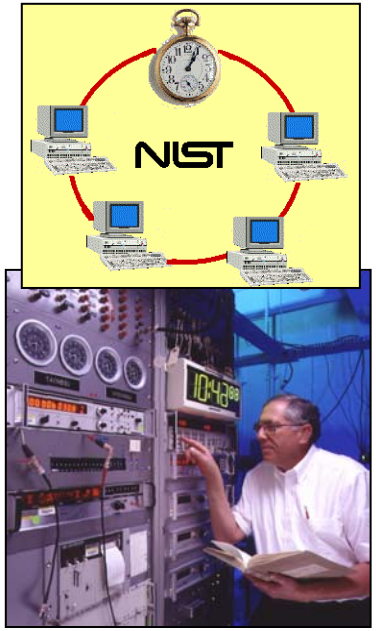
Tom O'Brian, Division Chief

NIST Time and Frequency Division



Develop and disseminate the highest accuracy time and frequency measurements and standards to support commerce, research, and the general public.

http://tf.nist.gov



NIST Time and Frequency Division

Division Programs:

- **National standard for time and participation in international timekeeping.**
  - 10^{-15} accuracy for NIST F1 cesium fountain clock.
  - UTC and other international time scales.

- **Wide range of measurement services, including direct public distribution.**
  - 1 billion requests per day to automatically set computer clocks.
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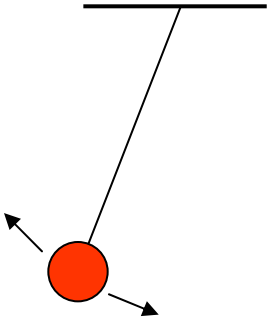
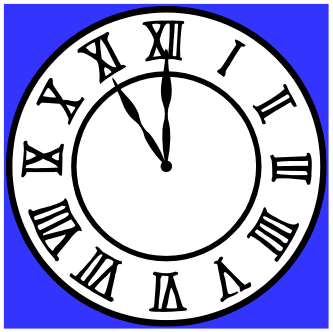
- **Research on future clocks.**
  - Laser-cooled ion and neutral atom optical clocks – potential for 10^{-18} accuracy.
  - Femtosecond frequency combs to directly link microwave and optical standards.
  - Miniature atomic clocks (~1 mm^3).

- **Quantum state engineering.**
  - Unique expertise in quantum state manipulation of trapped ions.
  - Future time and frequency standards.
  - NIST quantum information program.

What Makes a Clock (Time/Frequency Standard)?

Oscillator + **Counting Mechanism**

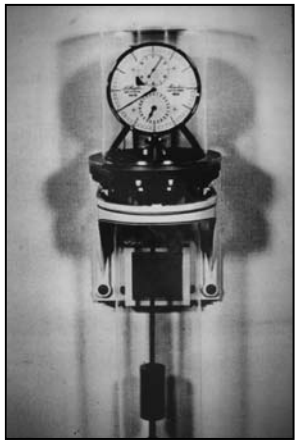




Earth Rotation
Pendulum
Quartz Crystal

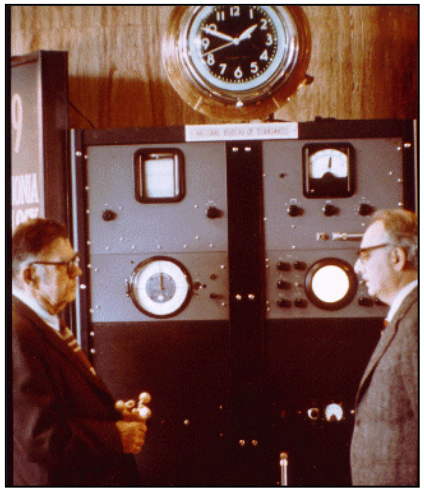
Sundial
Clock Gears/Hands
Electronic Counter

- **First NBS time standard 1904 - pendulum clock (10^{-8} , 1 second per 3 years).**
  - First pendulum clock invented by Huygens (1656) based on ideas of Galileo (1582).



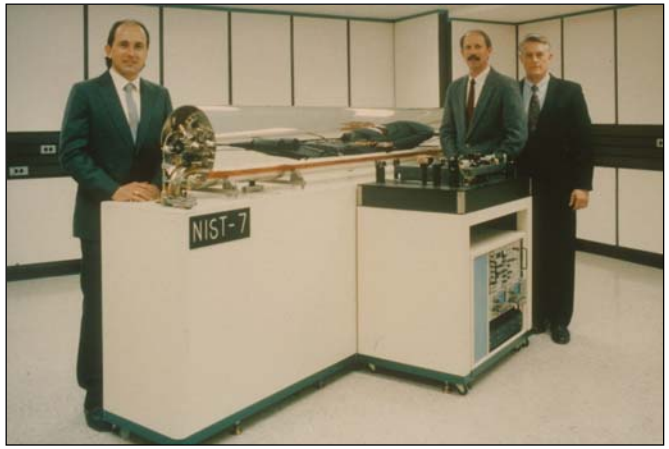
Atomic Clocks (Frequency Standards)

Oscillator	Counting Mechanism
Atomic/Molecular transition	Electronic Counter



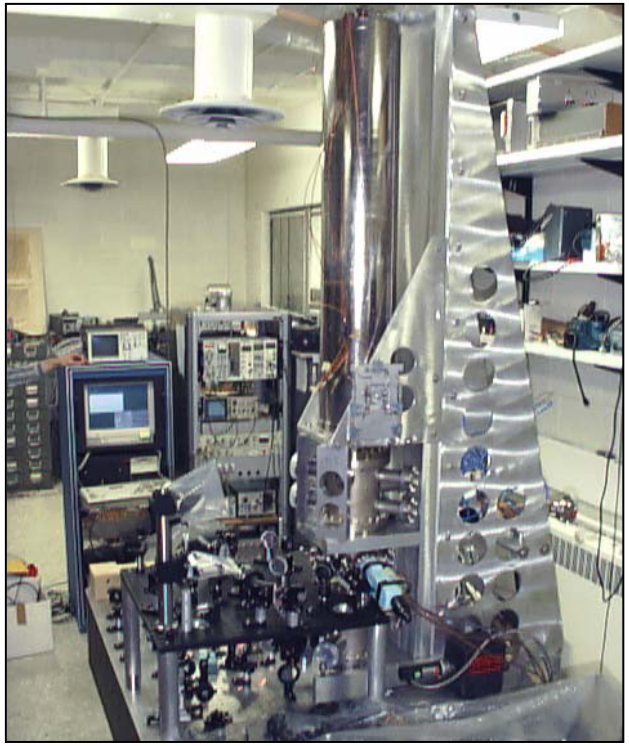
- **First atomic clock, NBS, 1949 (10^{-10} , 1 second per 300 years).**
  - Technology developed by Ramsey in 1940s.
  - Ammonia inversion, 25 GHz.

- **NIST-7 optically pumped cesium beam standard, 1994 (5×10^{-15} , 1 second per 6 million years).**
  - 9.2 GHz hyperfine transition.
  - Approaching limits of thermal beam standards.

