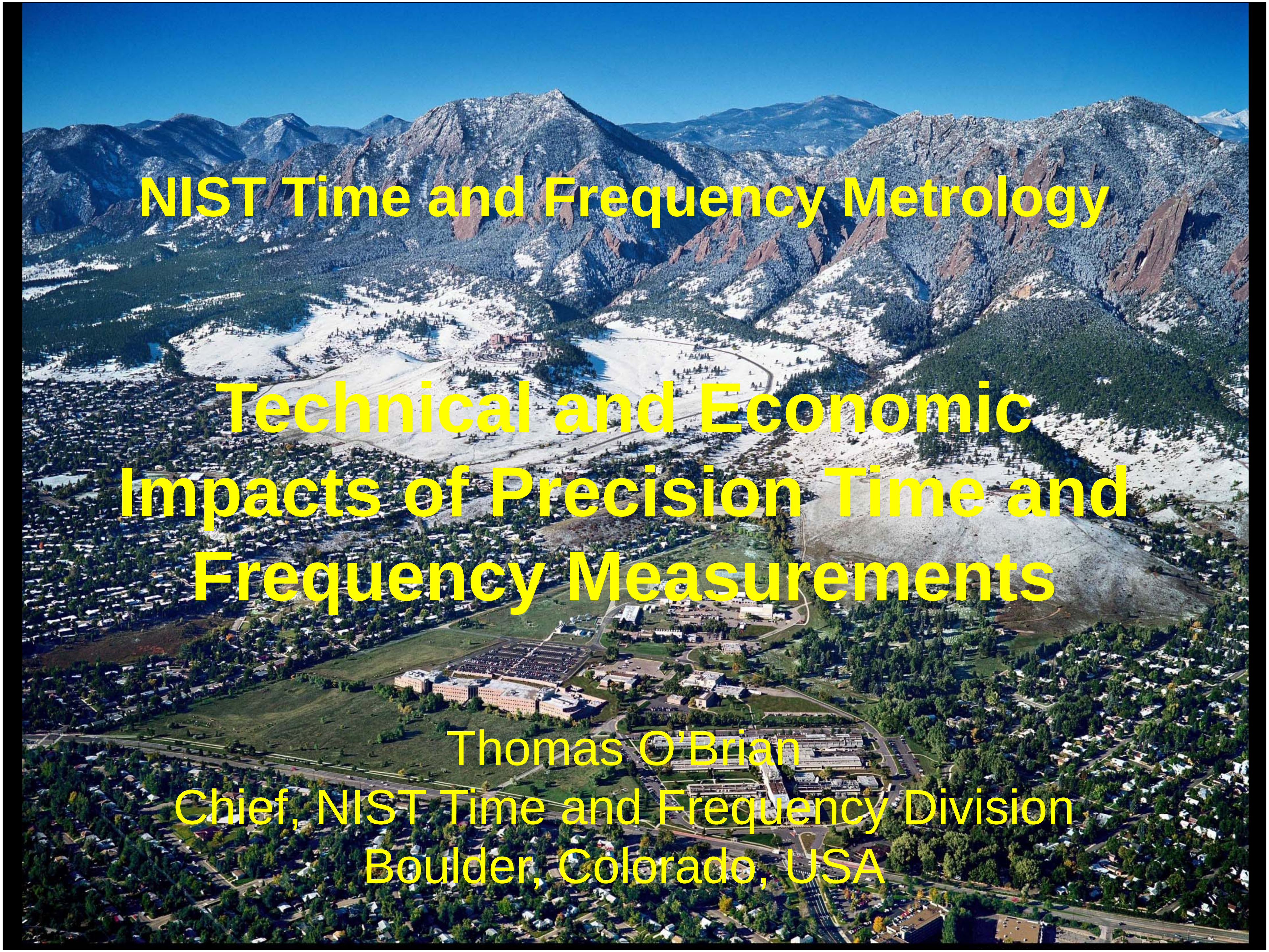
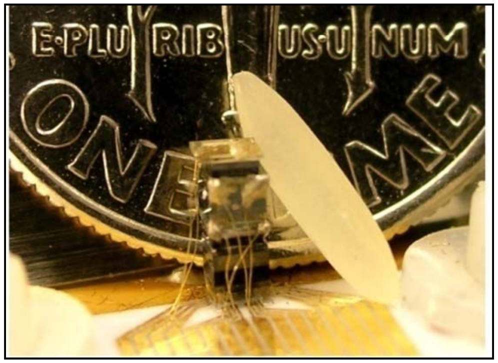


NIST Time and Frequency Metrology

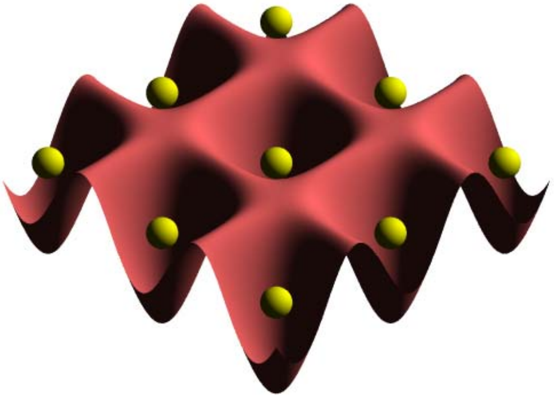
Technical and Economic Impacts of Precision Time and Frequency Measurements

Thomas O'Brian
Chief, NIST Time and Frequency Division
Boulder, Colorado, USA

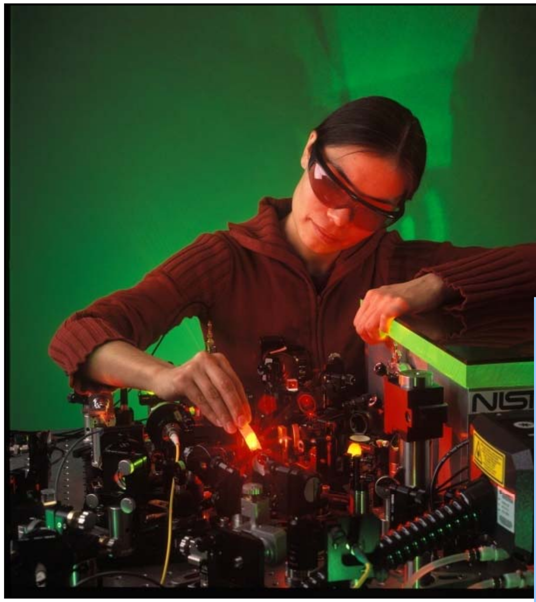
NIST Time and Frequency Division, Boulder, Colorado, USA

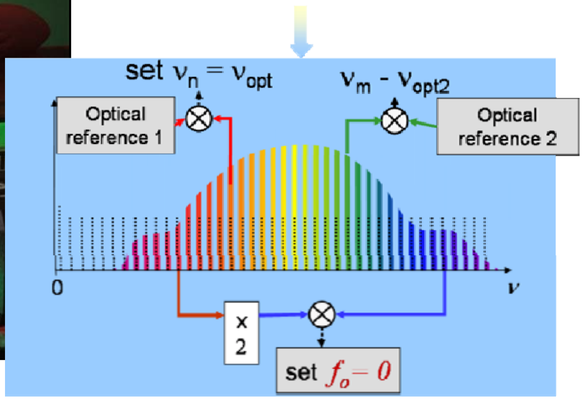


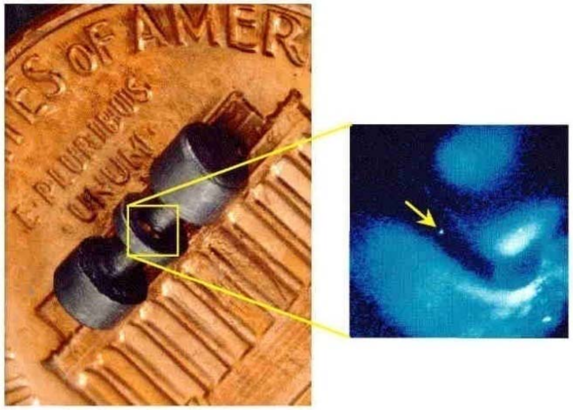
Develop and distribute the highest accuracy time and frequency measurements to support commerce, research, and the general public.



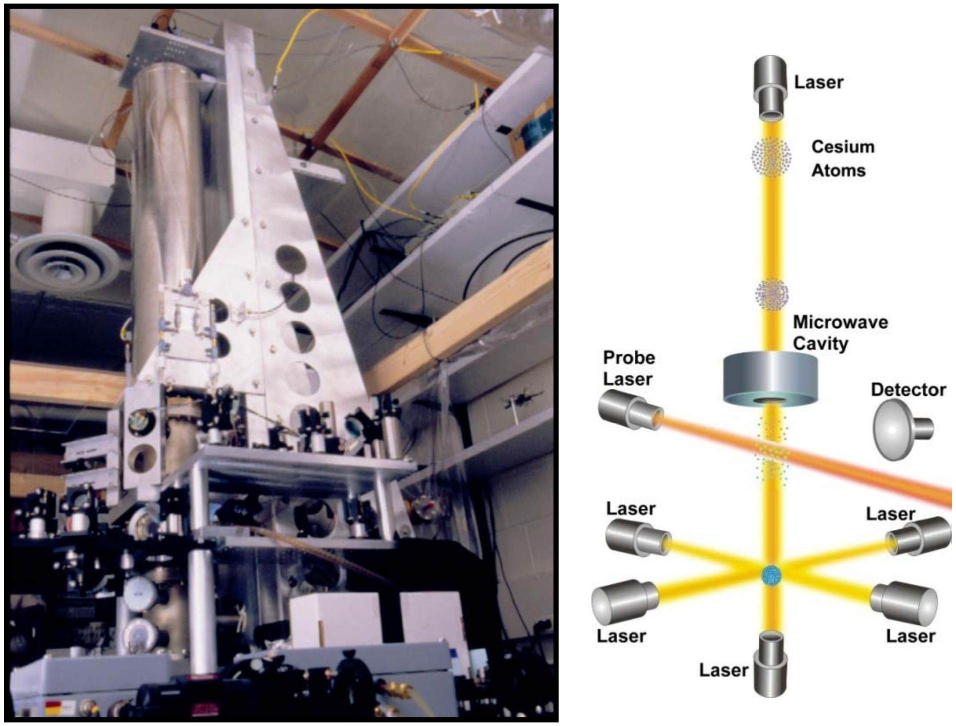
tf.nist.gov







NIST-F1 Atomic Fountain Clock
Primary Frequency Standard for the United States



NIST-F1 laser-cooled fountain standard
"atomic clock"

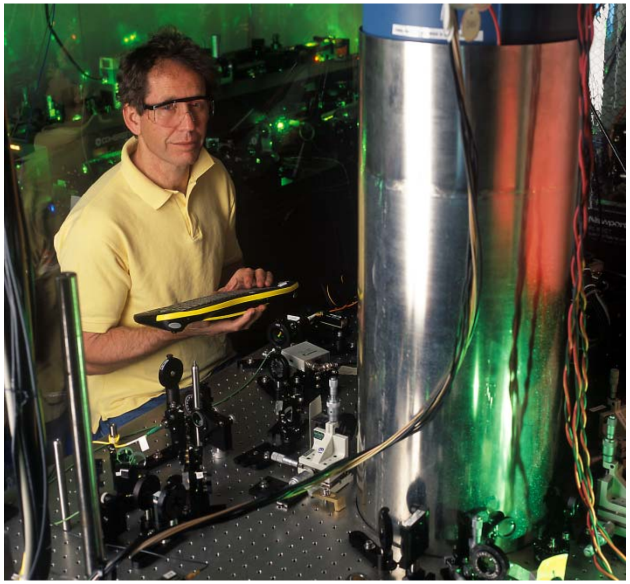
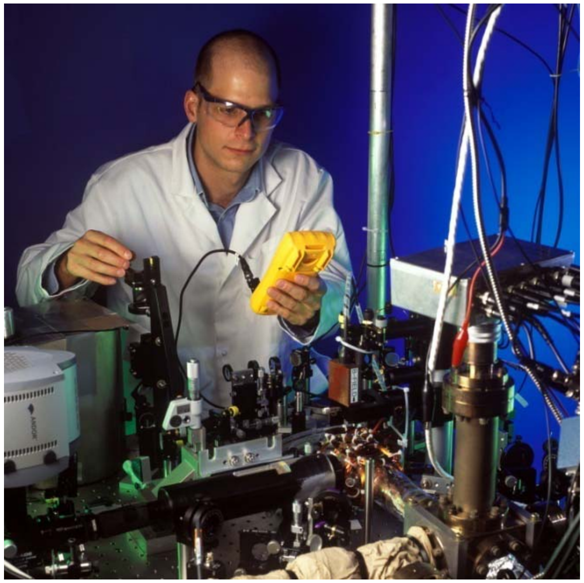
1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom.

Current accuracy (uncertainty):

- 3×10^{-16} second.
- 25 trillionths of a second per day.
- 1 second in 100 million years.

Equivalent to measuring distance from earth to sun (150,000,000 km) to uncertainty of about 45 μm (less than thickness of human hair).

NIST Mercury Ion Clock and Aluminum Ion Logic Clock Research Frequency Standards

- Research atomic clocks at NIST already at 8 x 10^{-18} uncertainty.
- 1 second in about 4 billion years.
- Rapidly improving.

Equivalent to measuring distance from earth to sun (150,000,000 km) to uncertainty of about 1 μm (size of a bacterium).

Why worry about precision time and frequency metrology?

Impacts of Accurate Timing and Synchronization

Telecommunication Networks

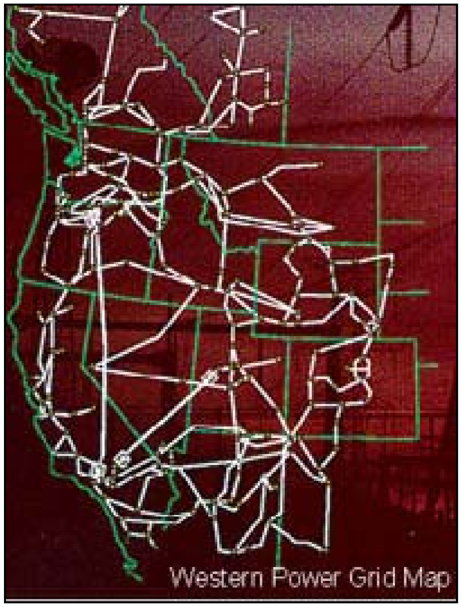
Synchronization to about 1 microsecond per day (10^{-11}) for Stratum 1 telecommunications.

Global wireline and wireless revenue in 2007: $US 1.65 trillion.
Projected global wireline and wireless revenue in 2012: $US 2.3 trillion.
(2/3 of projected 2012 revenue in wireless systems)

Source: Verizon

Impacts of Accurate Timing and Synchronization

Electric Power Generation and Distribution



Synchronization to about 1 microsecond per day (10^{-11}) for efficiency, fault location, etc.

