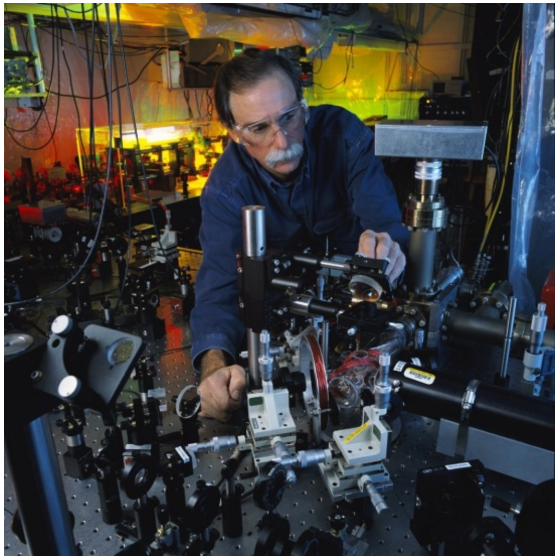
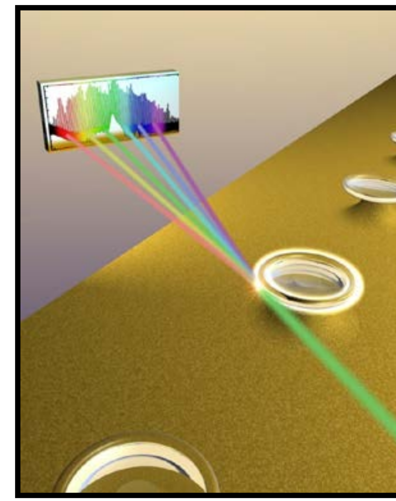
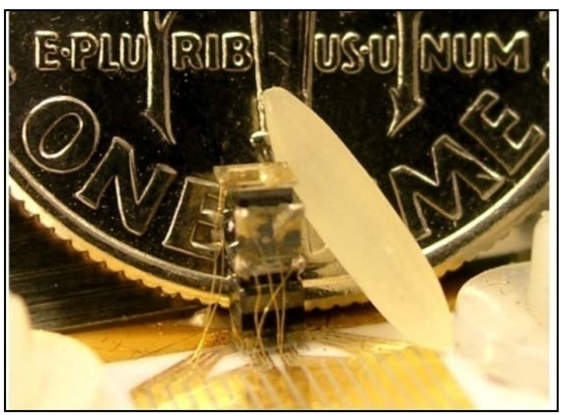
NIST Time and Frequency Division

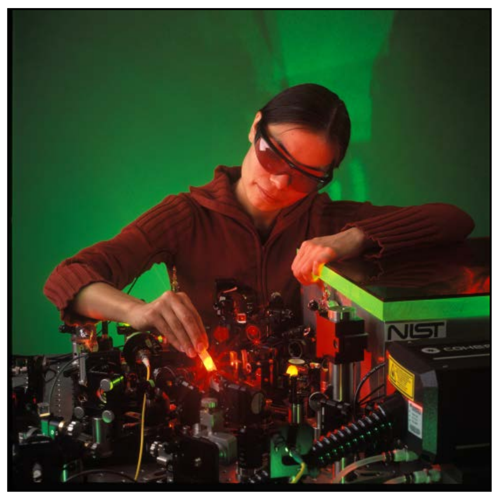


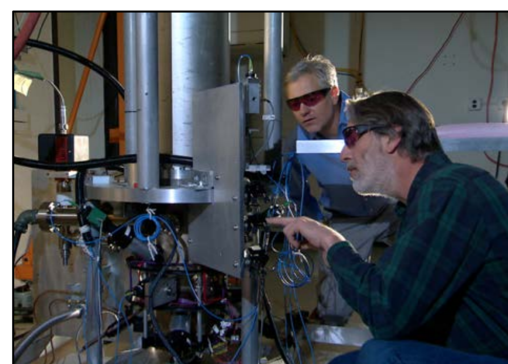
Develop and distribute the highest accuracy time and frequency measurements and related technologies to support commerce, research, national priorities and the general public.

tf.nist.gov









THANK YOU!

For your service in helping to assess the Time and Frequency Division, Physical Measurement Lab, and NIST.

A lot of work, and distraction from your regular responsibilities.

We find the formal and informal interactions very helpful as we continually strive to improve our programs.

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

1. Technical programs.
   - Quality of research compared to rest of world.
   - Are technical programs adequate to achieve stated mission?

2. Scientific expertise.
   - Quality of technical staff compared to rest of world.
   - Is technical staff expertise adequate to achieve stated mission?

3. Infrastructure.
   - Are quality of facilities, equipment, human resources adequate to achieve stated mission?

4. Dissemination of outputs.
   - How effectively does the organization disseminate/transfer its outputs?

Assessment of the NIST Time and Frequency Division

Strategic planning, external review of plans, input for planning for Time and Frequency Division, Physical Measurement Lab, NIST:

- Visiting Committee on Advanced Technology.
  - Industry, academia, government agencies.

- Department of Commerce (parent agency of NIST).

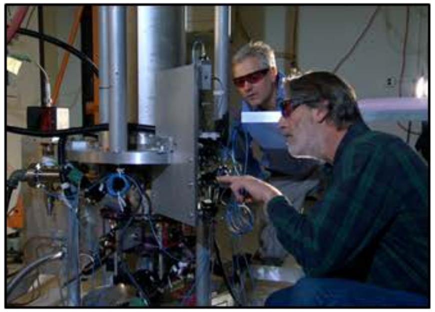
- Congress of the United States.

- Various customer and stakeholder workshops, conferences, seminars, surveys, etc.

- Multiple internal strategic planning exercises.
  - Division, Laboratory, NIST-wide.

NIST Time and Frequency Mission

UTC
Official Time



NIST-F2

Time Scale

US Public Law 110-69 *(2007, paraphrased)*:
Official time for the US is **Coordinated Universal Time (UTC)**: the time scale maintained through the General Conference of Weights and Measures and **interpreted for the United States by the Secretary of Commerce (NIST)** in coordination with the Secretary of the Navy (USNO).

NIST Time and Frequency Mission

Dissemination

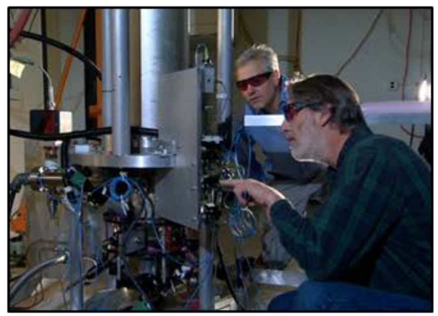
Radio broadcasts

Networks

Satellites

Noise metrology

UTC
Official Time



NIST-F2

Time Scale

NIST Time and Frequency Mission

Dissemination

UTC
Official Time

Research

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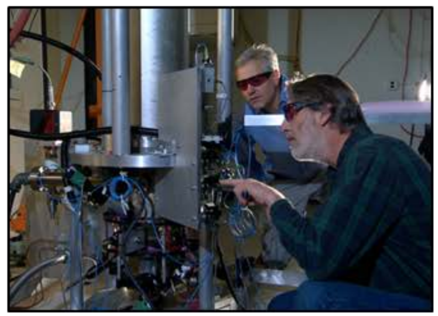
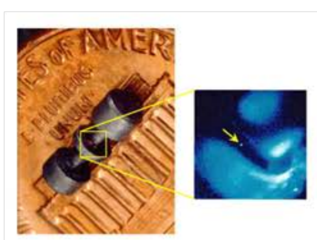
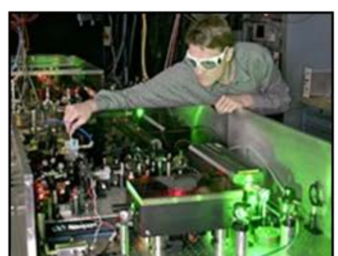


NIST-F2

Time Scale

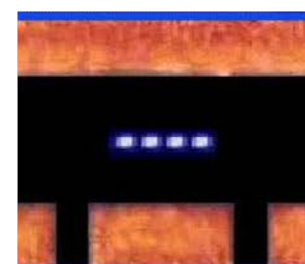


Optical clocks



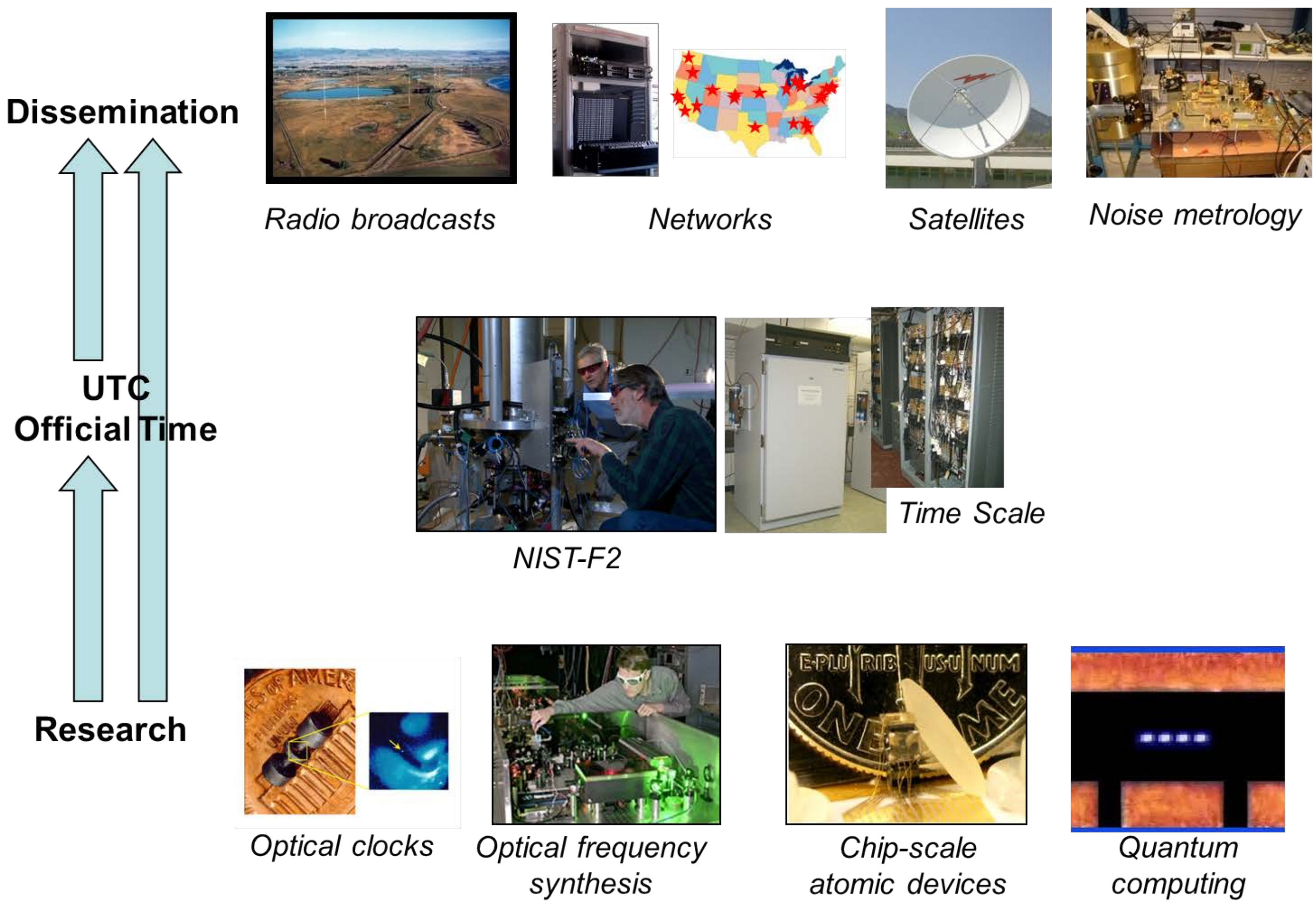
Optical frequency synthesis

Chip-scale atomic devices

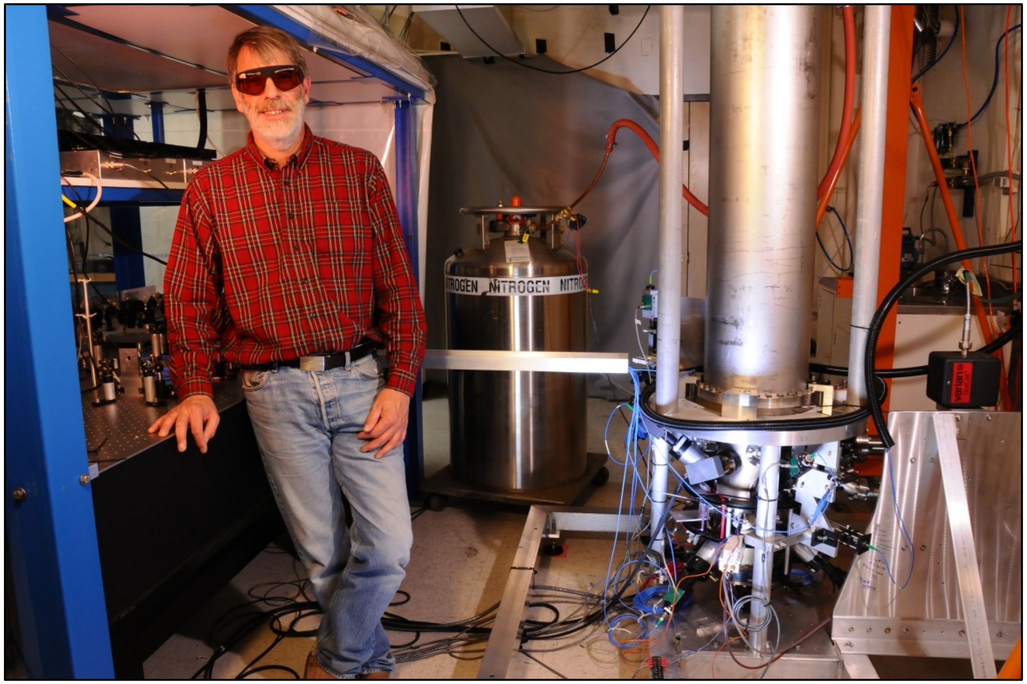


Quantum computing

Vertically integrated program of standards, measurements, research, innovation, and technology transfer.



NIST-F2 Atomic Fountain Clock
An Official Time Standard for the United States



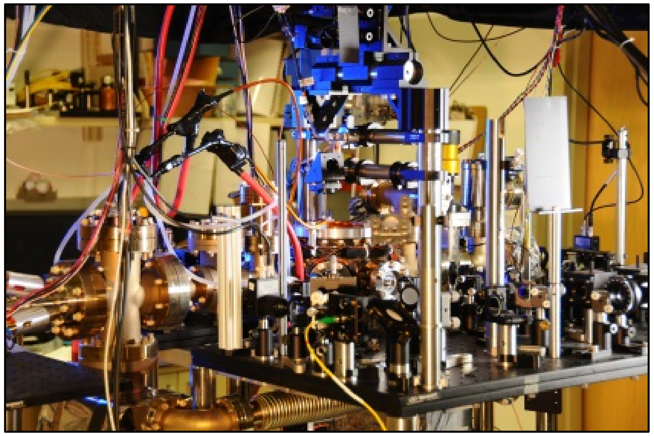
NIST-F2 laser-cooled fountain standard atomic clock

1 second is defined as the duration of 9,192,631,770 cycles of the cesium hyperfine transition.

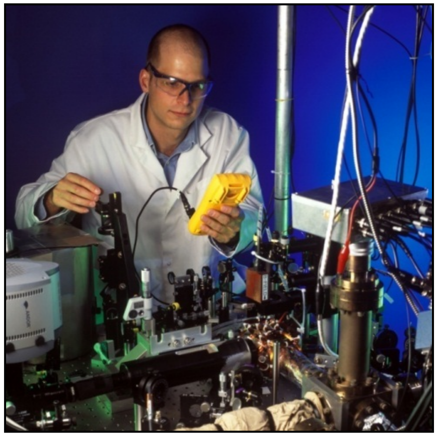
- Frequency uncertainty $\Delta f/f = 1 \times 10^{-16}$.
- 1 second in 300 million years.
- Enabled by NIST pioneering laser cooling and trapping.

Equivalent to measuring distance from earth to sun (150 million km) to uncertainty of about 15 microns (1/10 the thickness of a human hair).

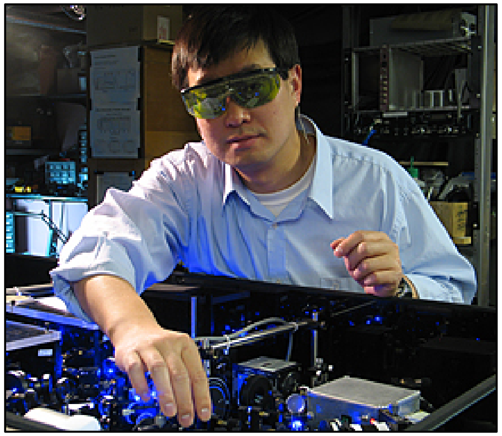
NIST Research Optical Frequency Standards



Ytterbium Lattice Clock
NIST



Aluminum Ion Logic Clock
NIST



Strontium Lattice Clock
NIST/JILA

- Research atomic clocks at NIST already at $\Delta f/f = 2 \times 10^{-18}$.
  - 1 second in about 15 billion years.
- Rapidly improving.
- NIST and JILA have five of the best types of atomic clocks in the world.
  - Applying NIST and JILA Nobel Prize breakthroughs (1997, 2005, 2012).

Equivalent to measuring distance from earth to sun (150 million km) to uncertainty of about 0.3 micron (size of a virus).

Who cares about precision timing?

Impacts of Accurate Timing and Synchronization

Telecommunications and Information Technology Networks

Requires frequency stability $\Delta f/f = 10^{-11}$.

Synch of about 1 microsecond per day.

Global telecom revenue in 2013:
$3.9 trillion, 2/3 from wireless.

Projected to grow to $4.6 trillion by 2017,
higher fraction from wireless.

Source: Telecommunications Industry Association

Impacts of Accurate Timing and Synchronization

Electric Power Generation and Distribution

Requires frequency stability $\Delta f/f = 10^{-11}$.

Synch of about 1 microsecond per day.

US electric power sales in 2013: $375 billion.

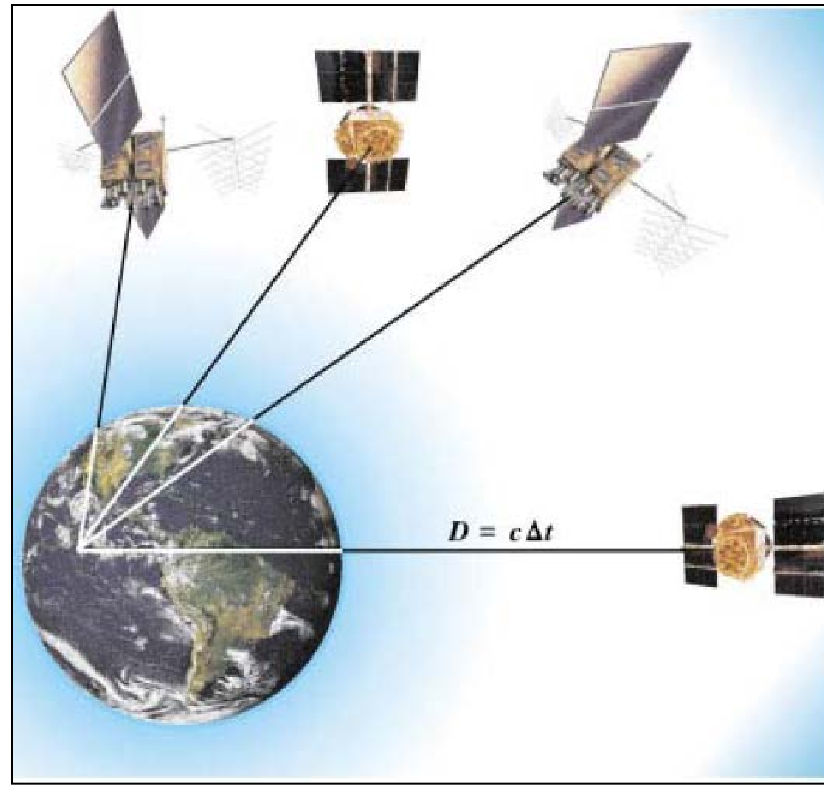
Precision timing demands increase with Smart Grid.

Source: US Energy Information Administration

Impacts of Accurate Timing and Synchronization

Global Navigation Satellite Systems (GNSS)

- GPS – US
- GLONASS – Russia
- Galileo – European Union
- BeiDou (Compass) – China
- Quasi-Zenith Satellite System – Japan
- Indian Regional Navigational Satellite System – India
- Others...



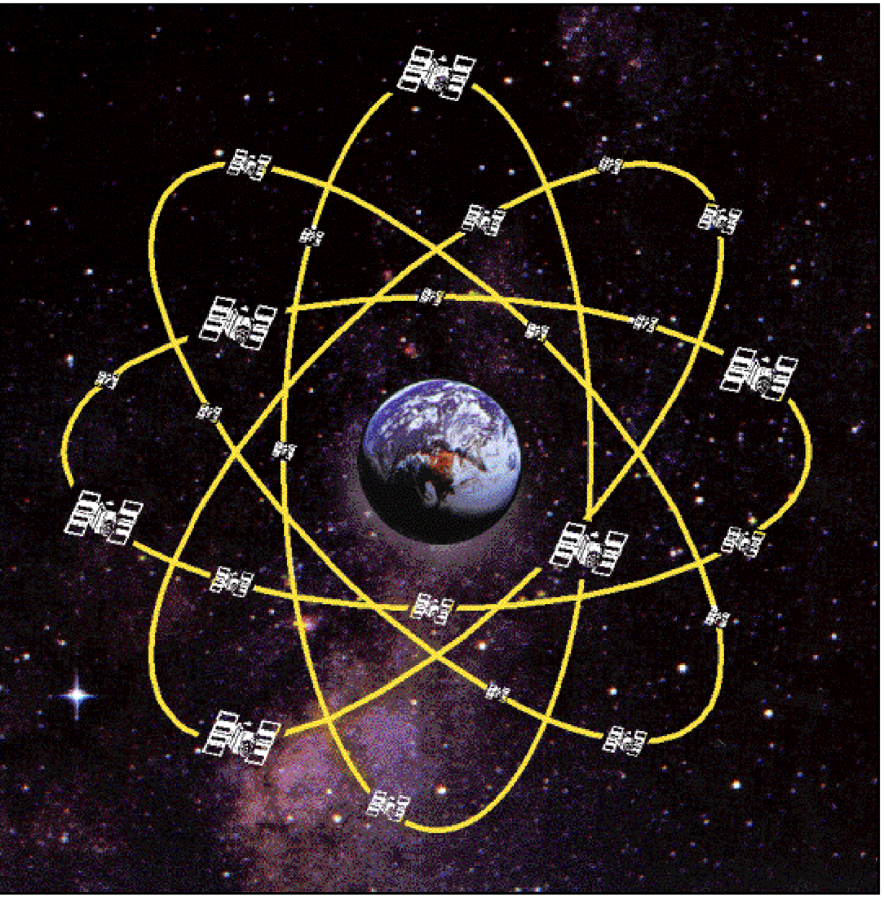
Requires frequency stability $\Delta f/f \sim 10^{-14}$.

Synch of about 1 nanosecond per day.

Civilian/Commercial GNSS Applications

Impacts of Accurate Timing and Synchronization

Global Navigation Satellite Systems (GNSS)



Economic benefits estimated 2011,
GPS only, only for US:
$125 billion, 3.3 million jobs.
Old estimate, gross underestimate

GPS receivers everywhere: smart phones, cell phones, tablets, etc.

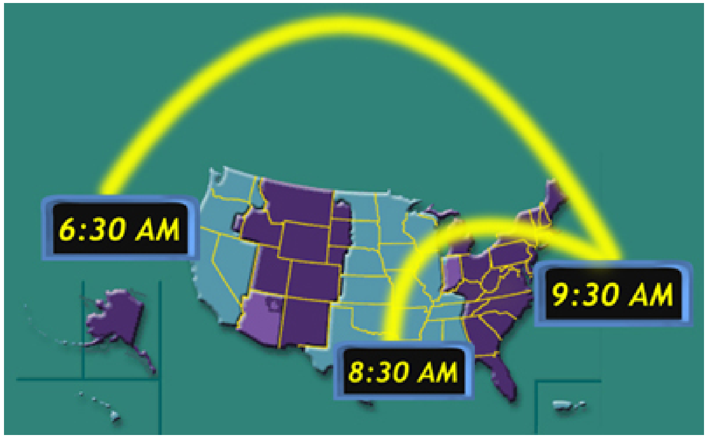
Applications rapidly expanding…

National security applications: Probably equivalent of trillions of US dollars…

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

Impacts of Accurate Timing and Synchronization

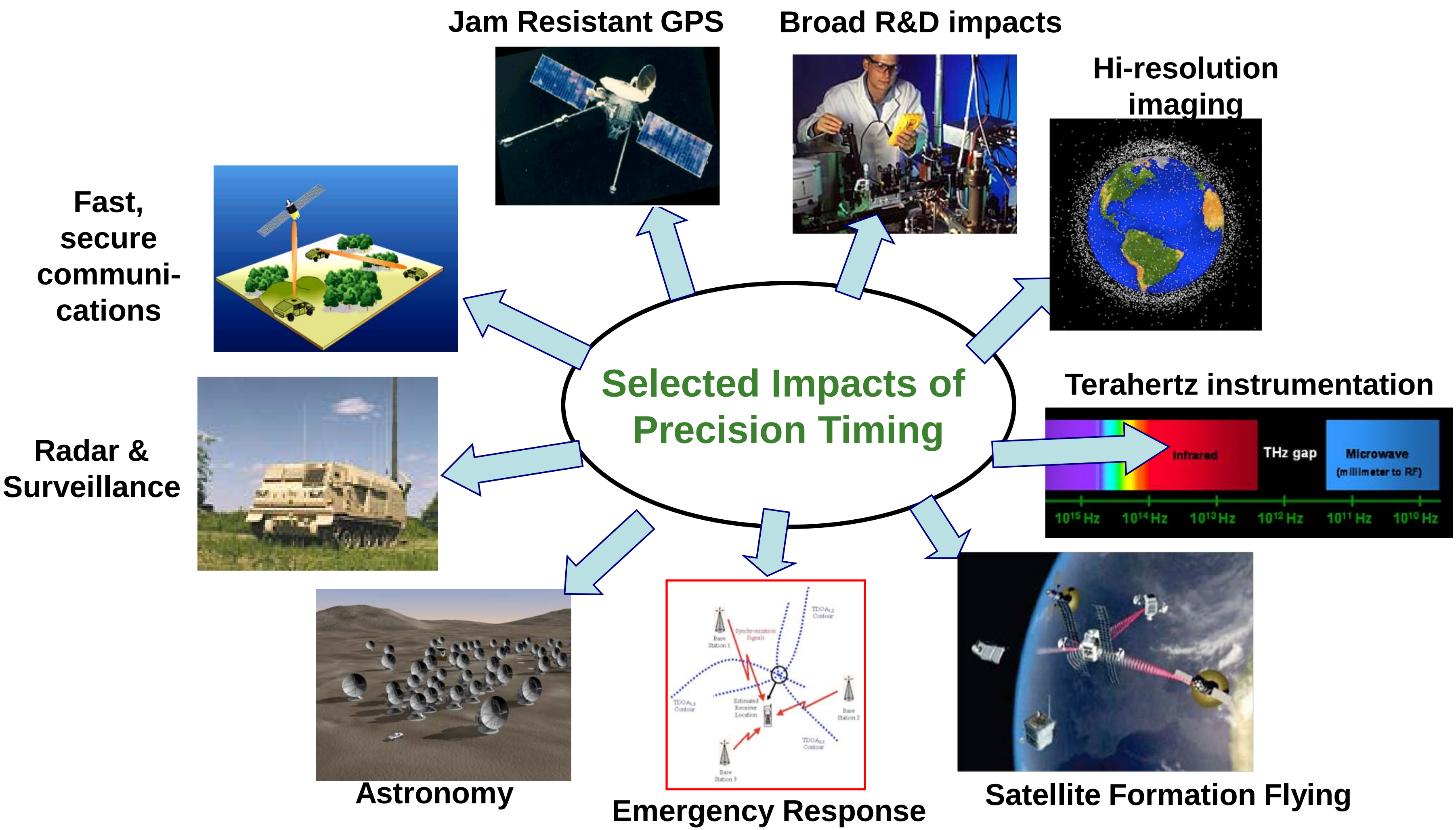
Electronic Financial Transactions



- US Financial Industry Regulatory Authority (FINRA) rules for electronic financial transactions for more than 800,000 businesses conducting billions of transactions daily through New York Stock Exchange, NASDAQ, other venues.
  - Overseen by U.S. Securities and Exchange Commission.
- All FINRA member electronic and mechanical time-stamping devices must be traceable to within one second of the "NIST atomic clock." *(FINRA Rule 7430)*
  - *Proposed to be tightened to 50 milliseconds in near future.*
- Hundreds of billions of dollars of daily electronic financial transactions in US.