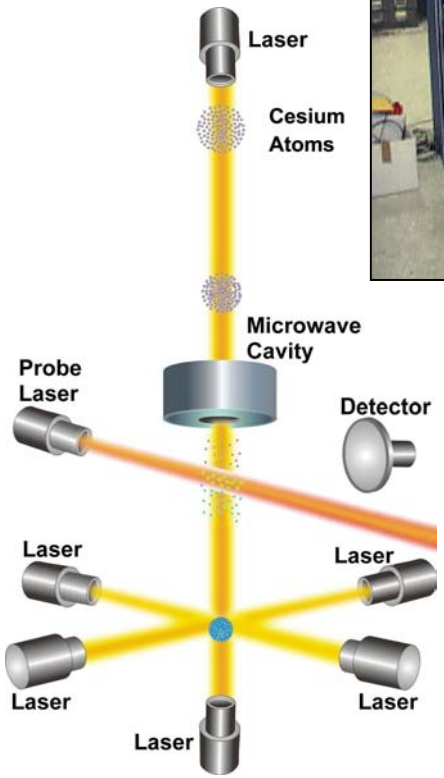


NIST Time and Frequency Standards

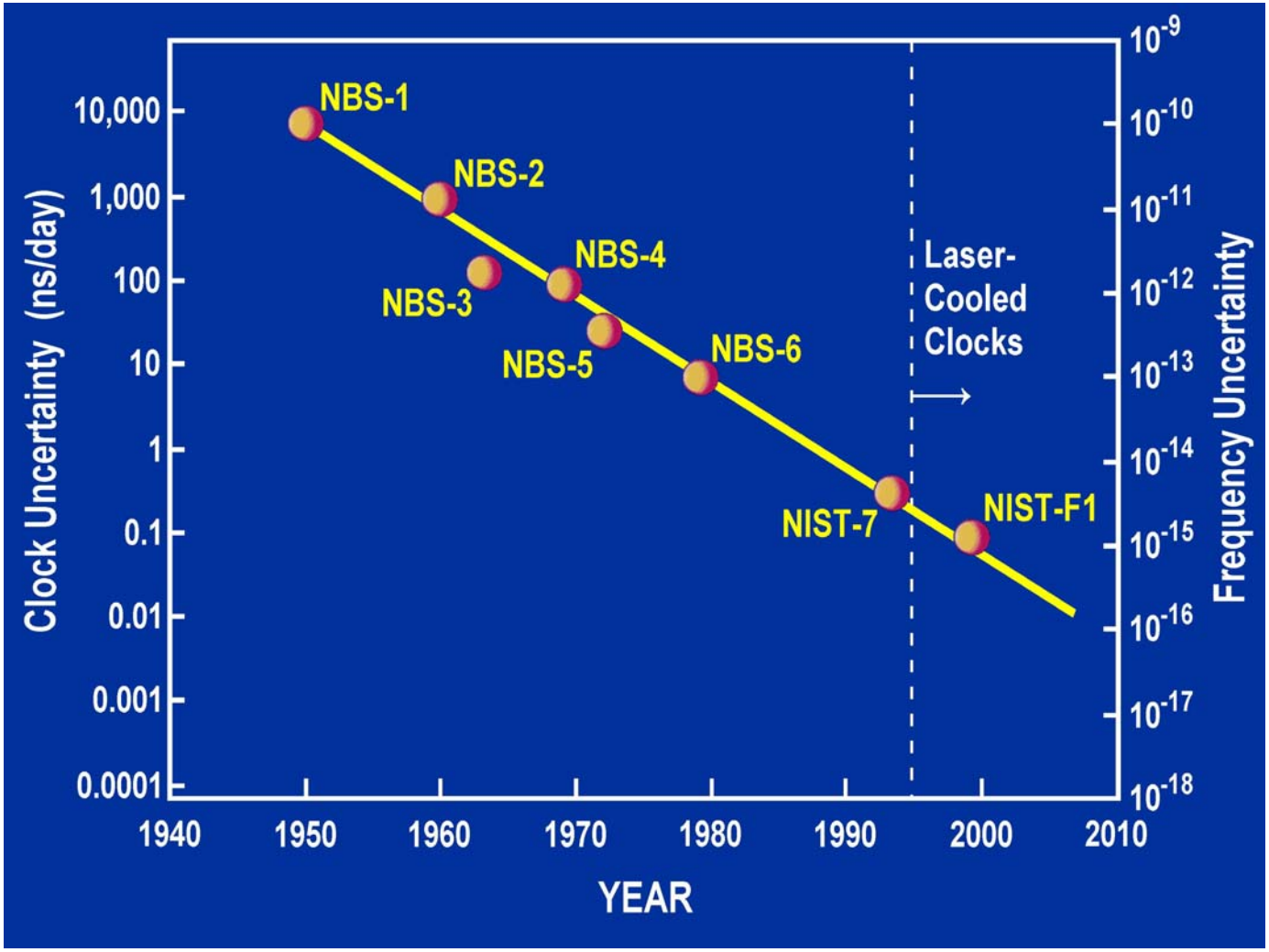
- **Today: NIST F1 - Laser-cooled atomic fountain clock.**
  - 1×10^{-15} , 1 second per 30 million years.
  - Expected improvements to ~1×10^{-16}.



- **Based on science and technology of laser cooling and trapping.**
  - Dave Wineland, first laser cooling of any atomic species, 1978.
  - Bill Phillips, first laser cooling of neutral atoms, 1982.
  - Eric Cornell & Carl Wieman, laser cooling to BEC limit, 1995.



NIST Time and Frequency Standards



- NIST primary standards improve by about a factor of 10 per decade.
- New applications, often unforeseen, always follow improvements in standards.

SI Base Unit	Definition	Realization*	Depends on Second
Second	The second is 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.	10^{-15}	Yes
Meter	The meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second.	10^{-12}	Yes
Kilogram	The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.	10^{-9}	No (future)
Ampere	The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.	10^{-7}	Yes
Mole	The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.	10^{-7}	No (future)
Kelvin	The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.	10^{-7}	No (future?)
Candela	The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.	10^{-3}	Yes

**Approximate relative uncertainty*

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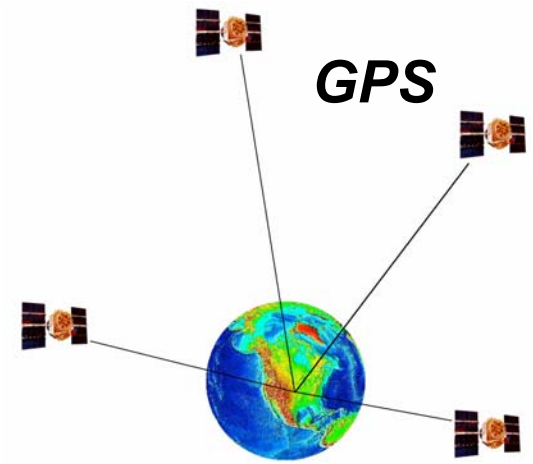
Time and Frequency Standards – Who Cares?

Electrical Power



Navigation, Geodesy

Tests of Physical Theory, Astronomy

All require timing ranging from one millionth to one billionth of a second.

Telecommunications

Applications of Precision Time and Frequency

Consumer
Watches & clocks
Cellular & cordless phones, pagers
Radio & hi-fi equipment
Color TV
Cable TV systems
Home computers
VCR & video camera
CB & amateur radio
Toys & games
Pacemakers
Other medical devices

Automotive
Engine control, stereo, clock
Trip computer, GPS

Industrial
Communications
Telecommunications
Mobile/cellular/portable radio, telephone & pager
Aviation
Marine
Navigation
Instrumentation
Computers
Digital systems
CRT displays
Disk drives
Modems
Tagging/identification
Utilities
Sensors

Military & Aerospace
Communications
Navigation
IFF
Radar
Sensors
Guidance systems
Fuses
Electronic warfare
Sonobouys

Research & Metrology
Atomic clocks
Instruments
Astronomy & geodesy
Space tracking
Celestial navigation

NIST Time and Frequency Services: Radio Broadcasts

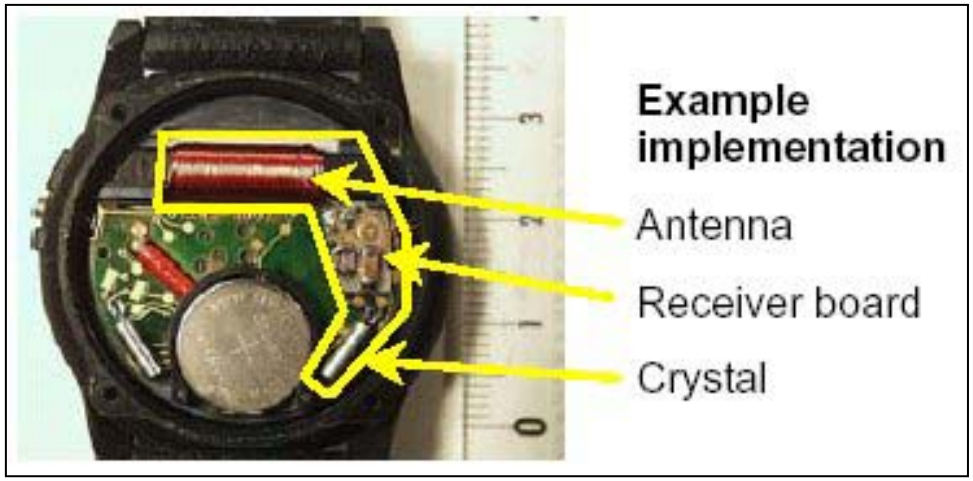
NIST radio station WWVB near Ft. Collins, Colorado: broadcasts of low frequency (60 kHz) time code.

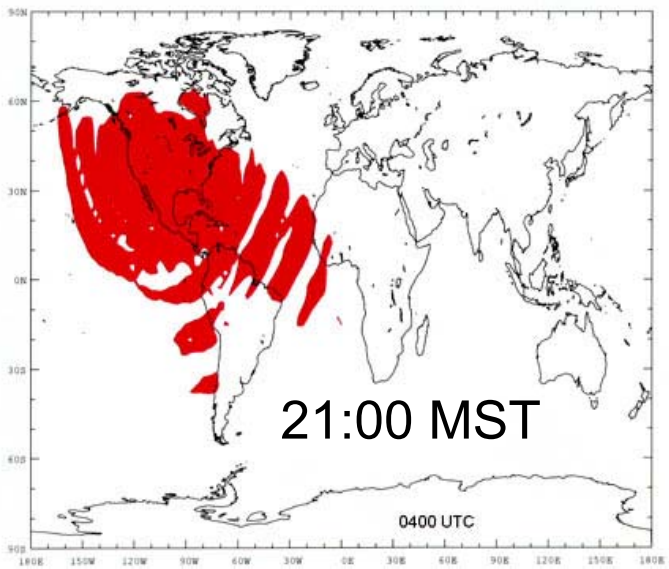
- Millions of WWVB-controlled timepieces in use.
- Sales projected to grow to 30 million new units per year in 2005.

Products Automatically Set by WWVB

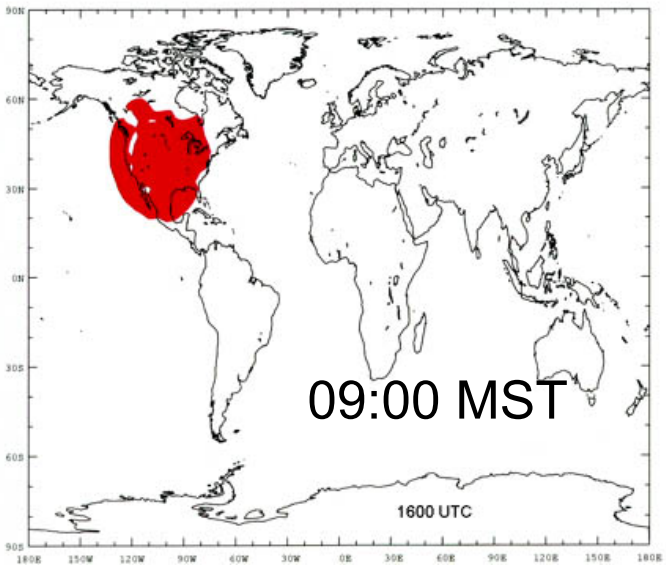
NIST Time and Frequency Services: Radio Broadcasts

WWVB-controlled wristwatch





WWVB coverage.



Broadcast power increased to 50 kW in 1999.