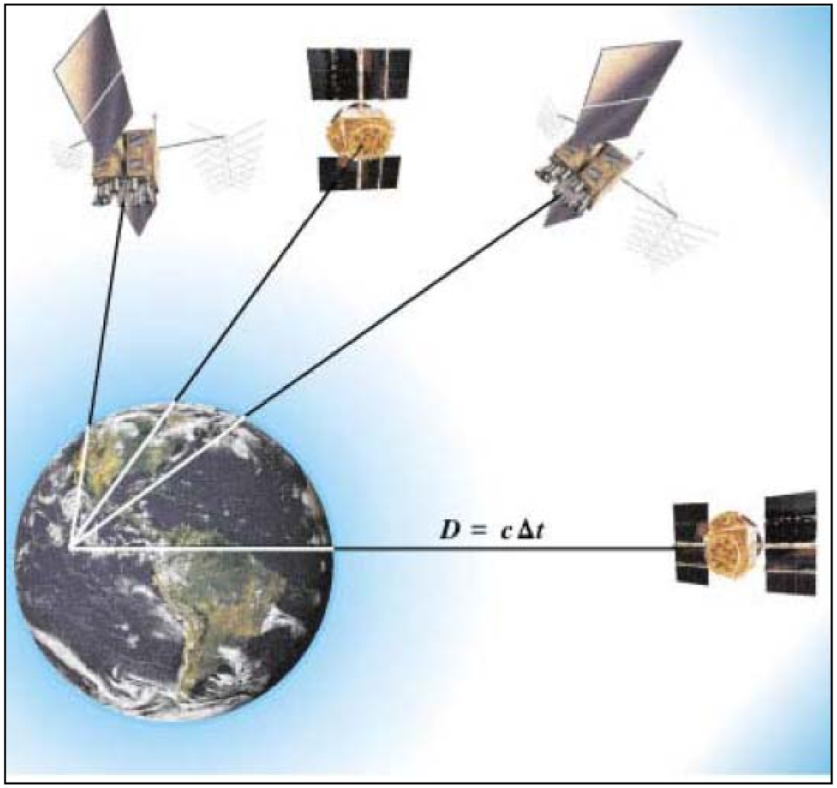
US electric power sales in 2008: $US 360 billion.
Smart Grid: Increased need for real-time, precision information on electric power generation, utilization, and distribution.

Source: US Energy Information Administration

Impacts of Accurate Timing and Synchronization

Global Navigation Satellite Systems (GNSS)

- GPS – US
- GLONASS – Russia
- Galileo – European Union
- COMPASS – China
- Quasi-Zenith Satellite System – Japan
- Indian Regional Navigational Satellite System – India
- Etc.



Synchronization to about one nanosecond per day (10^{-14}).

Broad Range of Civilian/Commercial GNSS Applications

Satellite Operations

Precision Agriculture

Surveying & Mapping

Aviation

Communications

Disease Control

Power Grids

Trucking & Shipping

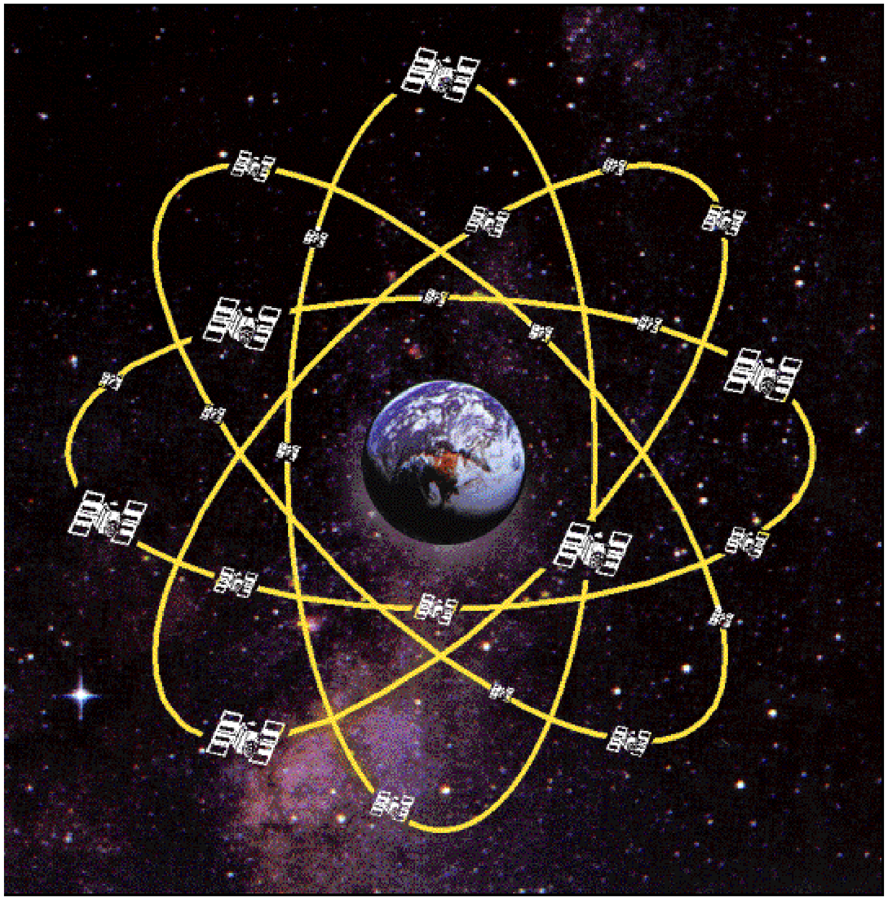
Oil Exploration

Fishing & Boating

Personal Navigation

Impacts of Accurate Timing and Synchronization

Global Navigation Satellite Systems (GNSS)



US civilian/commercial economic benefits estimated 2008: $US 70 billion.

Global civilian/commercial economic benefits estimated 2008: $US 250 billion.

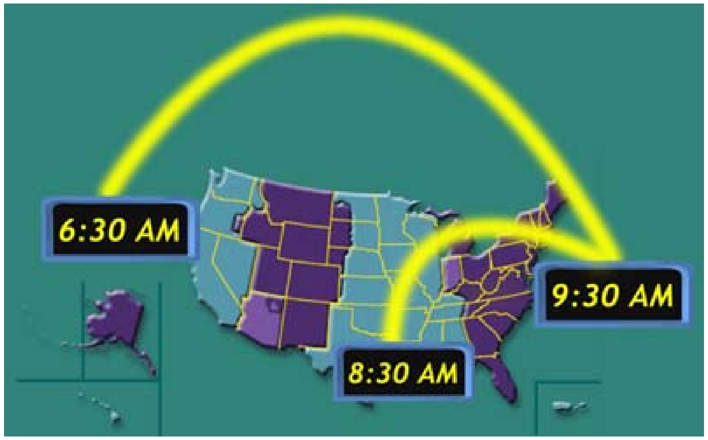
New applications and impacts rapidly growing…

National security applications: Extremely important, exceptionally high value, difficult to estimate economic impacts/benefits. (Probably equivalent of many trillions of US dollars…)

Source: US National Executive Committee for Space-Based Positioning, Navigation, and Timing

Impacts of Accurate Timing and Synchronization

Electronic Financial Transactions

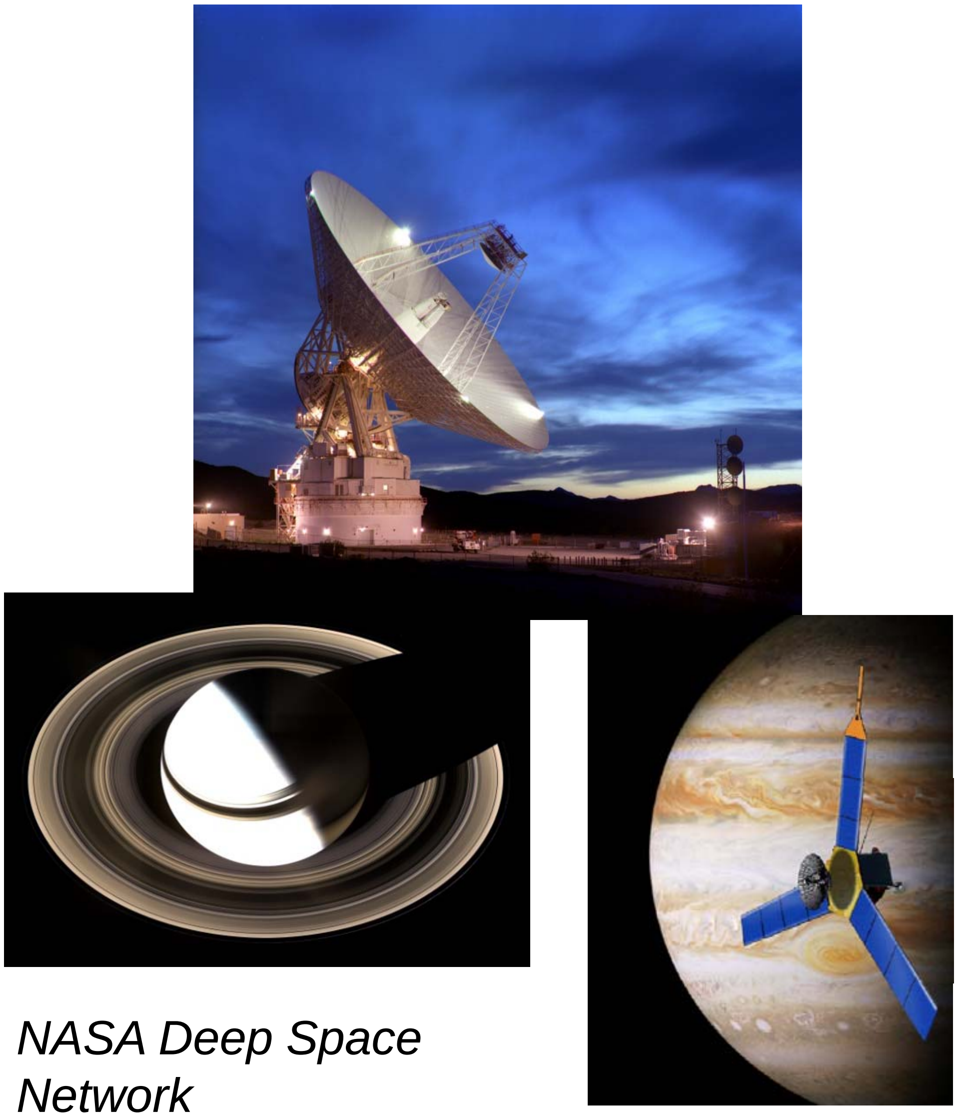


- US Financial Industry Regulatory Authority (FINRA) rules for electronic financial transactions. Rules reviewed and approved by US federal government.
- Rules apply to more than 800,000 businesses conducting billions of transactions daily through New York Stock Exchange, NASDAQ, and other venues.
- All FINRA member electronic and mechanical time-stamping devices must remain accurate to within 1 second of NIST time.
- Hundreds of billions of dollars of daily electronic financial transactions in US.
- Hundreds of trillions of dollars of financial transactions per year in US.

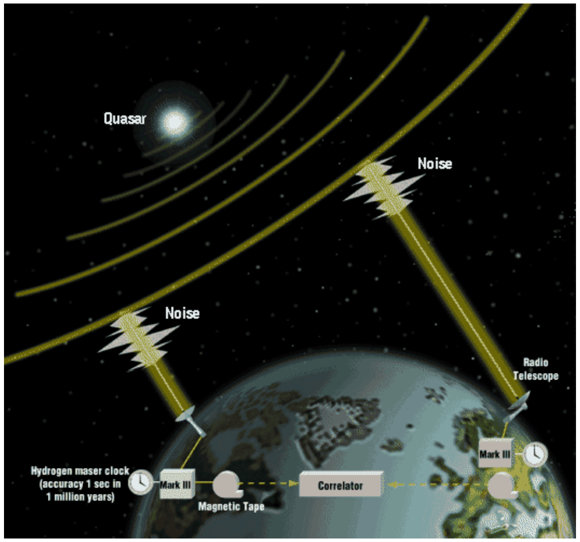
Source: US Financial Industry Regulatory Authority

Impacts of Accurate Timing and Synchronization

Science: Spacecraft Communications, Astrophysics



NASA Deep Space Network



Very Long Baseline Interferometry

Timing/synchronization to as stringent as 1 picosecond per day (10^{-16}).

Source: NASA

Impacts of Accurate Timing and Synchronization

Fundamental Science

$$T = \frac{T_0}{\sqrt{1 - \frac{v^2}{c^2}}} \approx T_0 \left(1 + \frac{v^2}{2c^2}\right) \qquad v << c$$

Time dilation
(special
relativity)

$$T = \frac{T_0}{\sqrt{1 - \frac{2GM}{Rc^2}}} \approx T_0 \left(1 + \frac{GM}{Rc^2}\right) \qquad \frac{2GM}{R} << c^2$$

Gravitational time dilation
(general relativity)

$$\alpha = e^2/4\pi\varepsilon_0\hbar c$$

Are fundamental constants
changing over time?
(fine structure constant)

Impacts of Accurate Timing and Synchronization

Fundamental Metrology: International System of Units (SI)

Time/frequency impacts or will impact nearly all other SI units

SI Base Unit	Approx. Relative Uncertainty	Depends on SI Second
Second	**10^{-15}**	**Yes**
Meter	10^{-12}	**Yes**
Kilogram	10^{-9}	Future SI redefinition
Ampere	10^{-7}	**Yes**
Mole	10^{-7}	Future SI redefinition
Kelvin	10^{-7}	Future SI redefinition?
Candela	10^{-3}	**Yes**

Impacts of Accurate Timing and Synchronization

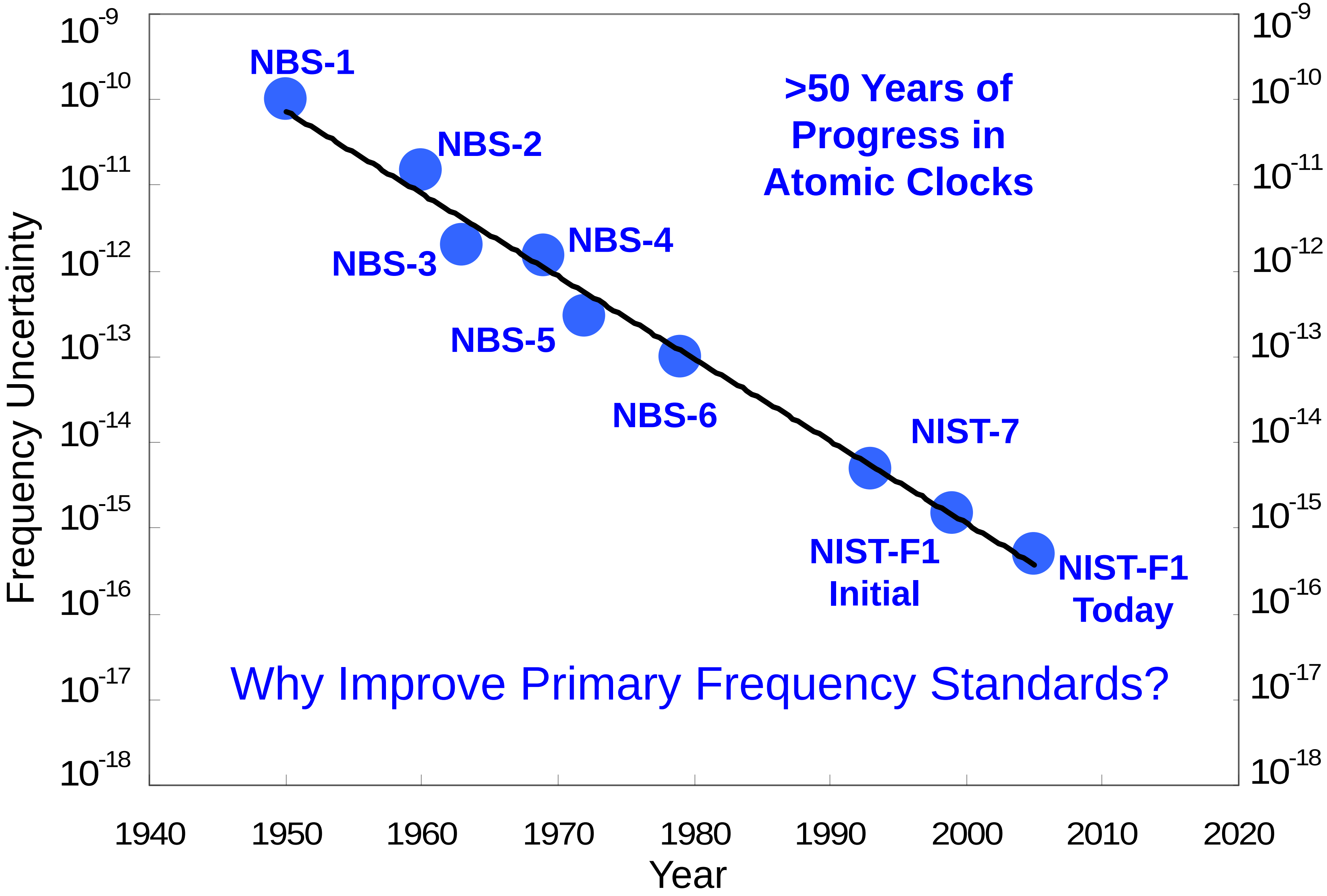
- Accurate timing and synchronization are a crucial part of the infrastructure of modern technology.