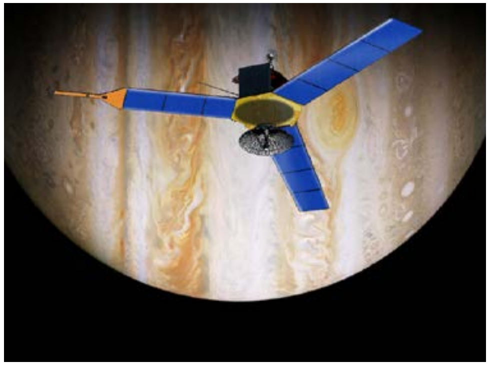
Source: US Financial Industry Regulatory Authority

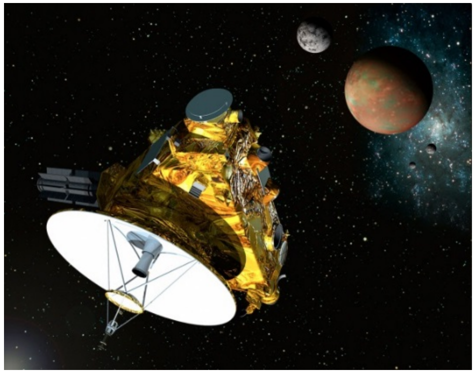
Impacts of Accurate Timing and Synchronization

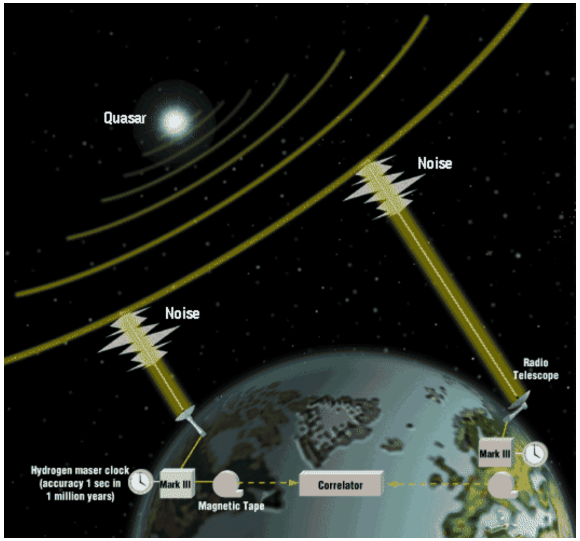


Impacts of Accurate Timing and Synchronization

Science: Spacecraft Communications, Astrophysics







Very Long Baseline Interferometry

NASA Deep Space Network

Frequency/synch demands as stringent as $\Delta f/f \sim 10^{-16}$, trillionths of seconds per day.

Source: NASA

Impacts of Accurate Timing and Synchronization

Science: Tests of Special and General Relativity

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

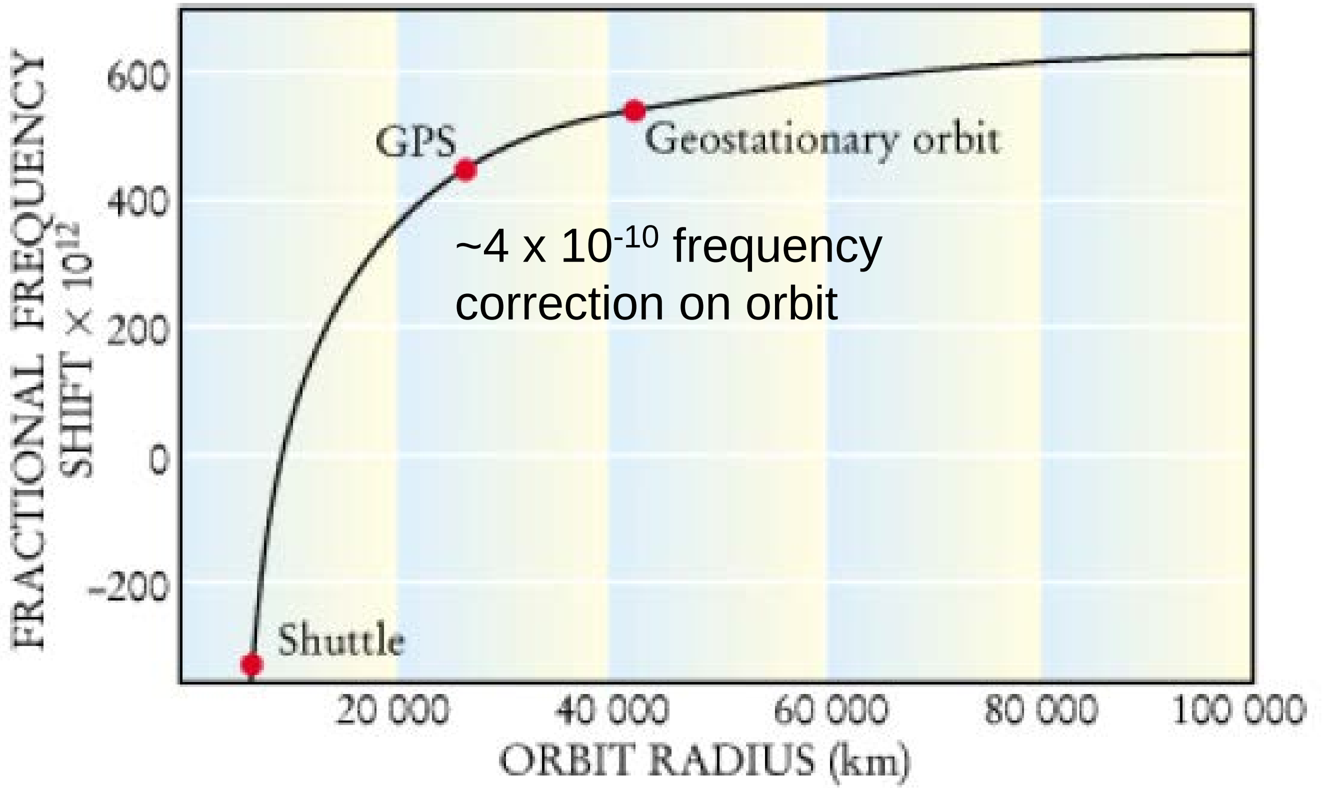
Time dilation (special relativity)

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

Gravitational time dilation (general relativity)

Impacts of Accurate Timing and Synchronization

Technology: GPS



Low orbit: Velocity (special relativity) dominates, red-shifted.

High orbit: Gravitational shift dominates, blue-shifted.

Impacts of Accurate Timing and Synchronization

Science: Possible temporal variation in fundamental constants

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

Fine structure constant

$$\frac{\Delta\alpha}{\alpha} = -0.72 \pm 0.18 \times 10^{-5}$$

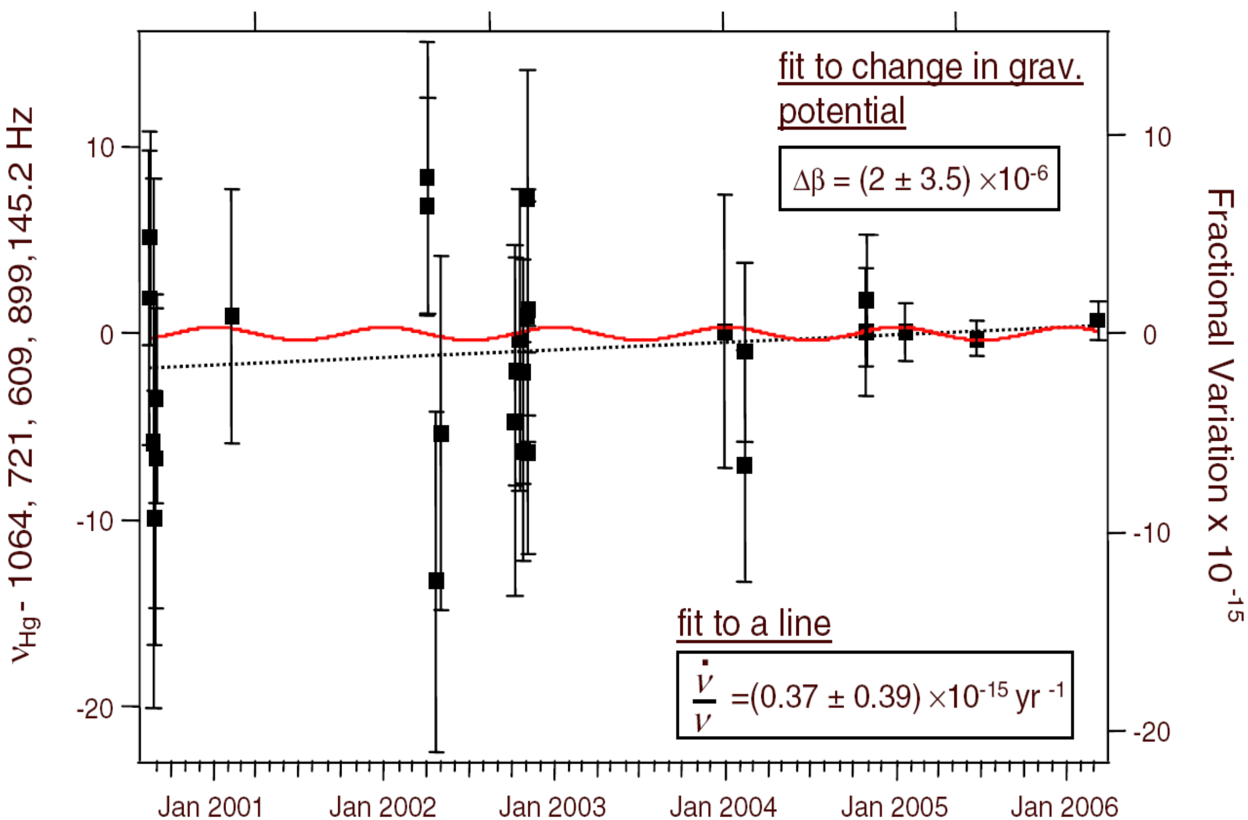
over ~ 10^{10} years from quasar observations.
Possible $\Delta\alpha/\alpha \sim 10^{-15}$/year.

J. K. Webb *et al.*, Phys. Rev. Lett. **87**, 091301 (2001)

Impacts of Accurate Timing and Synchronization

Possible temporal variation in fundamental constants

$$\nu_{Cs}/\nu_{Hg} \sim g_{Cs}(m_e/m_p)\alpha^{6.0}$$



Compare cesium, mercury ion, aluminum ion atomic clocks over several years.

$$\left|\frac{\Delta\alpha}{\alpha}\right| < 1.6 \text{ x } 10^{-17} \text{ / yr}$$

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 in Current SI	Proposed SI Redefinition
Second	10^{-15}	**Yes**	**(no change)**
Meter	10^{-12}	**Yes**	**c (m / s)** **(no change)**
Kilogram	10^{-9}		**h (J s)**
Ampere	10^{-7}	**Yes**	**e (A s)**
Mole	10^{-7}		N_A
Kelvin	10^{-7}		**k** $(kg\ m^2/s^2/K)$
Candela	10^{-3}	**Yes**	K_{cd} $(cd\ sr\ s^3/kg/m^2)$

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 – 10^{15} range in precision.
    - Timestamping of electronic financial transactions – 1 second precision.
    - Global Navigation Satellite Systems applications – 10^{-15} second precision.

- NIST and other National Metrology Institutes 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.

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

1. Technical programs.
   - Quality of research compared to rest of world.
   - Are technical programs adequate to achieve stated mission?

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NIST Time and Frequency Mission

Dissemination

Radio broadcasts

Networks

Satellites

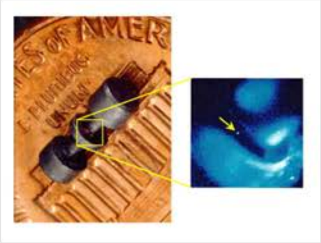
Noise metrology

UTC
Official Time

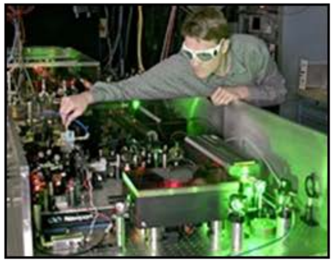
NIST-F2

Time Scale

Research

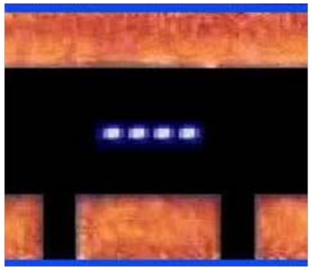


Optical clocks



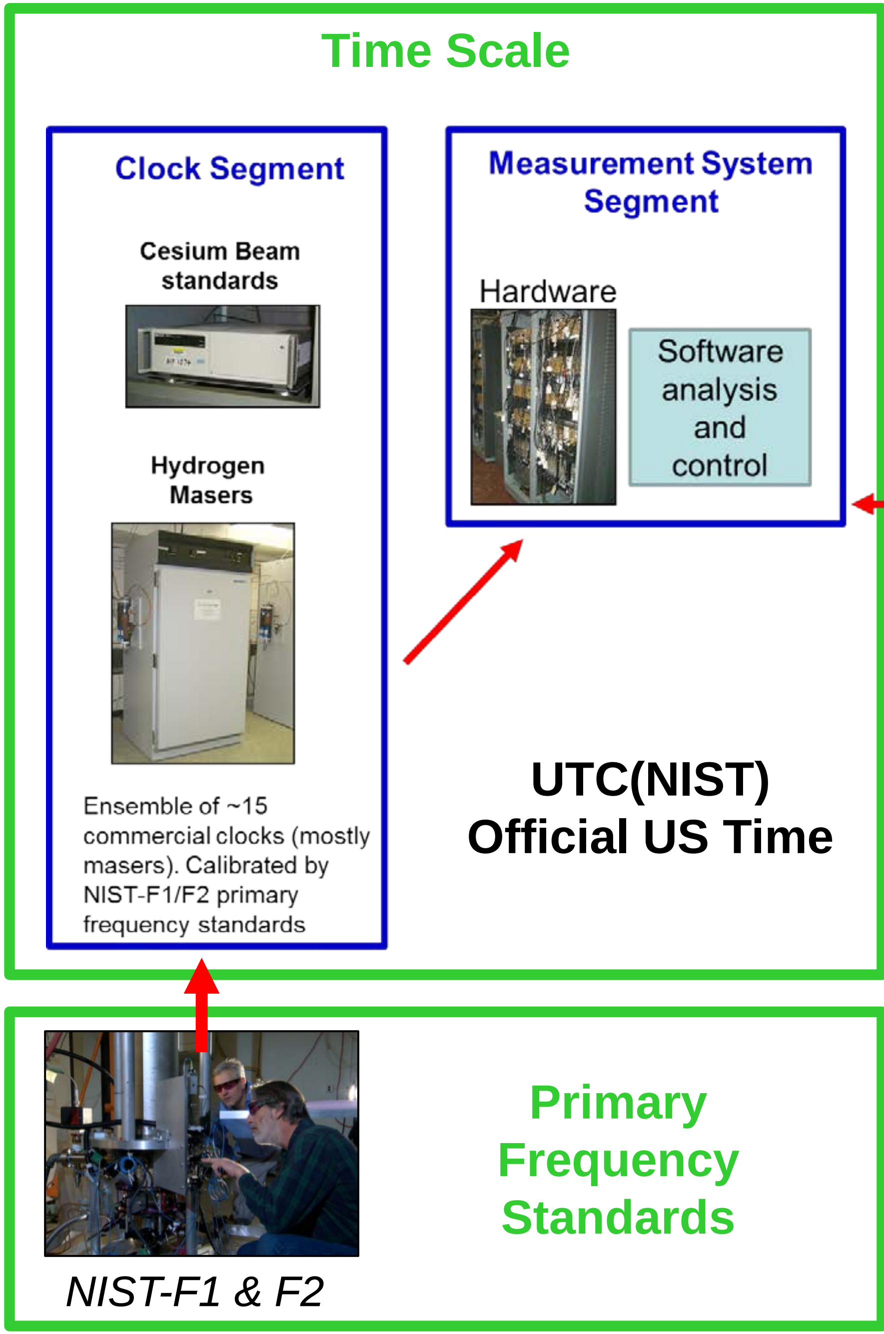
Optical frequency synthesis

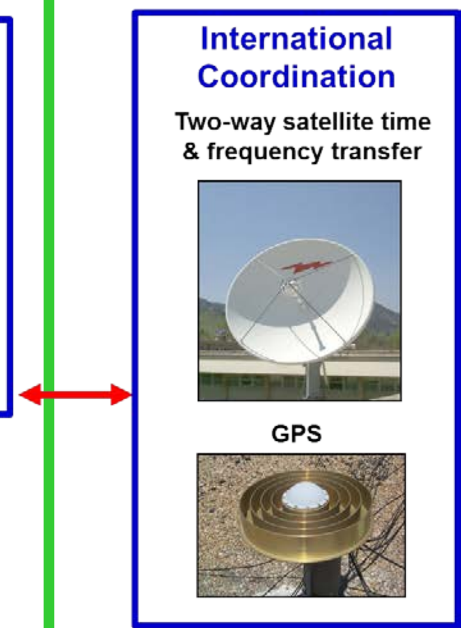
Chip-scale atomic devices



Quantum computing

NIST Time and Frequency Mission: UTC (Official Time)

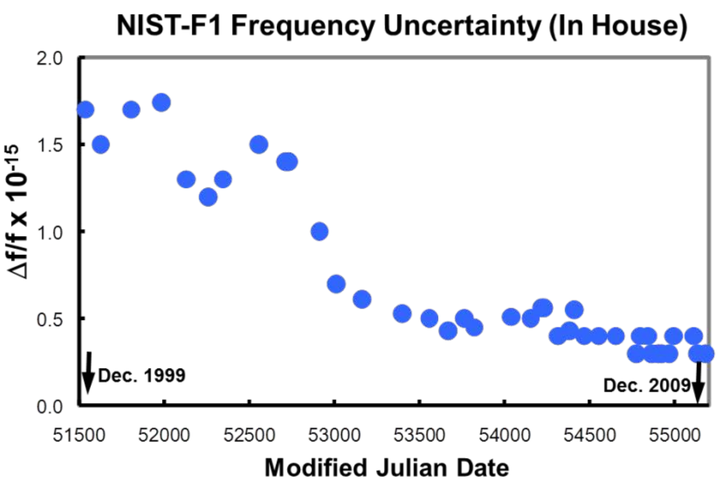




NIST and approximately 70 other timing laboratories across the world contribute to UTC realized by the International Bureau of Weights and Measures (BIPM):

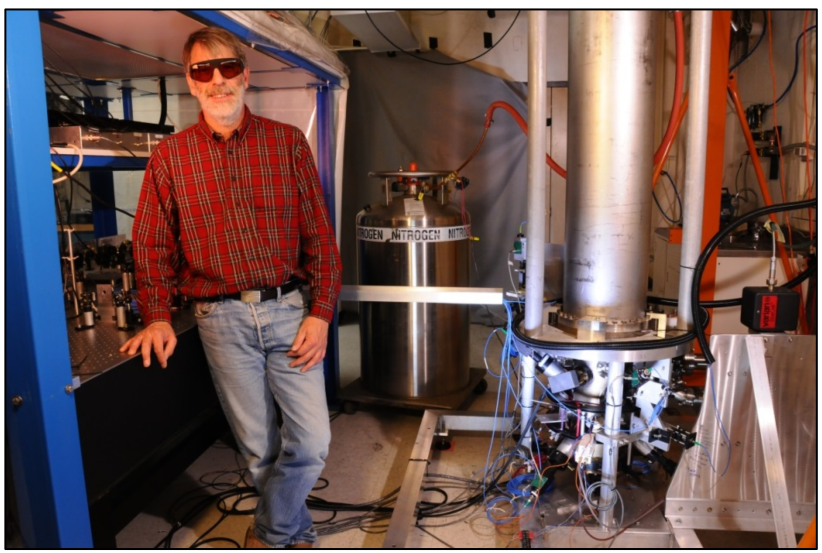
- Frequency of UTC (NIST-F1 & F2)
- Current value of UTC (Time Scale)

NIST Time and Frequency Mission: UTC (Official Time)
Primary Frequency Standards: UTC Frequency



NIST-F1 Cesium Fountain Standard

- NIST-F1 commissioned 1999.
- Initial $\Delta f/f = 17 \times 10^{-16}$.
- Ultimate $\Delta f/f = 3 \times 10^{-16}$ by 2009.



NIST-F2

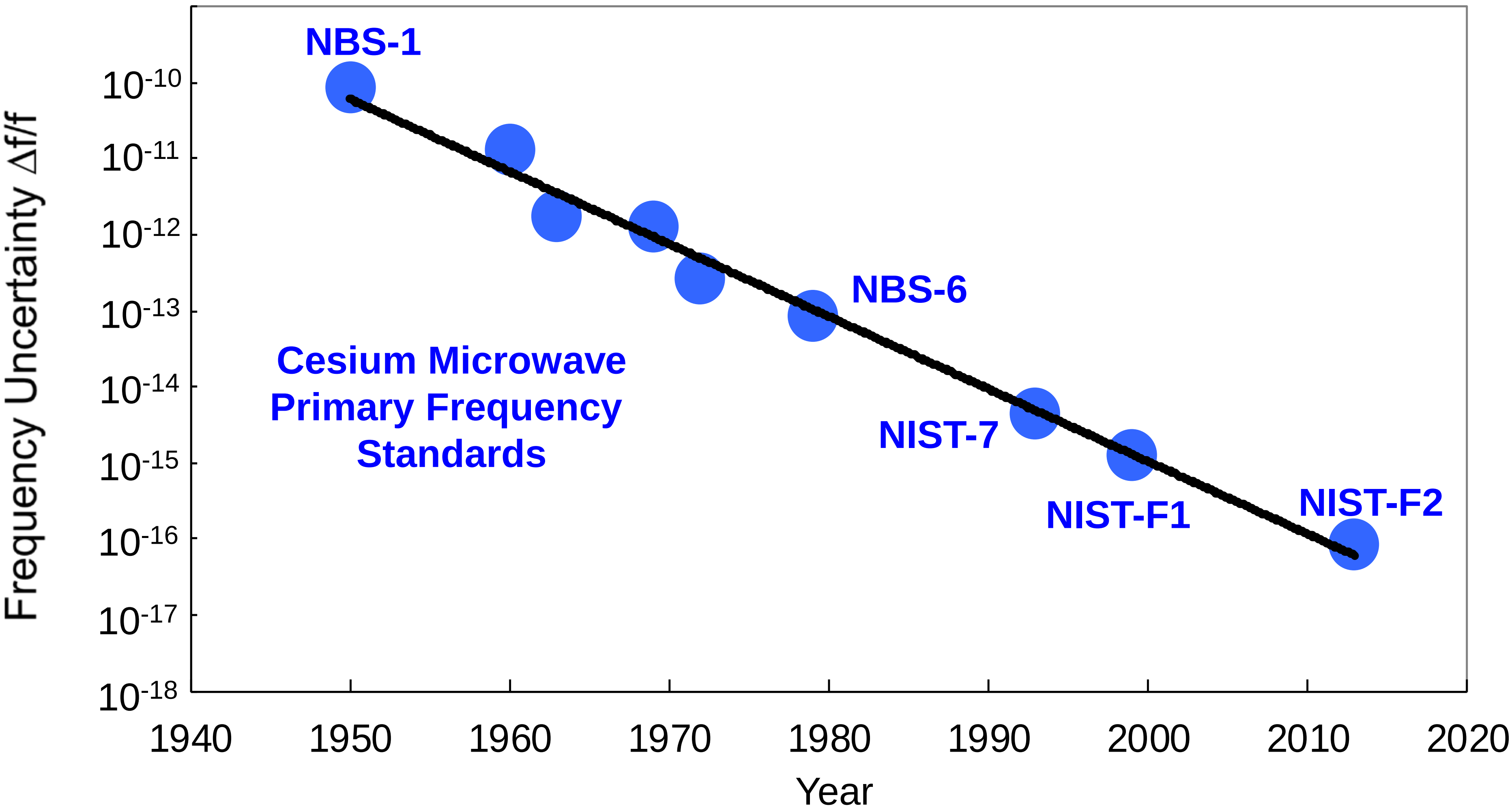
- NIST-F2 commissioned 2013.
    - Cryogenic drift tube.
    - Other improvements.
- Initial $\Delta f/f = 1 \times 10^{-16}$.
- Ultimate $\Delta f/f$ = ???
    - Perhaps x2-3 improvement???

NIST Time and Frequency Mission: UTC (Official Time)
Primary Frequency Standards: UTC Frequency

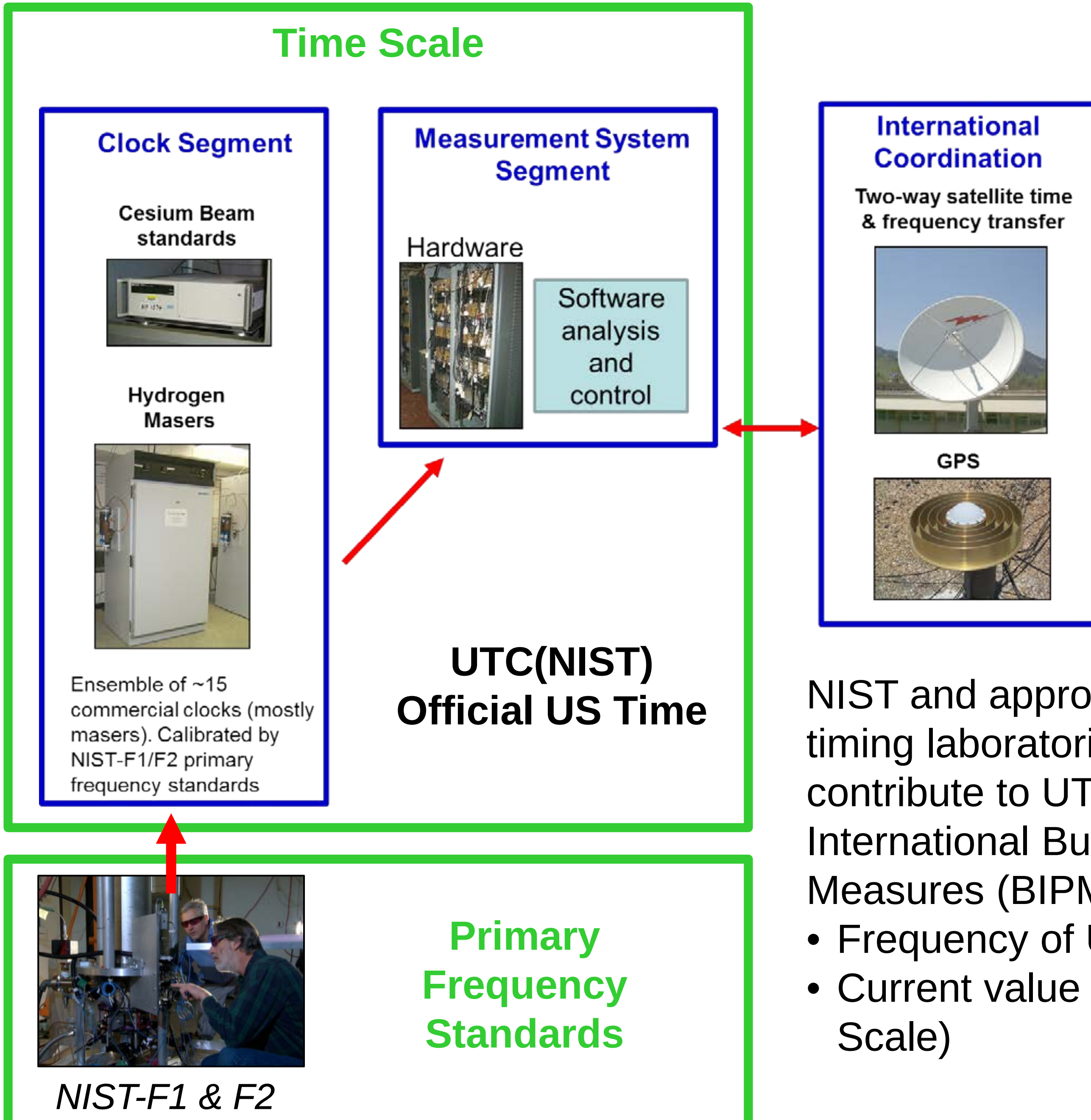
	Nation	Fountain	Uncertainty (10^{-15})
1	NIST (US)	NIST-F2	0.11
2	Italy	IT-CsF2**	0.18
3	UK	NPL-CsF2	0.23
4	France	SYRTE-FO2	0.23
5	NIST (US)	NIST-F1	0.31
6	France	SYRTE-FORb	0.32
7	France	SYRTE-FO1	0.37
8	Germany	PTB-CsF2	0.41
9	Russia	SU-CsFO2	0.50
10	Germany	PTB-CsF1	1.4
11	China	NIM5	1.4
12	India	NPLI-CsF1	2.5
13	Japan	NMIJ-F1	4.0

- Cesium fountain primary frequency standards.
- NIST-F2 world's most accurate primary frequency standard.
  - NIST-F1 was world's most accurate during most of its tenure and remains a top performer.
- **Note: IT-CsF2 is a copy of NIST-F2.
  - Designed and built at NIST for Italy's National Metrology Lab (INRIM).
  - INRIM scientists trained at NIST to master NIST-F2 and apply knowledge to IT-CsF2.