NIST Time and Frequency Services: Radio Broadcasts

Shortwave radio broadcasts (2.5 MHz to 20 MHz)

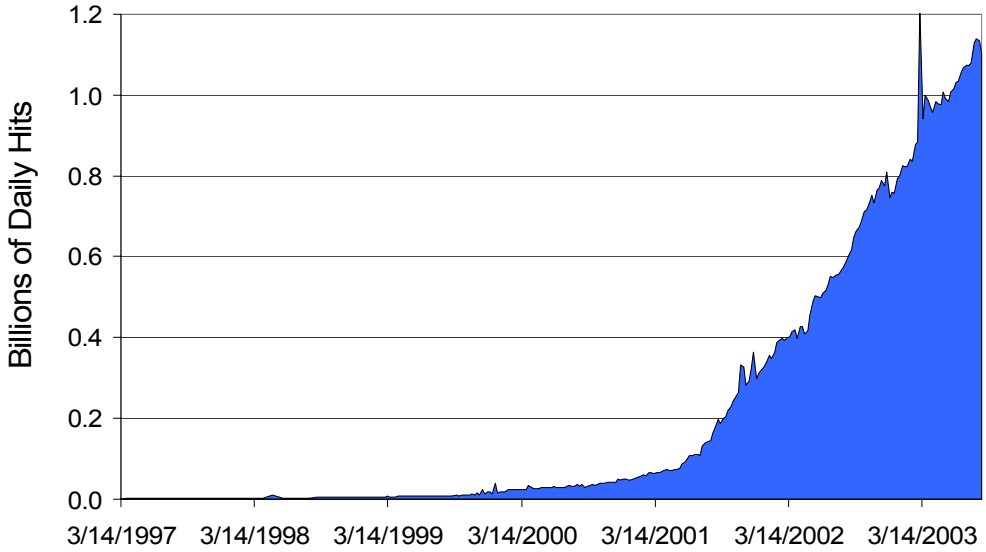
WWV, Ft. Collins, CO

WWVH, Kauai, HI

Information broadcast by both stations:

- Time Announcements
- Standard Time Intervals
- Standard Frequencies
- UT1 Time Corrections
- BCD Time Code
- Geophysical Alerts
- Marine Storm Warnings
- GPS Status Reports

NIST Time and Frequency Services: Network Time



- NIST Internet Time Service – time codes delivered over the Internet.
- More than 1 billion requests per day.
- Free software from NIST.
- Built into latest operating systems: Windows XP, Mac OS X, etc.

- *www.time.gov* web clock.
- Joint NIST/USNO program.
- About 300,000 hits/day.
- More than 1 million hits/day near Daylight Savings Time changes.

NASD/SEC Requires Time-Stamping to NIST Standards

"All computer system clocks and mechanical time stamping devices must be synchronized to within three seconds of the NIST atomic clock."

NASD Rules 6950 through 6957, approved by the SEC March 1998

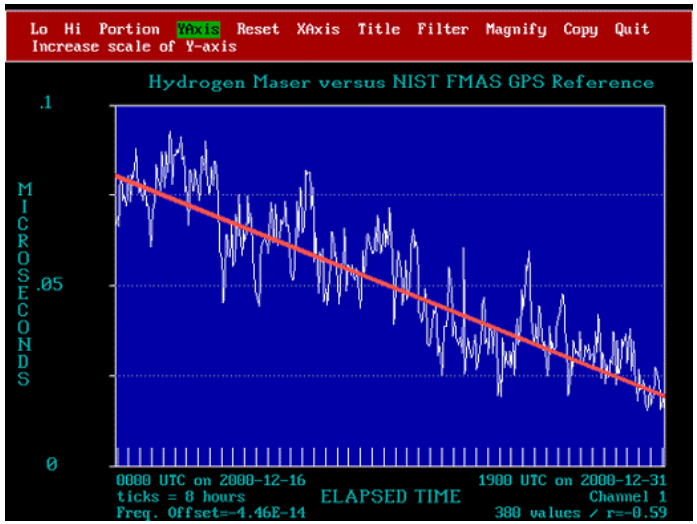
- NASD Order Audit Trail System (OATS).
- Rules apply to more than 600,00 businesses conducting tens of billions of dollars of transactions daily on NASDAQ.
- All NASD member electronic and mechanical time-stamping devices must remain accurate to within 3 seconds of NIST time during the trading day.
- NIST ACTS (dial-up service), Internet time service, radio stations, etc.

NIST Frequency Measurement Service

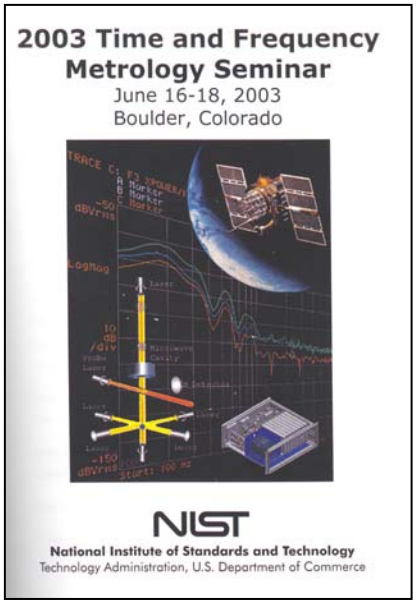
- Full measurement system ("black box") provided to about 60 customers with the most stringent demands.
  - Military and civilian calibration labs.
  - Instrument manufacturers.
  - Others.

- Frequency standard provided by NIST through GPS.

- NIST continually monitors customer's system through the Internet and provides proactive assistance to customer when problems occur –often before the customer knows there is a problem.



NIST Time and Frequency Services

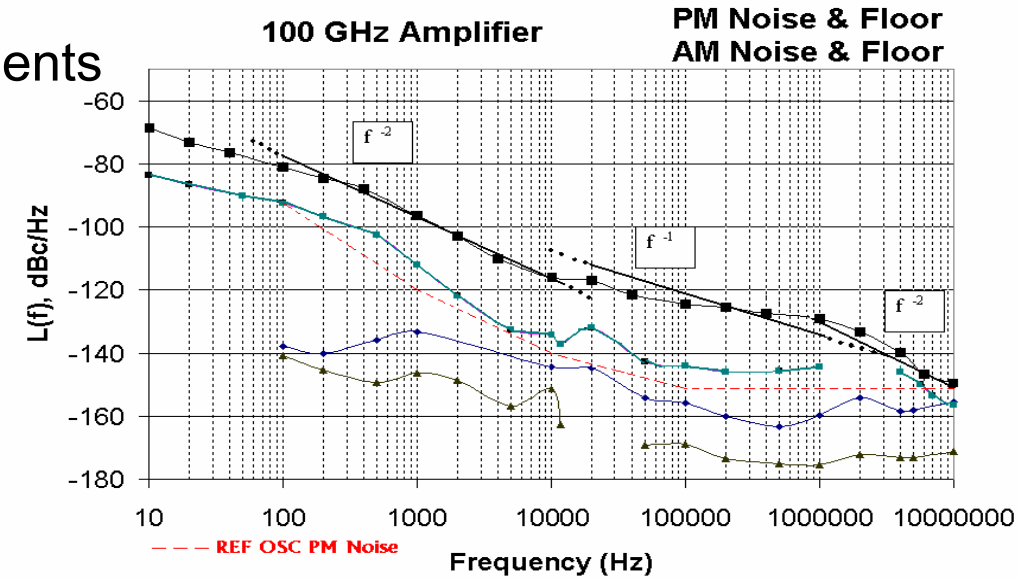


Division experts train time and frequency users and researchers:

- Annual Metrology Seminar
  - Industry
  - Military
  - Universities
  - National Labs
- Tutorials and Short Courses at conferences

Noise and spectral purity measurements

- **Cellular Telephone Systems**
- **Optical Telecommunications**
- **Advanced Radar**
- **Secure Communications**
- **Navigation Systems**
- **Aerospace Systems**
- **Primary Frequency Standards**
- **Josephson Volt Standards**



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Optical Clocks

Frequency uncertainty ~ $\frac{\Delta f}{f_0} \cdot \frac{1}{t} \cdot \frac{1}{\sqrt{N}}$

f_0 = transition frequency

Δf = linewidth

t = observation time

N = number of atoms

$$\frac{f_0 \text{ optical}}{f_0 \text{ microwave}} \approx \frac{10^{15}}{10^{10}} \approx 10^5$$

Laser-cooled Trapped Single Ions

- Narrow linewidth
- Long observation times
- *Small number of atoms*

Hg^+ , Yb^+ , Sr^+ , In^+

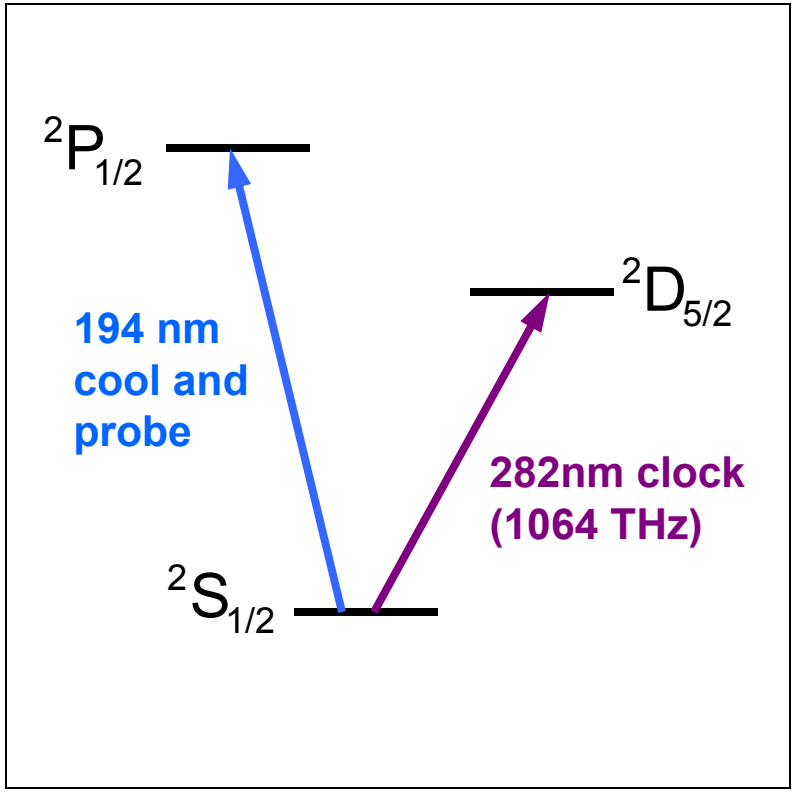
Laser-cooled Neutral Atom Clouds

- Large number of atoms 10^6 or more
- High signal/noise
- *Broader linewidths*

Ca, Sr, Mg, H

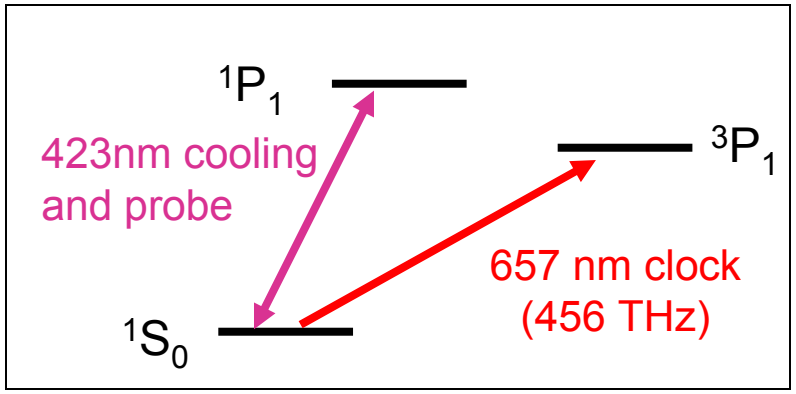
NIST Optical Clocks

$^{199}Hg^{+}$



- Single mercury ion
- Linewidth decreases with longer observation times: ~6 Hz at 0.1 sec