- Used continuously every day – although most users remain unaware of the use or impacts (part of the infrastructure).

- Needs of different users vary enormously – range of 10^{15} (fifteen orders of magnitude).
  - Timestamping of electronic financial transactions – 1 second precision.
  - Global Navigation Satellite Systems applications – 10^{-15} second precision.

- NIST and other NMIs provide broad range of timing and synchronization measurement services to meet this very broad range of needs.
  - Highest precision/accuracy for the most stringent requirements.
  - Easiest use/lowest cost (free) for the broadest applications.

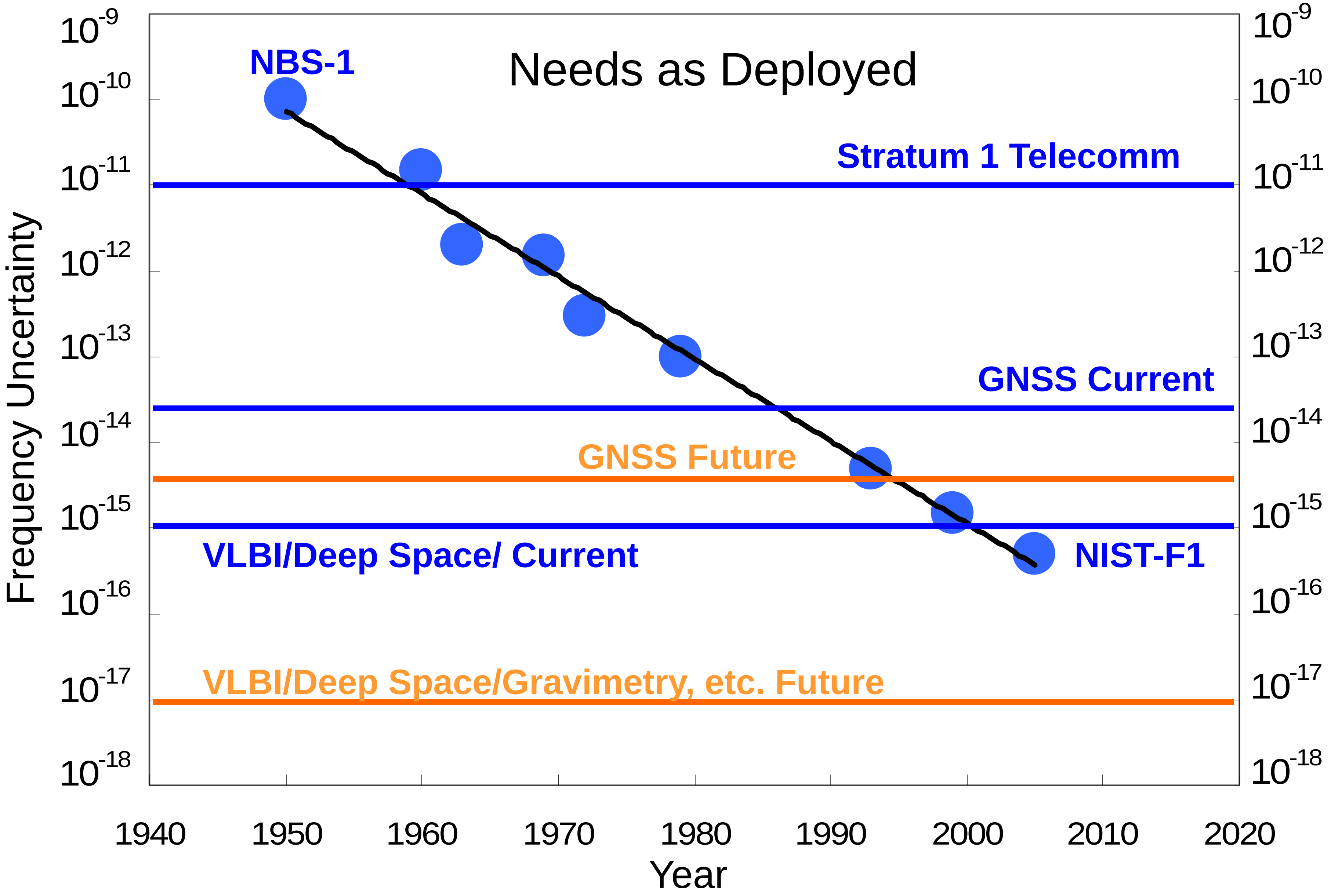
Improvements in Primary Frequency Standards



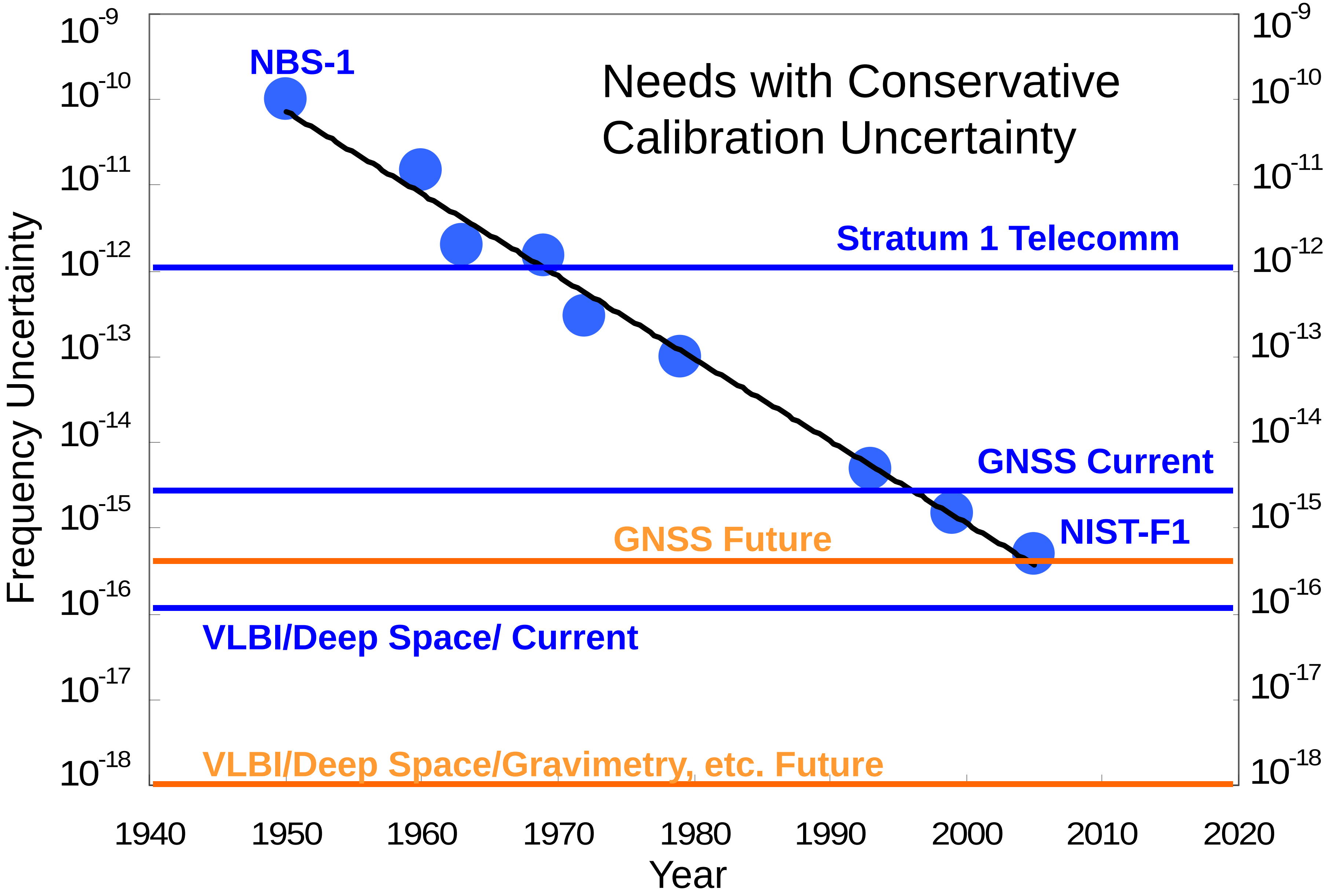
>50 Years of Progress in Atomic Clocks

Why Improve Primary Frequency Standards?

Improvements in Primary Frequency Standards



Improvements in Primary Frequency Standards



NIST Time and Frequency Standards and Distribution

Primary Frequency
Standard and
NIST Time Scale
Realization of SI second

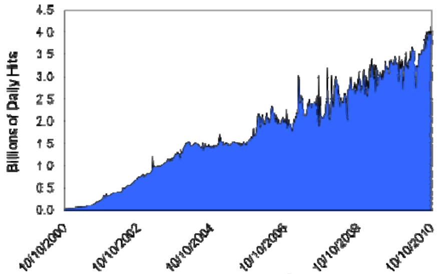
NIST-F1

Hydrogen Maser &
Measurement system

NIST Time and Frequency Standards and Distribution

Time and
Frequency
Distribution
Services

Radio broadcasts



Networks

Satellites

Noise metrology

Primary Frequency
Standard and
NIST Time Scale
Realization of SI second

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NIST Time and Frequency Standards and Distribution

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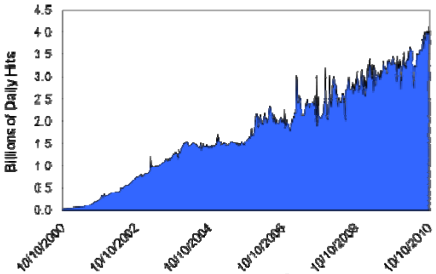

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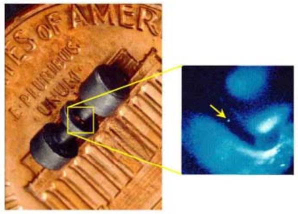
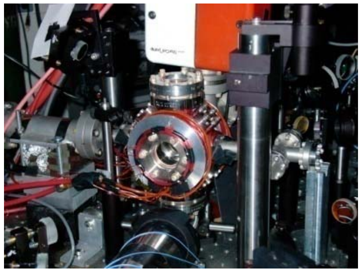
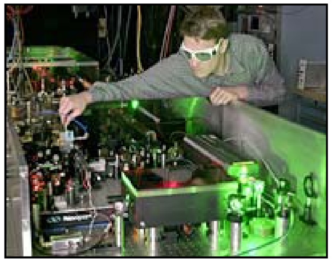
Research on
Future
Standards
and
Distribution



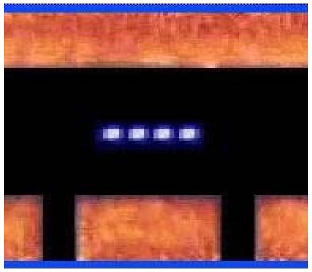
Mercury ion clock



Neutral calcium
clock



Optical frequency
synthesis



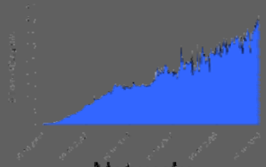
Quantum computing

One Model of Unique Role of National Metrology Institute

Special national assignments based on unique metrology expertise

Distribute measurements to wide variety of customers


Radio broadcasts


Networks


Satellites

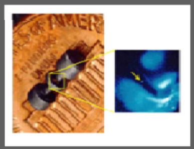

Noise metrology

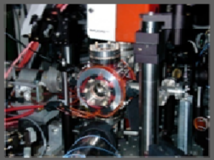
Realize SI units

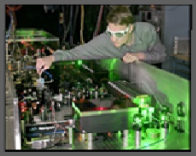

NIST-F1

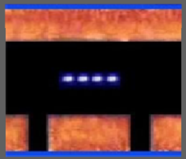

Hydrogen Maser & Measurement system

Research on future realization and distribution


Mercury ion clock


Neutral calcium clock


Optical frequency synthesis


Quantum computing

NIST Time Scale and Distribution

4 Cesium Beam standards

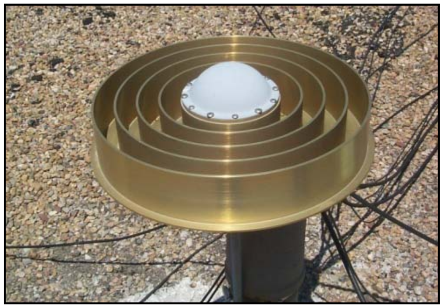
6 Hydrogen Masers

UTC(NIST)

Measurement System

Two-way satellite time & frequency transfer

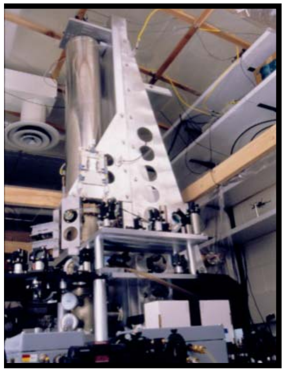
GPS



Calibrated by NIST-F1 primary frequency standard

International coordination of time and frequency: UTC, TAI, etc.

NIST Time and Frequency Metrology



- NIST-F1 primary frequency standard periodically calibrates NIST time scale.
- NIST-F1 also reports frequency information to BIPM, along with approximately 12 other primary frequency standards worldwide.

- NIST time scale is the source of NIST’s realization of Coordinated Universal Time , UTC(NIST).
- NIST time scale reports time of day information to BIPM, along with approximately 60 other timing laboratories world-wide.

- The NIST time scale, periodically calibrated by NIST-F1, is the ultimate source of all NIST time and frequency measurements.

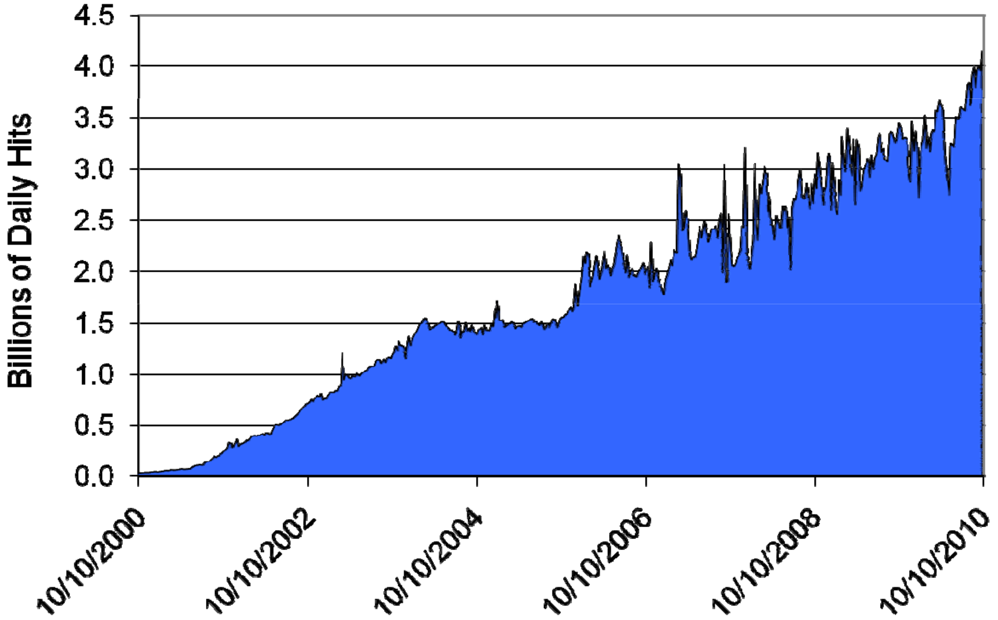
NIST Time and Frequency Distribution

NIST time distribution: Radio

WWVB low frequency broadcast of time code signals.
Near Ft. Collins, CO (since 1963).