NIST Time and Frequency Mission: UTC (Official Time)
Primary Frequency Standards: UTC Frequency



NIST Time and Frequency Mission: UTC (Official Time)



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- Current value of UTC (Time Scale)

NIST Time and Frequency Mission: UTC (Official Time)
Time Scale

Example timing labs contributing to UTC
~70 labs, ~300 clocks total across the world

NMI	Country	# Clocks for UTC
USNO	USA	103
NICT	Japan	35
NTSC	China	32
SP	Sweden	26
NIST	USA	14

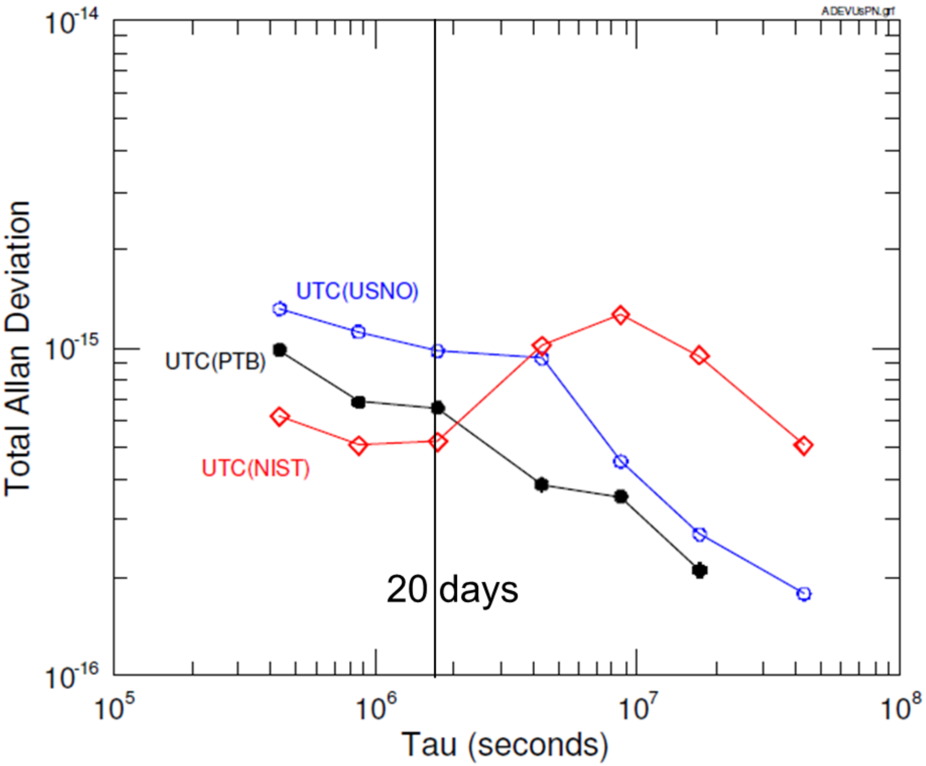
For traditional time scale ensemble of *N* clocks periodically calibrated (for example by primary frequency standard):

Time scale instability ~ $\dfrac{1}{\sqrt{N}}$

- Based solely on number of clocks in the time scale, UTC(NIST) would be expected to be mediocre performer.

- But number of clocks in an ensemble is far from the sole determinant of time scale performance in the 21st century.

NIST Time and Frequency Mission: UTC (Official Time) Time Scale

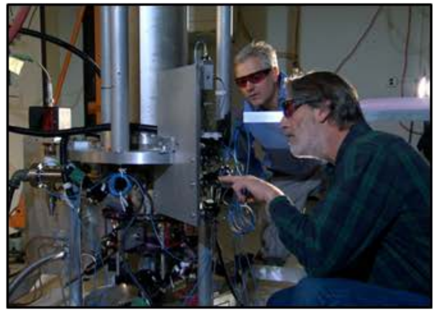


	5days	10days	20days	40days
1	NIST	NIST	NIST	Germany
2	France	Germany	France	France
3	Germany	France	Germany	USNO
4	USNO	USNO	USNO	NIST
5	Poland	Finland	Italy	Italy
6	Italy	Italy	Russia	Russia
7	Finland	Poland	Finland	Finland
8	UK	China	China	Poland
9	Japan(NM)	Russia	Poland	Japan(CT)
10	NIM	Japan(NM)	Japan(CT)	China
11	Japan(CT)	UK	Japan(NM)	Taiwan
12	Sweden	Japan(CT)	Taiwan	Japan(NM)
13	Korea	Sweden	Spain	Spain
14	Russia	Spain	UK	Sweden
15	Spain	Taiwan	Sweden	UK
16	Taiwan	Korea	Korea	Korea
17	Mexico	Mexico	Mexico	Mexico

- For most applications, short-term stability is most important.
- UTC(NIST) is one of the best time scales in the world.
- BUT we are pursuing two main approaches to improve both the near term and long-term stability of the NIST Time Scale – UTC(NIST).

NIST Time and Frequency Mission

UTC
Official Time



NIST-F2


Time Scale

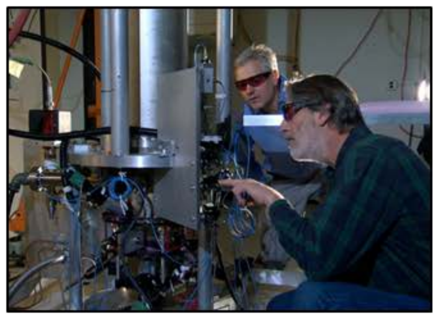
- Primary frequency standard (rate of UTC):
  - NIST-F2 is best in the world.
  - “Clone” of NIST-F2 (IT-CsF2) built by NIST is close second best.
  - NIST-F1 was best in the world for many years, remains in the top five.

- UTC(NIST) – Time Scale.
  - Best in the world for short to medium term.
    - Most important applications, including all NIST measurement services, use this range.

NIST Time and Frequency Mission

- **Research** to:
  - Improve primary frequency standard.
  - Improve time scale performance.

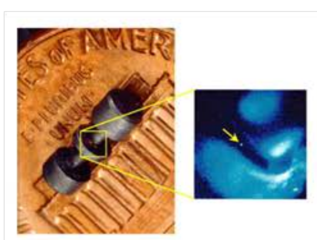
UTC
Official Time



NIST-F2

Time Scale

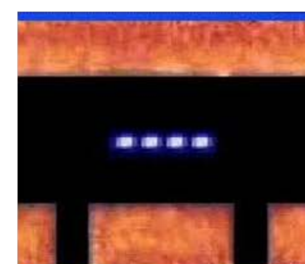
Research



Optical clocks

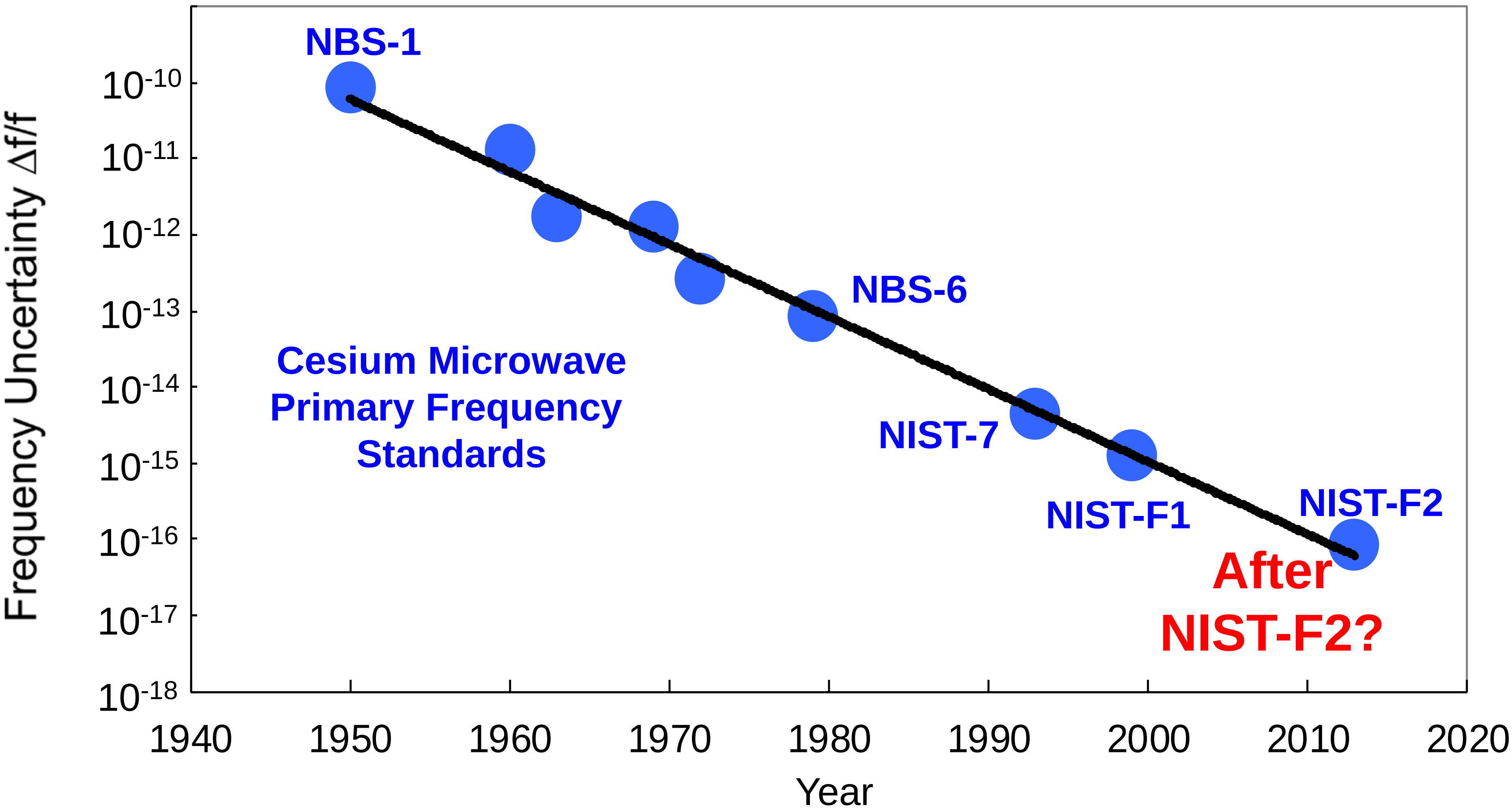
Optical frequency synthesis

Chip-scale atomic devices



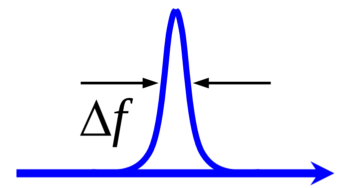
Quantum computing

NIST Time and Frequency Mission: UTC (Official Time)
Primary Frequency Standards: UTC Frequency



NIST Time and Frequency Mission: UTC (Official Time)
Primary Frequency Standards: UTC Frequency

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



Atomic Resonance

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

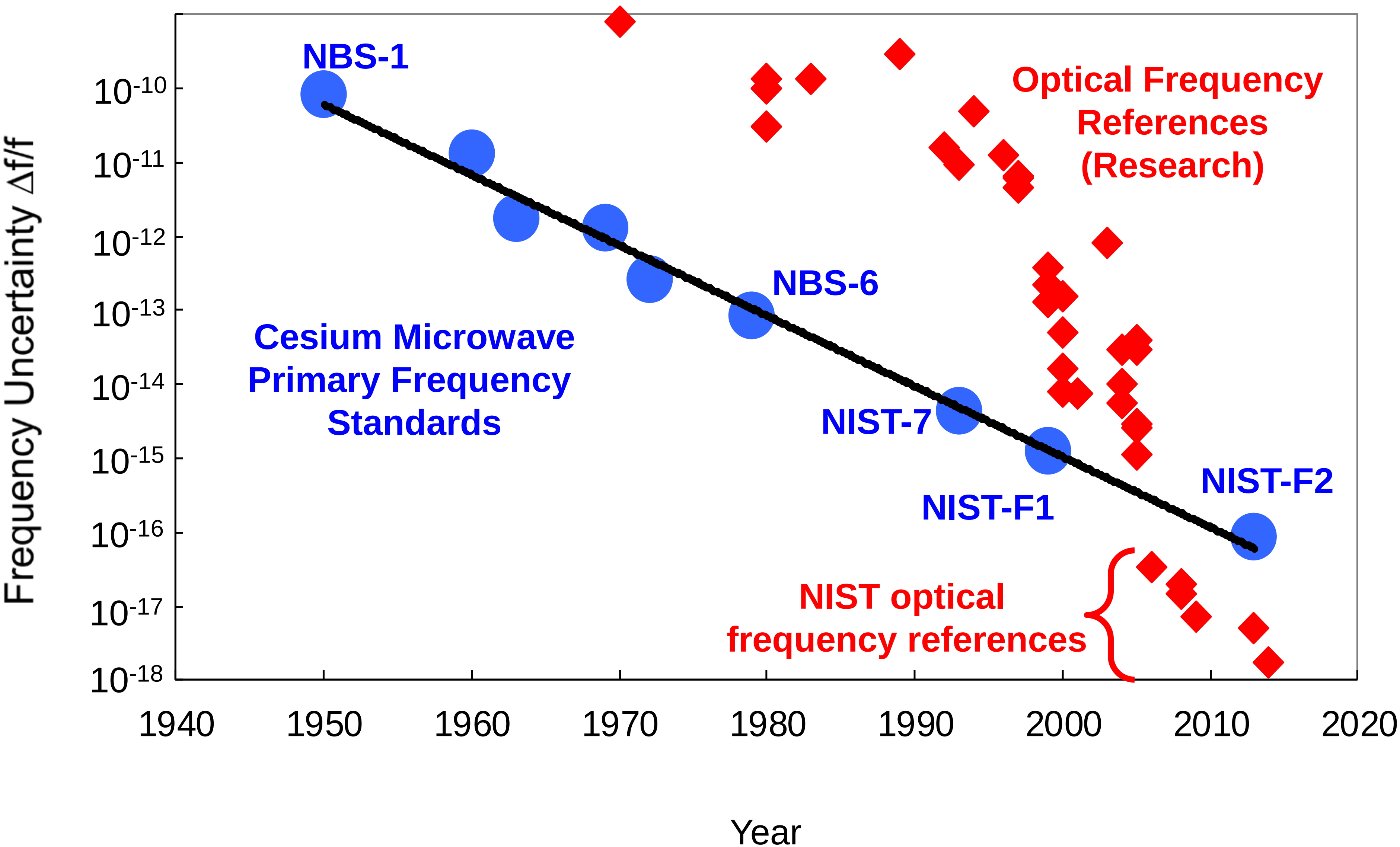
τ = observation time

N = number of atoms

NIST research atomic clocks

Al^+	1124 THz (1124 x 10^{12} Hz)	Optical
Hg^+	1064 THz	
Yb	520 THz	
Ca	456 THz	
Sr	429 THz	
Cs	0.0092 THz	Microwave

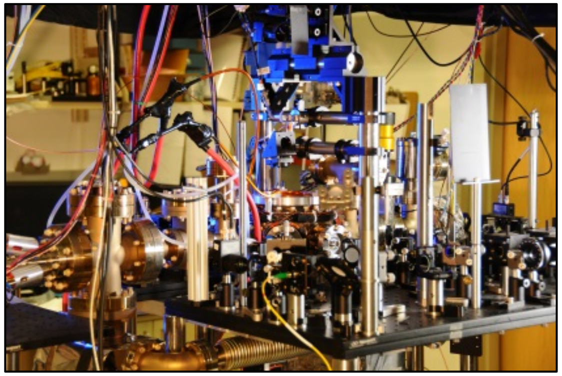
NIST Time and Frequency Mission: UTC (Official Time)
Optical Frequency Standards

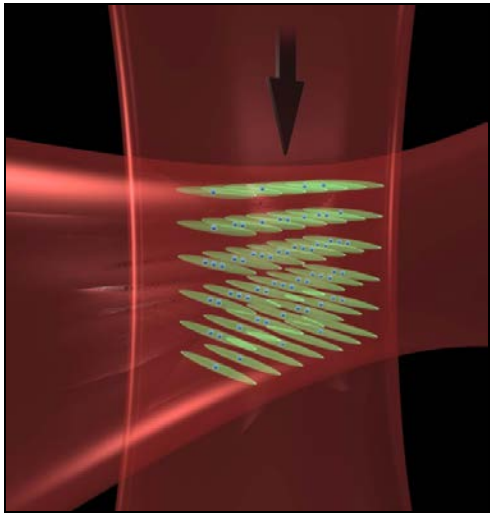


Optical Atomic Clocks at NIST

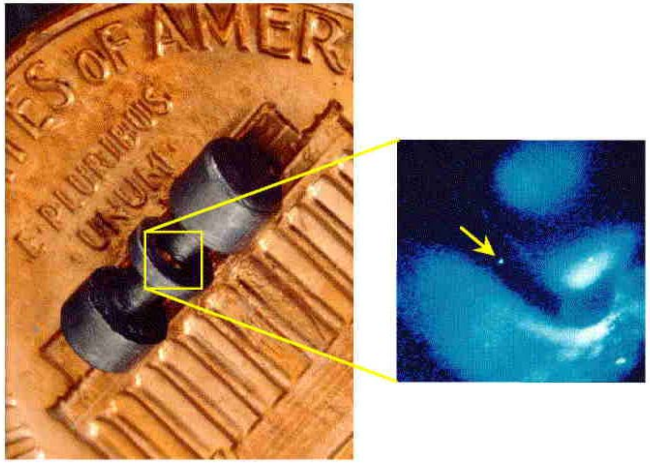
- High-frequency optical clocks outperform microwave (cesium) clocks.
- Potential to perform ~100 times better than best cesium clocks.
- Many years before SI second redefined to optical standard(s).

$\Delta f/f \sim 2 \times 10^{-18}$

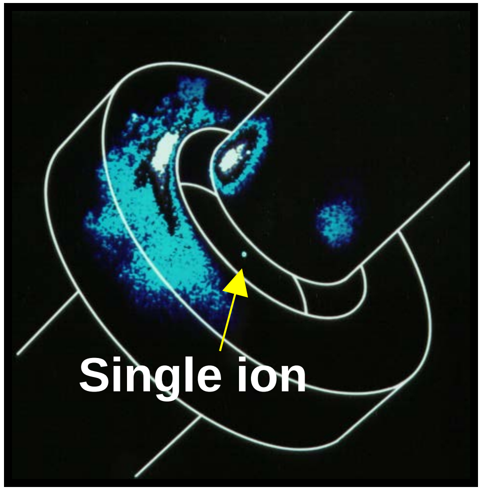




Strontium or Ytterbium optical lattice clocks

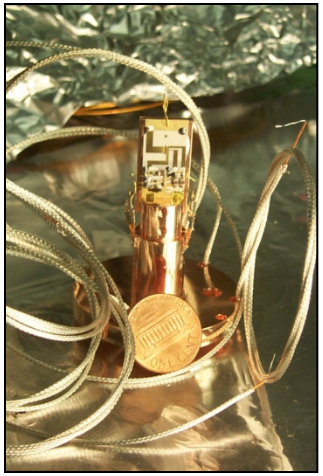


$\Delta f/f \sim 10 \times 10^{-18}$



Single mercury ion trap

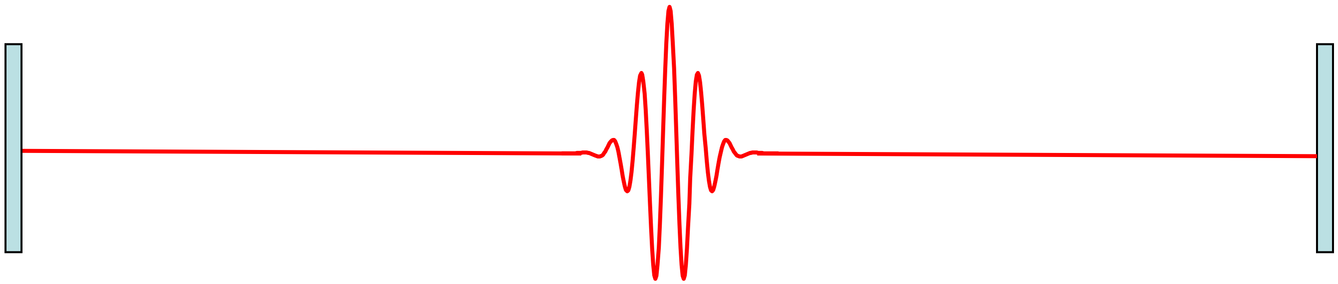
$\Delta f/f \sim 8 \times 10^{-18}$



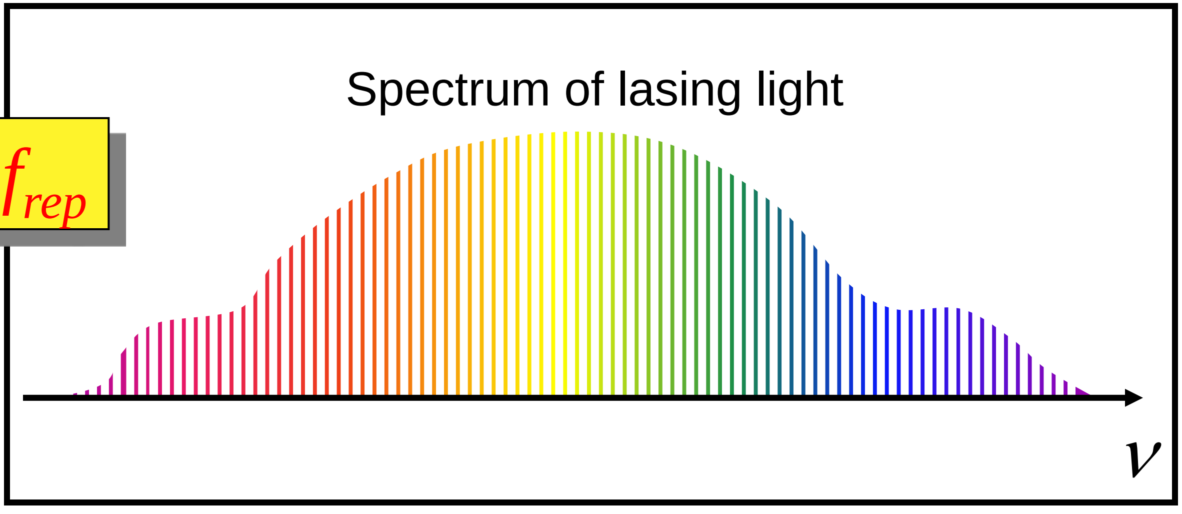
Aluminum ion logic clock

Femtosecond Laser Frequency Comb:
One Key to Optical Clocks

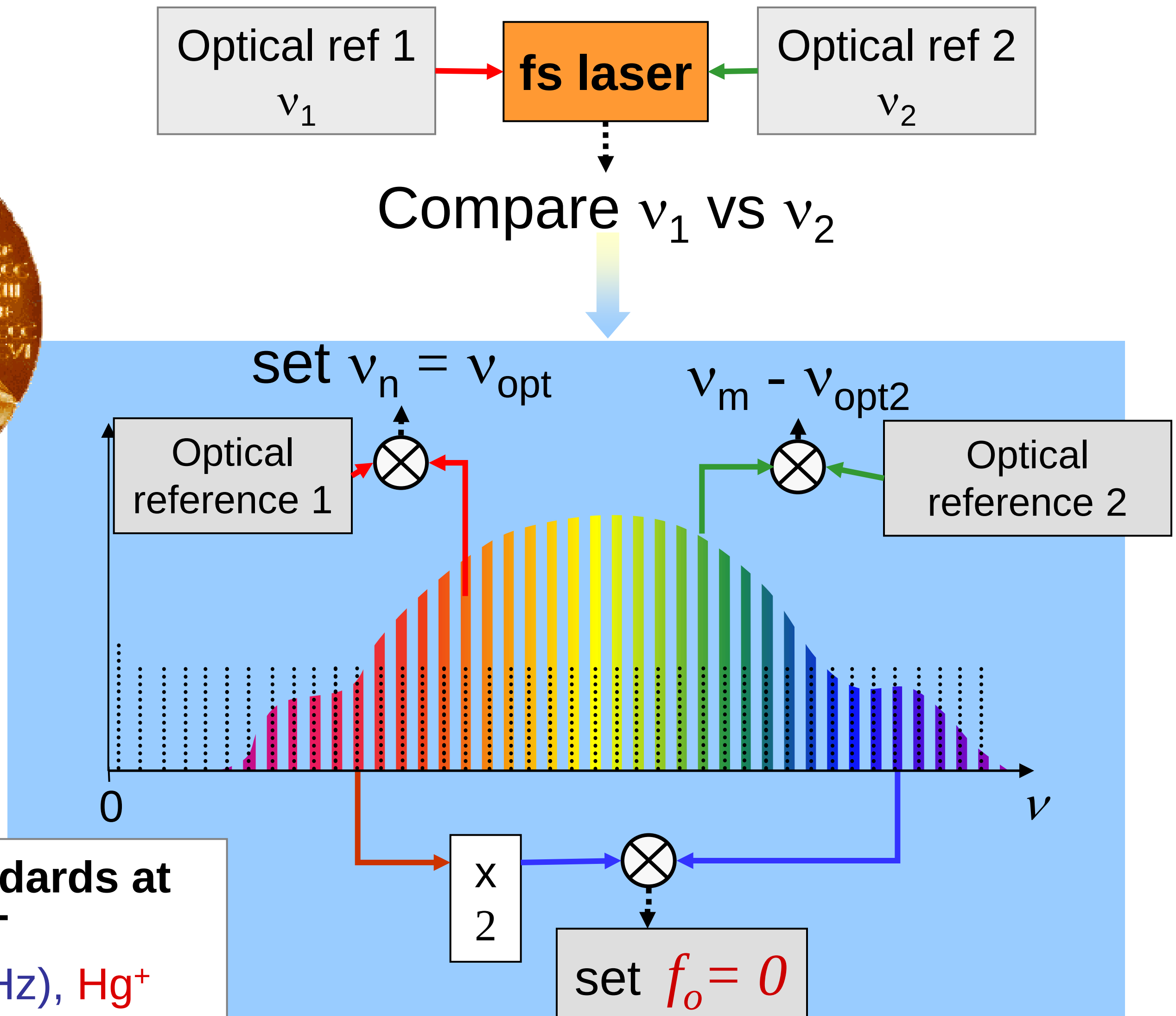
Coherent addition of longitudinal cavity modes → Pulse formation



$$\nu = n\,(c/\,2L) = n\,f_{rep}$$



Femtosecond Laser Frequency Combs: One Key to Optical Clocks



Optical standards at NIST

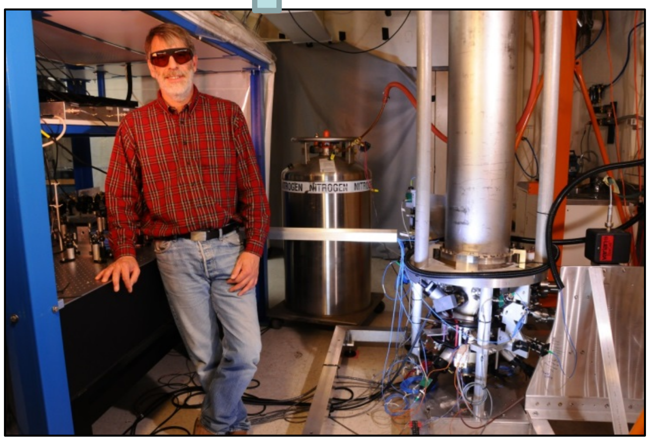
Al+ (1124 THz), Hg+ (1064 THz), neutral Yb (520 THz) and Sr (429 THz)

Direct comparison to Cs (0.0092 THz)

NIST Time and Frequency Mission: UTC (Official Time)
Time Scale Improvement Research #1
Maser Steered by "Continuously" Operating Fountain(s)

"fast steering"

"slow steering"

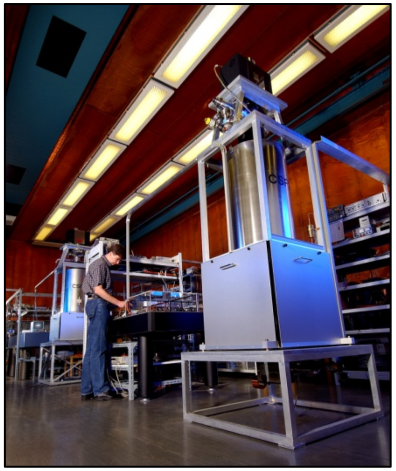


Near-Continuously operating NIST-F3 primary frequency standards (fountains). Under development. (NIST-F2 shown as example.)