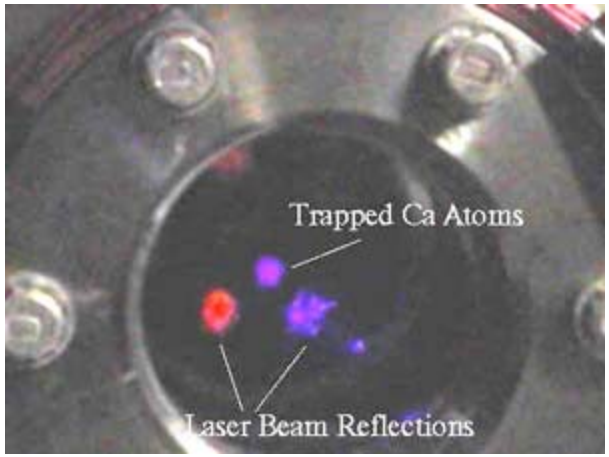
^{40}Ca



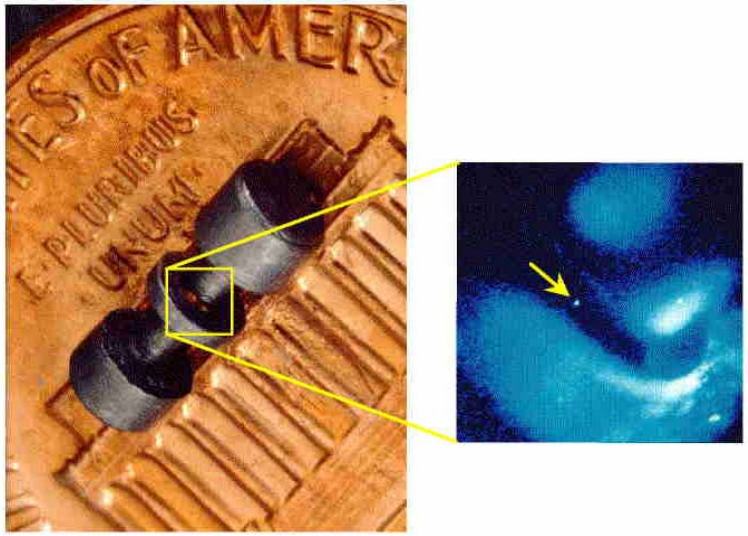
- ~10 million atoms confined in a magneto-optical trap
- 2mK cooling with 423nm line
- 10 μK atoms with second stage cooling

NIST Optical Clocks

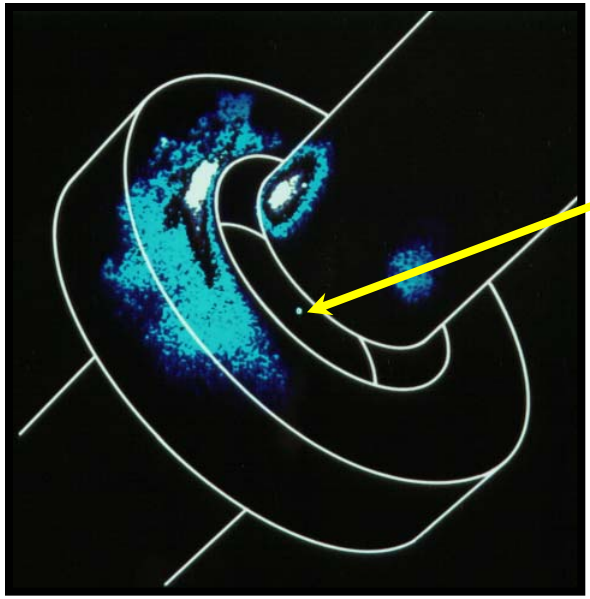
- Optical clocks have the *potential* for accuracy at the 10^{-18} level, 1000 times better than NIST F1.
- Likely to take many years to realize that potential.



Laser-cooled calcium trap.



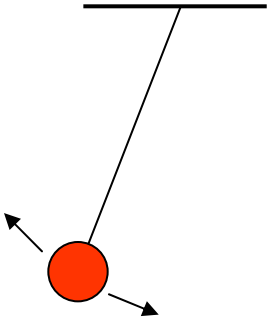
Single mercury ion trap.

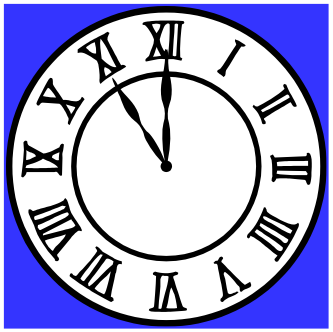


Single Ion.

Optical Clocks – Challenge

Oscillator + **Counting Mechanism**





Earth Rotation
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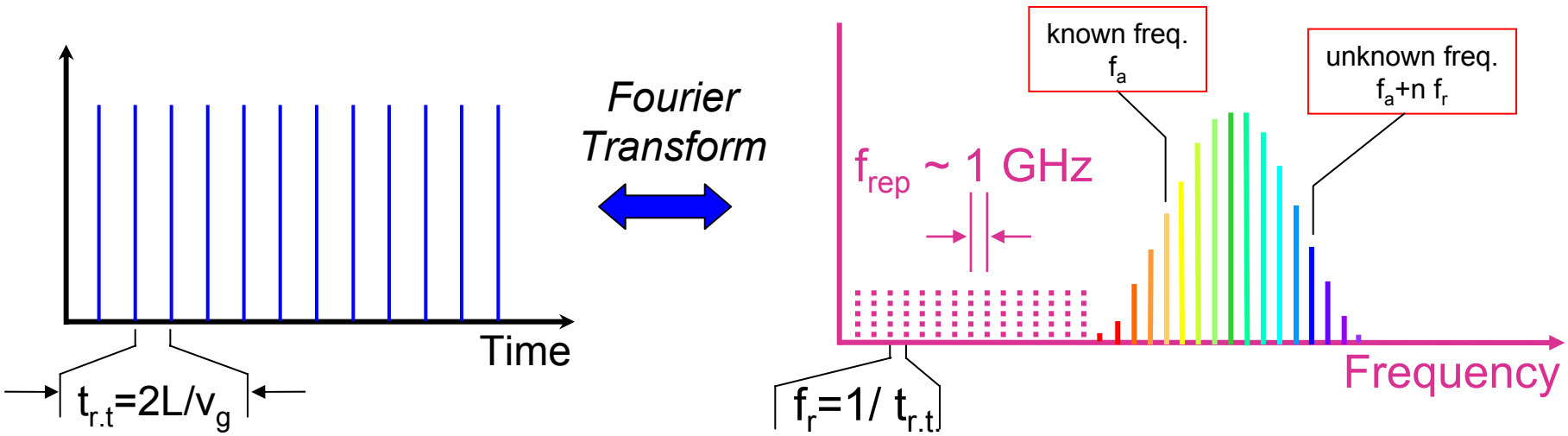
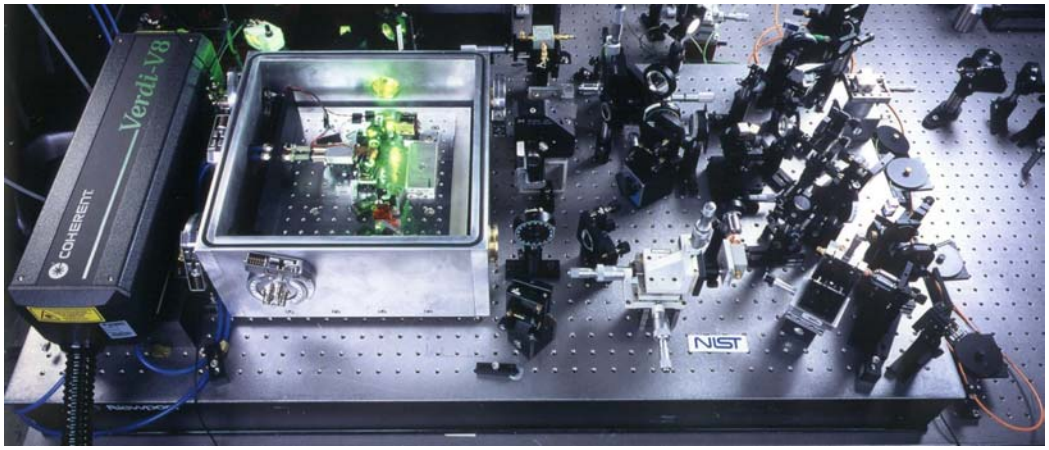
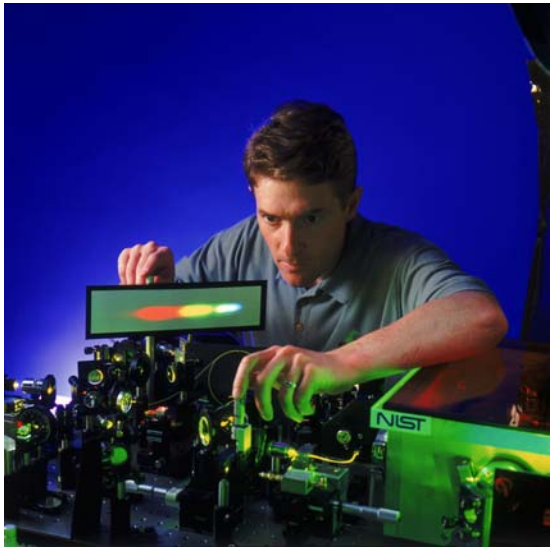
Microwave clock (10^{10} Hz) — Electronic Counter

Optical clock (10^{15} Hz) — ???