Sampling of radio-controlled products automatically set by WWVB time codes.

NIST Time and Frequency Distribution



- NIST Internet Time Service – time codes delivered over the Internet.
- 4 billion requests per day.
- Built into common operating systems: Windows, Mac, Linux, etc.
- 23 servers at 19 locations across the US.

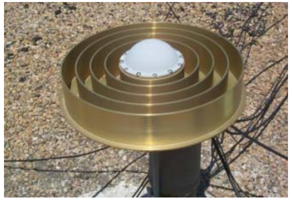
- Expected significant growth in need for auditable time-stamping at ever greater timing precision.

NY Stock Exchange
Automated Trading Anomaly
May 6, 2010

NIST Time and Frequency Distribution

Serve the most demanding needs of timing laboratories, research laboratories, telecomm industry, etc.

Provided remotely in the customer's lab.



Global Time Service

- Calibrate remote clock with respect to NIST time via Common-View GPS.
- 10 ns uncertainty.

Frequency Measurement and Analysis Service

- Full measurement system ("black box") with continuous remote monitoring by NIST.
- "In-house" $\Delta f/f \sim 2 \times 10^{-15}$.
- GPS transfer $\Delta f/f \sim 2 \times 10^{-13}$.

SIM Time Network: International Time Coordination

- SIM Time Network.

- Pioneered by CENAM, NIST, NRC-Canada.
  - Based on NIST FMAS experience.

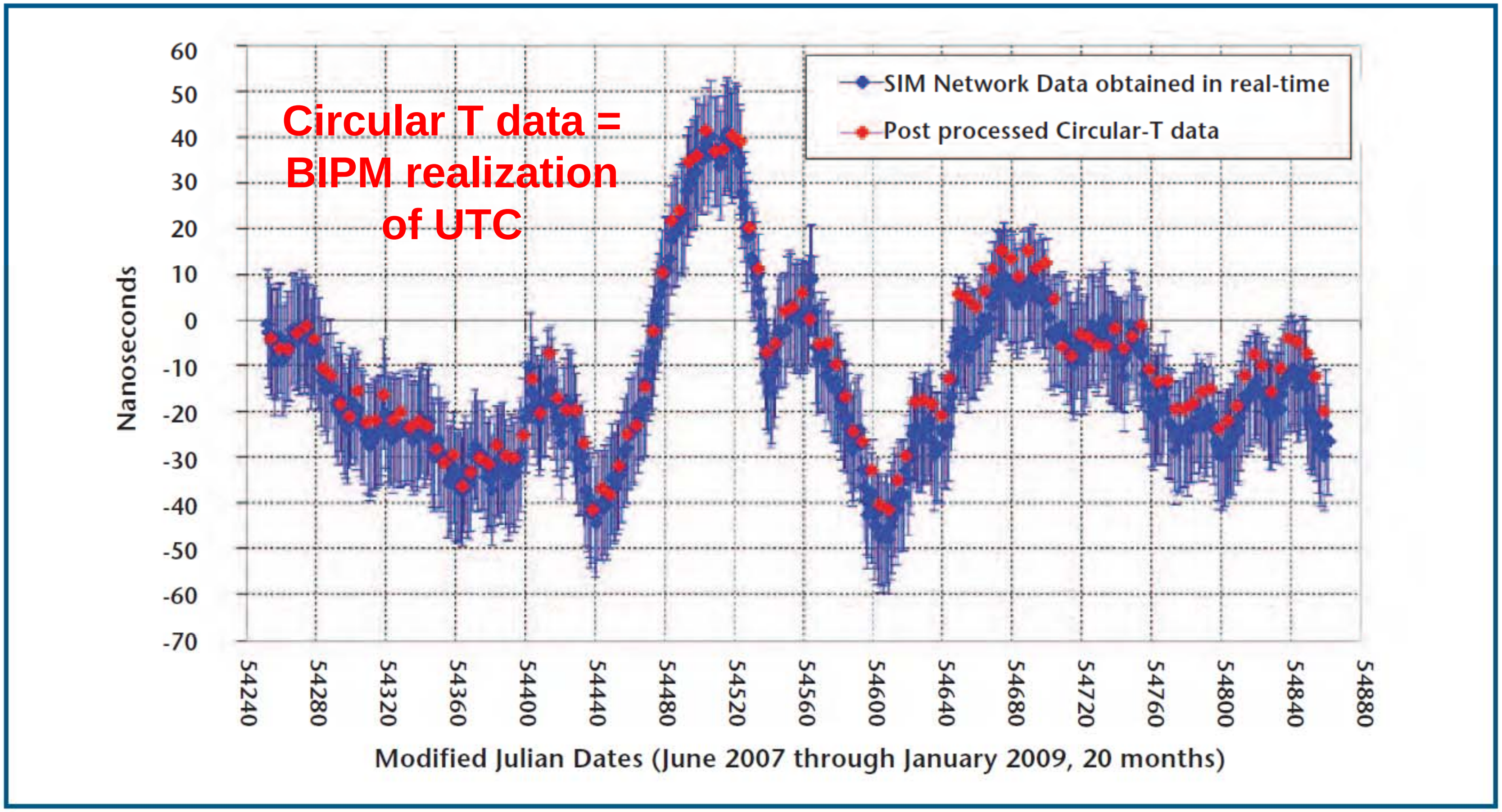
- 14 current partners in North, Central, and South America.
  - Additional partners planned.

- World's only near real-time international measurement system.

- World-class international measurement system available to broad range of national laboratories.

SIM Time Network: International Time Coordination

Real-time Comparison of NIST (USA) and CENAM (Mexico)
Time Scales through SIM Network



Real-time international time scale competitive with post-processed BIPM UTC realization (up to several weeks late) with much simpler and less-expensive equipment.

SIM Time Network: International Time Coordination

Real-time Comparison of NIST (USA) and CENAM (Mexico)
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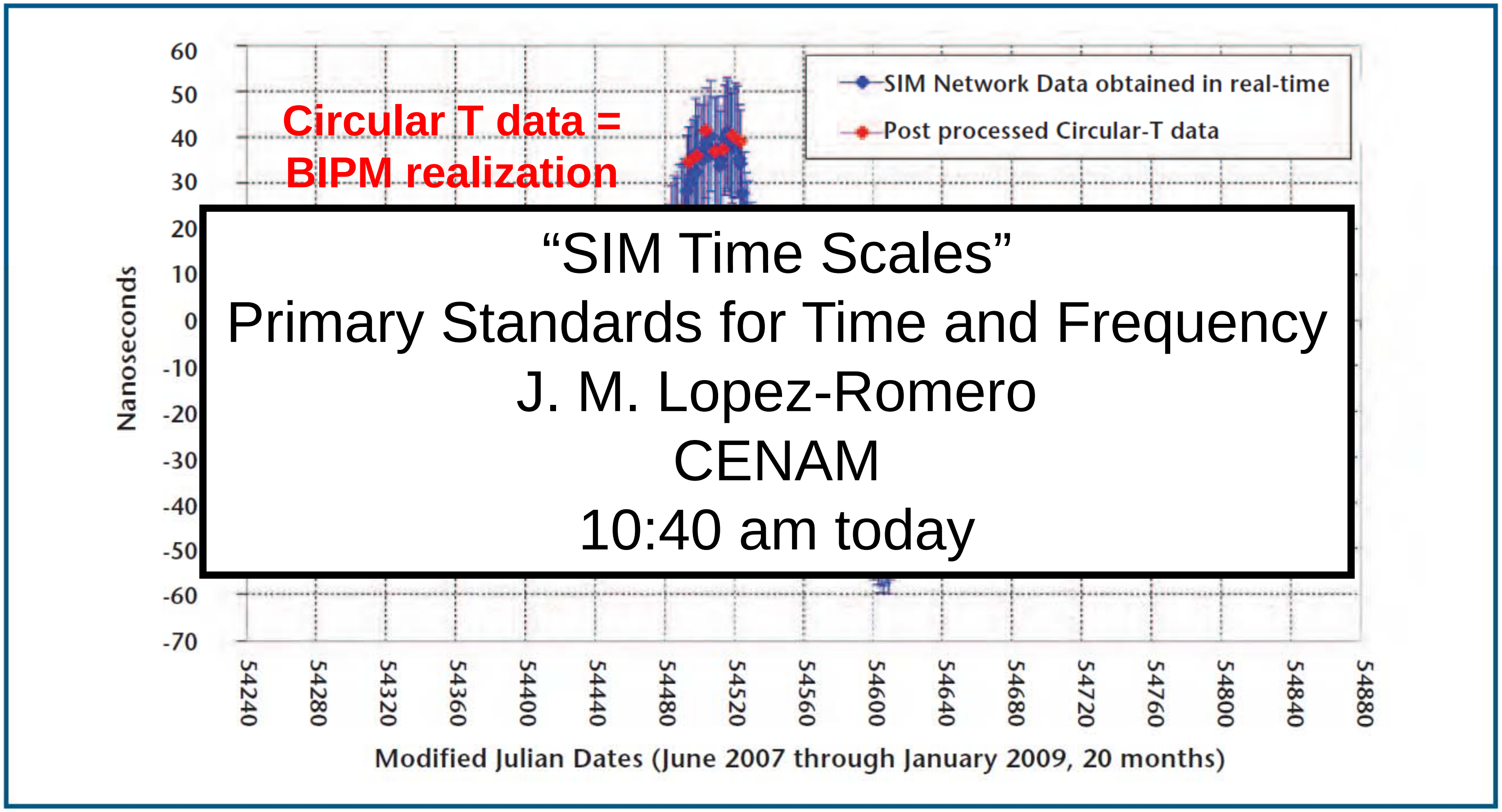
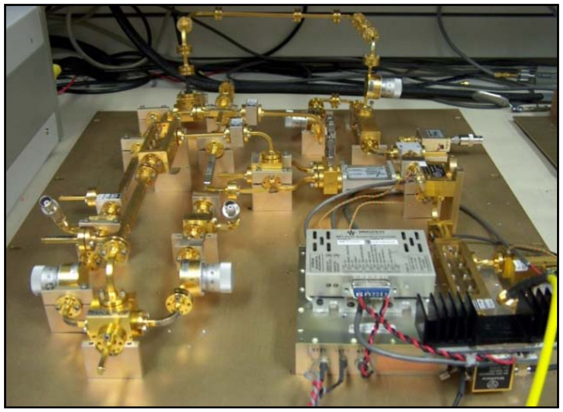


Circular T data =
BIPM realization

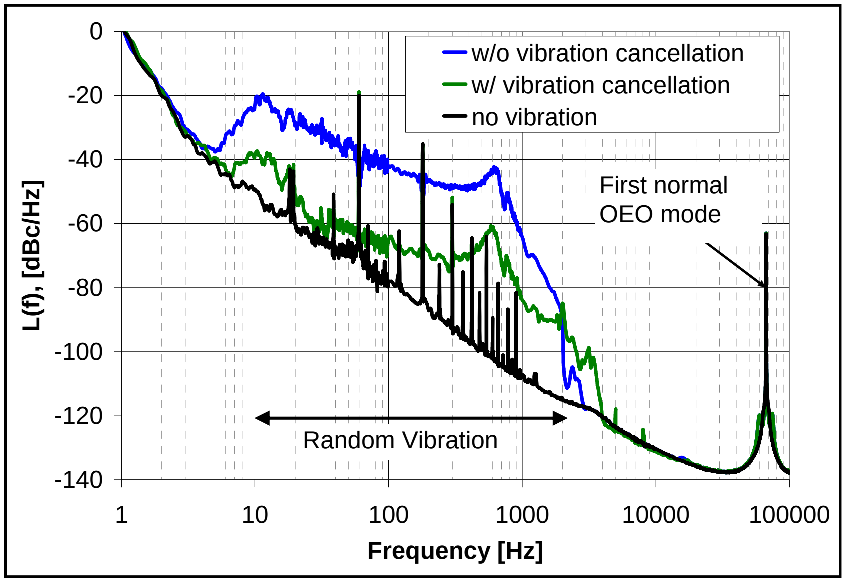
“SIM Time Scales”
Primary Standards for Time and Frequency
J. M. Lopez-Romero
CENAM
10:40 am today

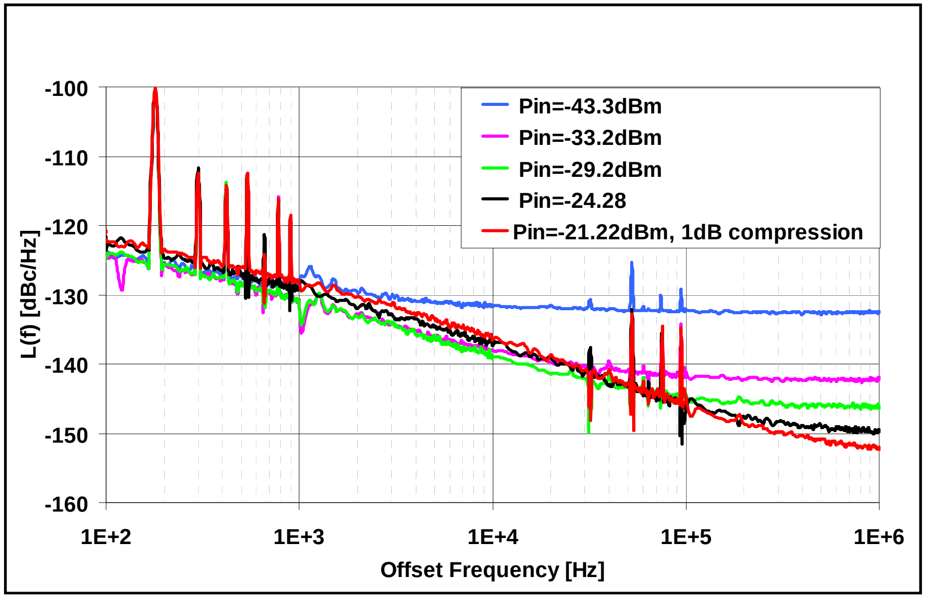
Real-time international time scale competitive with post-processed BIPM UTC realization (up to several weeks late) with much simpler and less-expensive equipment.

Phase Noise Measurements (Spectral Purity / “Timing Jitter”)



- Ultralow noise sources and metrology.
- Increasing applications in communications, navigation, remote detection, ultra-high-speed electronics, national security, etc.