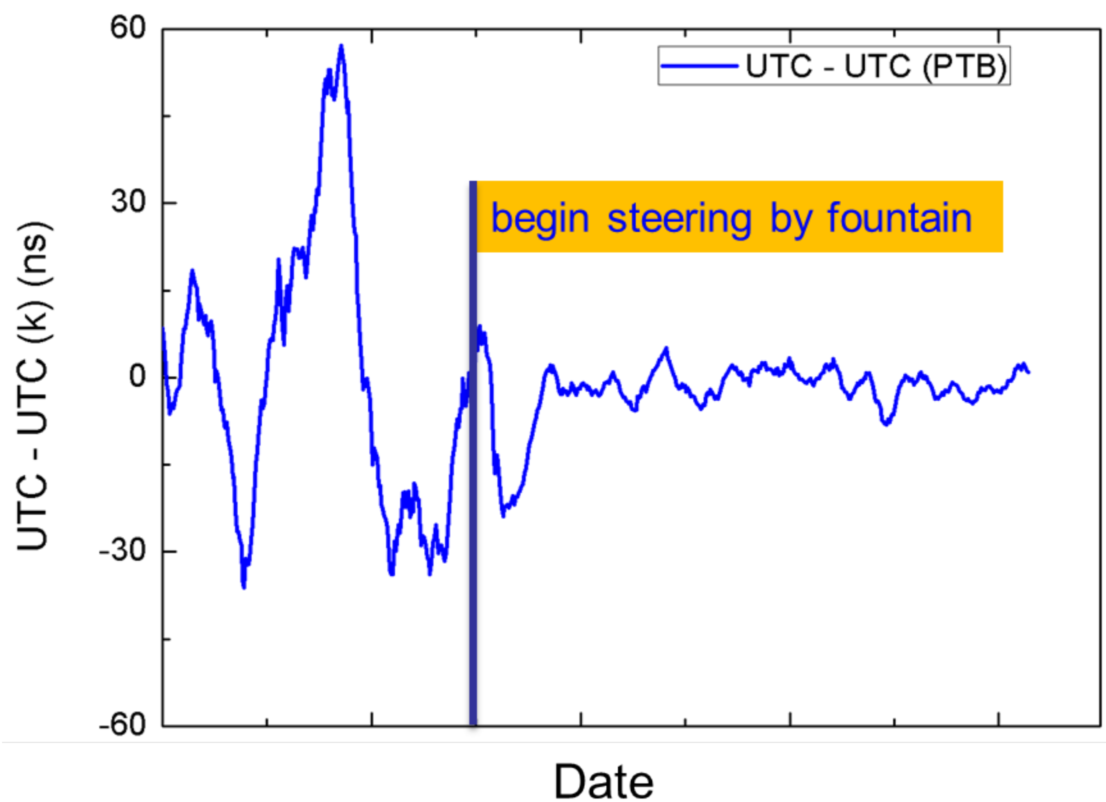
Maser
UTC(NIST)

UTC from
BIPM
Monthly
CircularT

NIST Time and Frequency Mission: UTC (Official Time)
Time Scale Improvement Research #1
Maser Steered by "Continuously" Operating Fountain(s)
Example from PTB (Germany)



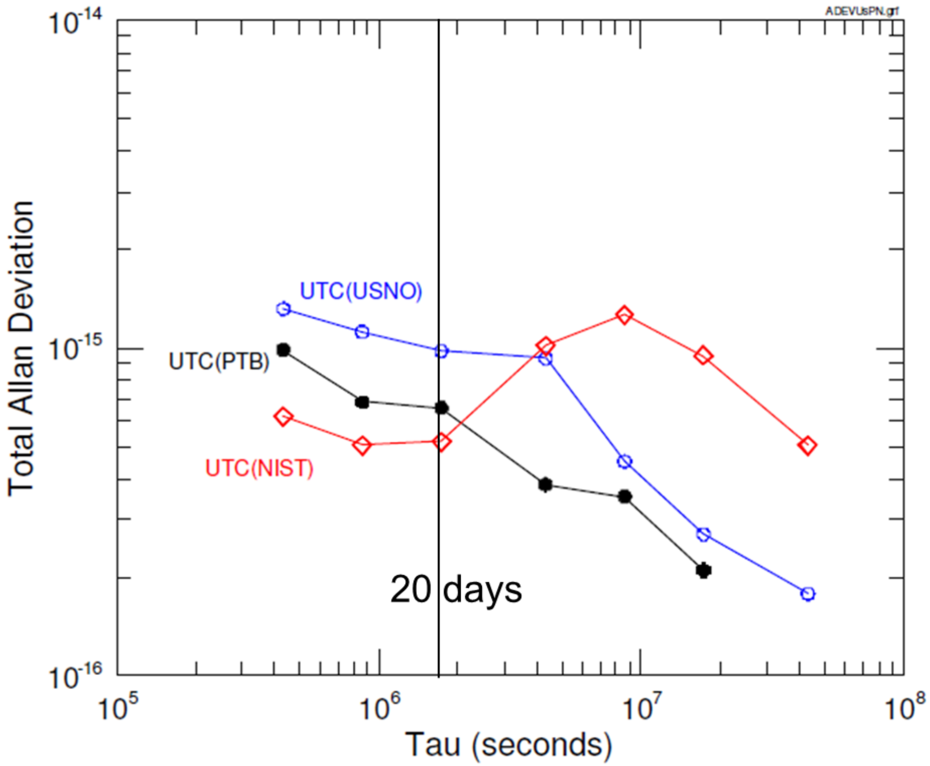
PTB-CsF2



- Availability of at least one fountain for ~6 hours/day provides excellent time scale performance.

- After initial "break-in" period to determine best steering parameters, PTB time scale improves by orders of magnitude.

NIST Time and Frequency Mission: UTC (Official Time) Time Scale

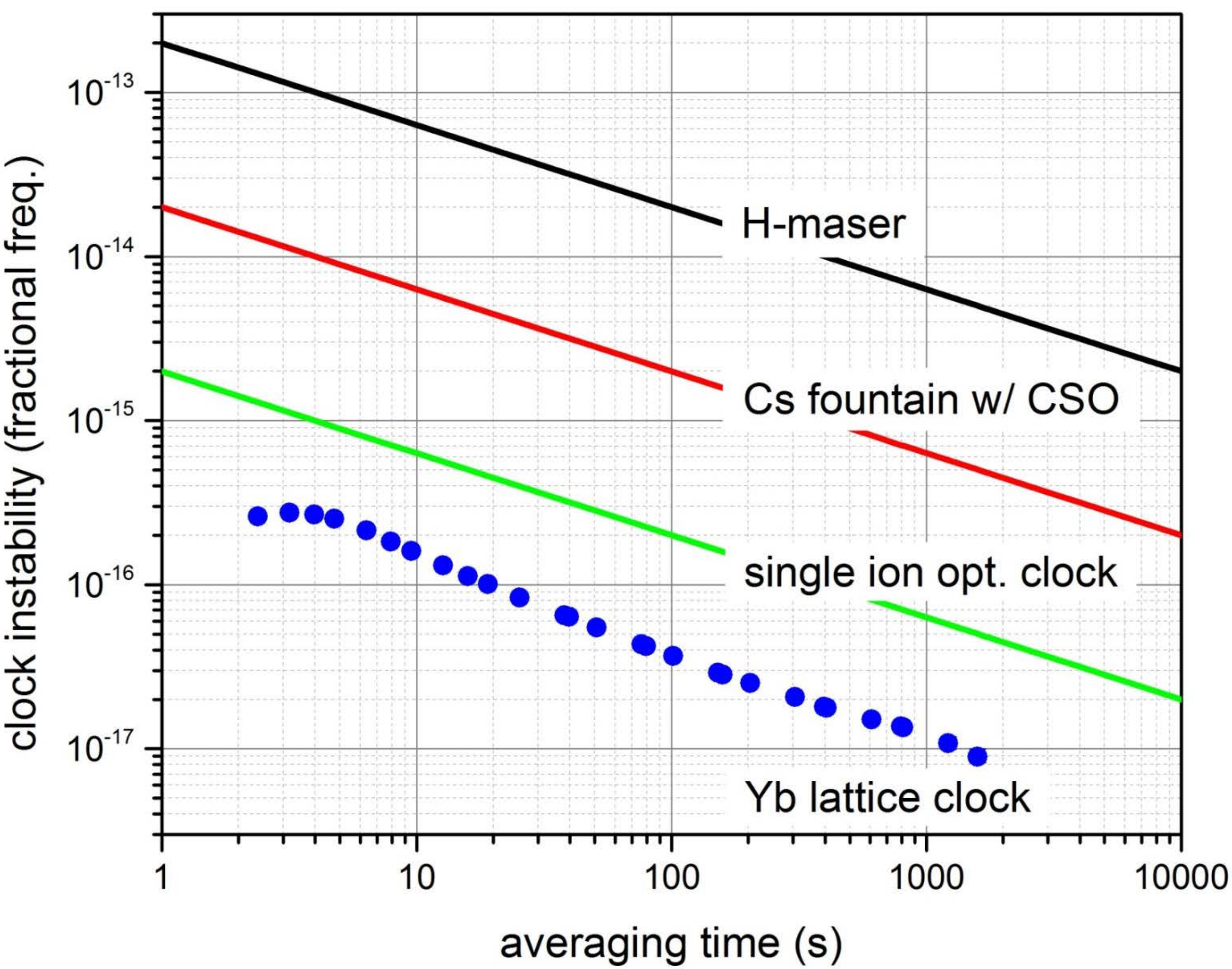


	5days	10days	20days	40days
1	NIST	NIST	NIST	Germany
2	France	Germany	France	France
3	Germany	France	Germany	USNO
4	USNO	USNO	USNO	NIST
5	Poland	Finland	Italy	Italy
6	Italy	Italy	Russia	Russia
7	Finland	Poland	Finland	Finland
8	UK	China	China	Poland
9	Japan(NM)	Russia	Poland	Japan(CT)
10	NIM	Japan(NM)	Japan(CT)	China
11	Japan(CT)	UK	Japan(NM)	Taiwan
12	Sweden	Japan(CT)	Taiwan	Japan(NM)
13	Korea	Sweden	Spain	Spain
14	Russia	Spain	UK	Sweden
15	Spain	Taiwan	Sweden	UK
16	Taiwan	Korea	Korea	Korea
17	Mexico	Mexico	Mexico	Mexico

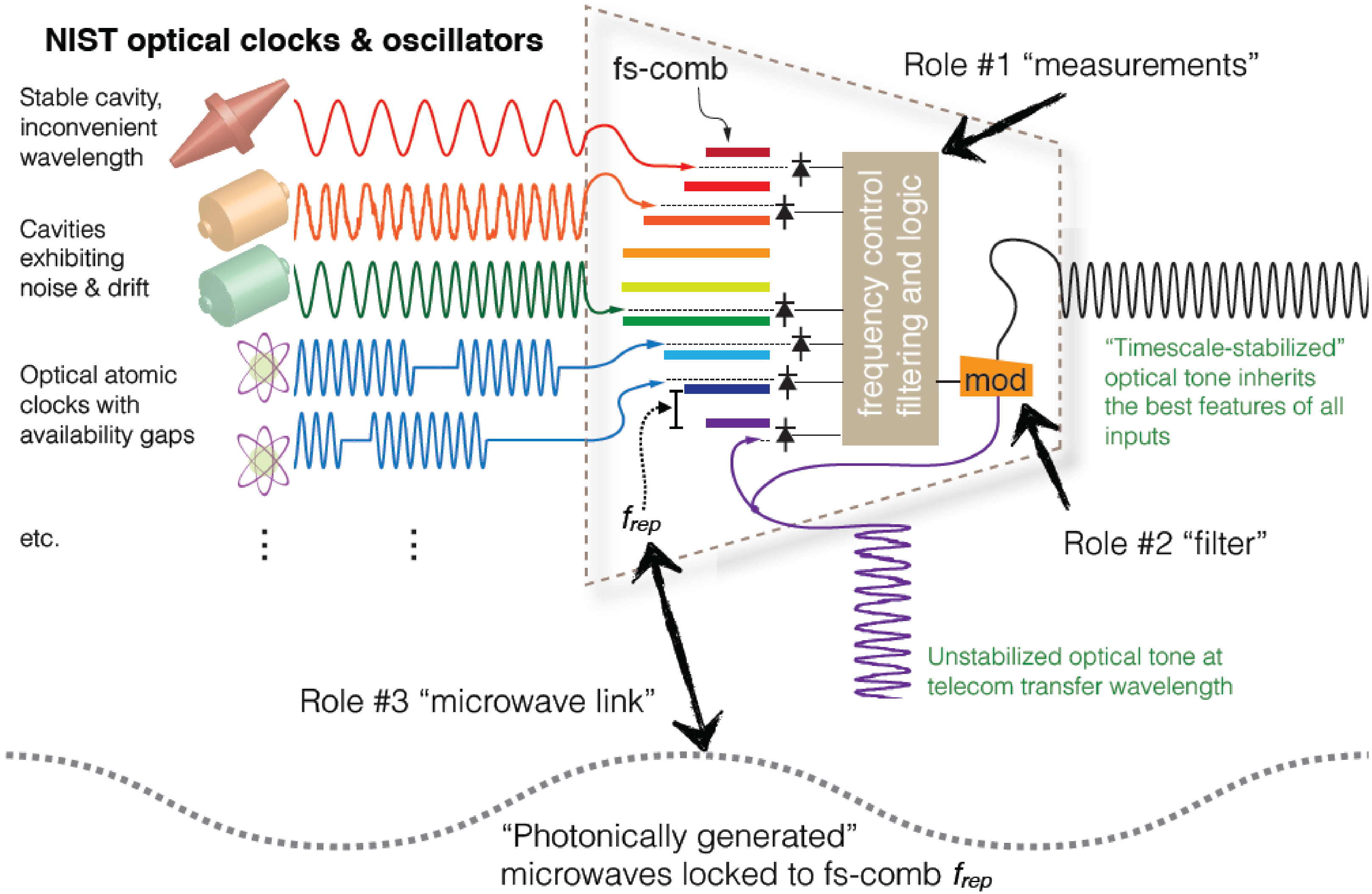
- Germany (PTB) and France (OP, not shown on graph) both use the “maser steered by fountain” approach to achieve excellent performance without massive investment in hydrogen maser ensemble (~$300k/each).

- NIST rapidly moving to this approach.
  - Personnel issue.

NIST Time and Frequency Mission: UTC (Official Time)
Time Scale Improvement Research #2
How to Utilize Improved Accuracy and Stability of Optical Clocks?

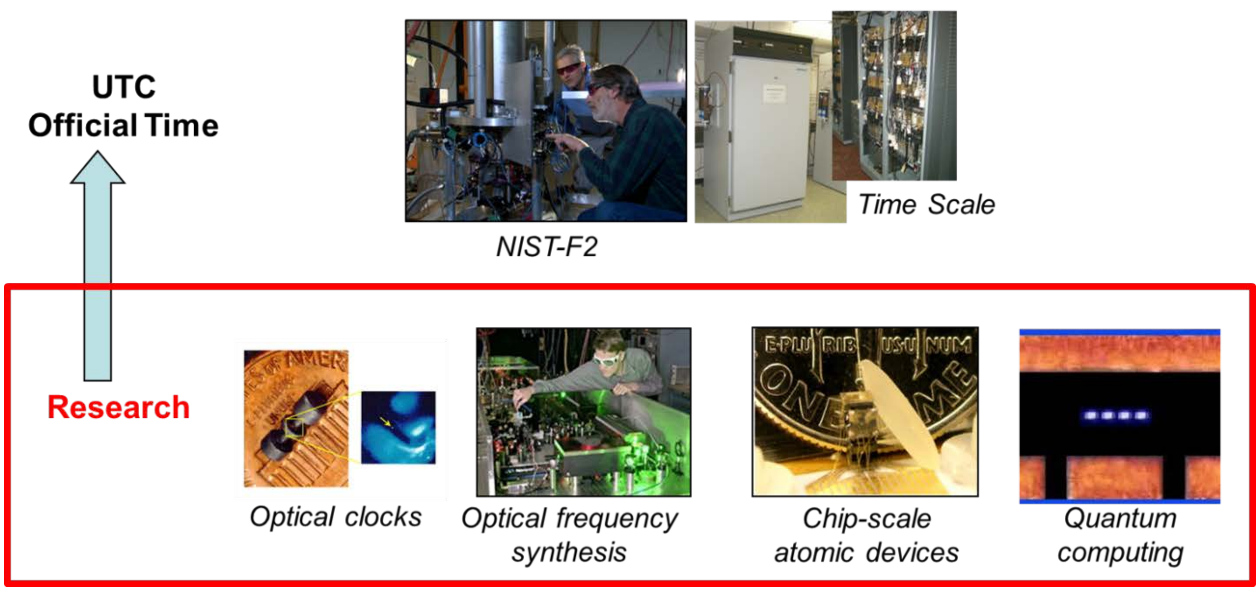


NIST Time and Frequency Mission: UTC (Official Time)
Time Scale Improvement Research #2
“Universal Time Scale” – “Optical Clock Ready”



NIST Time and Frequency Mission

- **Research** to:
  - Improve primary frequency standard.
    - Best in the world in highly competitive and evolving field.
  - Improve time scale performance.
    - Clear near-term path to improve already world-class performance (maser-steered fountain).
    - Innovative “universal time scale” approach.
      - Not practical at any other lab but NIST.



NIST Time and Frequency Mission

Dissemination

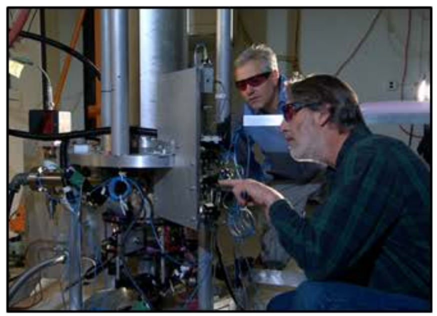
Radio broadcasts

Networks

Satellites

Noise metrology

UTC
Official Time



NIST-F2

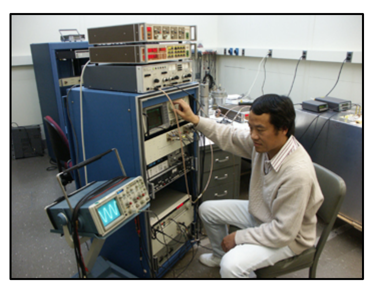
Time Scale

NIST Time and Frequency Mission: Dissemination

Customer needs calibration/measurement of device or system

Traditional Measurement Service Model

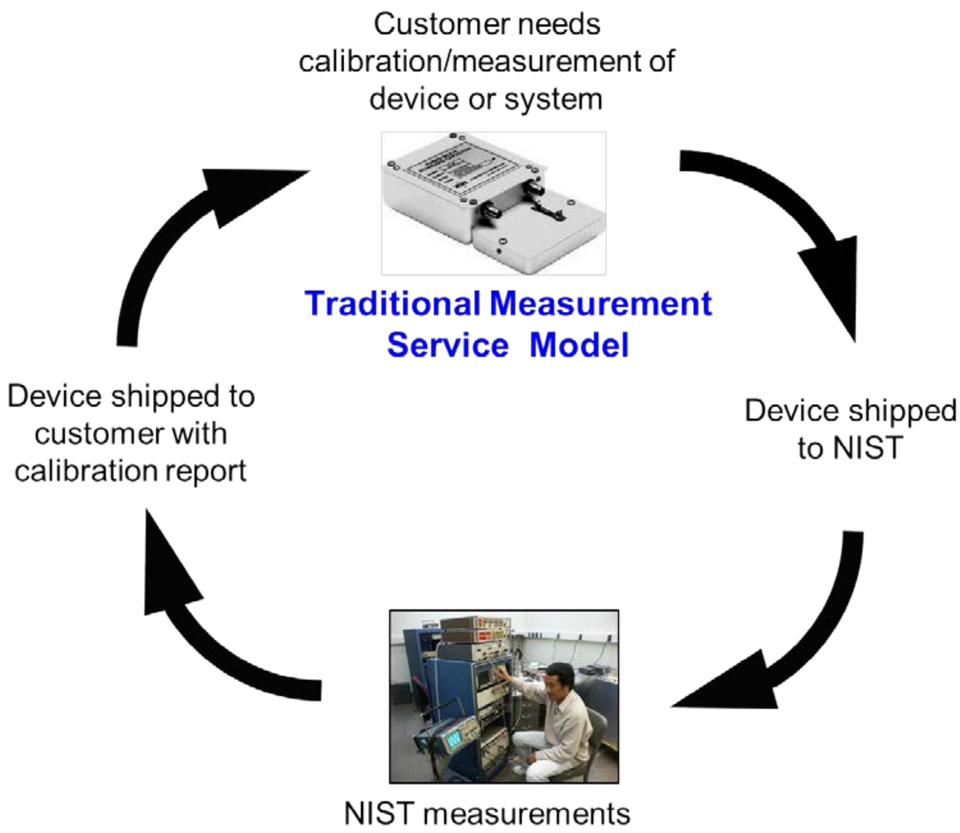
Device shipped to NIST



NIST measurements

Device shipped to customer with calibration report

NIST Time and Frequency Mission: Dissemination



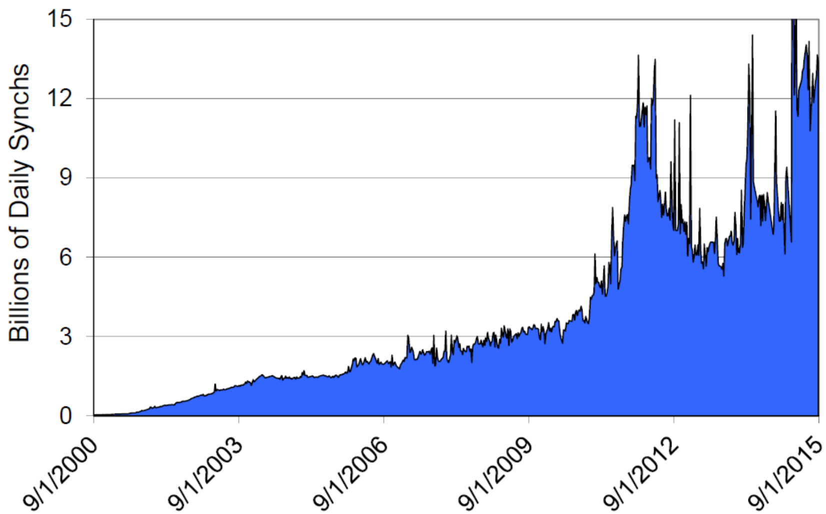
- NIST-Wide **APPROXIMATE** data:
    - FY2014.
    - 15,000 calibrations/tests.
    - $8 million fees.

- Time and Frequency Division data:
    - FY2014.
    - 8 “traditional” calibrations/tests.
    - $19.6k fees ($0.019 million).

NIST Time and Frequency Mission: Remote Dissemination

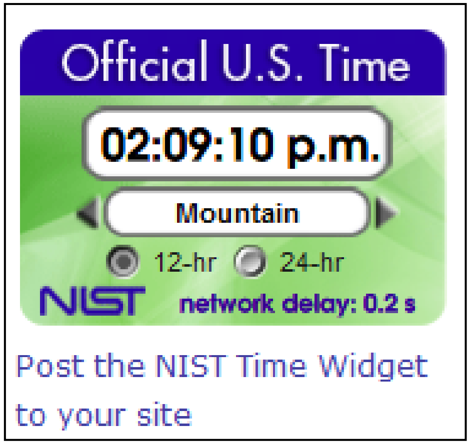
- Overwhelming use of Division measurement services is through **non-traditional broadcast services** that are:
  - Remotely provided. Information broadcast from NIST to customer's location.
    - Radio broadcasts.
    - Over the Internet.
    - Through telecom systems.
    - Through satellite systems.
  - Received/used directly by user at user location.
  - No exchange of devices with customer.
  - No user fees.
  - Available to user continuously in real time.
  - Users remain anonymous to NIST.
  - No exchange of reports or other information.
  - Number of direct users for NIST time and frequency broadcast services far exceeds direct customers for all other NIST measurement services combined.

NIST Time and Frequency Mission: Remote Broadcast Services



- **NIST Internet Time Service** – time codes delivered over the Internet.
- >12 billion automated synchs per day.
- Built into common operating systems: Windows, Mac, Linux, etc.
- Servers at 15 locations across the US.

NIST Time Widget: Official NIST Time displayed on any website

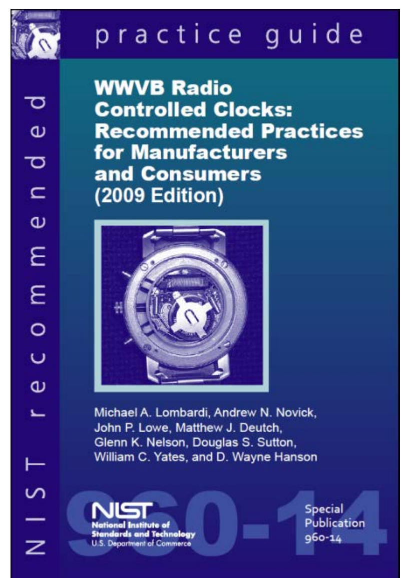


NIST Time and Frequency Mission: Remote Broadcast Services

NIST radio station WWVB low frequency broadcast of time code signals. Near Ft. Collins, CO.

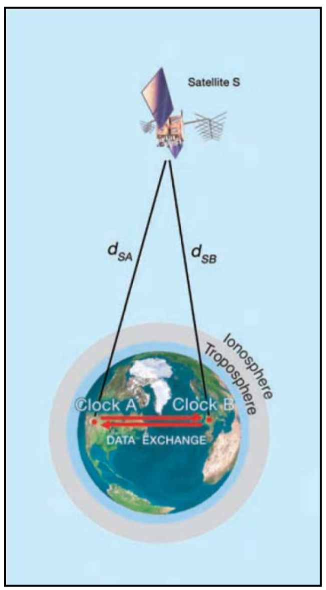
Sampling of radio-controlled products automatically set by WWVB time codes.

- New WWVB broadcast format implemented in 2013 improves reception by more than a factor of 10.
- New applications beyond consumer clocks/watches with more reliable reception.



- Free practice guide to manufacturers and consumers to optimize use of WWVB signals.

NIST Time and Frequency Mission: Hybrid Remote Broadcast Services



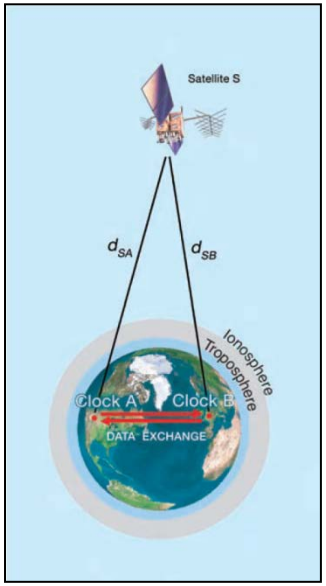
Frequency Measurement and Analysis Service
Time Measurement and Analysis Service

- Full measurement system (“black box”) with continuous remote monitoring by NIST.
  - Continuous measurements in the customer’s laboratory at any location, 24/7/365.
  - “Plug and play” system.
  - Customer calibrates as many systems as desired, as frequently as desired.

- Frequency measurement in customer’s lab to better than 5 x 10^{-14} referenced directly to UTC (NIST) (official source of US time and frequency).

- Time measurement in customer’s lab to better than 15 ns referenced directly to UTC(NIST).