“Gears” of the Optical Clock – Femtosecond Laser Frequency Combs

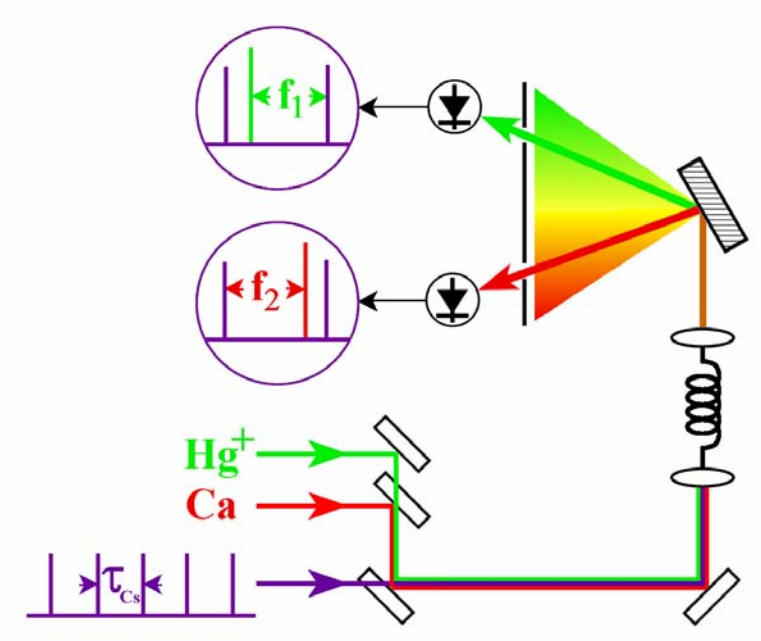


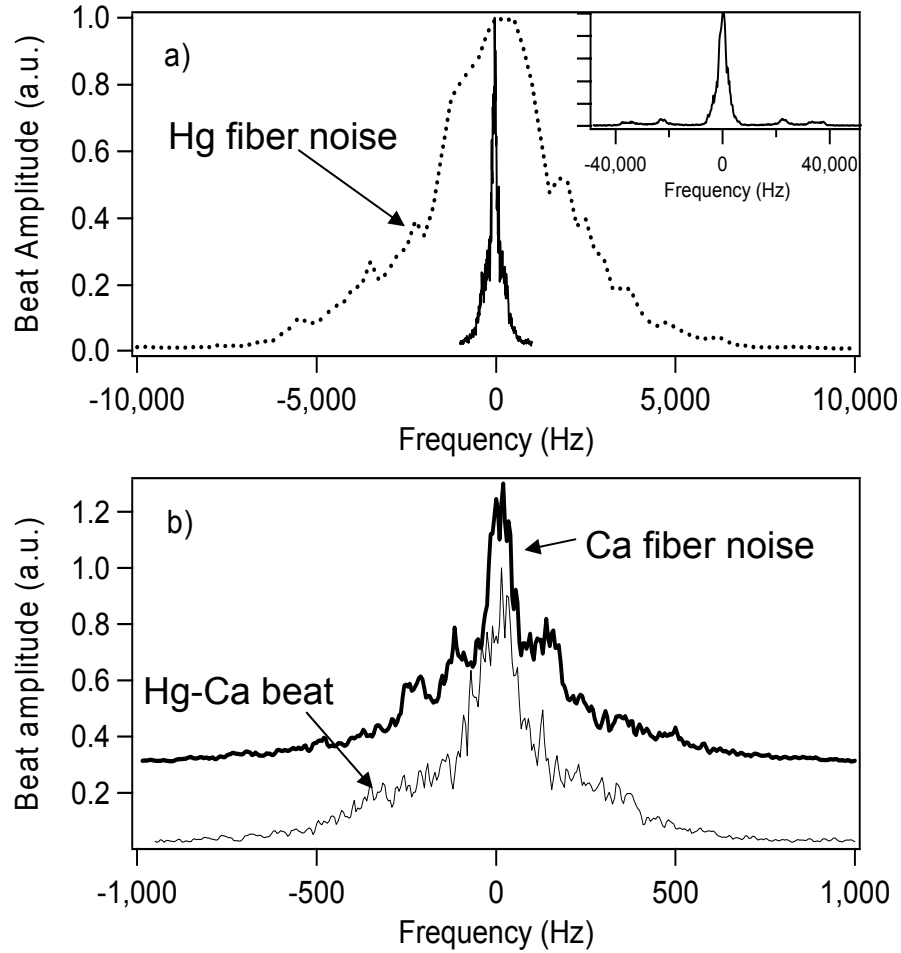




Hansch (Garching, 1999), Hall and Cundiff (JILA, Quantum Physics Division), Time and Frequency Division

Frequency Comb – Connect Optical and Microwave Standards

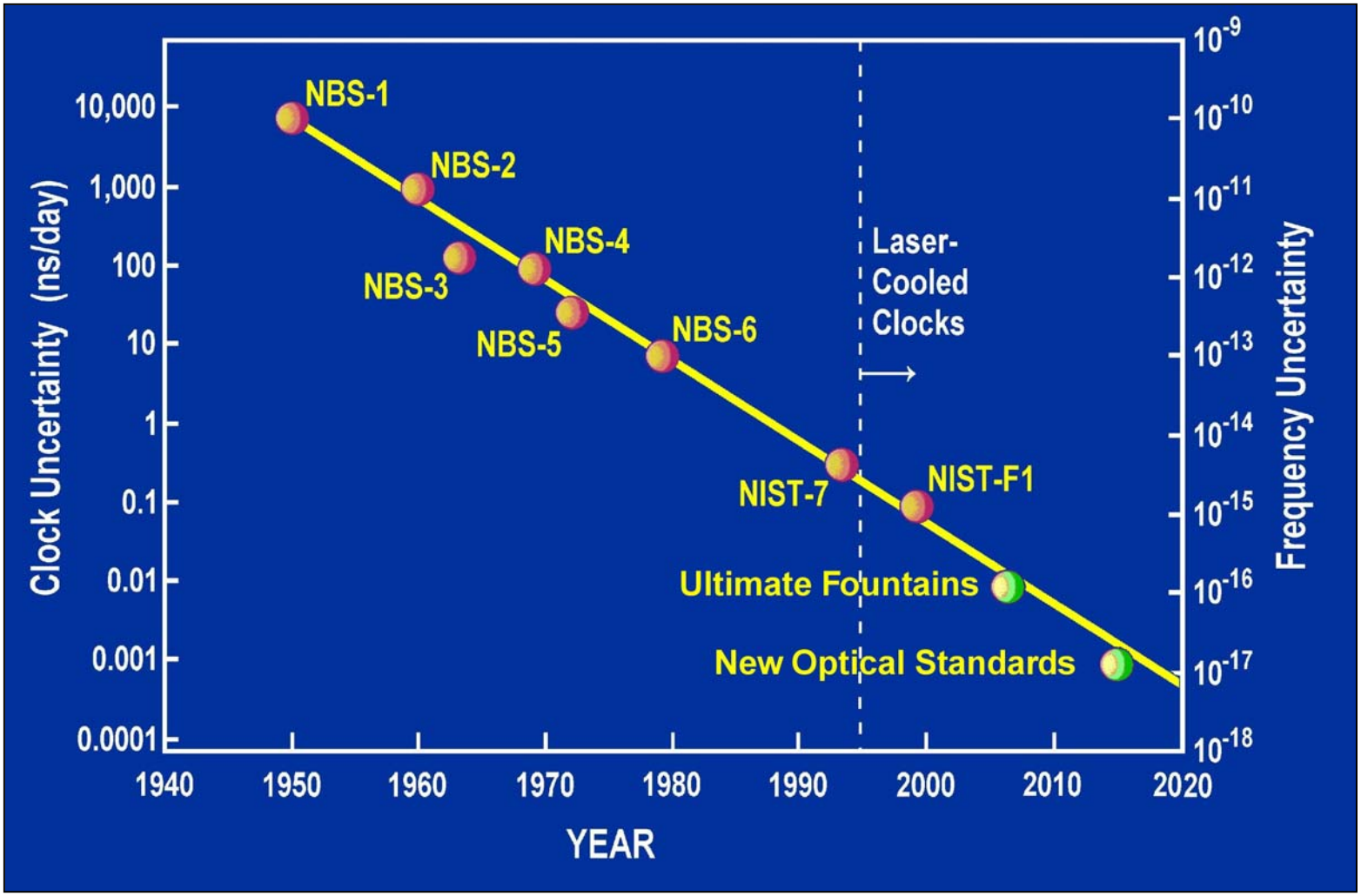




- Direct comparison of cesium standard (fountain clock, 0.009 THz) to mercury ion clock (532 THz), and to calcium atom clock (456 THz).
- Direct intercomparison of mercury ion and calcium clocks.