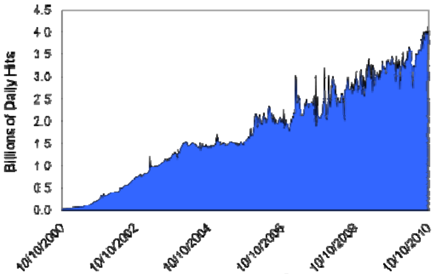




NIST Time and Frequency Standards and Distribution

Time and
Frequency
Distribution
Services

Radio broadcasts



Networks

Satellites

Noise metrology

Primary Frequency
Standard and
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NIST-F1

Hydrogen Maser &
Measurement system

Research on
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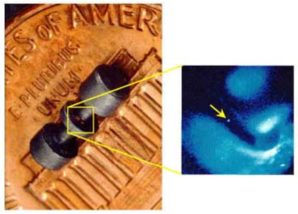
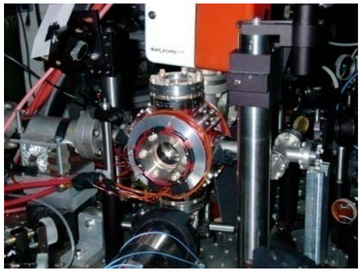
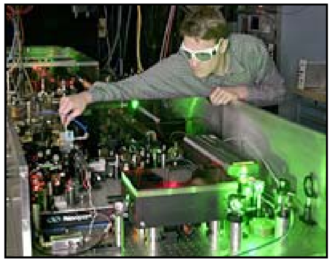


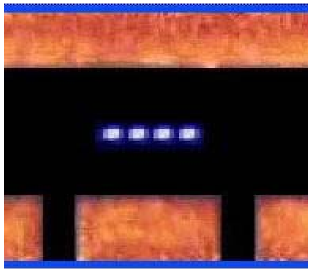
Mercury ion clock



Neutral calcium
clock

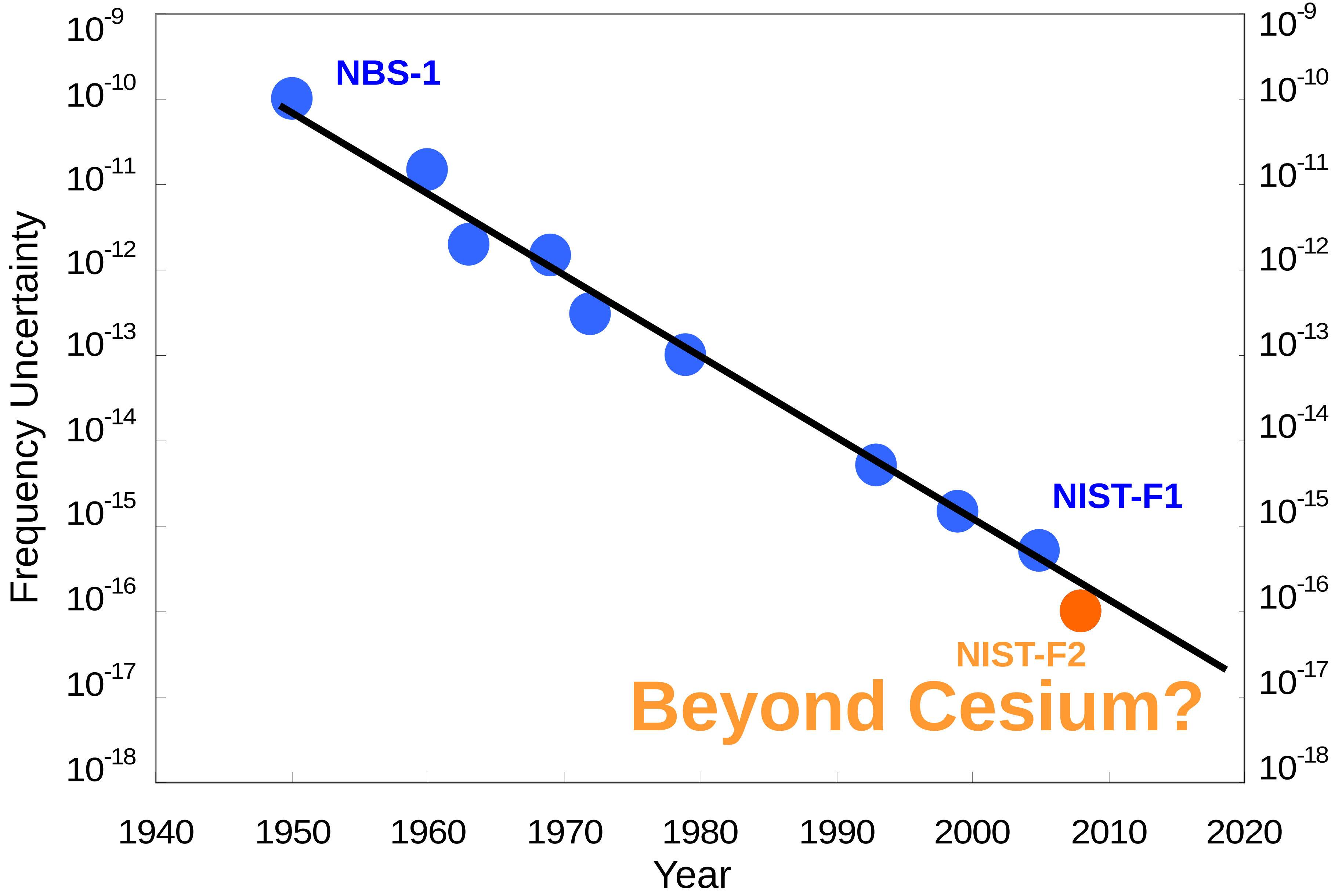


Optical frequency
synthesis



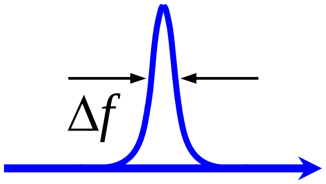
Quantum computing

Improvements in Primary Frequency Standards



Improvements in Primary Frequency Standards

Frequency uncertainty $\sim \dfrac{\Delta f}{f_0} \cdot \dfrac{1}{\sqrt{\tau}} \cdot \dfrac{1}{\sqrt{N}}$



Atomic Resonance

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

τ = observation time

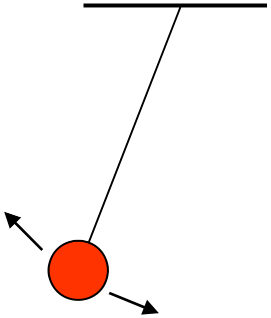
N = number of atoms

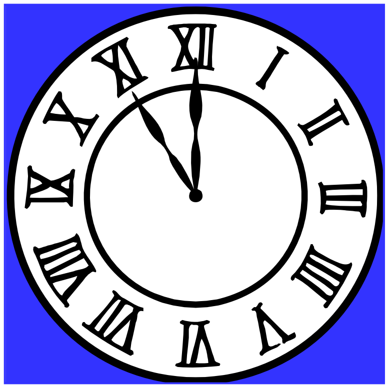
NIST research atomic clocks

Al^+	1124 THz (1124 x 10^{12} Hz)	Optical
Hg^+	1024 THz	
Yb	520 THz	
Ca	456 THz	
Sr	430 THz	
Cs	0.0092 THz	Microwave

What is a clock?

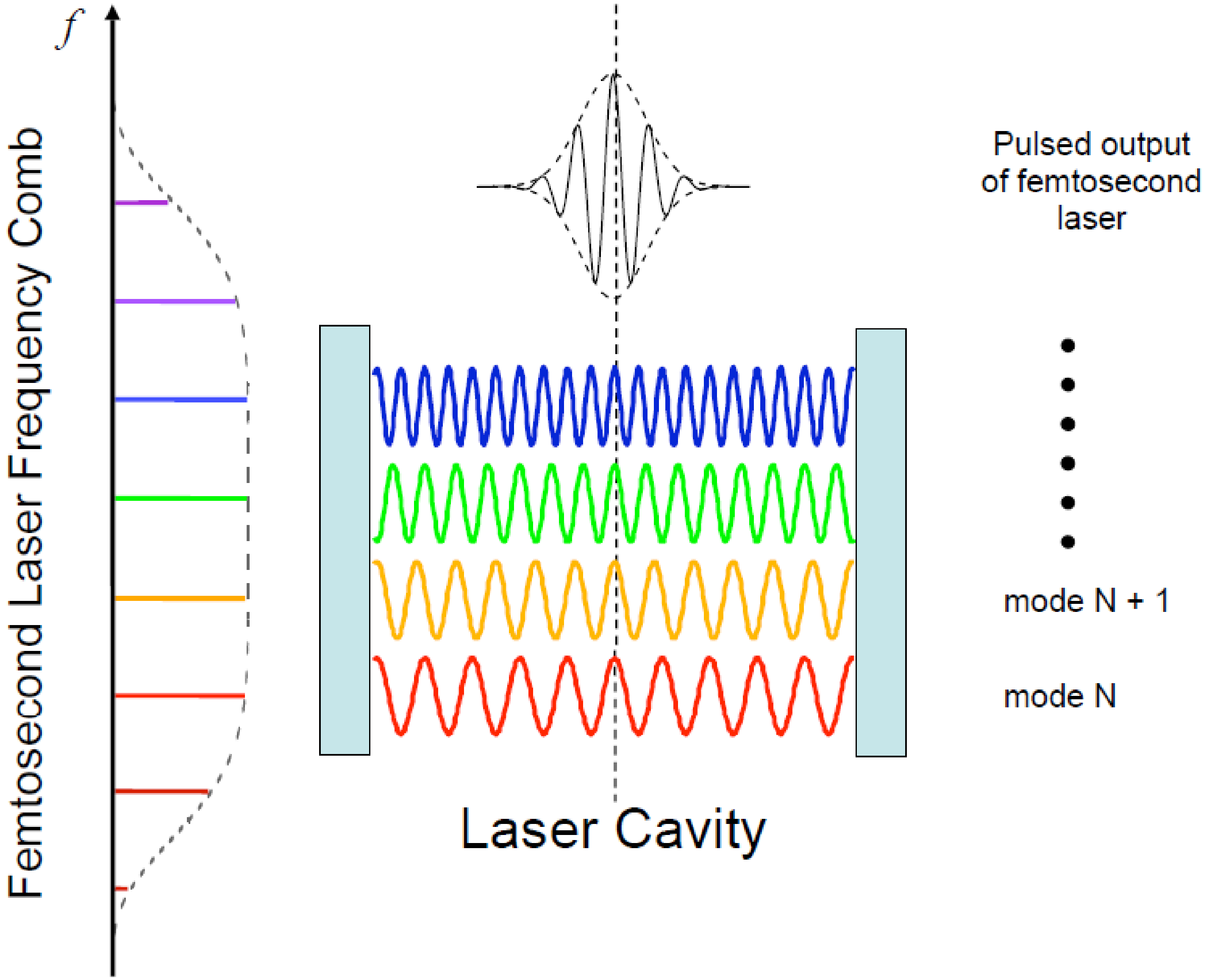
Repeating Motion + Counting Mechanism





Repeating Motion	Counting Mechanism
Earth Rotation	Sundial
Pendulum Swing	Clock Gears and Hands
Quartz Crystal Vibration	Electronic Counter
Cesium Atomic Transition	Microwave Counter
Optical Atomic Transition	**?? Counter ??**