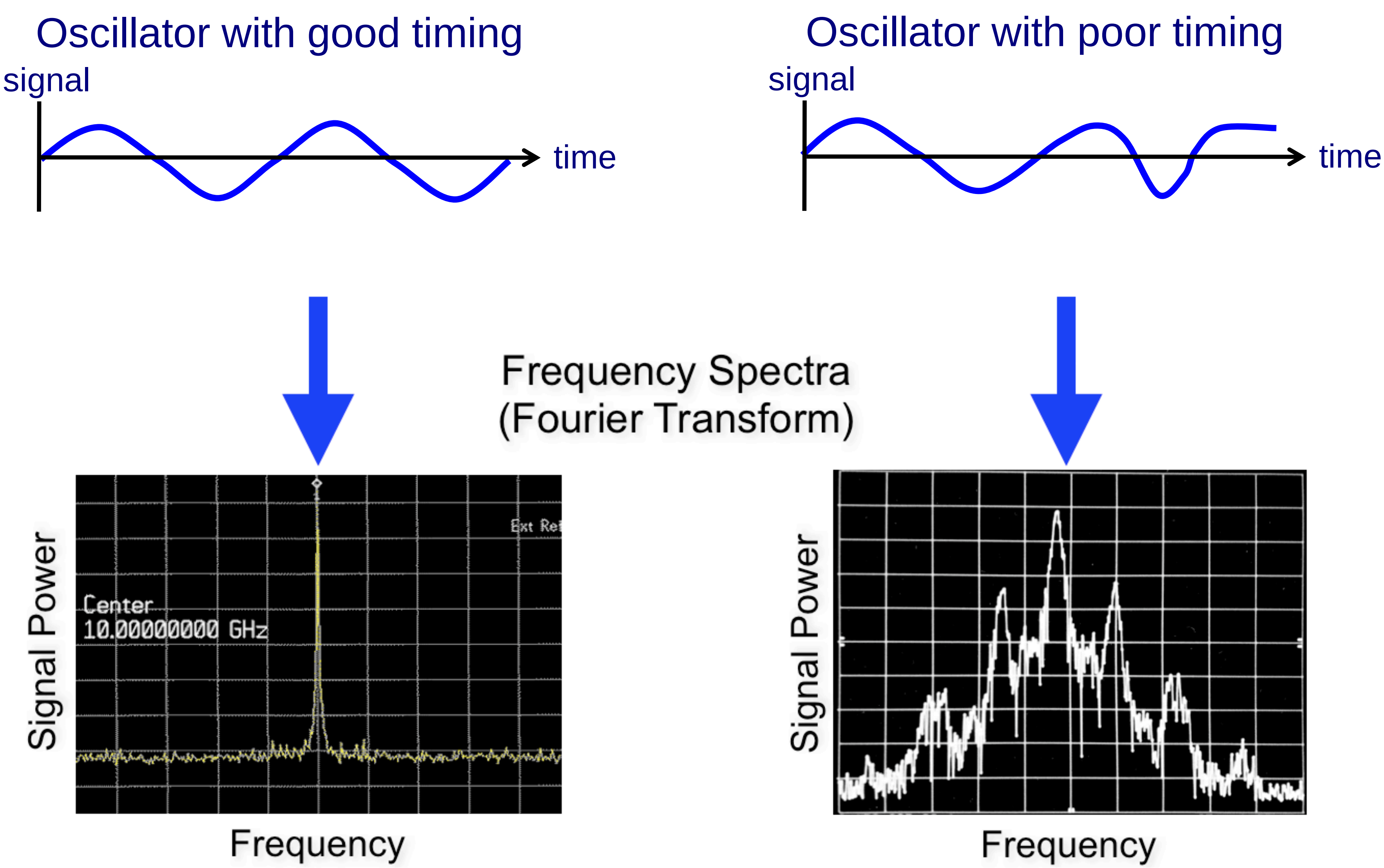
NIST Time and Frequency Mission: Hybrid Remote Broadcast Services



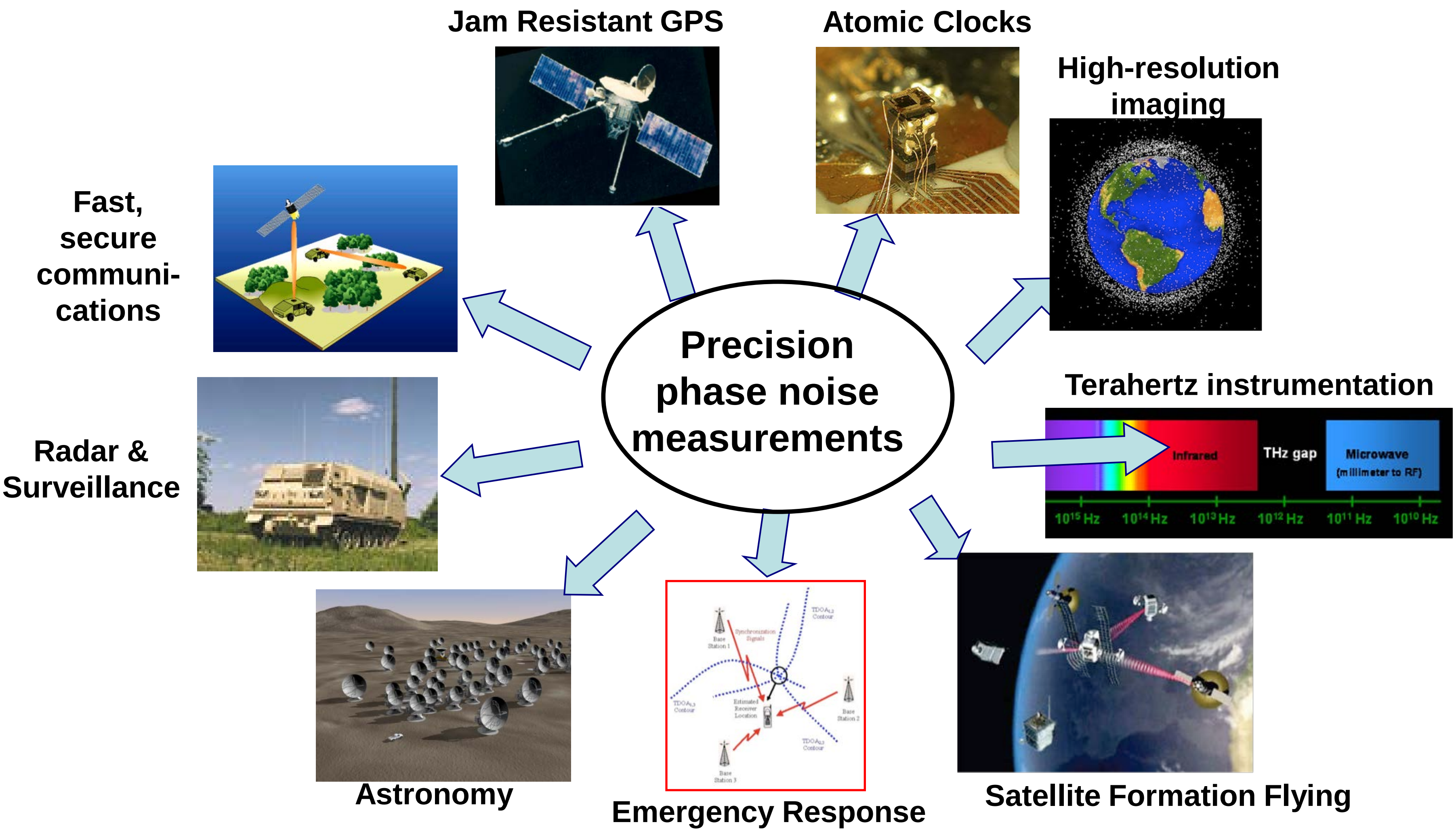
Frequency Measurement and Analysis Service
Time Measurement and Analysis Service

- ~45 customers using continuous NIST remote services:
- Telecommunications.
  - ITT, Allied Signal, Microsemi, Brandywine, etc.
- Defense/Aerospace.
  - Lockheed-Martin, Honeywell, Hughes, Raytheon, BAE, Electric Boat Company, etc.
- Instrumentation/Electronics.
  - Fluke, Harris, SIMCO Electronics, AH Electronics, FEI-Zyfer, Annritsu, etc.
- Finance/Business Systems.
  - Certichron, Brandywine, Perseus, Microsemi, etc.
- Government.
  - Army Primary Standards, Navy Primary Standards, AF Primary Standards, Naval Underwater Systems, Eglin AFB, etc.

NIST Time and Frequency Mission: Phase Noise (Timing Jitter) Metrology



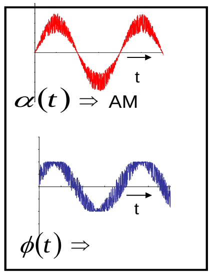
NIST Time and Frequency Mission: Phase Noise (Timing Jitter) Metrology

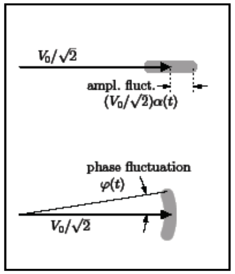


NIST Time and Frequency Mission: Phase Noise (Timing Jitter) Metrology

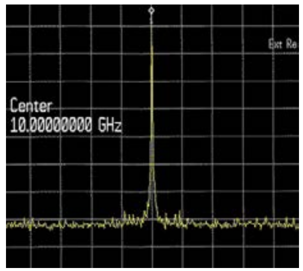
Noisy Sinusoidal Signal

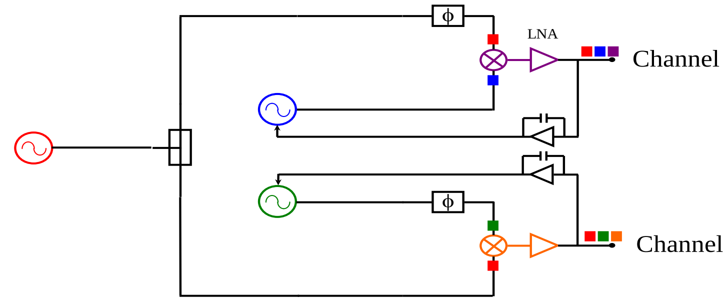
$$v(t) = V_0\left[1+\alpha(t)\right]\cos\left[2\pi\nu_0 t+\phi(t)\right]$$



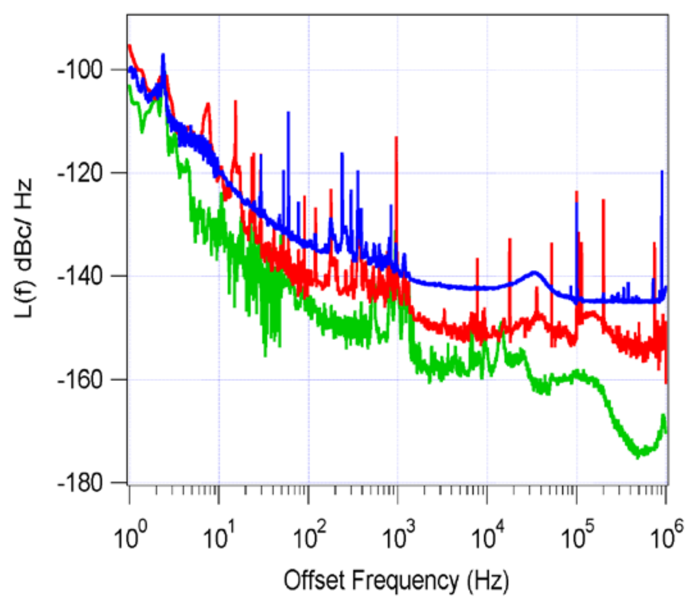


Phasor diagram



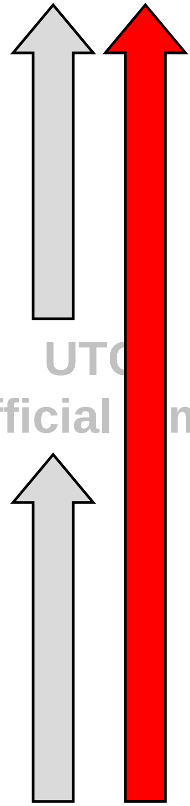


$$S_\phi(f)_{\mathrm{Cross}_{1,2}} = S_\phi(f)_{\mathrm{DUT}} + \frac{S_\phi(f)_{\mathrm{Ref}_1} + S_\phi(f)_{\mathrm{Ref}_2} + S_\phi(f)_{\mathrm{System}_1} + S_\phi(f)_{\mathrm{System}_2}}{\sqrt{N_{\mathrm{Averages}}}}$$



NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination

Dissemination



UTC
Official Time

Research

Radio broadcasts

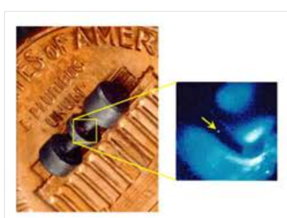
Networks

Satellites

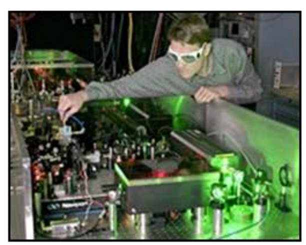
Noise metrology

NIST-F2

Time Scale

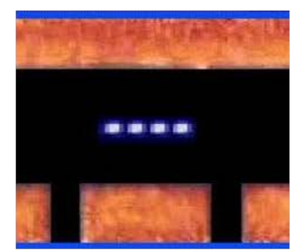


Optical clocks



Optical frequency synthesis

Chip-scale atomic devices

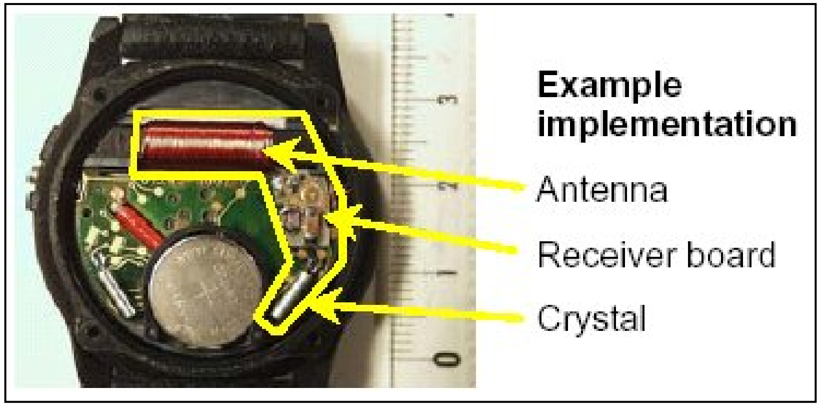


Quantum computing

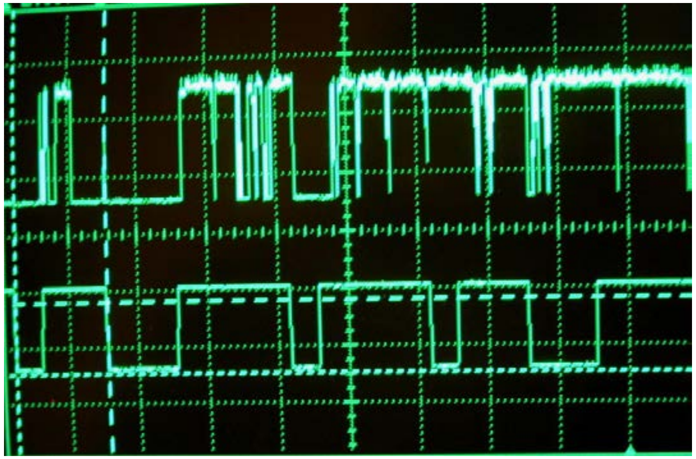
NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination

Improve reception of WWVB signals:

- Partnership with industry.
- New phase-shift keying modulation technology implemented.
- Improves reception by more than 10 dB with no additional broadcast power.
- New commercial products and services.



WWVB-controlled wristwatch



Hardware/Software signal processing

NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination


GPS jammers

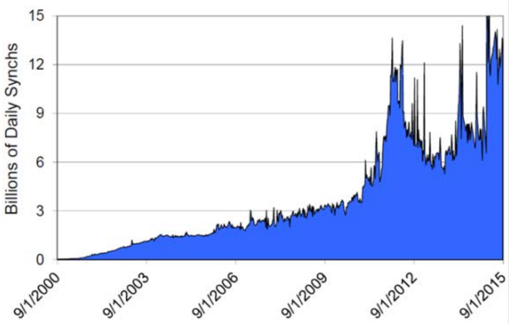
- GPS critical infrastructure for timing and position.
- GPS extremely susceptible to inadvertent or intentional jamming (civilian access channels).
- Need alternate system to provide broadly available 10^{-11} timing stability with minimal disruption risks.

Research to develop cheap, widely distributed timing/positioning ground stations.

- When GPS operating, ground stations learn to precision timing/location by comparing GPS and NIST radio station signals.
- Data continually published on Internet.
- In absence of GPS, “smartened” NIST radio signals take over precision timing, positioning.

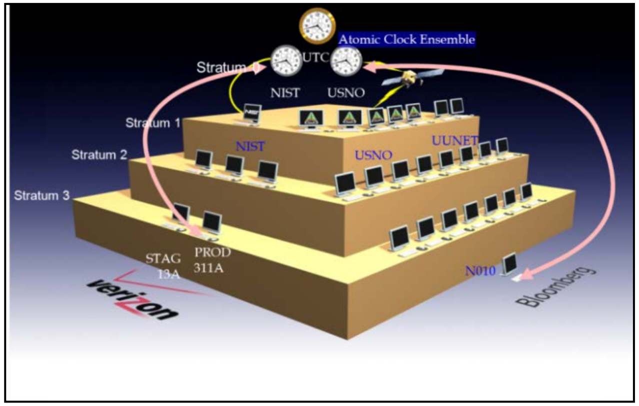
NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination

NIST Internet Time Service:

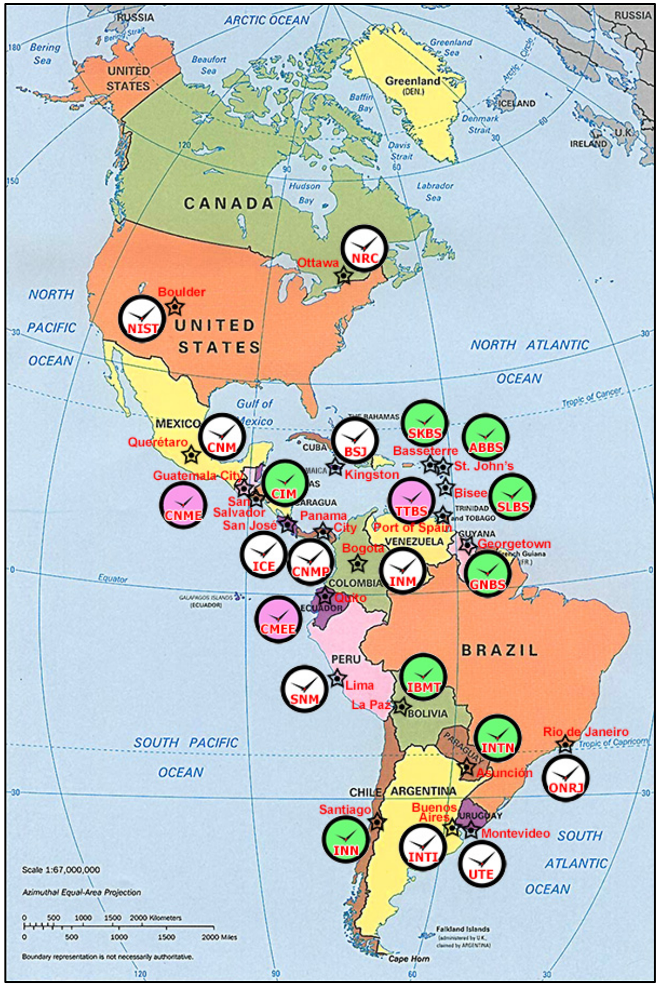


- Best performance ~ 1 ms, ~ 10^{-8} frequency stability.
- Insufficient for many high value applications.
  - Telecom, etc. requires 10^{-11} stability.
- Partner with companies to provide current ITS.
  - Can develop premium services.

- **Invest in R&D on precision time and frequency transfer over telecom fiber and wire networks.**
  - Precise Time Protocol (PTP).
  - Demonstration with NIST/telecom companies/USNO/DHS of 10^{-12} or better stability through telecom networks.



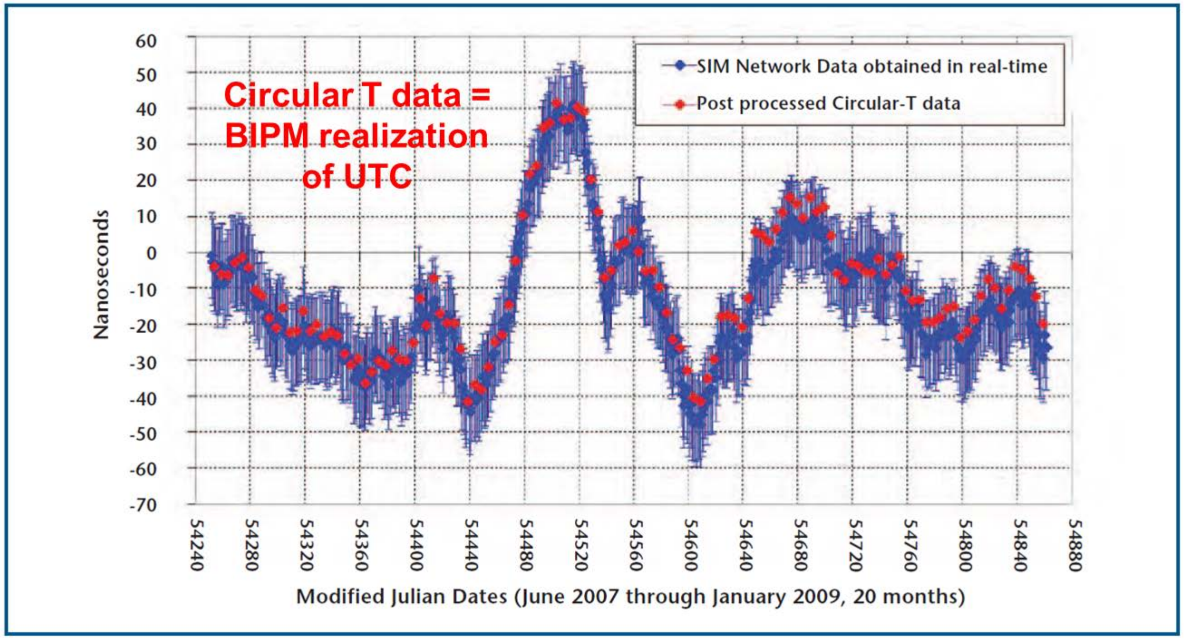
NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination: International UTC Alternatives



- Pioneered by NIST, CENAM (Mexico), NRC-Canada.
- 23 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.

NIST Time and Frequency Mission: Dissemination
Research to Improve Dissemination: International UTC Alternatives

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

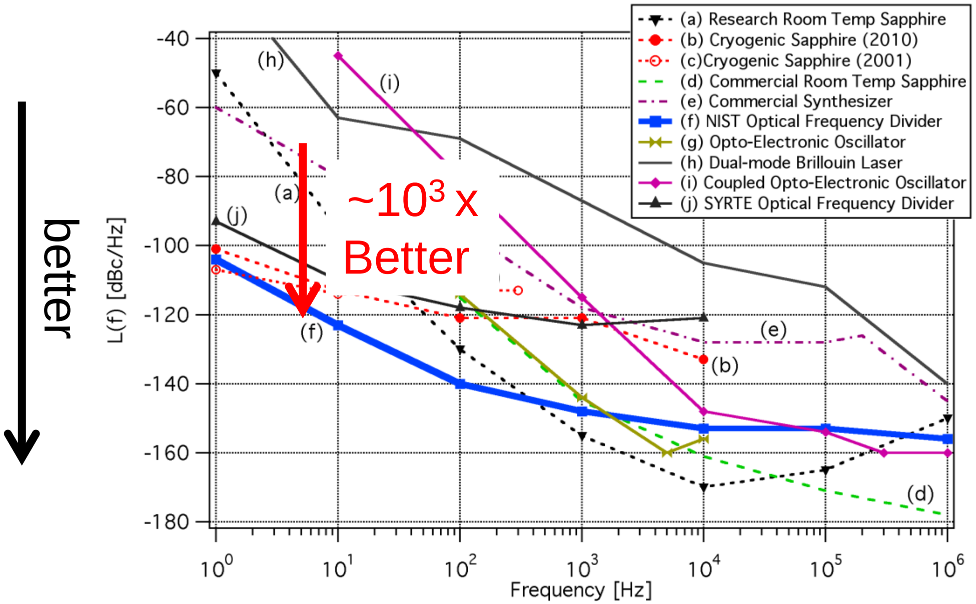


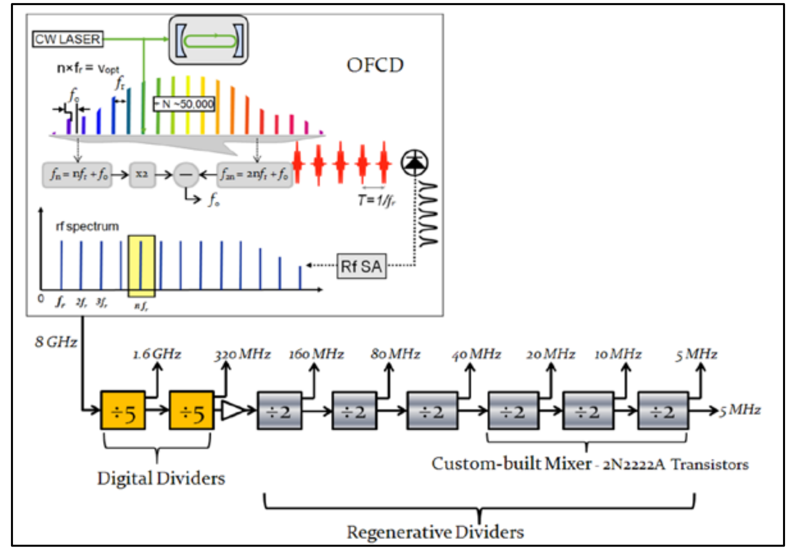
- Real-time international time scale competitive with post-processed BIPM UTC realization (up to several weeks late) with much simpler and less-expensive equipment.

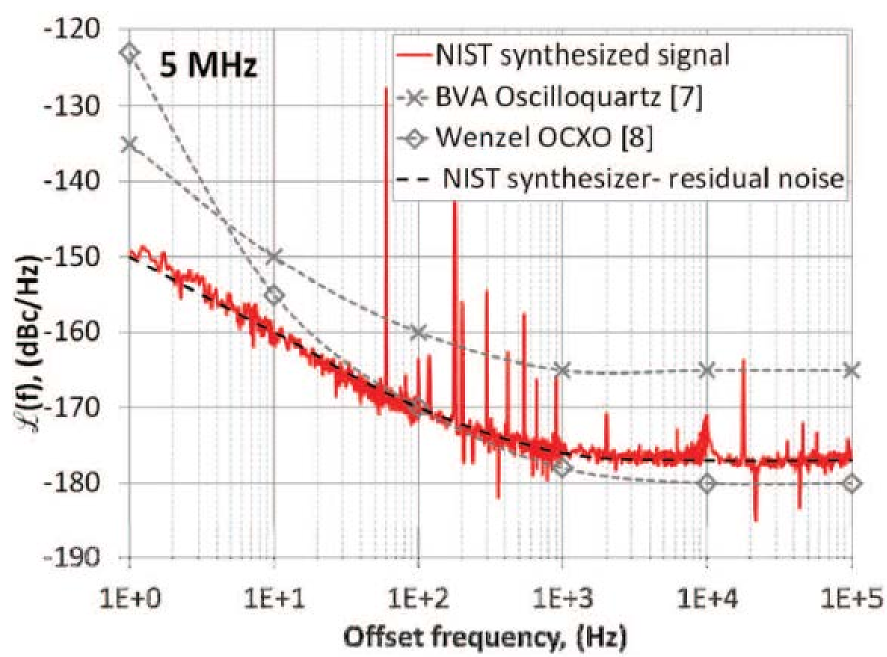
- Enables labs with modest resources to participate in UTC for first time.

- Sets example for future of global real-time UTC.

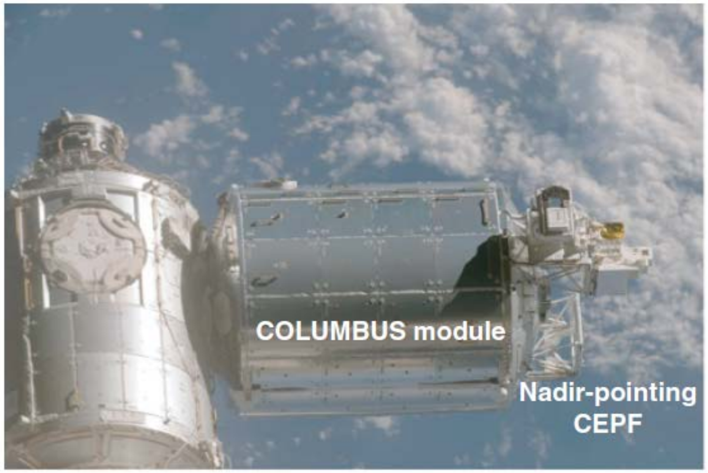
NIST Time and Frequency Mission: Dissemination Research: Ultrastable Microwaves from Optical Frequency Combs

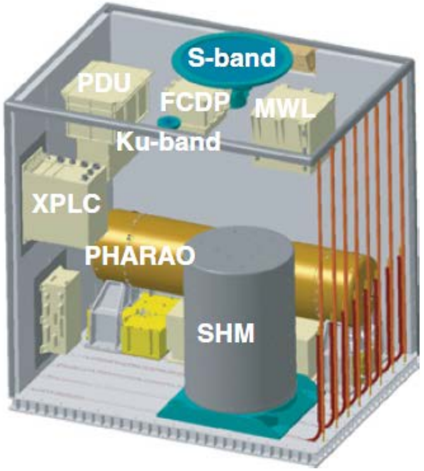


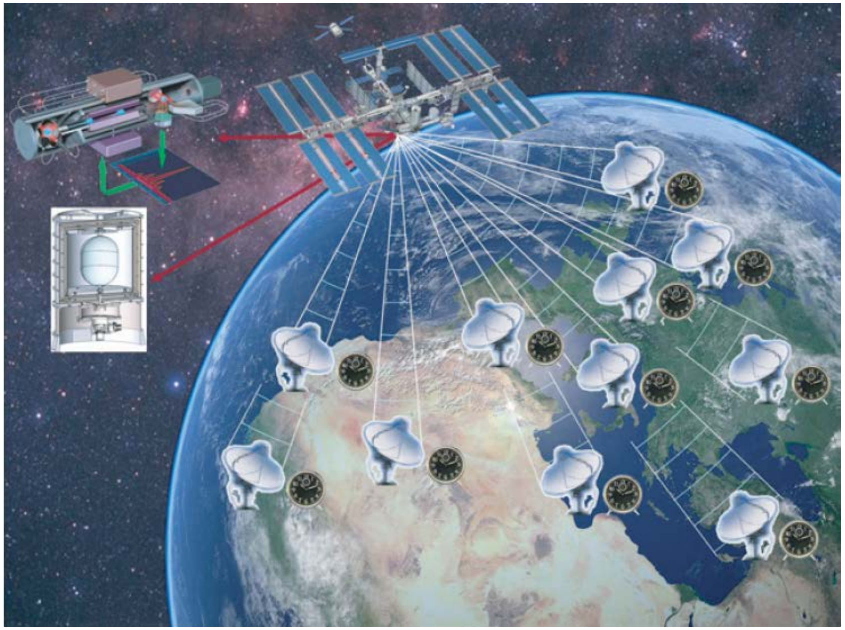




NIST Time and Frequency Mission: Dissemination Research: NIST Participation in ESA/NASA Time Transfer Experiments

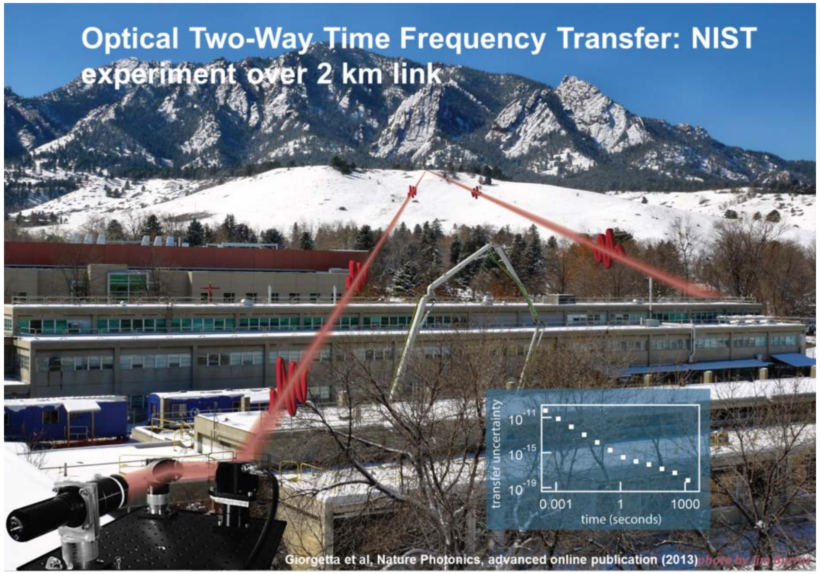






- High performance atomic clocks in space.
- Atomic Clock Ensemble in Space (ACES).
  - Cold atom cesium clock.
  - Hydrogen maser.
- International Space Station 2016?
- Microwave link for enhanced time and frequency transfer.
- Expected ~ 1 ps per ISS orbital pass.