"Beat" between Ca and Hg across 76 THz

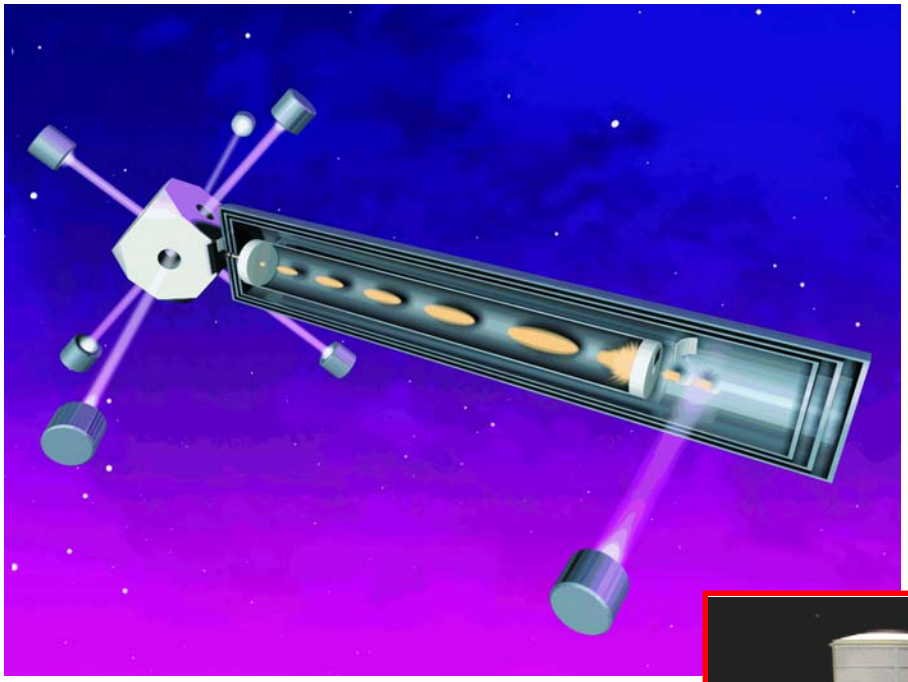
NIST Time and Frequency Standards: Optical Clocks



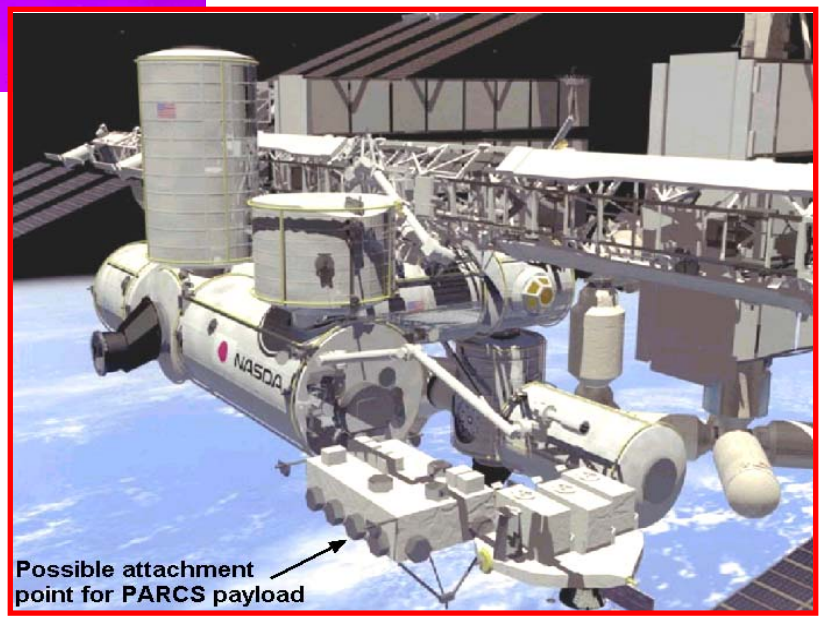
- On track for continuing improvements.
- New applications, often unforeseen, always follow improvements in standards.

Future Clocks: Laser-Cooled Space Clock

Primary Atomic Reference Clock in Space

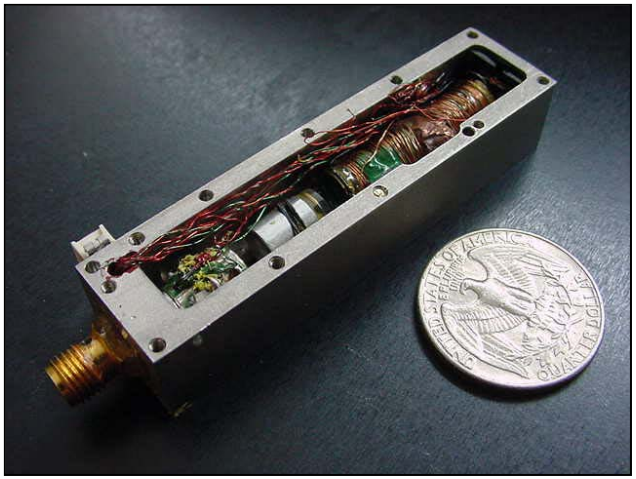


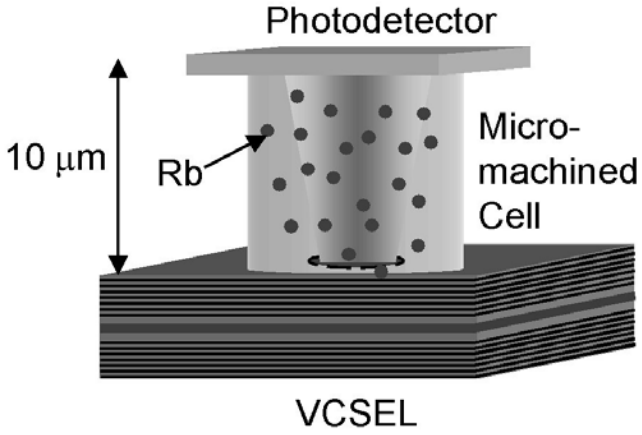
- Uncertainty less than 1×10^{-16}.
- Flight 2008 (?) on International Space Station.
- NIST, JPL, others.



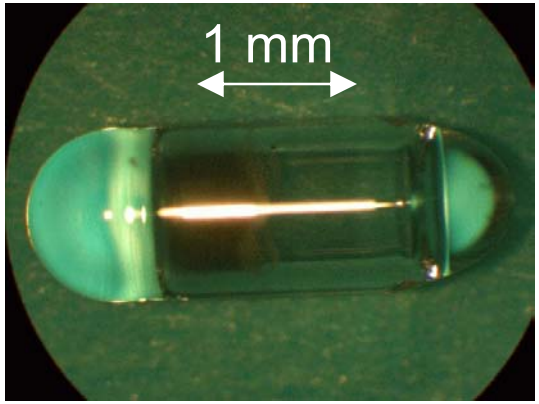
- Tests of relativity.
- Improved accuracy of the second.
- Studies of the Global Positioning System.

Future Clocks: Miniature Atomic Clocks





- New approach (coherent population trapping) eliminates need for bulky microwave cavity.
- Working on ~1 mm^3 “chip scale” design.
- Applications include:
  - Telecommunications.
  - Encrypted communications.
  - Inertial guidance systems.



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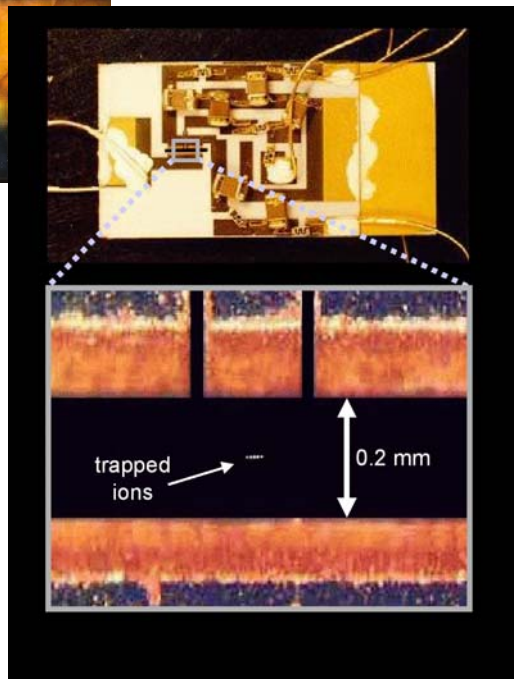
  - High accuracy automated frequency measurements by satellite with Internet control.

- **Research on future clocks.**
  - Laser-cooled ion and neutral atom optical clocks – potential for 10^{-18} accuracy.
  - Femtosecond frequency combs to directly link microwave and optical standards.
  - Miniature atomic clocks (~1 cm^3).

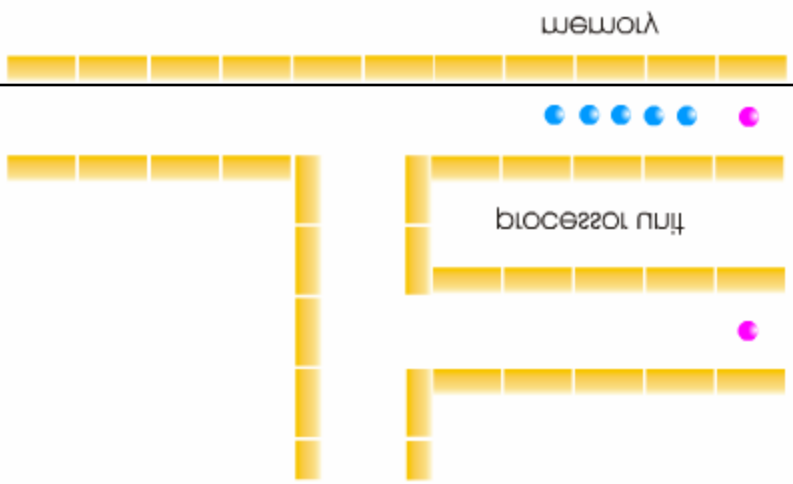
- **Quantum state engineering.**
  - Unique expertise in quantum state manipulation of trapped ions.
  - Future time and frequency standards.
  - NIST quantum information program.