Femtosecond Laser Frequency Combs: Key to Optical Clocks



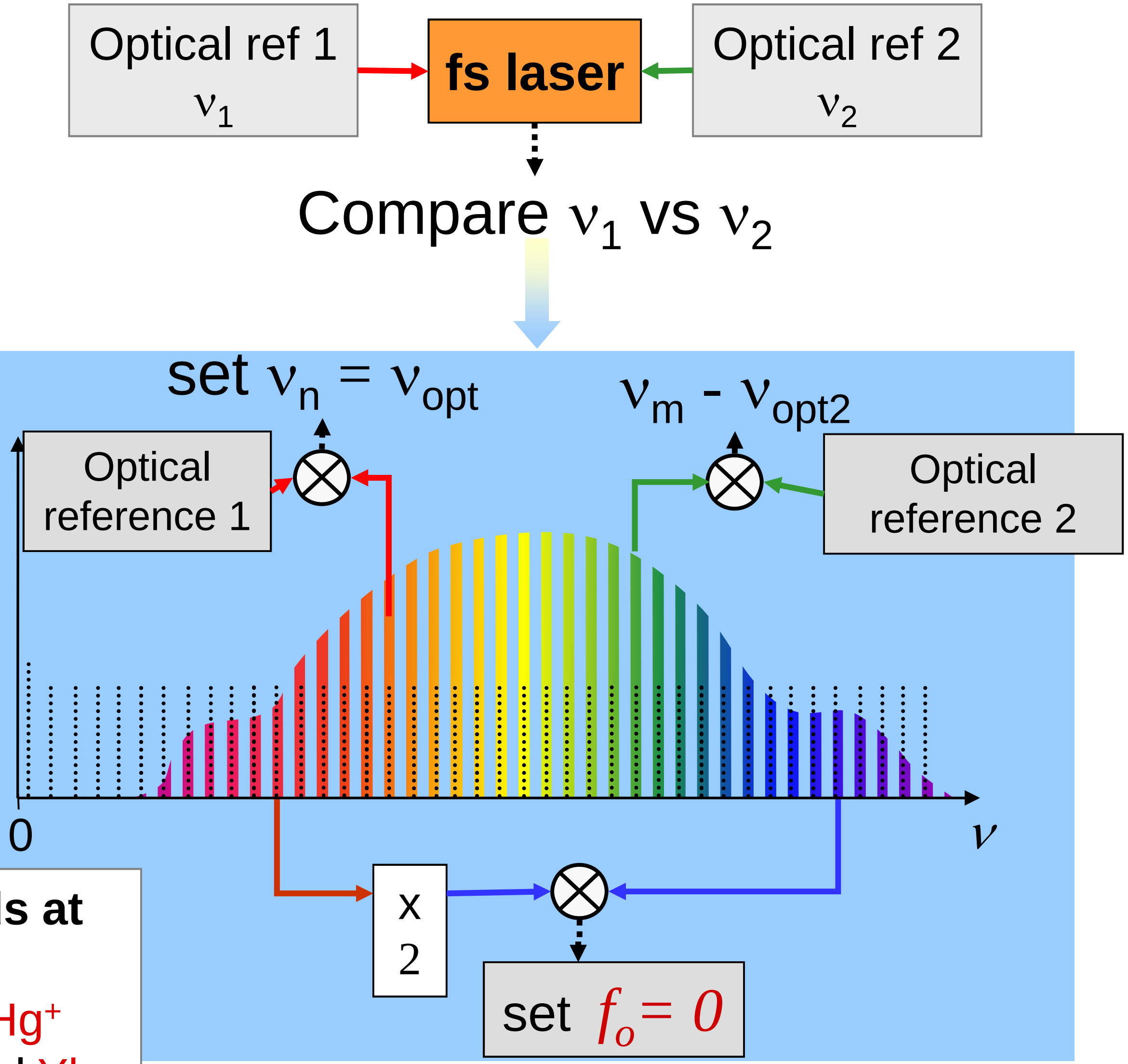
Pulsed output
of femtosecond
laser

mode N + 1

mode N

Laser Cavity

Femtosecond Laser Frequency Combs: Key to Optical Clocks



Optical ref 1
ν_1

fs laser

Optical ref 2
ν_2

Compare ν_1 vs ν_2

set $\nu_n = \nu_{opt}$

$\nu_m - \nu_{opt2}$

Optical reference 1

Optical reference 2

0

ν

x 2

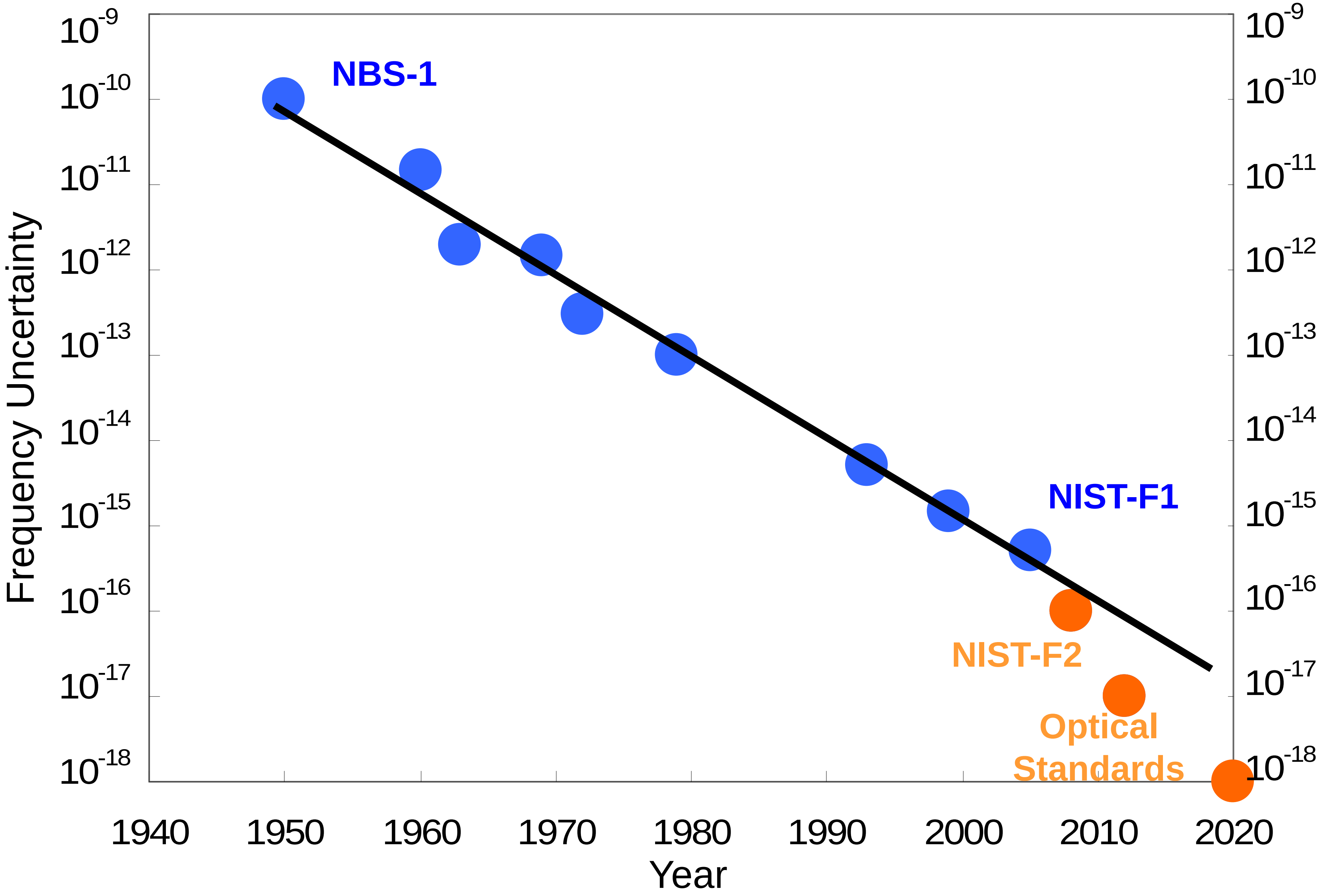
set $f_o = 0$

Optical standards at NIST

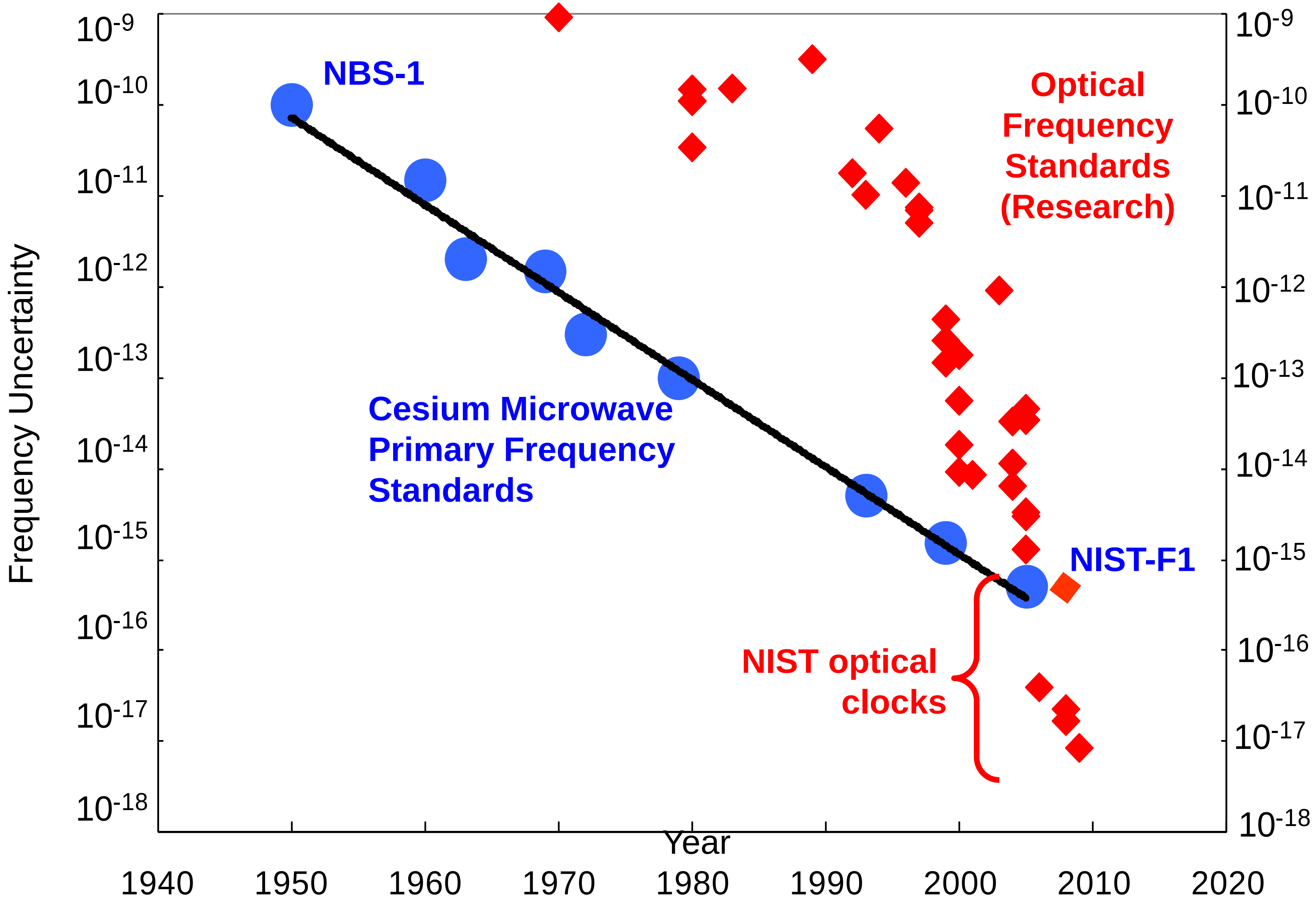
Al⁺ (1124 THz), Hg⁺ (1064 THz), neutral Yb (520 THz) and Ca (456 THz)

Direct comparison to Cs (0.0092 THz)

Improvements in Primary Frequency Standards: Optical Clocks

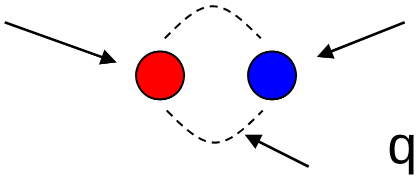


Improvements in Primary Frequency Standards: Optical Clocks



Improvements in Clocks: Quantum “Logic Clock”

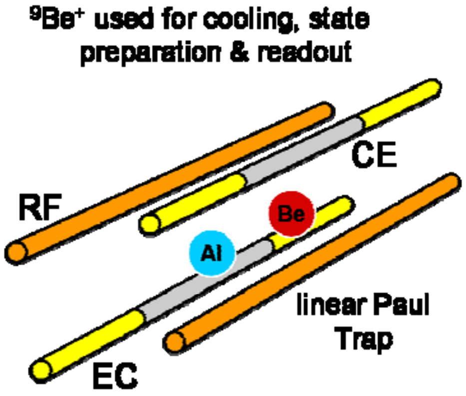
Aluminum Ion Logic Clock

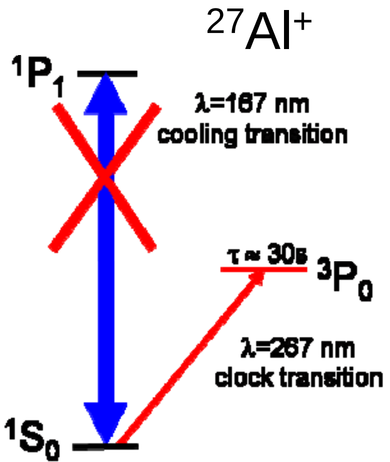


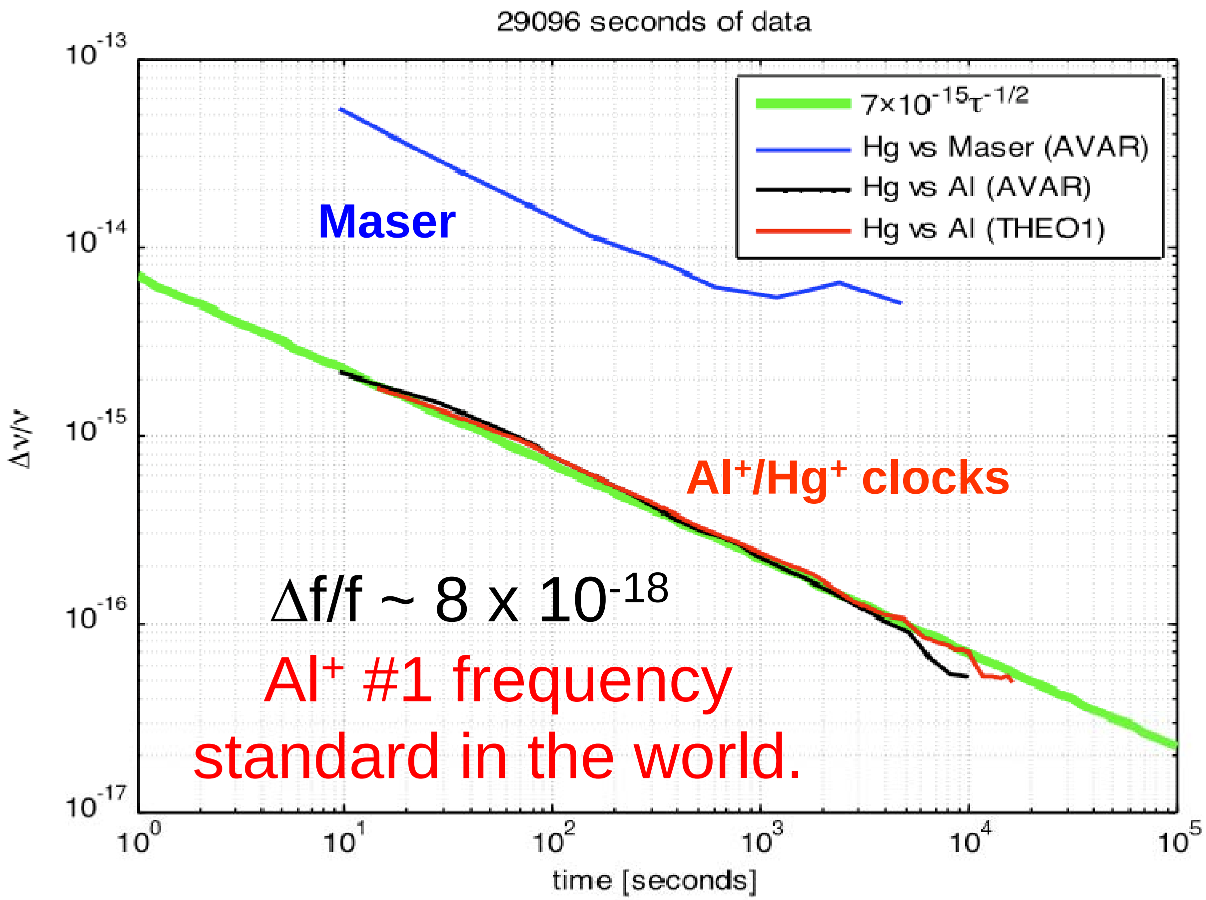
“Logic” ion e.g., **^{9}Be$^+$**

“Clock” ion e.g. **Al$^+$**

quantized motional-mode coupling





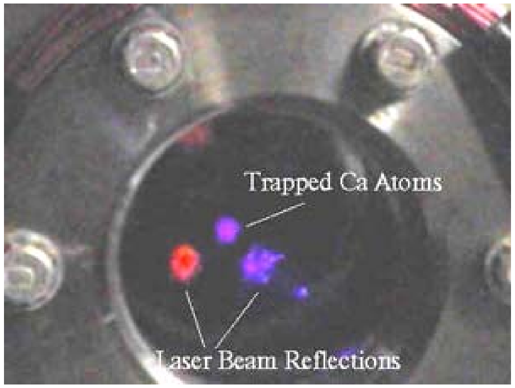


$\Delta f/f \sim 8 \times 10^{-18}$

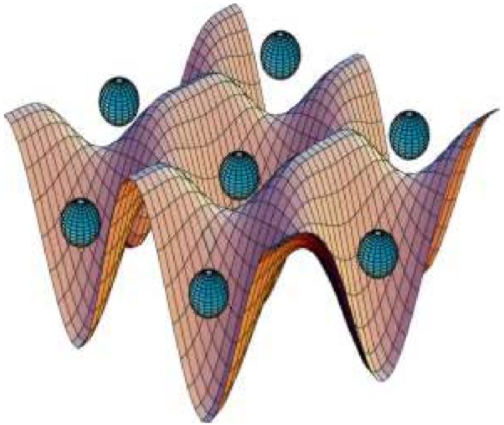
Al$^+$ #1 frequency standard in the world.

Improvements in Primary Frequency Standards: Optical Clocks

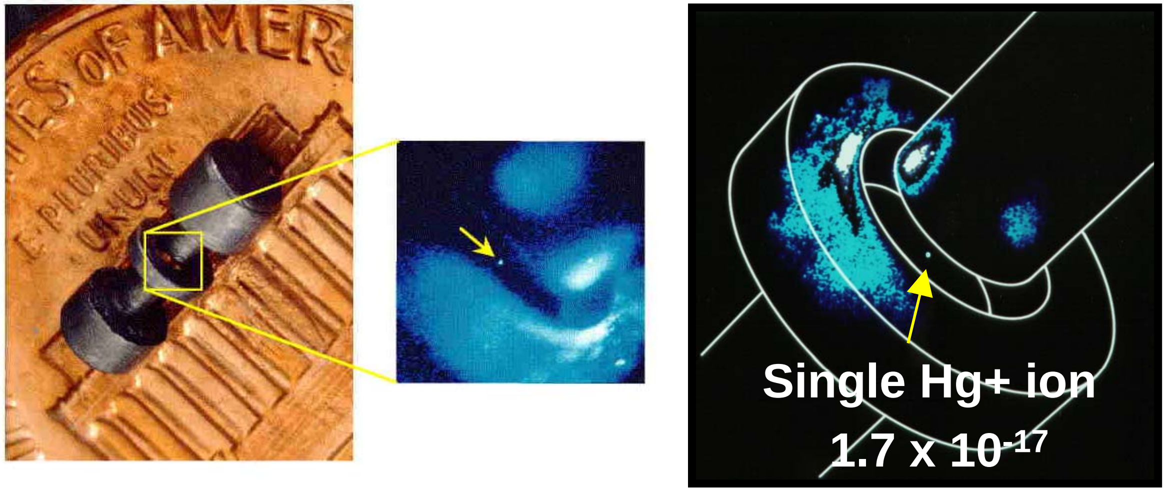
- High-frequency optical clocks outperform microwave clocks.
- NIST research optical clocks already performing better than 1 x 10^{-17}.
- Potential for accuracy at the 10^{-18} level, 100 times better than NIST-F1.
- Likely to take many years to realize that potential.