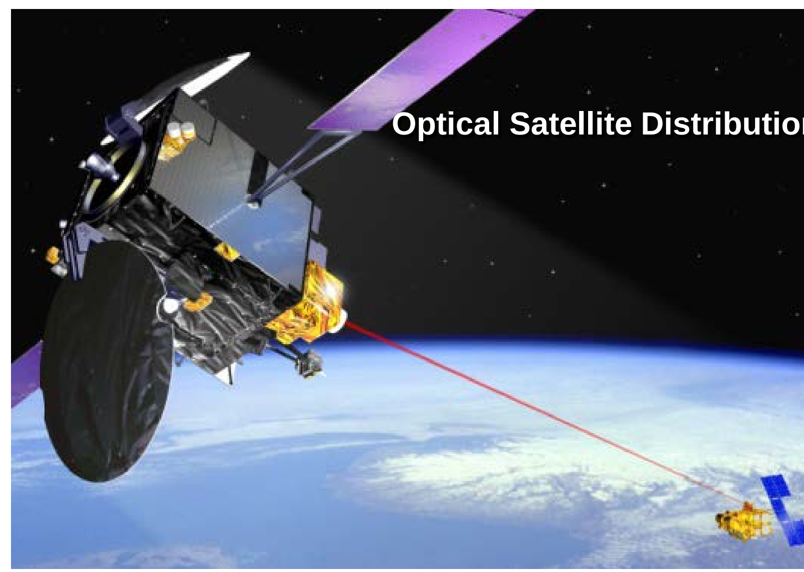
NIST Time and Frequency Mission: Dissemination Research: Free Space Optical Time and Frequency Transfer



- Future infrastructure for widely available free-space optical time and frequency transfer?

Work of Division 686 in partnership with 688

- Economic and political challenges probably more significant than technical challenges.



NIST Time and Frequency Mission

Dissemination

Radio broadcasts

Networks

Satellites

Noise metrology

- Remote broadcast services.
    - Best in the world, most heavily used of all NIST measurement services.
    - Unique high performance services to industry users.

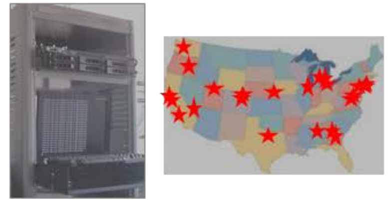
- Phase noise metrology.
    - Best in the world new ultralow noise measurement capabilities.

- Unique real-time SIM international time scale.
    - Setting standard for future of UTC.

NIST Time and Frequency Mission: Research

Dissemination

Radio broadcasts



Networks

Satellites

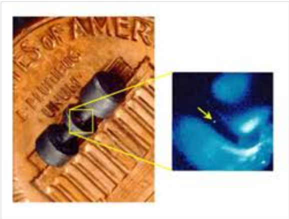
Noise metrology

UTC
Official Time

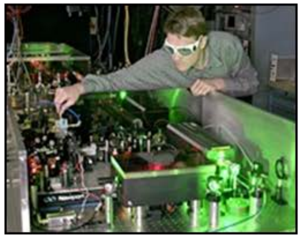
NIST-F2

Time Scale

Research

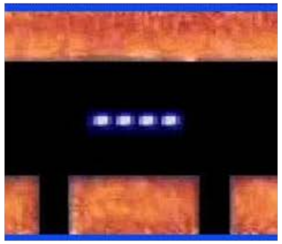


Optical clocks



Optical frequency synthesis

Chip-scale atomic devices



Quantum computing

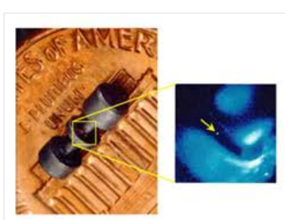
NIST Time and Frequency Mission: "Opportunistic" Research

A significant portion of Division mission-directed research that seeks to improve UTC or Dissemination naturally evolves to other highly productive "opportunistic" technologies, measurements and research areas.

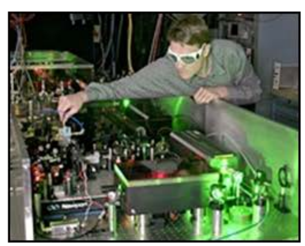
Where these technologies, measurements and research areas remain related to frequency measurements (core Division capability), the Division vigorously pursues these opportunities – commensurate with funding, skill sets, etc.

Some examples follow (not comprehensive).

Research

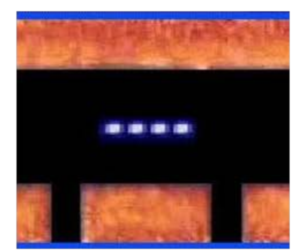


Optical clocks



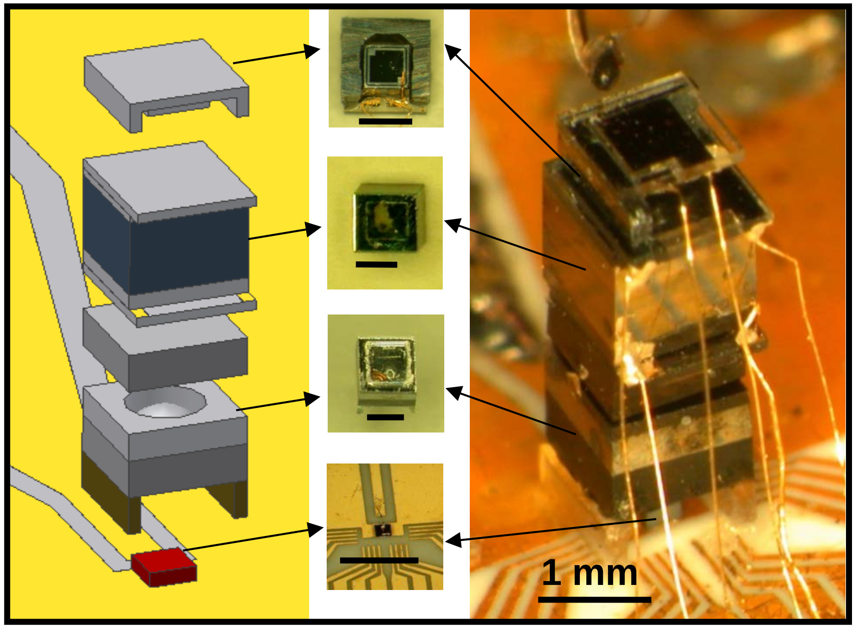
Optical frequency synthesis

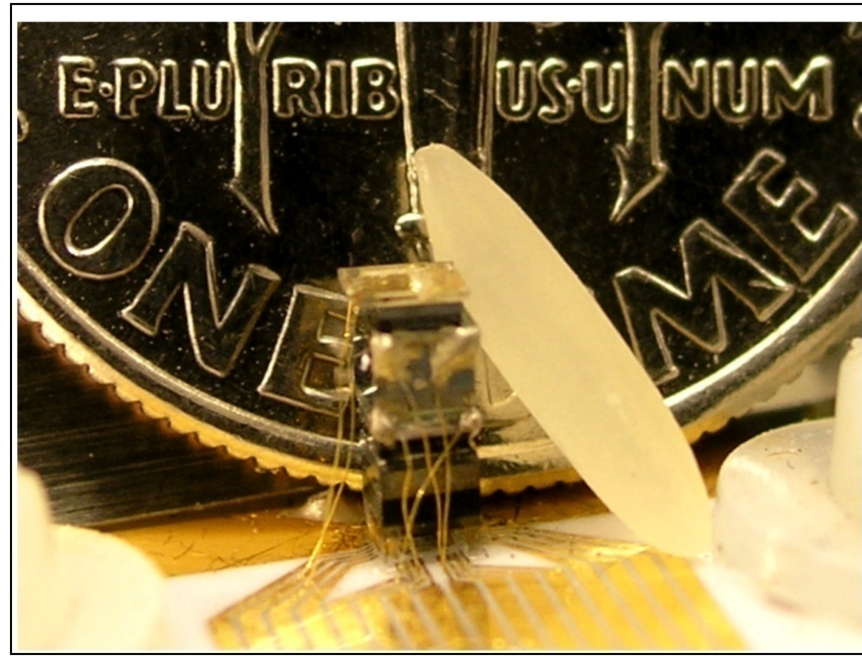
Chip-scale atomic devices



Quantum computing

NIST Time and Frequency Mission: “Opportunistic” Research
NIST Chip-Scale Atomic Devices





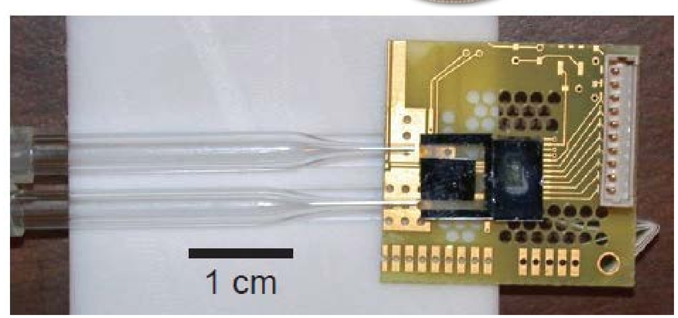
Symmetricom (now Microsemi): First commercial CSAC. $\Delta f/f \sim 10^{-11}$.

Chip-scale atomic clock

Chip-scale atomic magnetometer

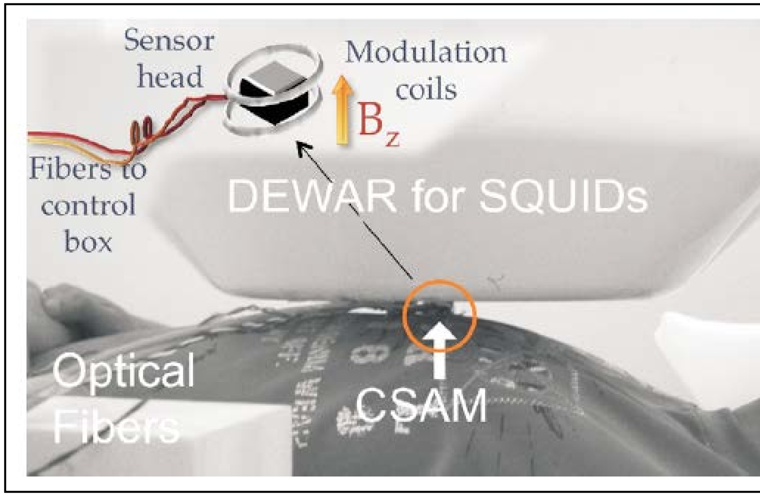
Ultraminiature gyroscope

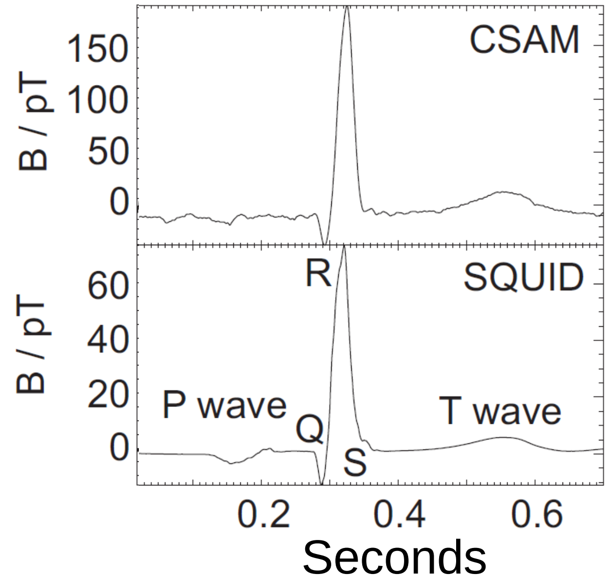
Future atom-based sensors

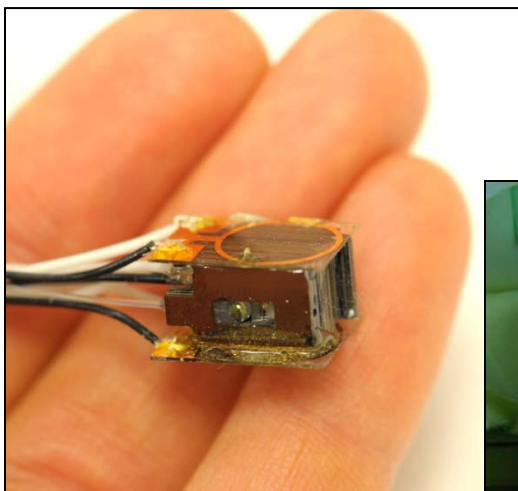


Zero-field NMR for “remote” chemical analysis and zero-field MRI.

NIST Time and Frequency Mission: "Opportunistic" Research
NIST Chip-Scale Magnetometers



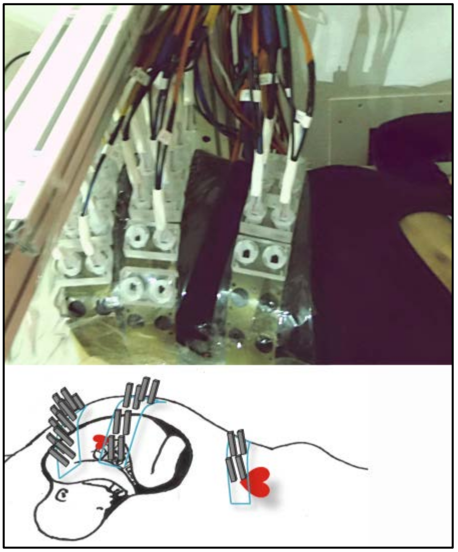


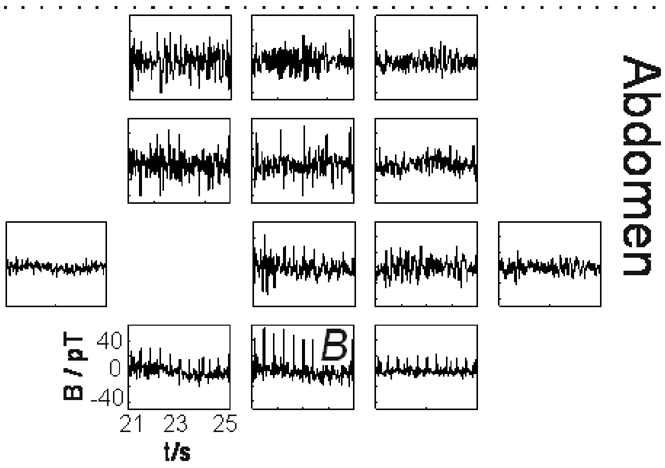


Biomagnetic fields.

Heart, brain, muscles.

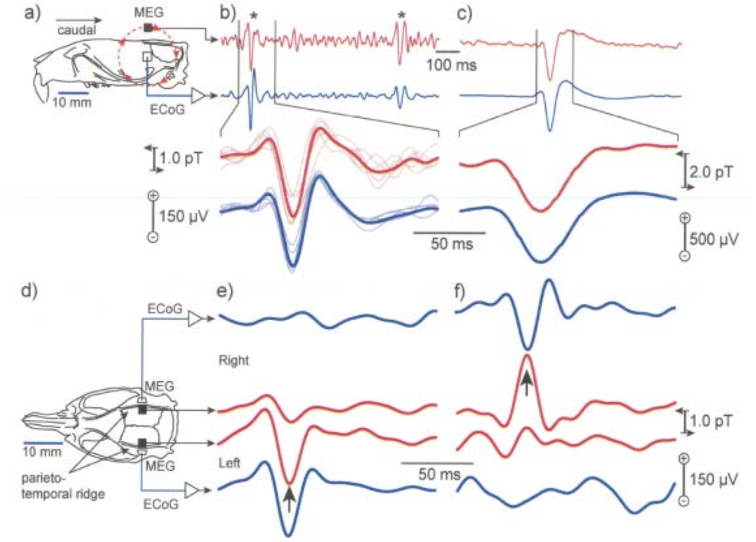
NIST Time and Frequency Mission: "Opportunistic" Research
NIST Chip-Scale Magnetometers

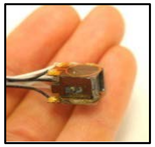




- Fetal *magneto*cardiography.
- Non-invasive fetal *electro*cardiography is impractical.
- Replaces very large, expensive, cryogenic, single-point SQUID systems.
- Completely non-invasive.

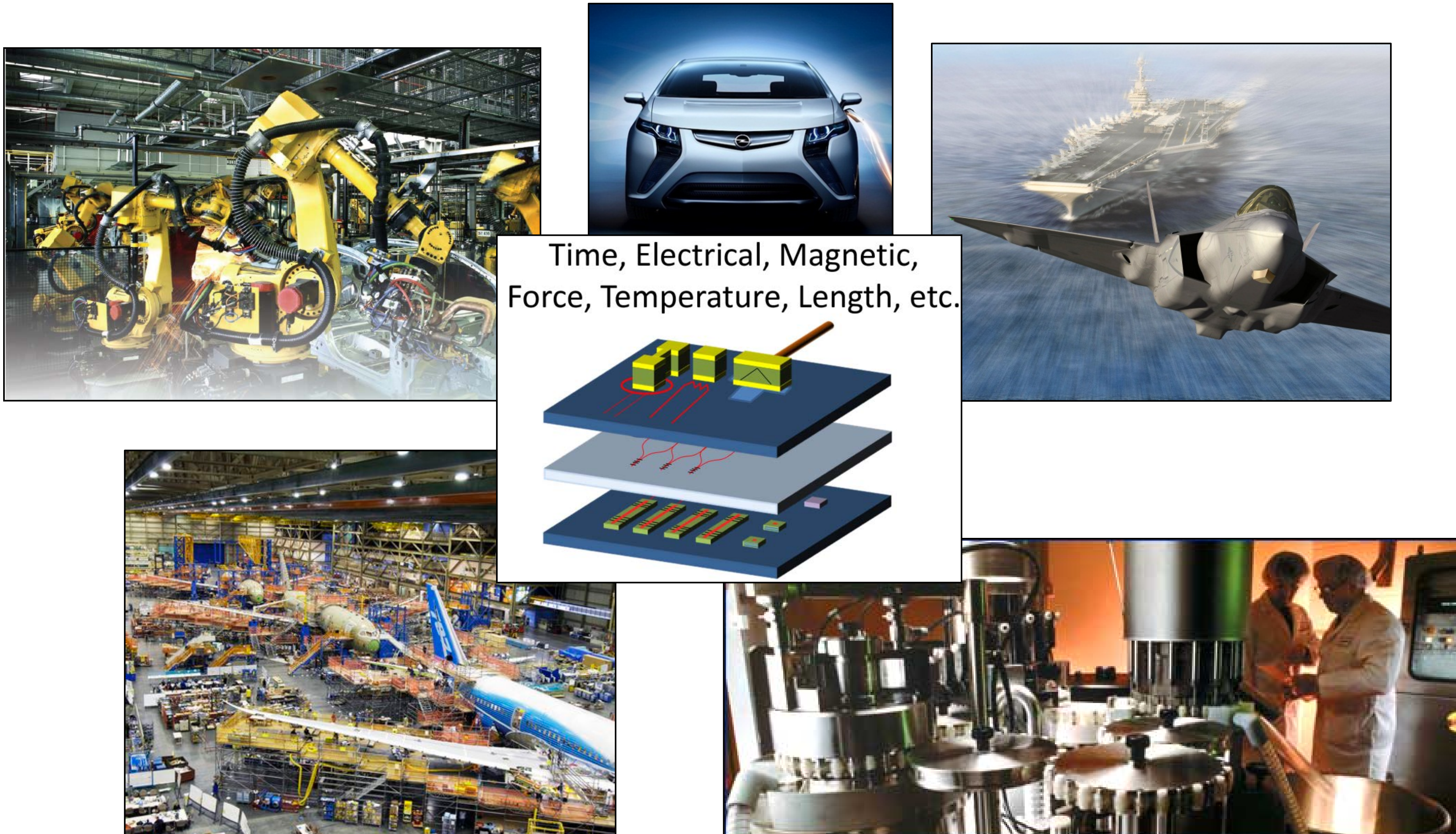
- Many brain *electrical* signal details absorbed or distorted by skull. *Magnetic* signals undistorted.
- Replaces very large, expensive, single point, cryogenic SQUID systems.
- Completely non-invasive.





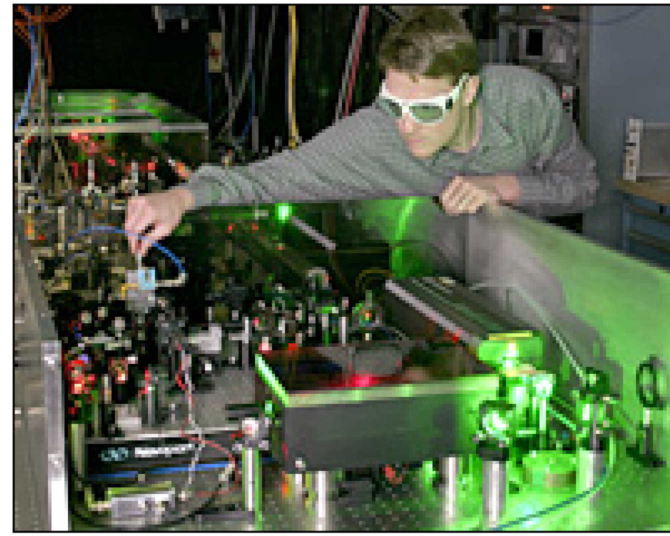
NIST Time and Frequency Mission: "Opportunistic" Research
"NIST on a Chip"

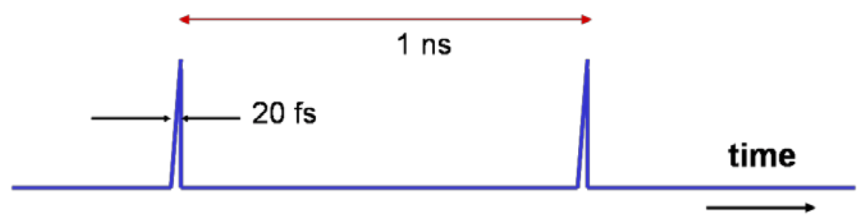
Ubiquitous precision measurements based on atomic and quantum sensors,
Including frequency-based sensors.



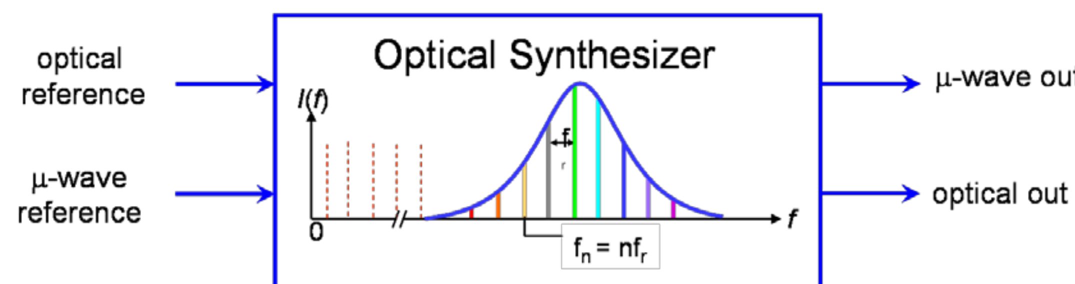
NIST Time and Frequency Mission: “Opportunistic” Research
Frequency Comb Development and Applications

- Femtosecond laser frequency combs largely developed to improve optical atomic clocks.
  - Enable direct counting of 10^{15} Hz signals for the first time.
  - Wildly successful for optical clocks.
- Now pursuing ever-growing range of frequency comb technologies and applications.

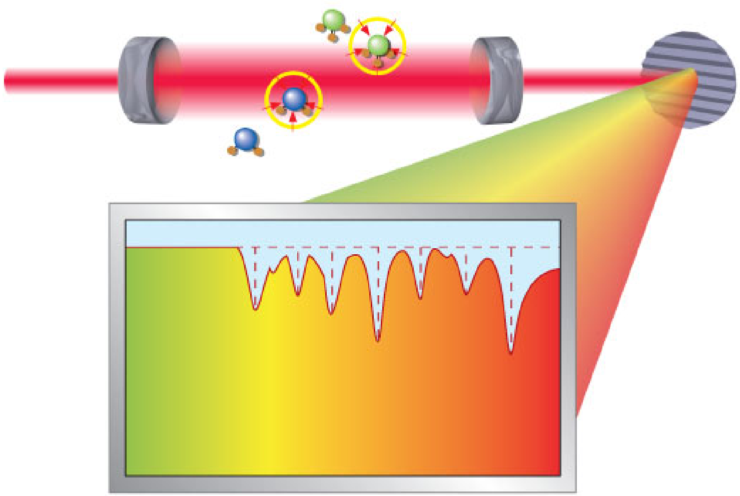




Repetitive pulse train ◇ Frequency Comb ◇ “ruler for frequency/time”



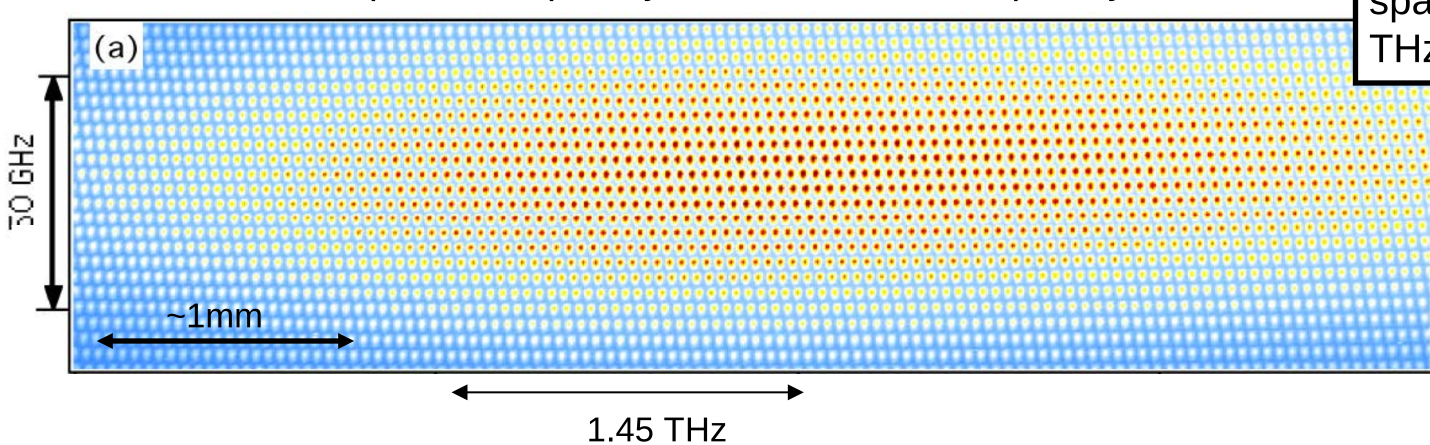
NIST Time and Frequency Mission: "Opportunistic" Research
Frequency Comb Development and Applications



- Massively parallel spectroscopy.
  - Bio, remote sensing, climate metrology…
- Multichannel detection/spectroscopy.
- Communications security.
- Communications efficiency.
- Quantum control.
- And???