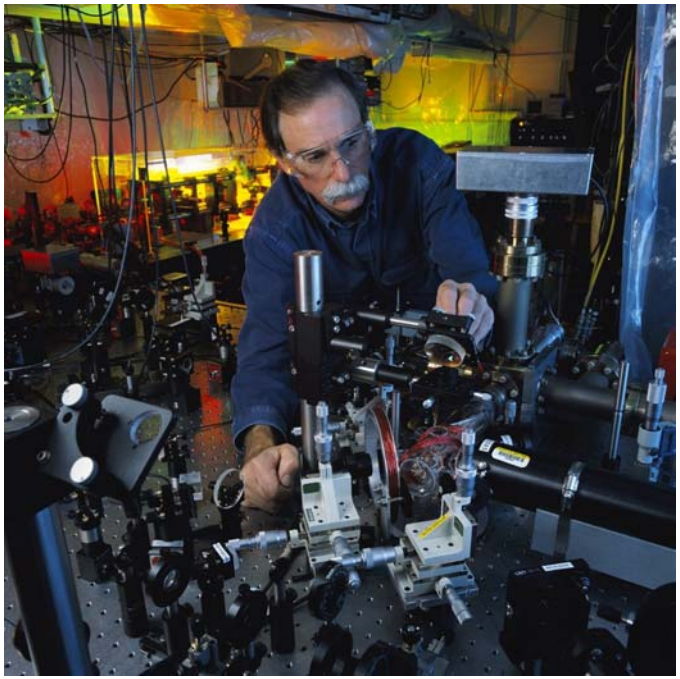
Quantum State Engineering



- Extremely powerful computers.
- Secure communications.
- Tests of fundamental quantum mechanics.
- Potential new clocks.
- NIST Quantum Information Program:
  - Physics Lab.
  - Electronics & Electrical Engineering Lab.
  - Information Technology Lab.
  - Top quantum information theorist joined NIST-Boulder/CU this fall.

Quantum Computing





Cooling ion, $^{24}Mg^{+}$

Qubit ion, $^{9}Be^{+}$

- Demonstration of all components of a scalable quantum computer using trapped ions.
- Only successful approach thus far.

NIST Time and Frequency

Unique aspects of NIST time and frequency:

- **Time is one of the seven fundamental SI units.**
  - Three of the other six units depend directly on time (length, ampere, candela).
  - Two more likely to depend on time in the future (kilogram, mole).

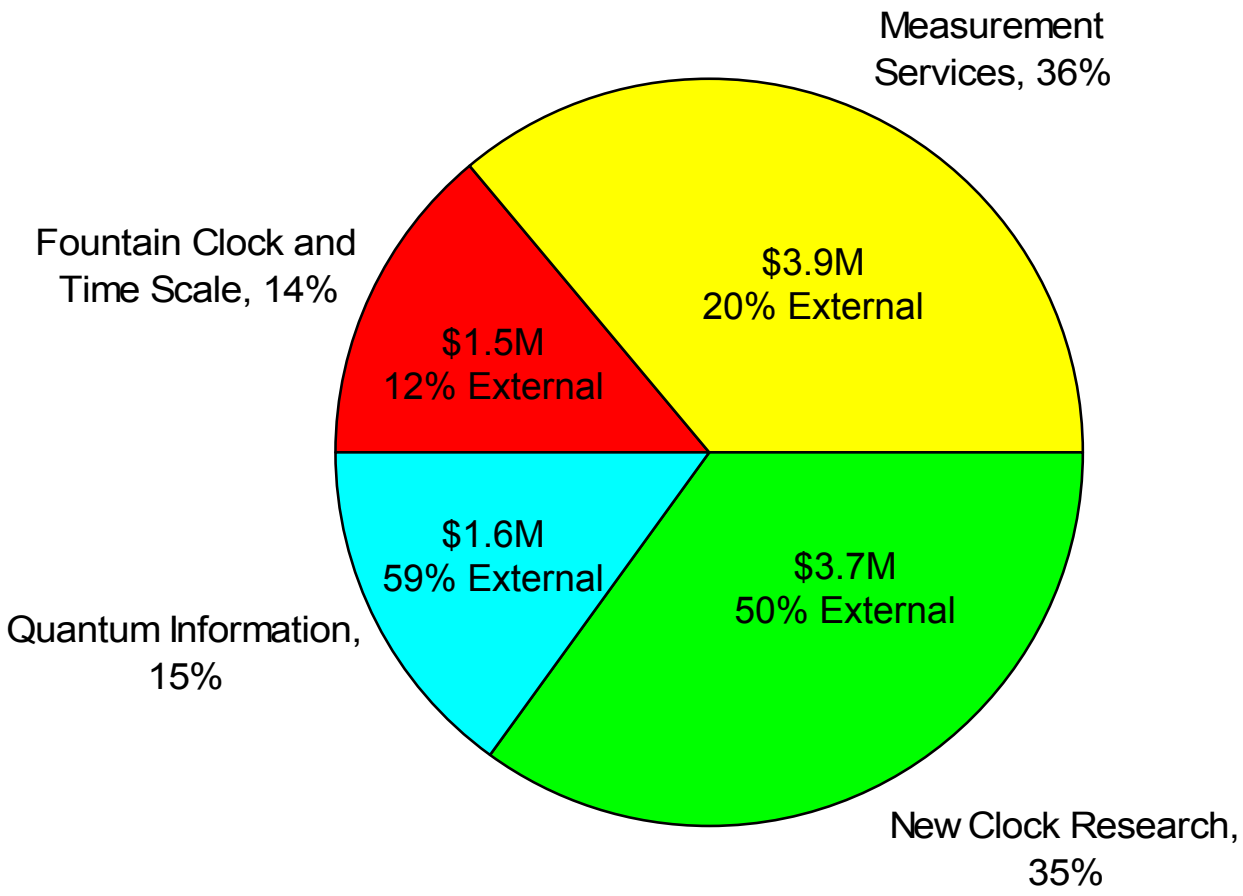
- **Time is by far the most accurately known fundamental SI unit.**
  - 1000 times more accurate than length. 10^{12} more accurate than candela.

- **Division's program is fully integrated and focused.**
  - From delivery of services to general public to operation of world's best primary standards to world-leading research on future standards.

- **Time is by far the most heavily used NIST measurement service.**
  - 1 billion requests per day for NIST Internet Time Service.
  - By 2005, annual sales of 30 million WWVB-synchronized timepieces.
  - About 10 million users per month for NIST/USNO web clock (www.time.gov).

- **Time is arguably the NIST function best understood and most widely recognized by the general public.**
  - Many members of the public equate NIST/NBS with the "atomic clock."
  - Everyone intuitively understands time and the importance of accurately measuring time.

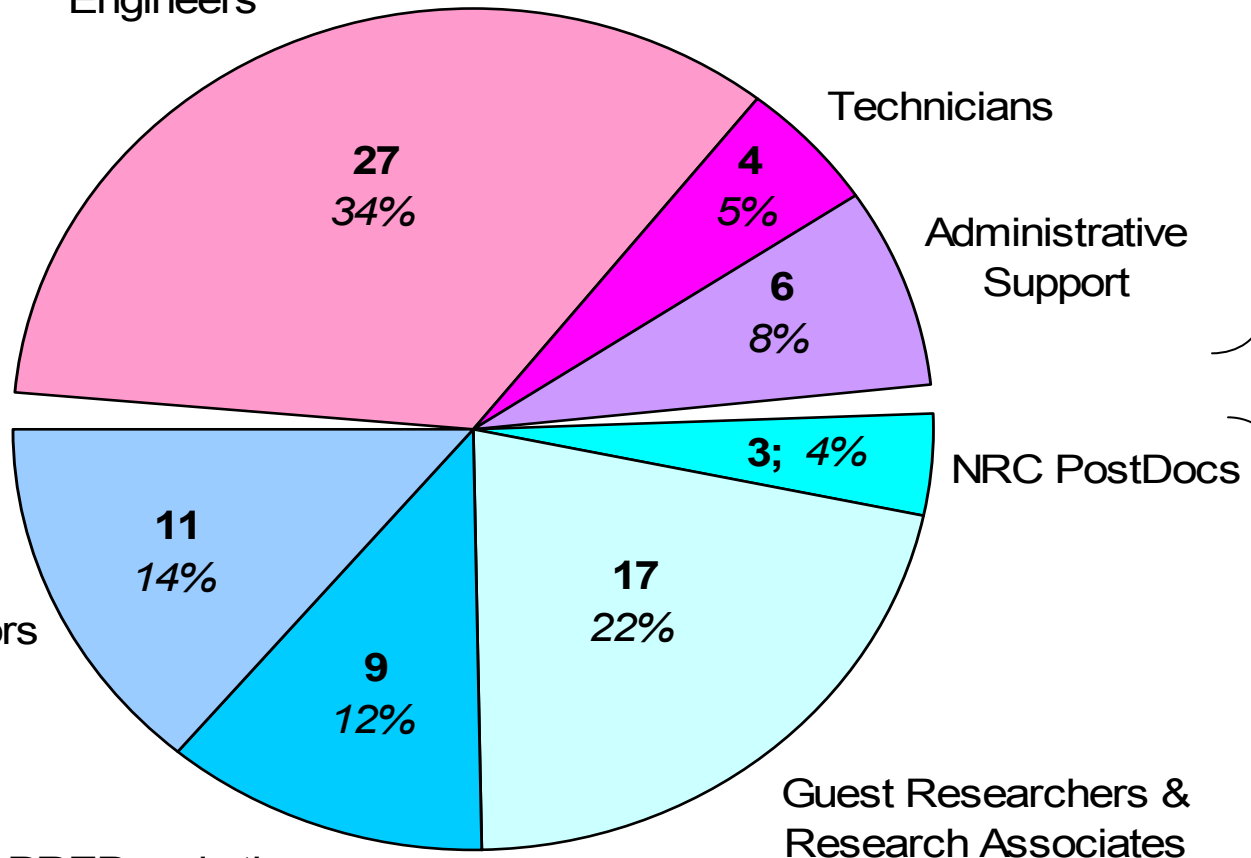
NIST Time and Frequency Division Estimated Budget



$10.7M total program budget (FY03)*
36% external

**Does not include overhead functions*

NIST Time and Frequency Division Staff



Permanent NIST Staff
37 *(48%)*

Associates*
40 *(52%)*

**Numbers vary throughout the year*

Time and Frequency Division – Examples of Collaborations with Other NIST Programs

- **Wavelength metrology for fiber optic telecommunications.**
  - Electronics & Electrical Engineering Lab's Optoelectronics Division and Time and Frequency Division.
  - Precise frequency/wavelength metrology for 1300 to 1500 nm range using optical frequency comb.

- **Research on length metrology.**
  - Manufacturing Engineering Lab's Precision Engineering Division and Time and Frequency Division.
  - Explore use of "factory floor" optical frequency comb calibrated against GPS frequency standards.