Laser-cooled calcium atoms.



Ytterbium atoms in optical lattice.



Single Hg+ ion

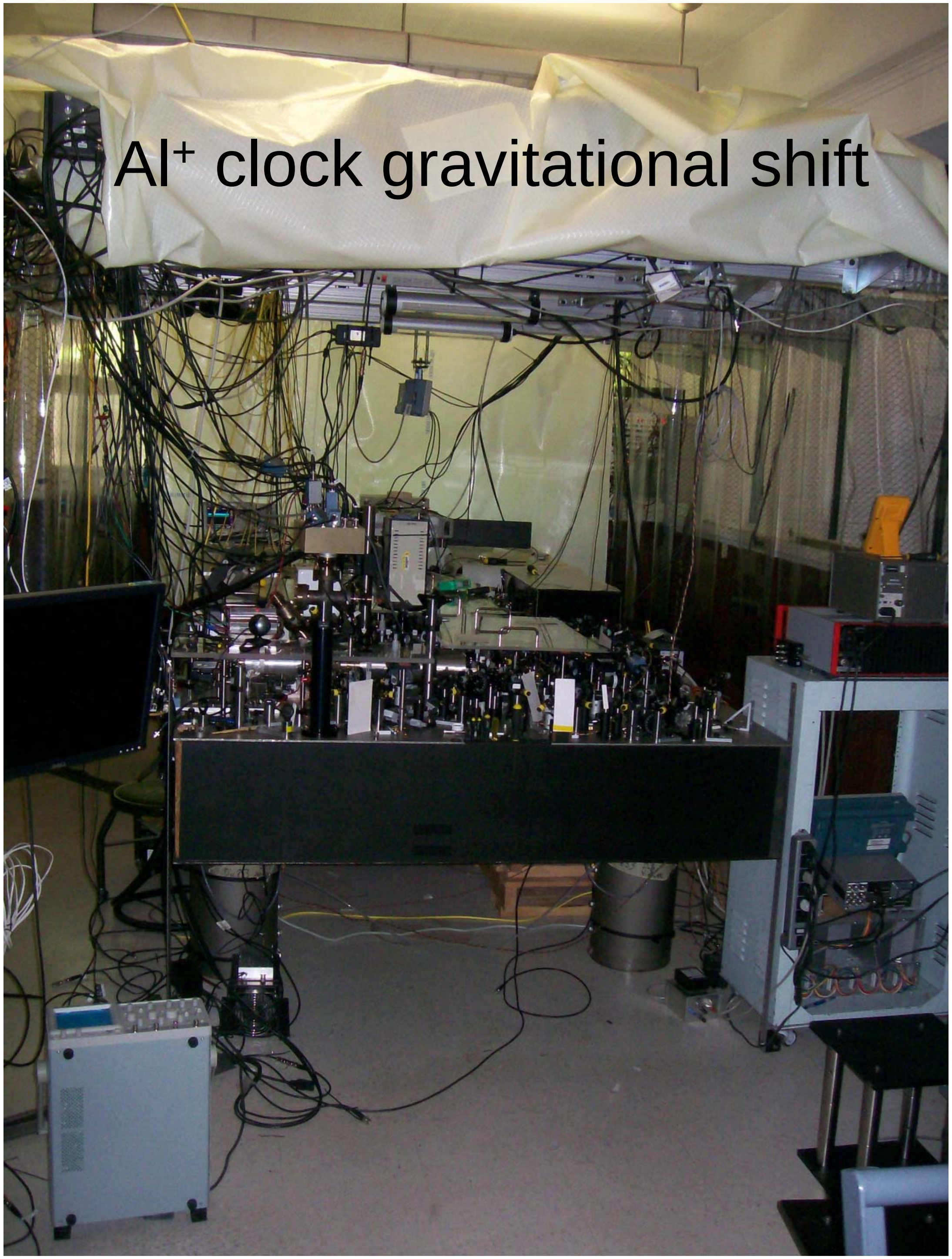
1.7 x 10^{-17}

Single mercury ion trap.

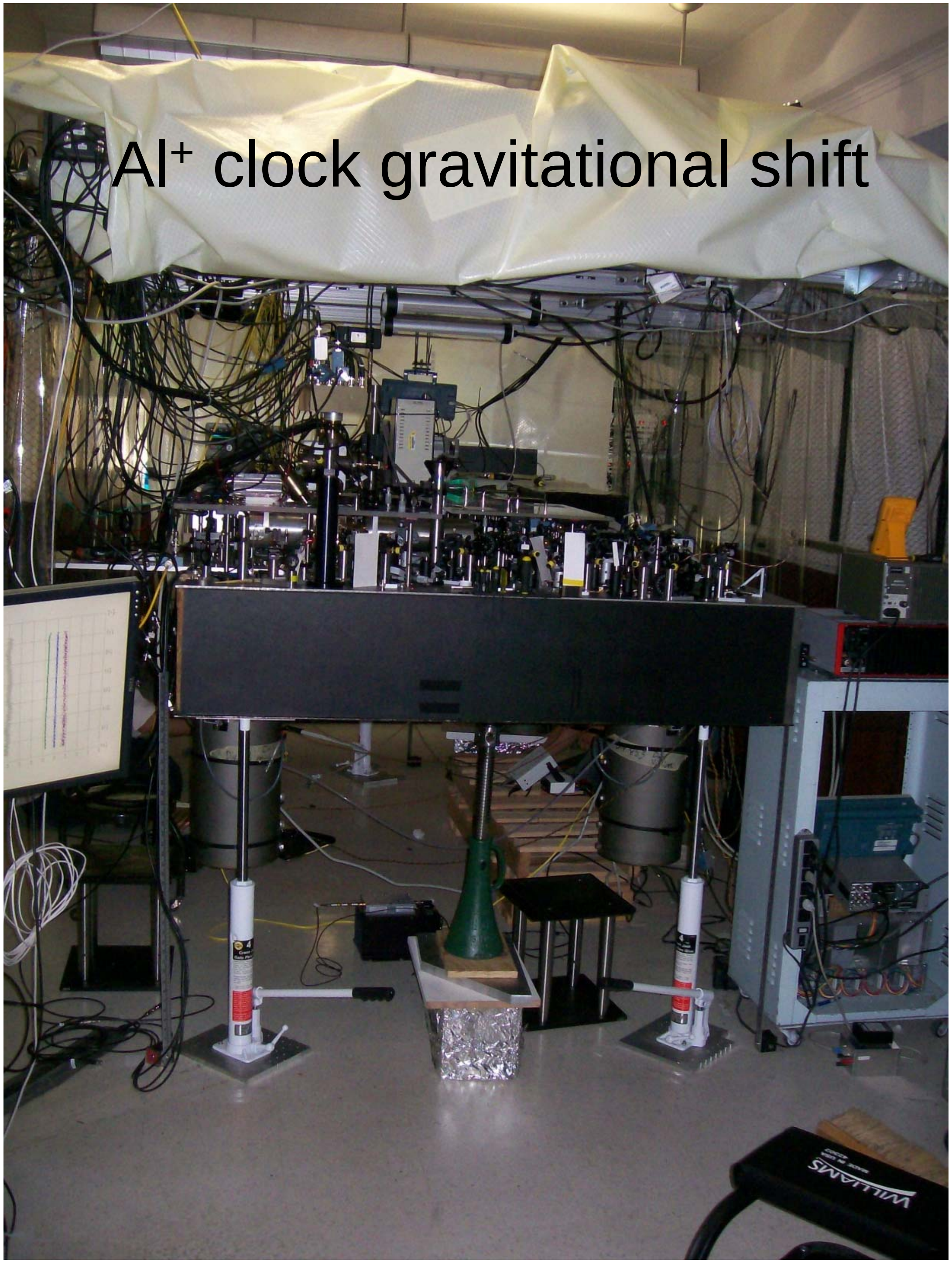
~8 x 10^{-18}

Al^+ quantum logic optical clock.

Al^+ clock gravitational shift



Al$^+$ clock gravitational shift



Measure frequency shift by raising clock as little as 10 cm.

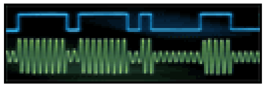
Measure frequency shift by moving Al+ ion as slow as walking speed (about 1 m/second).

Extreme precision optical clocks may initially be most useful as exquisitely precise atomic sensors:

- Gravity.
- Magnetic fields.
- Acceleration.
- Temperature.
- Other quantities…

Improvements in Frequency Standards and Clocks

NIST-F1



10^{-15} clocks (0.1/month) → 10^{-13} clocks (10/month) → 10^{-11} clocks (1,000/month) → 10^{-9} clocks (100,000/month)

- Master clocks (long term synchronization)
- Secure communications
- Deep space navigation
- GPS Master clock (ground)

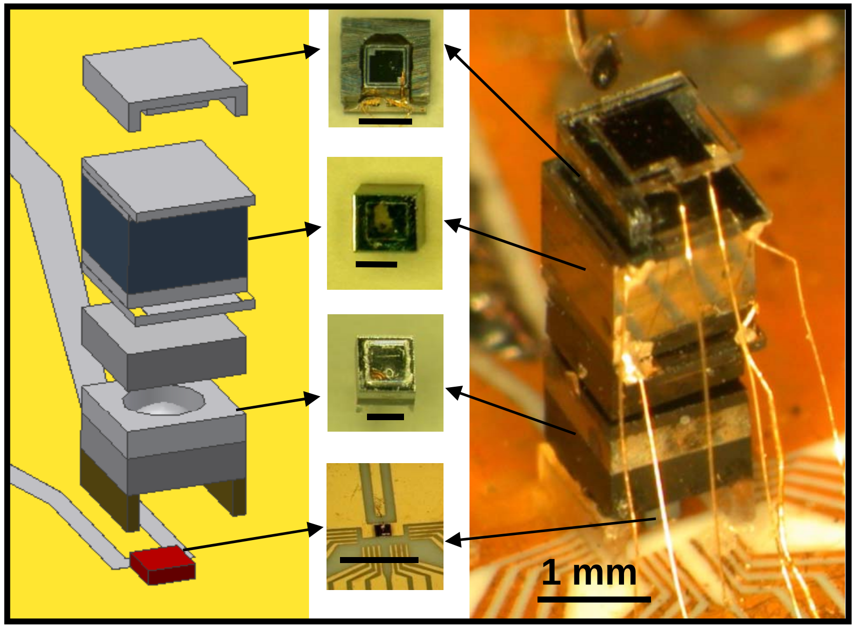
- Large scale communications systems
- Power grids
- GPS Space Clocks
- Local synchronization

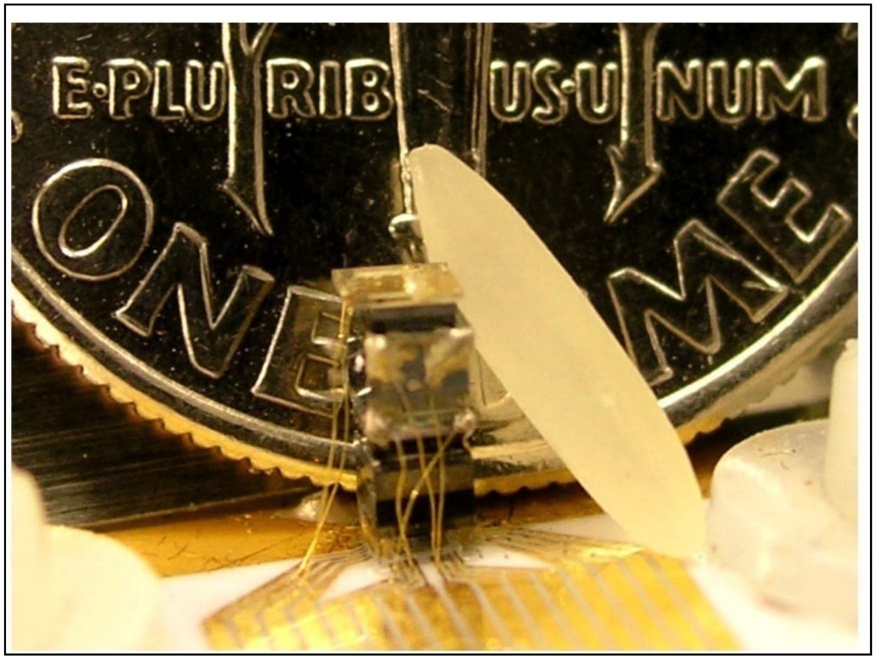
- Local communications hubs
- Instrumentation level flywheels

- Short haul navigation
- Local communications

Opportunities for Improvement?

Improvements in Clocks: Emerging Technologies





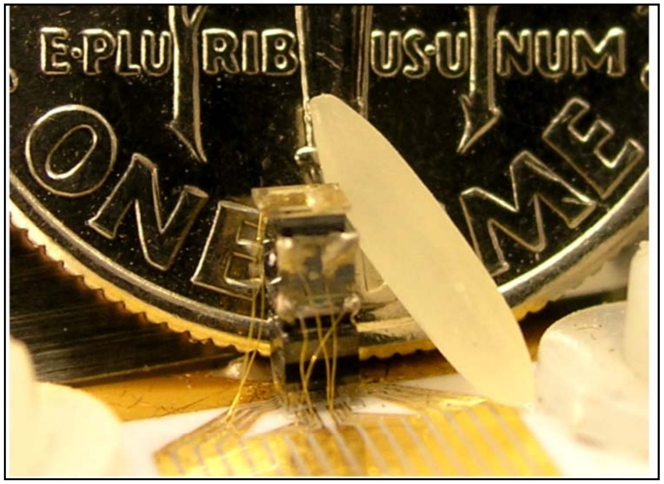
Chip-scale atomic clock

Chip-scale atomic magnetometer

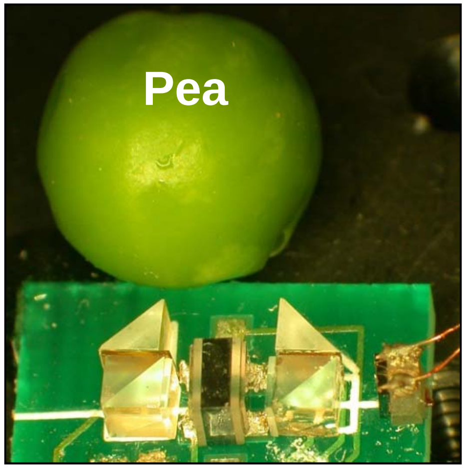
Ultraminiature gyroscope

Future atom-based sensors

Improvements in Clocks: Emerging Technologies



Chip-scale atomic clock



Ultraminiature spectrometer

Chip-scale atomic clocks:

- $\Delta f/f$ 10^{-11} or better.
- Runs on AA battery.
- Potential for low-cost mass production.

Chip-scale atomic magnetometers:

- 10^{-15} sensitivity: SQUID performance with no cryogens.

Ultraminiature NMR gyroscopes:

- Navigation grade (0.002 degree).

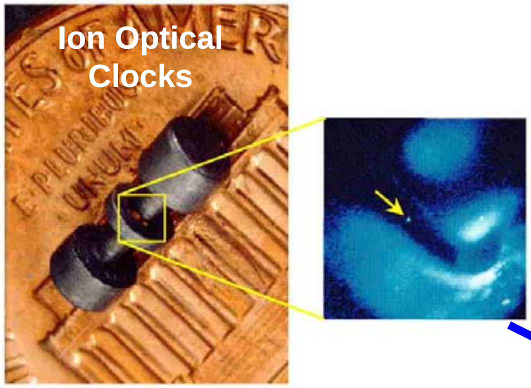
Related devices:

- **Ultraminiature spectrometer** for telecommunications, chemical identification, atmospheric research, etc.