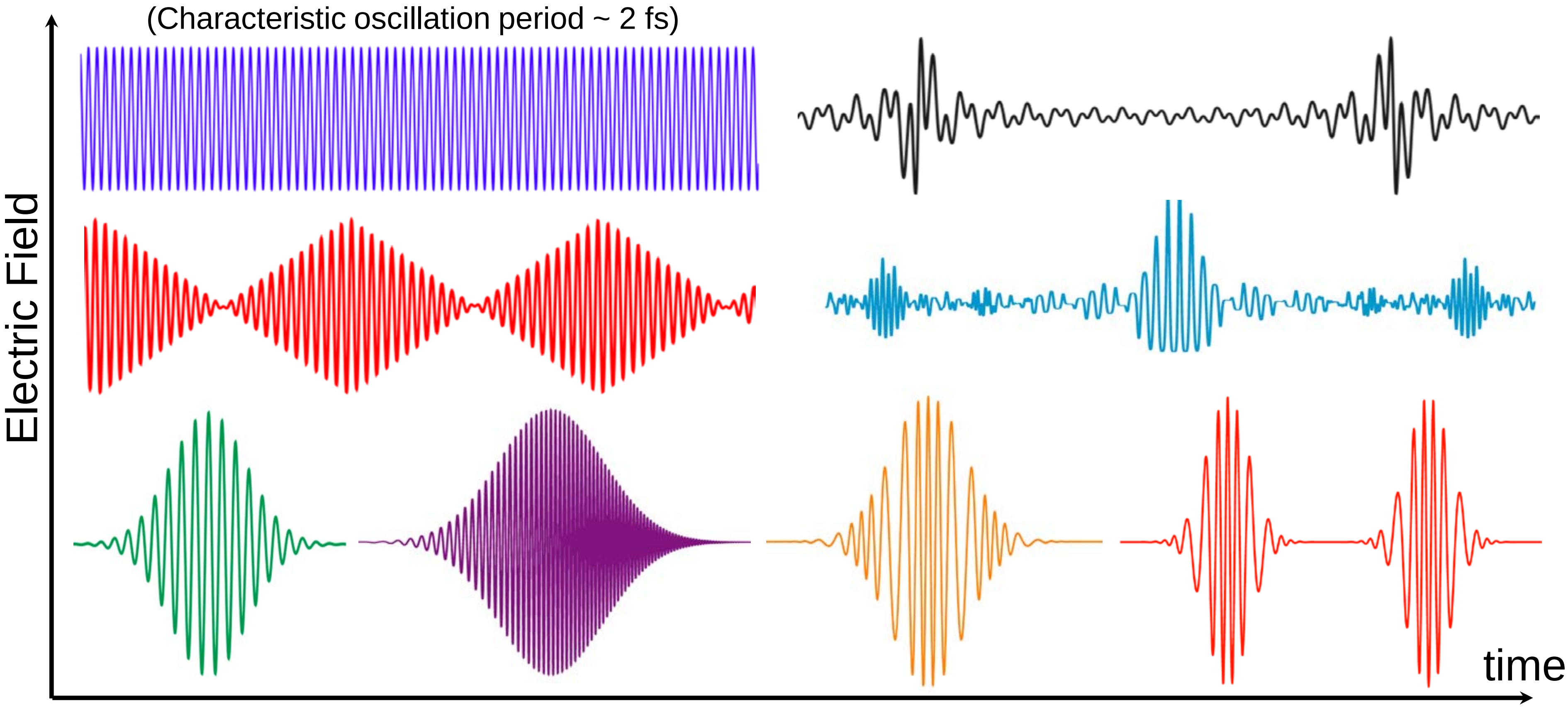
1-d Optical Frequency "Comb" ⇒ 2-d Frequency "Brush"

~2000 modes spanning 5.8 THz



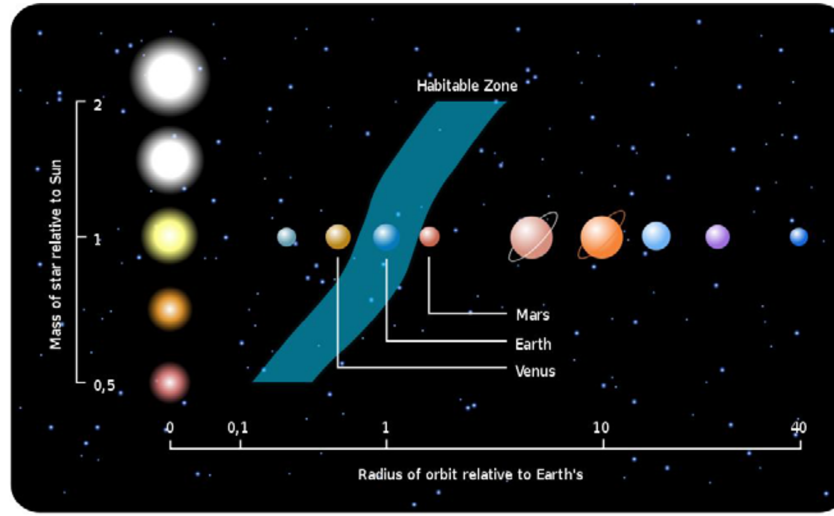
NIST Time and Frequency Mission: "Opportunistic" Research
Frequency Comb Development and Applications

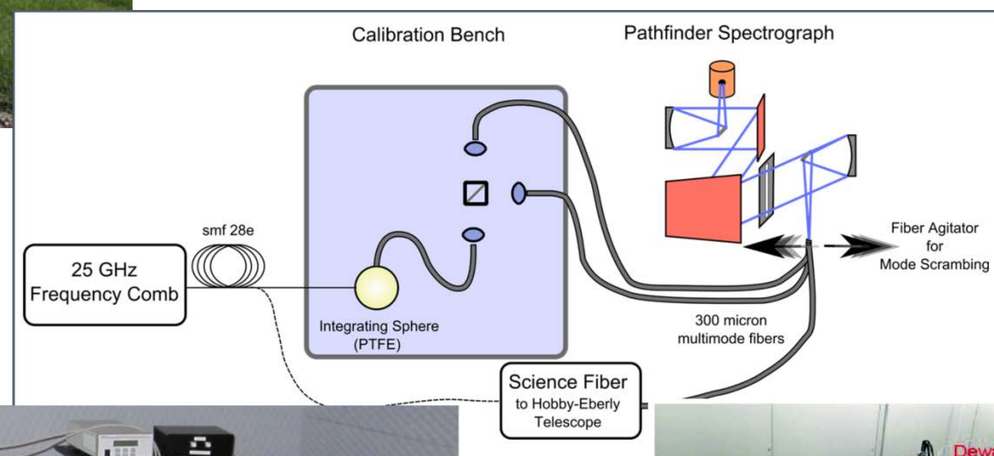
The generation of nearly any imaginable optical waveform of arbitrary duration with femtosecond (10^{-15} s) timing precision

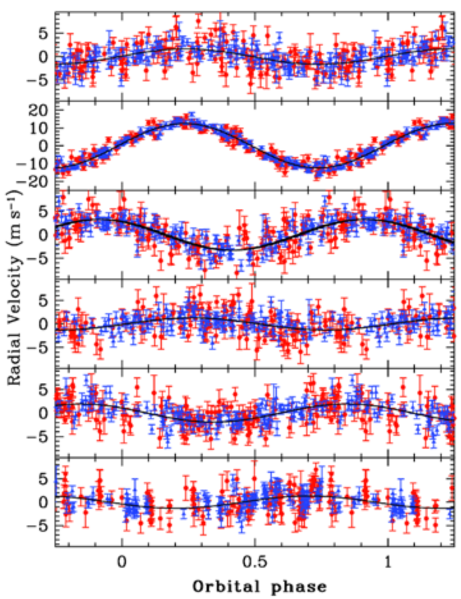


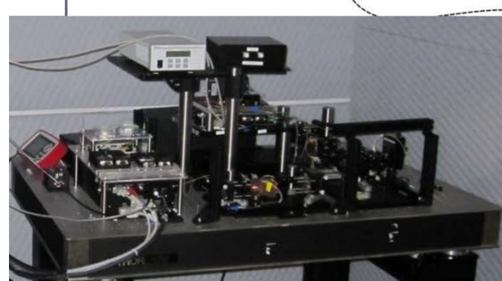
In short: To carry out in the optical domain what is easily accomplished in the electronic (<1 GHz) domain

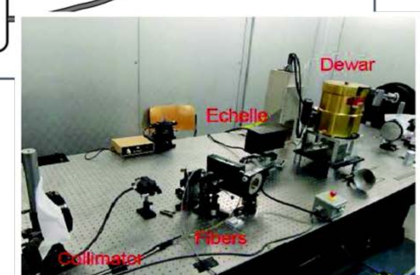
NIST Time and Frequency Mission: "Opportunistic" Research
Frequency Comb Development and Applications



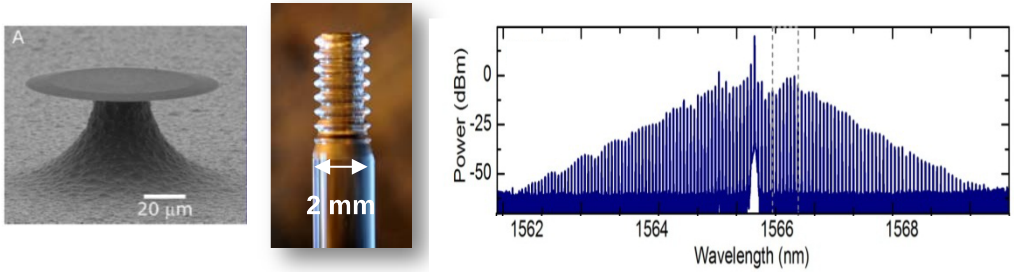




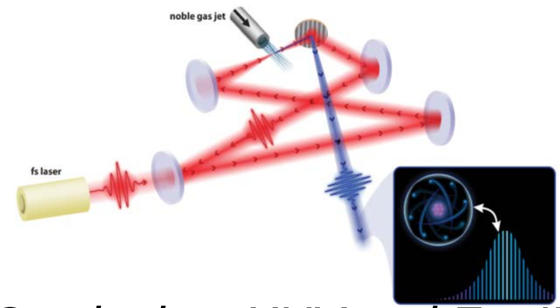




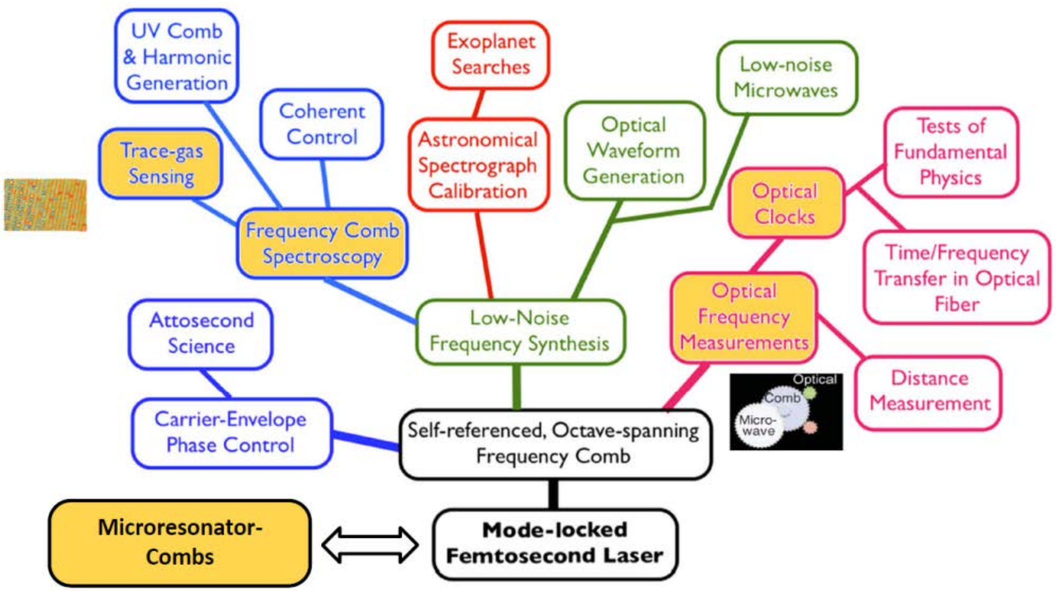
NIST Time and Frequency Mission: "Opportunistic" Research Frequency Comb Development and Applications

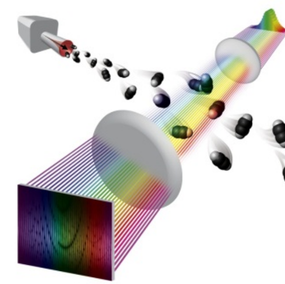


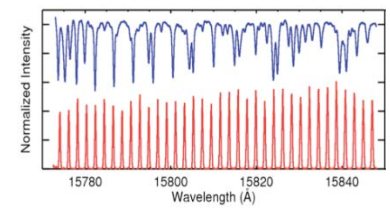
Microcombs

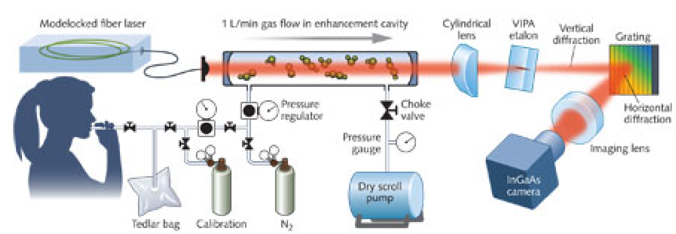


Combs into XUV and Far IR





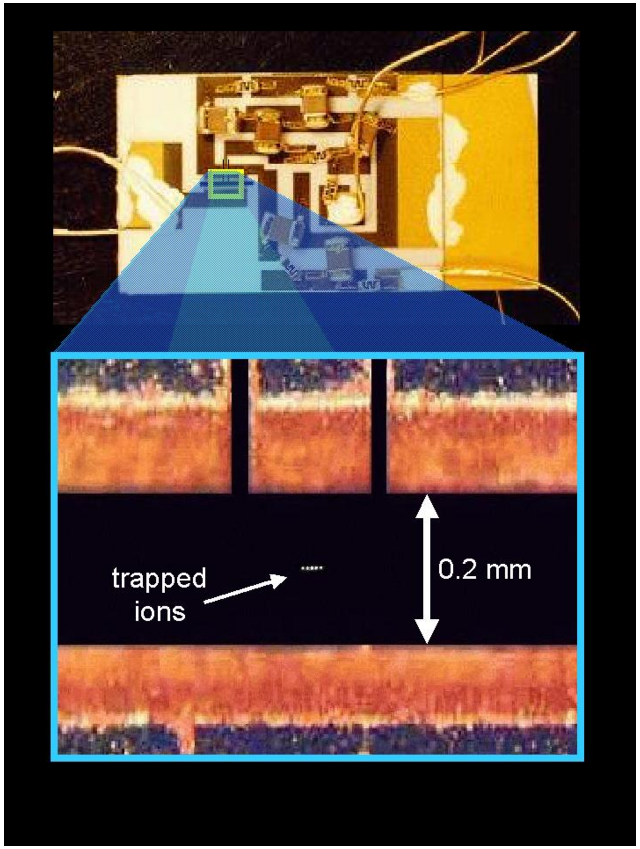




NIST Time and Frequency Mission: "Opportunistic" Research
Quantum Information Processing

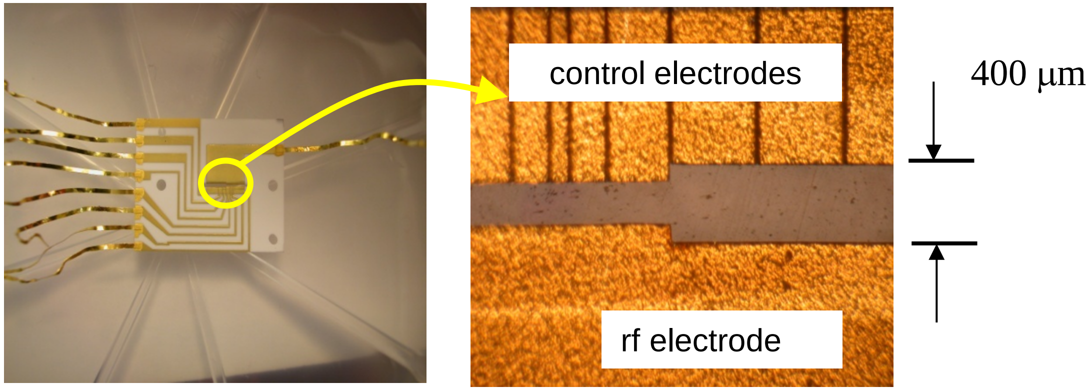
Quantum Computing

- Exploit entanglement and superposition.
- 300 qubits store ~ 10^{90} numbers simultaneously – more than the number of elementary particles in the universe.

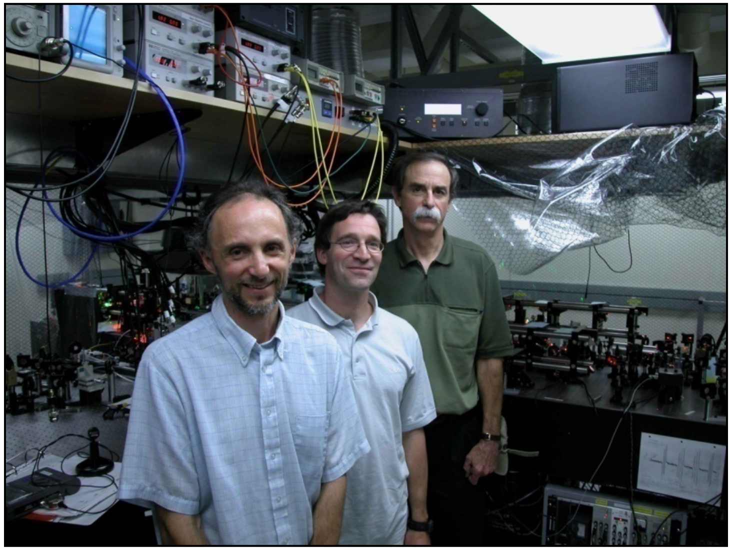


Why Time and Frequency and QC?

- NIST work on quantum computing with ions evolved directly from ion clock research.
- Trapped ion QC research leading to new types of clocks and other quantum-based measurements.



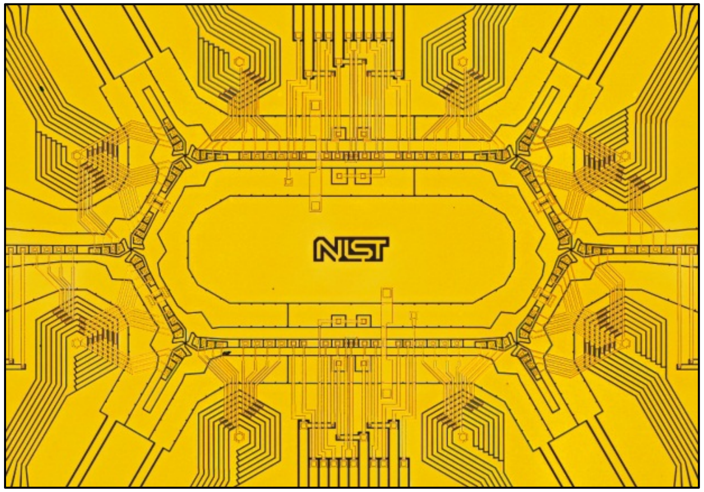
NIST Time and Frequency Mission: “Opportunistic” Research
Quantum Information Processing



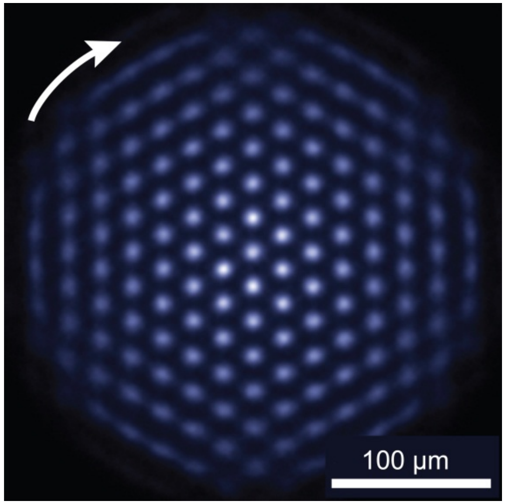
- World-class trapped ion quantum computing project as part of NIST-wide Quantum Information Program.

- Only demonstration of all the components of a scalable quantum computer (DiVincenzo criteria).
- Only demonstration of arbitrarily programmable logic gate operations.
- Multiple world’s firsts and world’s bests in quantum computing.

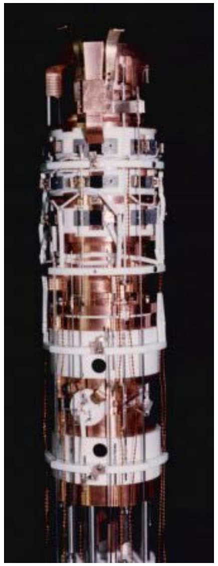
NIST Time and Frequency Mission: “Opportunistic” Research Spin-Offs of Quantum Information Processing



Planar ion traps capable of processing many dozens of ion qubits

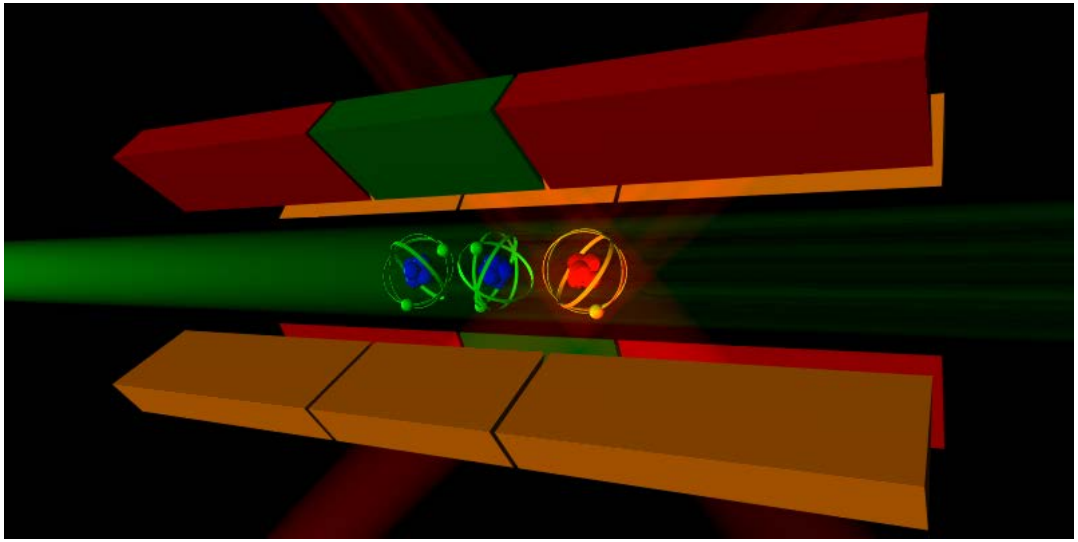


Quantum simulation with 10^{100} memory…



10^{-24} Newton force metrology

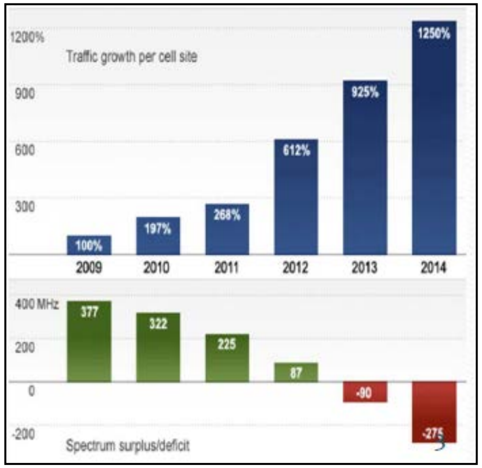
NIST Time and Frequency Mission: "Opportunistic" Research Spin-Offs of Quantum Information Processing



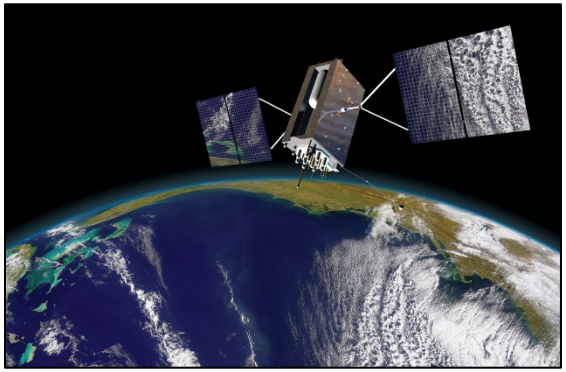
Aluminum ion logic clock

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

NIST Time and Frequency Mission: Timing Research
Some Applications of Better Timing



- Advanced communications.
  - Spectrum crunch.
  - Communications security.



- Improved positioning.
  - Future GPS and other positioning systems.

- Fundamental research.

Many more applications of ***<u>timing</u>***…

NIST Time and Frequency Mission: Timing Research

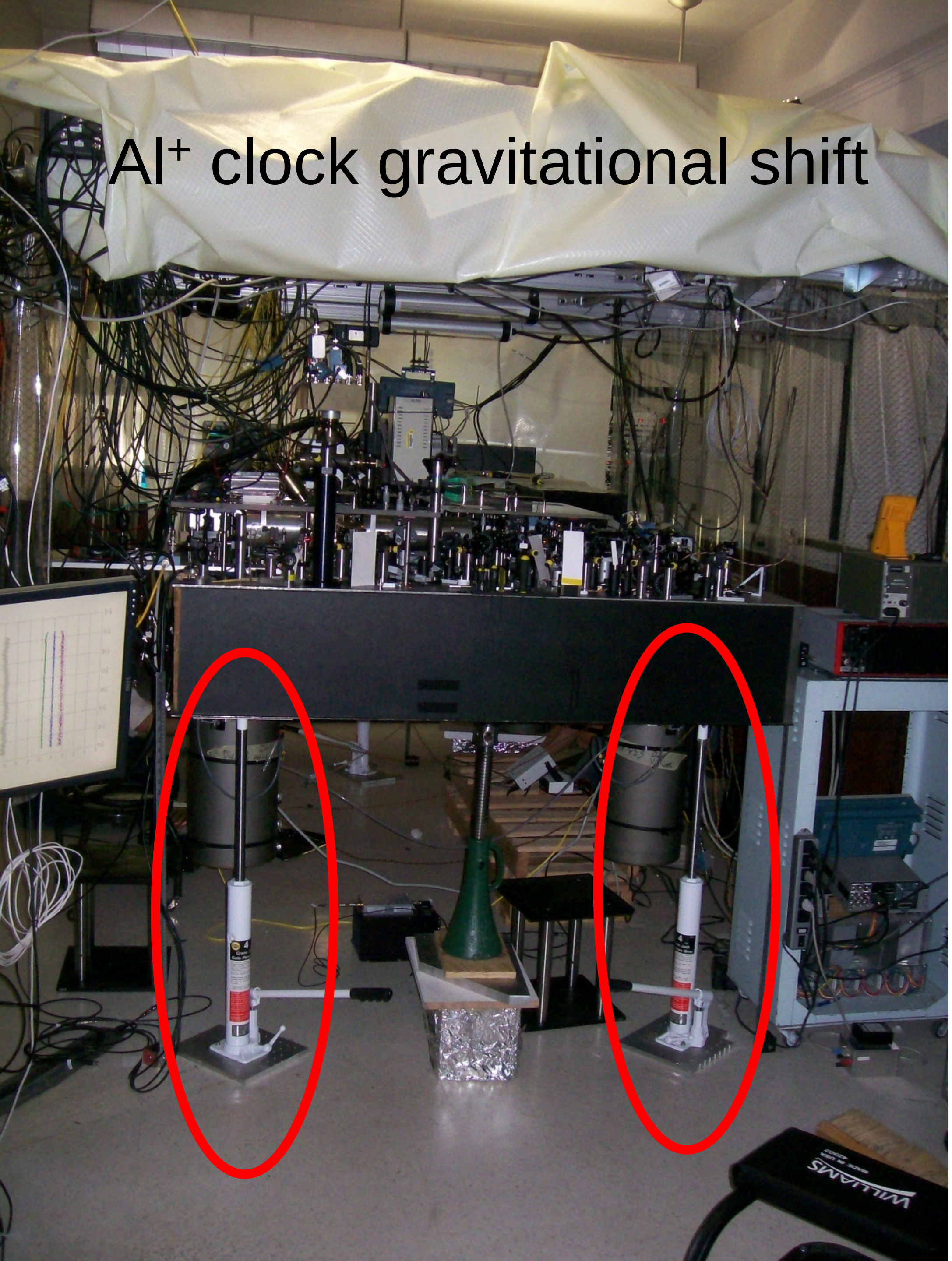
• “Post-Timing” Applications of Time and Frequency Metrology.

- **Precision sensors based on time and frequency measurements.**
  - Magnetic fields.
  - Gravity.
  - Electrical quantities.
  - Temperature.
  - Acceleration.
  - Many other quantities…

Next decade likely to demonstrate new applications and substantial impacts using ultraprecise time and frequency measurements for a broad range of measurements and technologies other than direct time and frequency measurements...