- **Quantum Information.**
  - Extensive program involving Electronics & Electrical Engineering Lab, Information Technology Lab, and several Physics Lab Divisions.

- **Laser metrology.**
  - JILA's Quantum Physics Division and Time and Frequency Division (both of the NIST Physics Lab).
  - Many projects.
  - Highly productive exchange of students, postdocs, staff, ideas.

NIST Time and Frequency Division – Customer Focus

- **Broad base of customers.**
  - Daily, extensive use of Division services by general public. Highest volume, lower accuracy.
  - Broad use for industry and military applications. High volume, moderate to high accuracy.
  - Crucial use in scientific applications. Lower volume, highest accuracy.

- **Customer surveys.**
  - Response data posted on Division website: tf.nist.gov

- **Seminars, short courses, tutorials.**
  - Industry, military, national labs, researchers.
  - Feedback on surveys and direct interactions.

- **National and international standards-developing organizations.**
  - Time and frequency.
  - Telecommunications.
  - GPS.
  - IT.
  - Potential opportunities for broader productive participation.

- **Vigorous scientific publication, conference, and seminar programs.**

NIST Time and Frequency Division – Technical Challenges

- **Continued improvement of primary standards ("atomic clock").**
  - NIST F2 expected to reach 10^{-16} uncertainty.
  - Optical clocks expected to reach 10^{-17} to 10^{-18} uncertainty.
  - 10^{-17} corresponds to relativistic frequency shift at walking speed; 10^{-18} corresponds to gravitational frequency shift by changing elevation 1 cm.

- **Dissemination of future highly accurate standards.**
  - Current 10^{-15} uncertainty at limit of existing satellite time transfer technology.
  - Research to improve systems planned. Finalist FY2004 Competence proposal to improve satellite time and frequency transfer – not funded.
  - Explore optical fiber transmission using frequency combs.

- **Responsiveness to new applications of time and frequency standards.**
  - Increasingly distributed communications/information networks, such as "Smart Personal Objects Technology," cell phone location systems, RF product ID systems, etc.
  - Flexibility to respond to unforeseen applications.

NIST Time and Frequency Division – Program Challenges

- **People.**
  - Increasing reliance on Associates rather than permanent staff is a challenge and an opportunity.
  - Key technical leadership replacements.
  - Retention of top early career scientists and engineers.

- **Resources.**
  - Division appropriated funds (STRS) eroding.
  - Continuity of external funding is uncertain, and much federal funding is shifting from longer-term research to shorter-term technology./product development.

- **Facilities.**
  - 50-year-old Boulder facilities inadequate to support cutting edge Division research.
  - Module-by-module renovations too costly, too time-consuming, too ineffective.

- **Customer focus.**
  - Developing productive relationships with new potential customers, such as electric power industry, to better understand and respond to their technical needs.
  - Capitalizing on the NIST “brand” for accurate time.

- **Planning.**
  - Continue and strengthen successful short-term and long-term planning to meet technical goals and customer needs.

Time and Frequency Division Customer Survey

Address http://tf.nist.gov/timefreq/survey/survey.htm Go Links

Physics Laboratory
Time & Frequency Division

NIST
National Institute of Standards and Technology

Home
Welcome
Current Time
Exhibits
FAQ
Glossary
Links
Publications
Staff

Radio Stations
WWV
WWVH
WWVB

Services
Computer Time
Telephone Time
Calibrations
Seminars
Survey Results

Standards
NIST-F1
Space Clock
History

Results of 2001 Customer Satisfaction Survey

The Time and Frequency Division of the National Institute of Standards and Technology conducted a customer use survey from April through September, 2001. The bar graphs on the following pages illustrate the results of the survey.

Three methods were used to advertise the availability of the survey. A voice announcement was placed on the WWV / WWVH high frequency broadcast, advertisements were placed in several trade magazines dealing with time-and-frequency technology, and a link was established from this web site. Nearly 15,000 people responded to this survey with the vast majority of submissions arriving via the internet. This more than doubles the responses received in the last customer satisfaction survey conducted by the Time and Frequency Division in 1987.

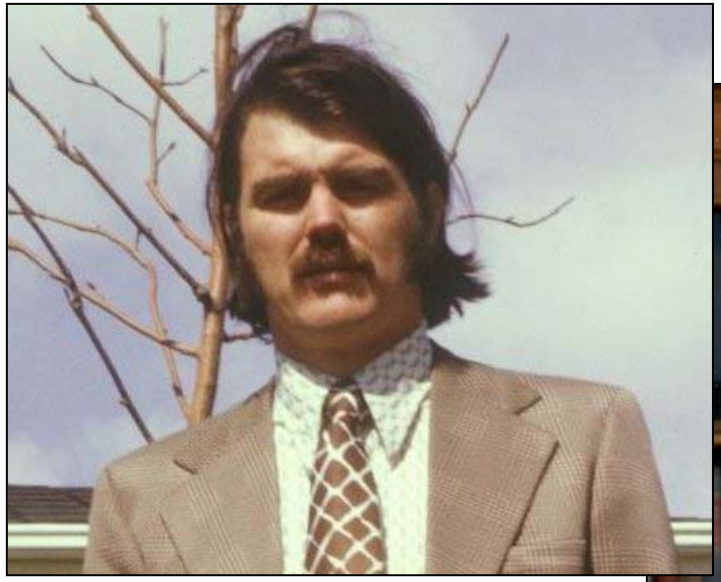
Please keep in mind that a large segment of our customers were difficult to alert to the availability of the survey. These include users of the WWVB low frequency broadcast, the Internet Time Service and the Automated Computer Time Service. We have direct evidence of the popularity of these services and yet the survey does not directly reflect this due to the low participation rate of these customers.

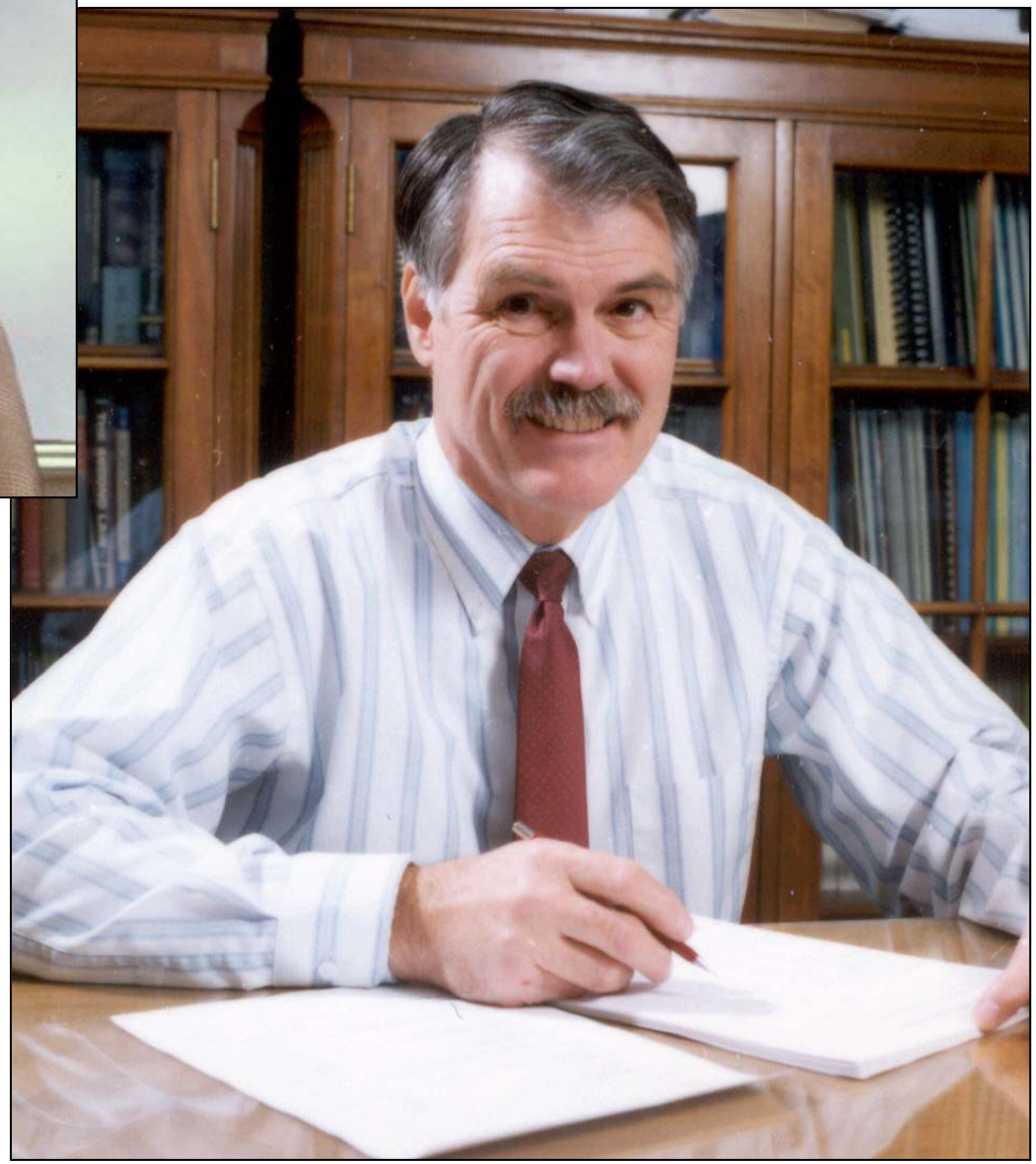
Survey Results

- WWV and WWVH
- WWVB
- Overview of Other Services
  - -- ACTS
  - -- Internet Time Service
  - -- Web Page
  - -- Telephone Time-of-Day Service
- Miscellaneous Questions
- Customer Data

Nearly 15,000 responses.
About 2/3 “consumer” applications, about 1/3 “technical” applications.

- *“You're doing a great job. Wish my income taxes were spent as wisely elsewhere in the government!”*
- *“Wonderful service. Have used it for years. One of the best functions the US Gov't furnishes.”*
- *“Great service - if more people knew about it, it would be used more.”*





Don Sullivan

- Joined NBS 1967.
- Became Time and Frequency Division Chief 1984.
- Retired 2003.