NIST chip-scale atomic device program since August 2004:

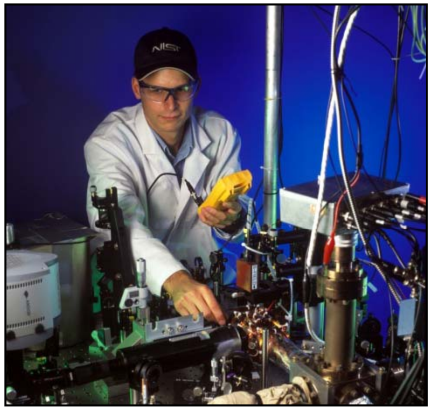
- *Three NIST patents.*
- *More than 60 NIST publications on chip-scale atomic devices.*
- *Dozens of conference and workshop presentations.*

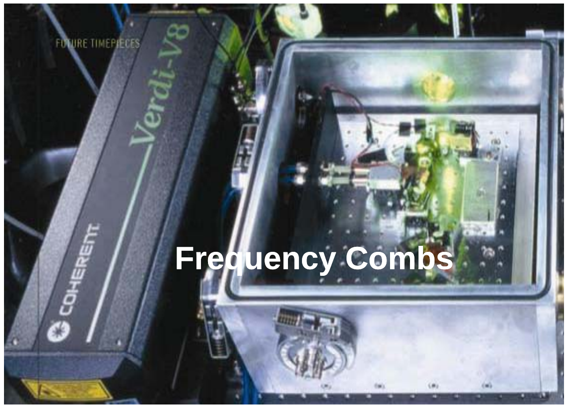
Improvements in Time and Frequency Distribution



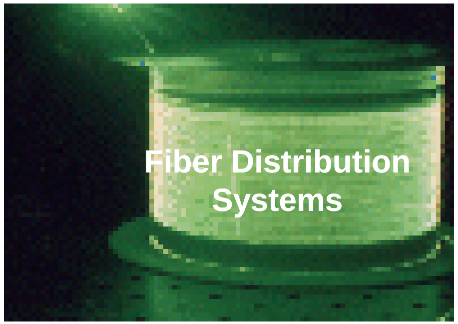
Future optical clocks

$\Delta f/f \sim 1\times10^{-18}$





- Directly compare optical frequencies spanning more than an octave.
- Link optical to microwave frequencies.



- High accuracy.
- Direct reference of optical applications to optical standards.
- New applications.

Crucial topic… For another talk….

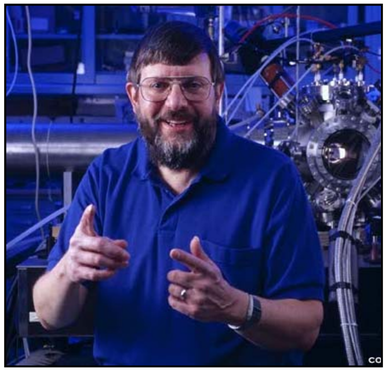
Time, Timekeeping and Time Distribution

- Modern time and frequency metrology results from and has stimulated some of the most interesting and important developments in science and technology over about the past 100 years:
  - Atomic theory.
  - Quantum mechanics.
  - Relativity.
  - Radio (including microwaves).
  - Electronics.
  - Materials science.
  - Lasers.
  - Laser cooling and trapping.
  - Femtosecond laser frequency combs.
  - Etc.

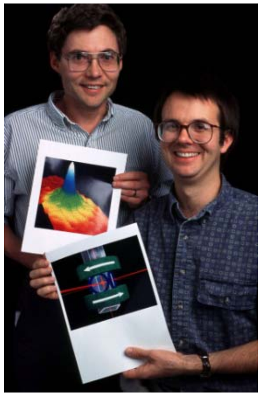
- 104 Nobel Physics Prizes from 1901 through 2010.
  - About 20% directly or indirectly related to science and technology of timekeeping.

Some Nobel Prizes Related to Atomic Time and Frequency Metrology

1943	Otto Stern	Molecular/atomic beam spectroscopy.
1944	Isidor Rabi	Atomic beam resonance technique.
1955	Polykarp Kusch	Magnetic moment of electron; early atomic clocks.
1964	Charles Townes, Nicolai Basov, Alexandr Prokhorov	Quantum electronics, including maser/laser principles.
1966	Alfred Kastler	Optical pumping methods.
1989	Norman Ramsey, Hans Dehmelt, Wolfgang Paul	Atomic clock techniques; trapped ion spectroscopy.
1997	Steven Chu, Claude Cohen-Tannoudji, **Bill Phillips**	Laser cooling of neutral atoms.
2001	**Eric Cornell, Carl Wieman**, Wolfgang Ketterle	Bose-Einstein condensate.
2005	Roy Glauber, **Jan Hall,** Ted Hansch	Laser spectroscopy, including laser frequency combs.



Bill Phillips, NIST



Carl Wieman, CU-Boulder
Eric Cornell, NIST

Jan Hall, NIST

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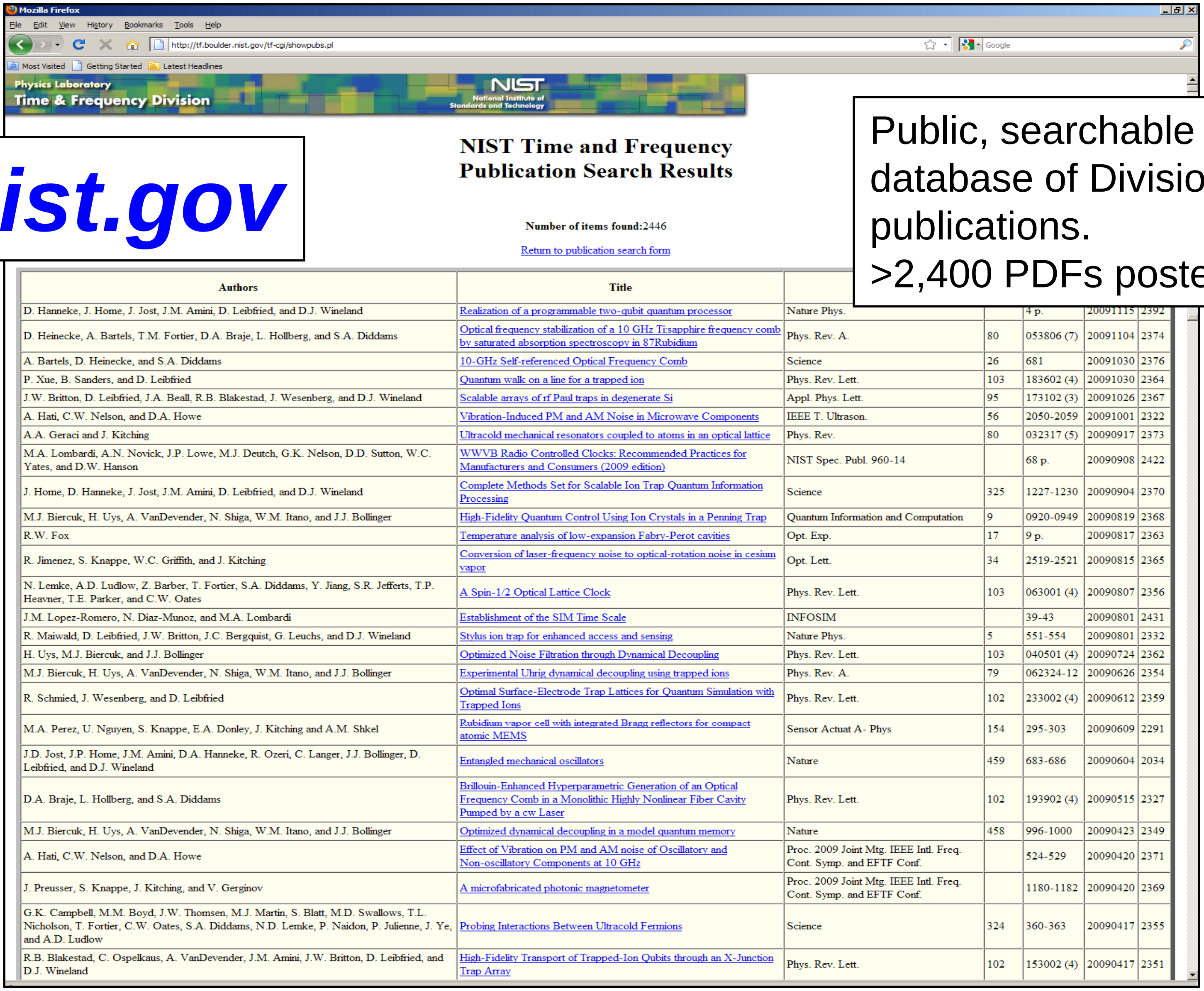

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Authors	Title					
D. Hanneke, J. Home, J. Jost, J.M. Amini, D. Leibfried, and D.J. Wineland	Realization of a programmable two-qubit quantum processor	Nature Phys.		4 p.	20091115	2392
D. Heinecke, A. Bartels, T.M. Fortier, D.A. Braje, L. Hollberg, and S.A. Diddams	Optical frequency stabilization of a 10 GHz Ti:sapphire frequency comb by saturated absorption spectroscopy in 87Rubidium	Phys. Rev. A.	80	053806 (7)	20091104	2374
A. Bartels, D. Heinecke, and S.A. Diddams	10-GHz Self-referenced Optical Frequency Comb	Science	26	681	20091030	2376
P. Xue, B. Sanders, and D. Leibfried	Quantum walk on a line for a trapped ion	Phys. Rev. Lett.	103	183602 (4)	20091030	2364
J.W. Britton, D. Leibfried, J.A. Beall, R.B. Blakestad, J. Wesenberg, and D.J. Wineland	Scalable arrays of rf Paul traps in degenerate Si	Appl. Phys. Lett.	95	173102 (3)	20091026	2367
A. Hati, C.W. Nelson, and D.A. Howe	Vibration-Induced PM and AM Noise in Microwave Components	IEEE T. Ultrason.	56	2050-2059	20091001	2322
A.A. Geraci and J. Kitching	Ultracold mechanical resonators coupled to atoms in an optical lattice	Phys. Rev.	80	032317 (5)	20090917	2373
M.A. Lombardi, A.N. Novick, J.P. Lowe, M.J. Deutch, G.K. Nelson, D.D. Sutton, W.C. Yates, and D.W. Hanson	WWVB Radio Controlled Clocks: Recommended Practices for Manufacturers and Consumers (2009 edition)	NIST Spec. Publ. 960-14		68 p.	20090908	2422
J. Home, D. Hanneke, J. Jost, J.M. Amini, D. Leibfried, and D.J. Wineland	Complete Methods Set for Scalable Ion Trap Quantum Information Processing	Science	325	1227-1230	20090904	2370
M.J. Biercuk, H. Uys, A. VanDevender, N. Shiga, W.M. Itano, and J.J. Bollinger	High-Fidelity Quantum Control Using Ion Crystals in a Penning Trap	Quantum Information and Computation	9	0920-0949	20090819	2368
R.W. Fox	Temperature analysis of low-expansion Fabry-Perot cavities	Opt. Exp.	17	9 p.	20090817	2363
R. Jimenez, S. Knappe, W.C. Griffith, and J. Kitching	Conversion of laser-frequency noise to optical-rotation noise in cesium vapor	Opt. Lett.	34	2519-2521	20090815	2365
N. Lemke, A.D. Ludlow, Z. Barber, T. Fortier, S.A. Diddams, Y. Jiang, S.R. Jefferts, T.P. Heavner, T.E. Parker, and C.W. Oates	A Spin-1/2 Optical Lattice Clock	Phys. Rev. Lett.	103	063001 (4)	20090807	2356
J.M. Lopez-Romero, N. Diaz-Munoz, and M.A. Lombardi	Establishment of the SIM Time Scale	INFOSIM		39-43	20090801	2431
R. Maiwald, D. Leibfried, J.W. Britton, J.C. Bergquist, G. Leuchs, and D.J. Wineland	Stylus ion trap for enhanced access and sensing	Nature Phys.	5	551-554	20090801	2332
H. Uys, M.J. Biercuk, and J.J. Bollinger	Optimized Noise Filtration through Dynamical Decoupling	Phys. Rev. Lett.	103	040501 (4)	20090724	2362
M.J. Biercuk, H. Uys, A. VanDevender, N. Shiga, W.M. Itano, and J.J. Bollinger	Experimental Uhrig dynamical decoupling using trapped ions	Phys. Rev. A.	79	062324-12	20090626	2354
R. Schmied, J. Wesenberg, and D. Leibfried	Optimal Surface-Electrode Trap Lattices for Quantum Simulation with Trapped Ions	Phys. Rev. Lett.	102	233002 (4)	20090612	2359
M.A. Perez, U. Nguyen, S. Knappe, E.A. Donley, J. Kitching and A.M. Shkel	Rubidium vapor cell with integrated Bragg reflectors for compact atomic MEMS	Sensor Actuat A- Phys	154	295-303	20090609	2291
J.D. Jost, J.P. Home, J.M. Amini, D.A. Hanneke, R. Ozeri, C. Langer, J.J. Bollinger, D. Leibfried, and D.J. Wineland	Entangled mechanical oscillators	Nature	459	683-686	20090604	2034
D.A. Braje, L. Hollberg, and S.A. Diddams	Brillouin-Enhanced Hyperparametric Generation of an Optical Frequency Comb in a Monolithic Highly Nonlinear Fiber Cavity Pumped by a cw Laser	Phys. Rev. Lett.	102	193902 (4)	20090515	2327
M.J. Biercuk, H. Uys, A. VanDevender, N. Shiga, W.M. Itano, and J.J. Bollinger	Optimized dynamical decoupling in a model quantum memory	Nature	458	996-1000	20090423	2349
A. Hati, C.W. Nelson, and D.A. Howe	Effect of Vibration on PM and AM noise of Oscillatory and Non-oscillatory Components at 10 GHz	Proc. 2009 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf.		524-529	20090420	2371
J. Preusser, S. Knappe, J. Kitching, and V. Gerginov	A microfabricated photonic magnetometer	Proc. 2009 Joint Mtg. IEEE Intl. Freq. Cont. Symp. and EFTF Conf.		1180-1182	20090420	2369
G.K. Campbell, M.M. Boyd, J.W. Thomsen, M.J. Martin, S. Blatt, M.D. Swallows, T.L. Nicholson, T. Fortier, C.W. Oates, S.A. Diddams, N.D. Lemke, P. Naidon, P. Julienne, J. Ye, and A.D. Ludlow	Probing Interactions Between Ultracold Fermions	Science	324	360-363	20090417	2355
R.B. Blakestad, C. Ospelkaus, A. VanDevender, J.M. Amini, J.W. Britton, D. Leibfried, and D.J. Wineland	High-Fidelity Transport of Trapped-Ion Qubits through an X-Junction Trap Array	Phys. Rev. Lett.	102	153002 (4)	20090417	2351

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Mike Lombardi
Radio stations, Internet Time Service, etc.
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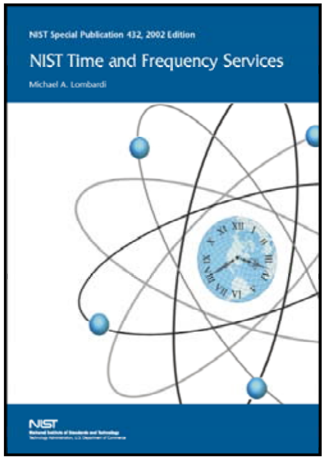

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