Often combining frequency metrology/transduction with other quantum-based sensing…

Al^+ clock gravitational shift



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

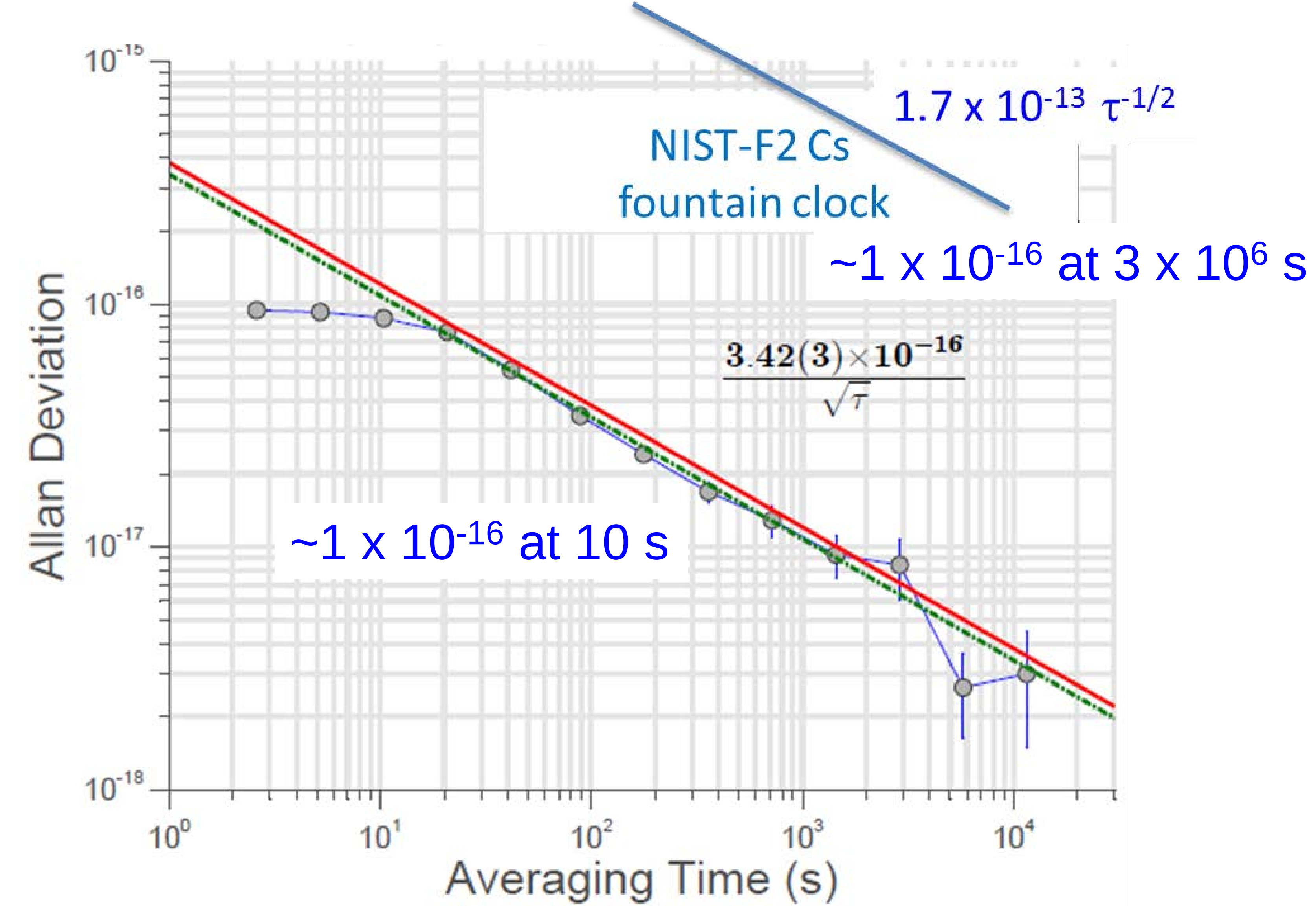
Measure frequency shift by moving Al^+ ion as slowly as jogging speed (about 3 m/second).

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

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

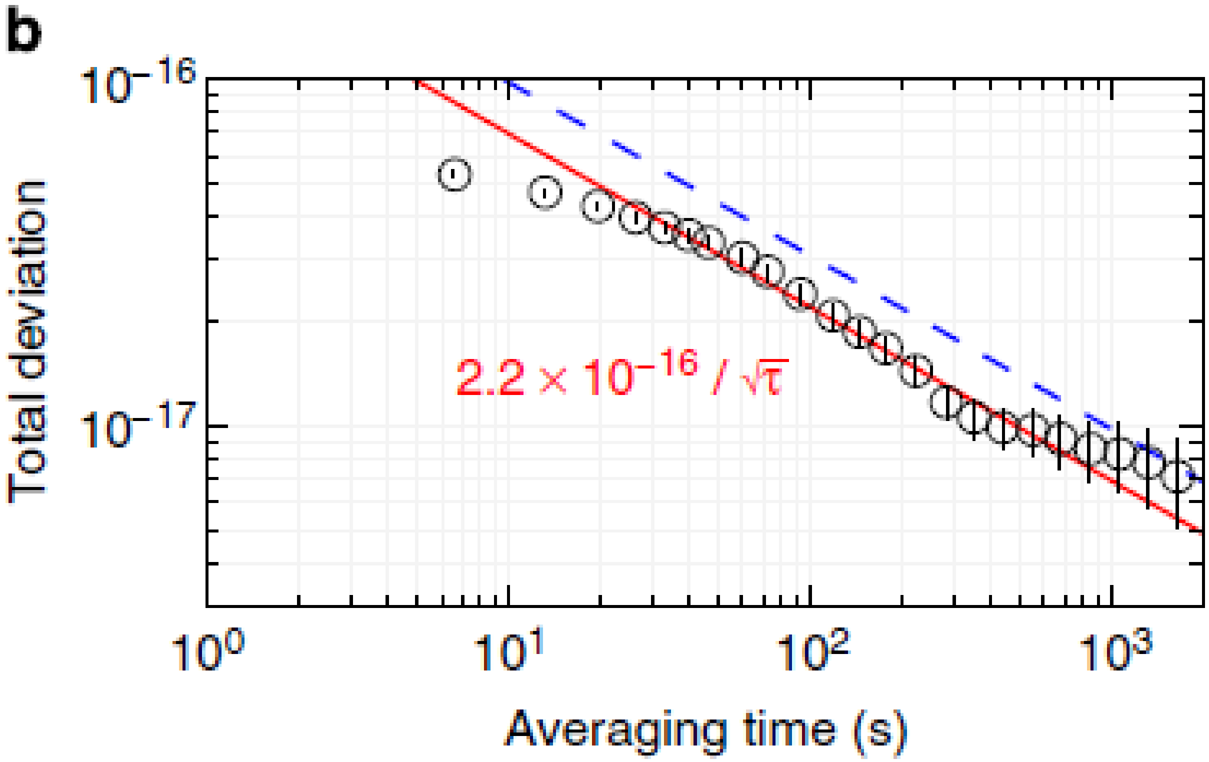
Stability vs. Accuracy for Frequency Standards

Optical and microwave clock stabilities



Stability vs. Accuracy for Frequency Standards

Latest Sr optical lattice clock results



~1 x 10^{-16} at 5 seconds for Sr lattice clock

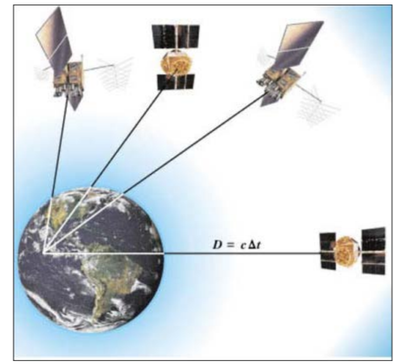
vs.

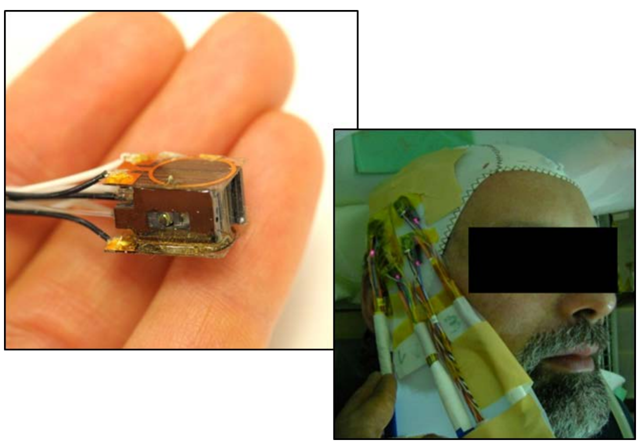
~1 x 10^{-16} at 10^6 seconds for NIST-F2

Atomic Clocks – Stability and Accuracy

For many traditional timing applications and developing “post-timing” applications, ***stability*** is more important than accuracy.

Timing applications

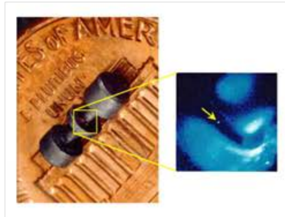


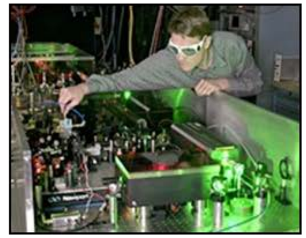


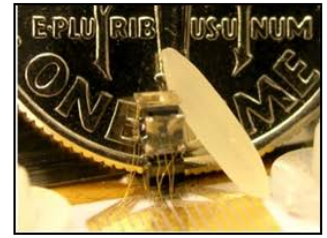
“Post-Timing” applications

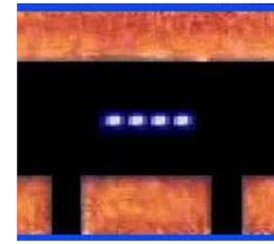
NIST Time and Frequency Mission

Opportunistic Research


Optical clocks


Optical frequency synthesis


Chip-scale atomic devices


Quantum computing

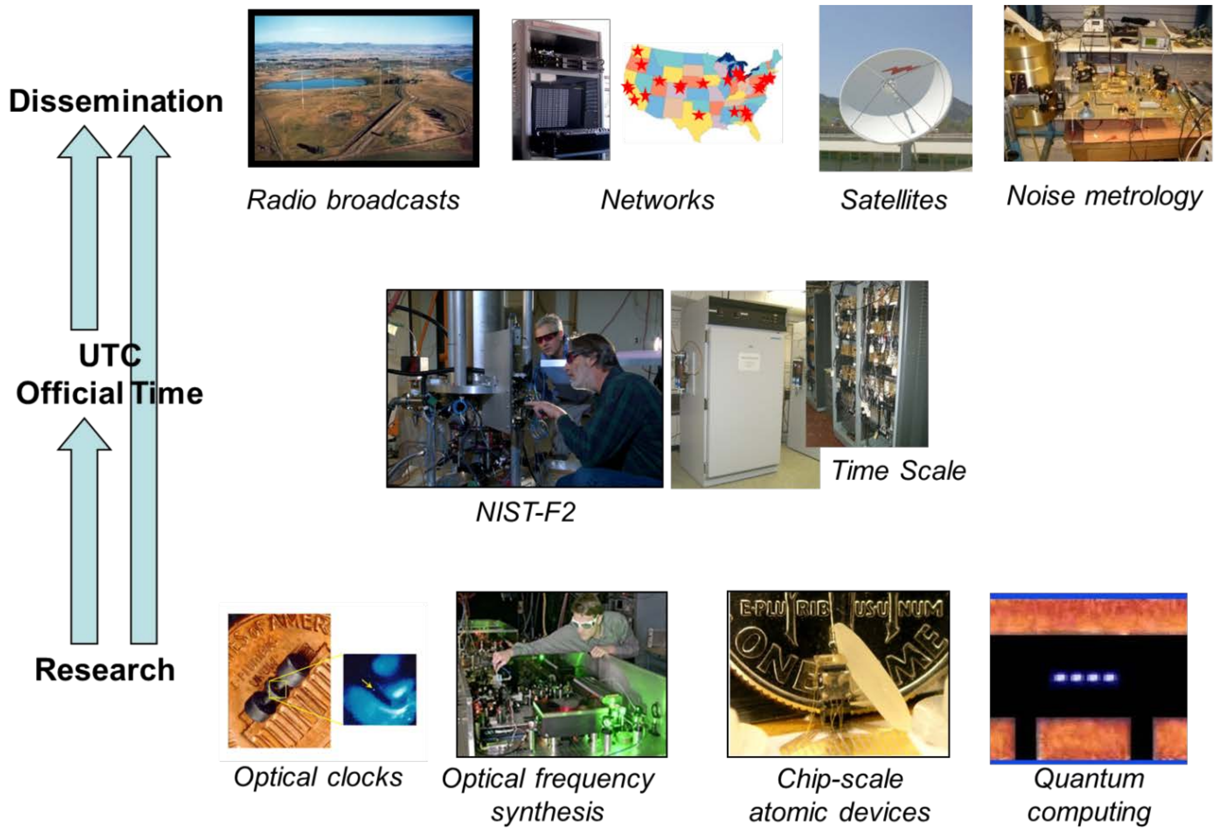
- Optical clocks.
  - Several best in the world, using diverse technologies.

- Frequency comb development and applications.
  - Multiple best in the world capabilities and unique applications.

- Chip-scale atomic devices.
  - Multiple best in the world / world unique capabilities.
  - Main initiator for NIST on a Chip program.

- Trapped ion quantum computing.
  - Widely recognized as best in the world.
  - Multiple spin-offs.

NIST Time and Frequency Mission



- Best in the world in all major technical/scientific areas.
    - Opportunities for improvement in certain aspects.

- No other organization in the world has the broad range of vertically integrated capabilities in time and frequency metrology, research, and related “opportunistic” research.

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

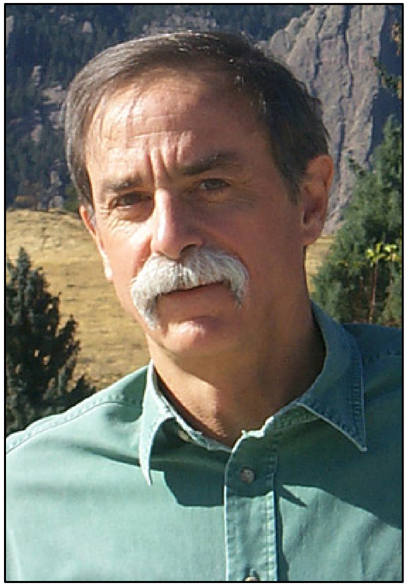
1. Technical programs.
   - Quality of research compared to rest of world.
   - Are technical programs adequate to achieve stated mission?

2. Scientific expertise.
   - Quality of technical staff compared to rest of world.
   - Is technical staff expertise adequate to achieve stated mission?

3. Infrastructure.
   - Are quality of facilities, equipment, human resources adequate to achieve stated mission?

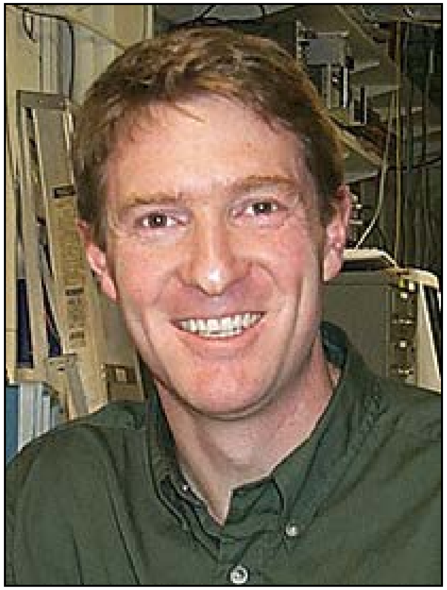
4. Dissemination of outputs.
   - How effectively does the organization disseminate/transfer its outputs?

NIST Fellows in Time and Frequency Division



Dave Wineland
Quantum Information Science, Clocks

Judah Levine
Network Time Services



Scott Diddams
Laser Frequency Comb Development and Applications

John Kitching
Chip-scale Atomic Devices

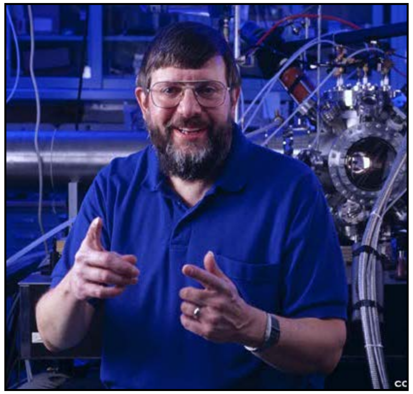
- 40 Total Fellows across NIST representing top ~2% of NIST scientists.
- 4 Fellows in Time and Frequency represent 10% of all NIST Fellows, despite Division representing ~2% of NIST scientists.
- 4 Fellows in Quantum Physics Division (JILA).
- Time & Frequency + Quantum Physics together represent ~3% of NIST scientists, but 20% of NIST Fellows.

Dave Wineland Nobel Prize 2012

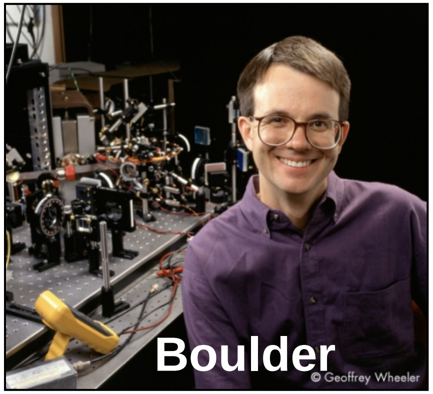
Awarded to Dave Wineland and Serge Haroche:

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

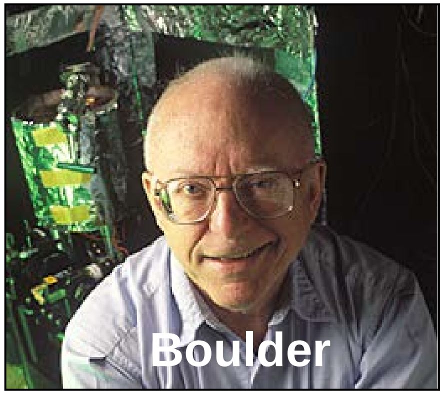
NIST Nobel Research: World-leading Science with Direct Mission Impact



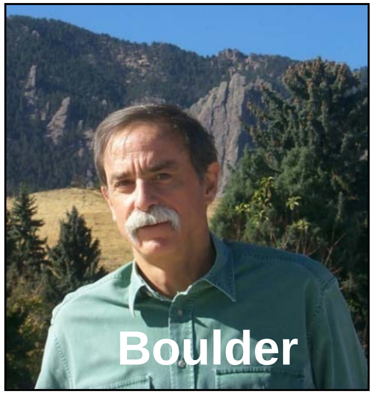
Bill Phillips, 1997
Laser cooling of neutral atoms. Used every day for NIST-F1/F2 primary frequency standards, source of all NIST time and frequency measurements. Crucial to many other precision measurements.



Eric Cornell, 2001
BEC (quantum degenerate gases). New laboratory for fundamental research in superconductivity, magnetic phenomena, quantum information and simulation, etc. Many potential precision metrology applications.

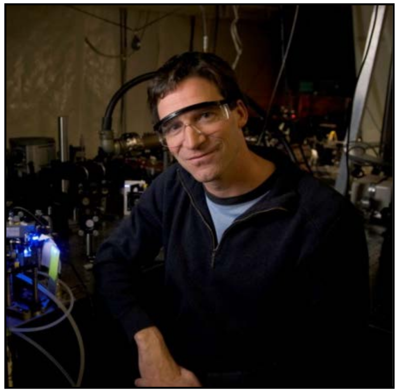


Jan Hall, 2005
Laser frequency comb. Biggest revolution in precision measurements since laser (1960). Used in atomic clocks, medical diagnostics, remote chemical analysis, communications, identifying exoplanets, much more…



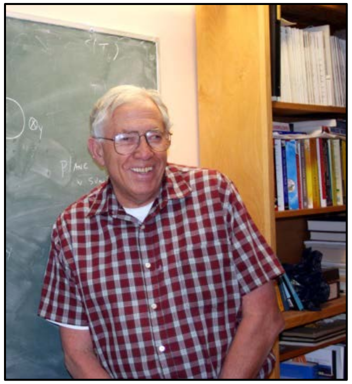
Dave Wineland, 2012
Quantum state measurement and manipulation. Used in world's most accurate atomic clocks, quantum computing, quantum simulation, 10^{-24} newton force measurements, future precision metrology.

Scientific Awards in Time and Frequency Division

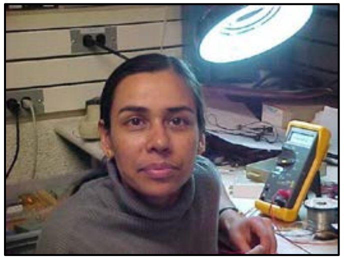


Dietrich Leibfried
Arthur S. Flemming Award
(Basic Science)
Quantum computing

John Kitching
IEEE Sensors Council
Technical Achievement
Chip-scale devices



Judah Levine
Presidential Rank Award
Network time services

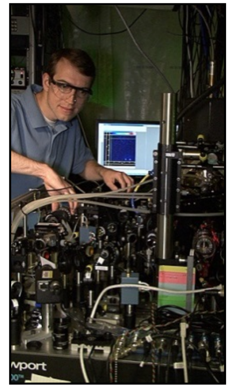


Dave Howe, Craig Nelson, Archita Hati
NIST Astin Measurement Science Award
Innovative phase noise metrology

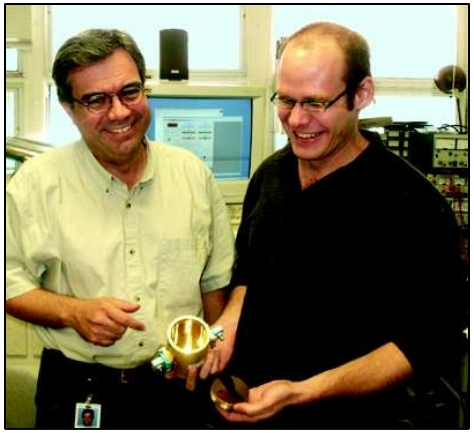
Jim Bergquist
European Frequency and
Time Forum Award
Mercury ion clock, lasers

Scientific Awards in Time and Frequency Division

Scott Diddams
Arthur S. Flemming Award
(Applied Science)
Frequency Combs

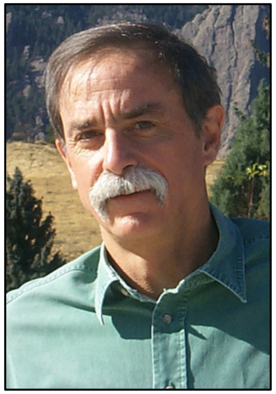


David Hanneke
Albert Michelson
Postdoctoral Prize
Quantum computing



Dave Howe, Craig Nelson
DoC Bronze Medal
Phase noise metrology

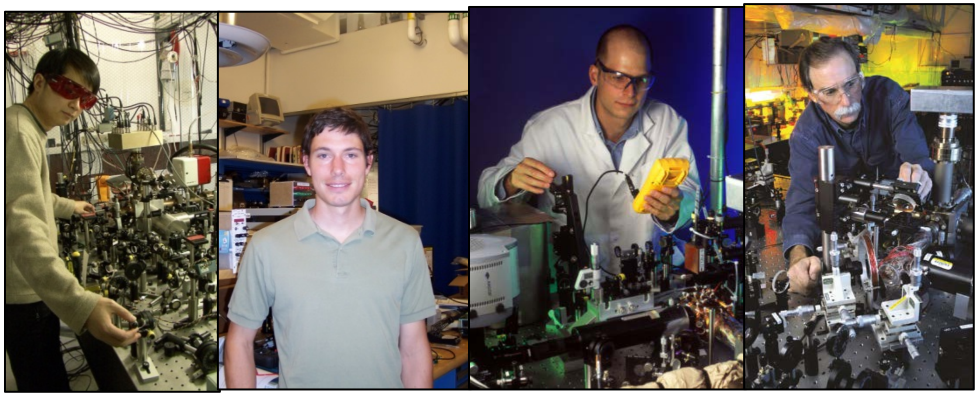
Mke Lombardi
NCSLI Wildhack Award
Remote measurement
services



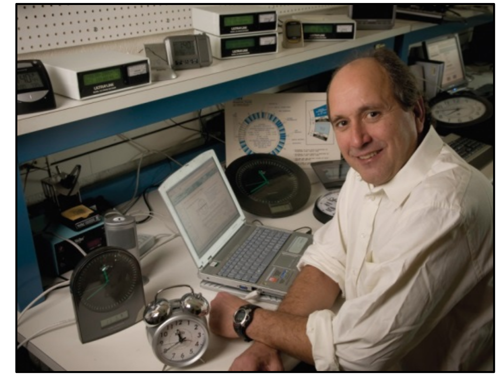
Dave Wineland
Benjamin Franklin Medal
Quantum state engineering

Pascal Del'Haye
Humboldt Fyodor Lynen
Research Fellowship
Frequency combs

Scientific Awards in Time and Frequency Division



James Chou, David Hume, Till Rosenband, Dave Wineland
NIST Condon Award
Outstanding publication (Al^+ logic clock)



John Lowe
DoC Bronze Medal
Partnering with industry to innovate radio station WWVB

Frank Quinlan
European Frequency and Time Forum Young Scientist
Frequency combs, ultralow noise RF

Liz Donley, John Kitching, Svenja Knappe
DoC Gold Medal
Chip-scale atomic devices

Scientific Awards in Time and Frequency Division


Archita Hati


Craig Nelson


Corey Barnes


Danielle Lirette


Tara Fortier


Frank Quinlan

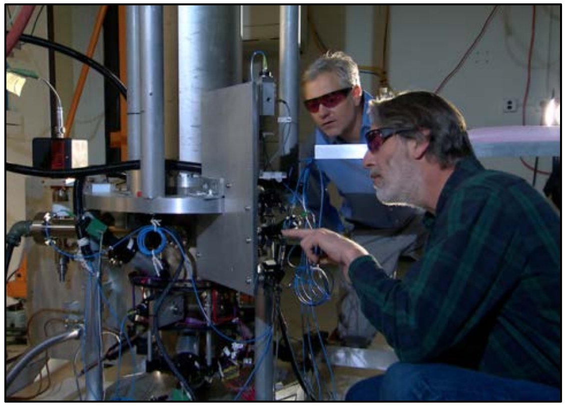

Jason Desalvo


Andrew Ludlow

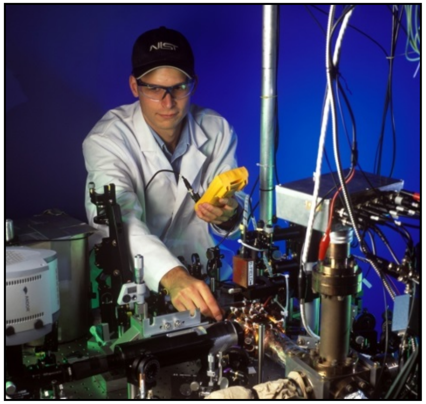

Scott Diddams


Dave Howe

IEEE Outstanding Paper
Ultralow noise RF signals from frequency combs



Steve Jefferts, Tom Heavner
DoC Gold Medal
NIST-F2



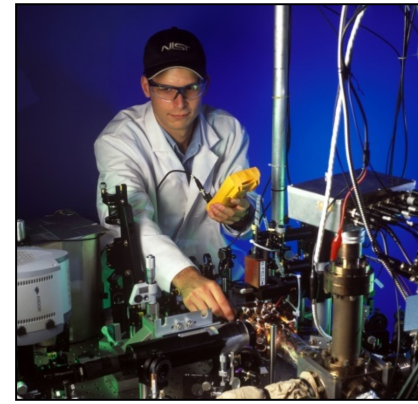
Till Rosenband
IUPAP Young Scientist
Al^+ logic clock

Tom O’Brian
DoC Silver Medal
Leadership of
new Boulder lab
building (PML)

Scott Diddams
NIST Rabinow Award
(Innovation)
Frequency combs

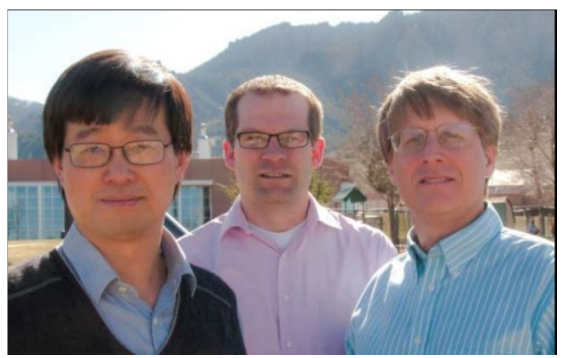
Scientific Awards in Time and Frequency Division

Andrew Novick and Mike Lombardi
NIST Judson French Award
Measurement services

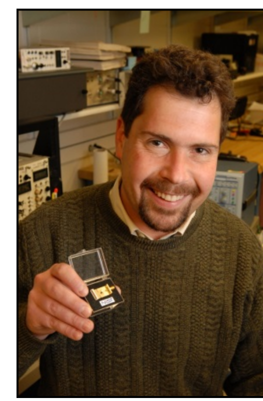


Till Rosenband
Arthur S. Flemming Award
Basic Science
Al^+ logic clock

Scott Diddams
DoC Silver Medal
Frequency Combs



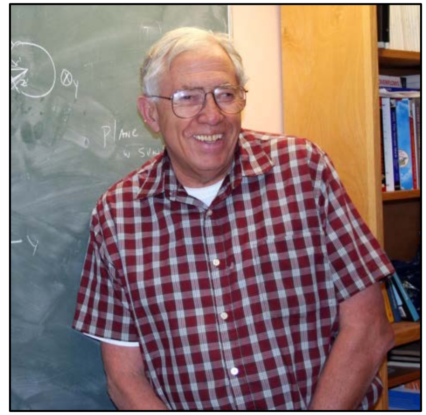
Jun Ye, Andrew Ludlow, Chris Oates
DoC Gold Medal
Optical lattice clocks



John Kitching
Arthur S. Flemming Award
(Applied Science)
Chip-scale devices

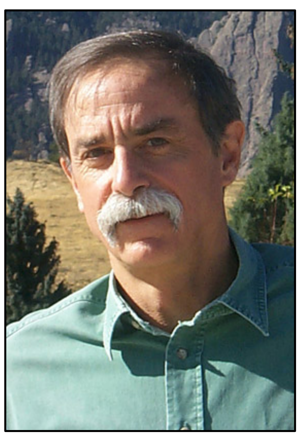
Scientific Awards in Time and Frequency Division

Andrew Ludlow
European Frequency and Time Forum Young Scientist
Yb lattice clock

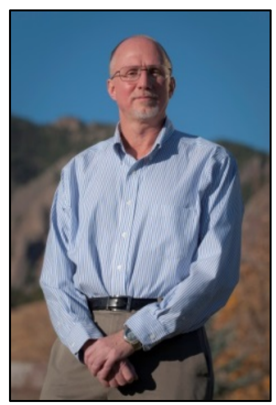


Judah Levine
IEEE Rabi Award
Time scales

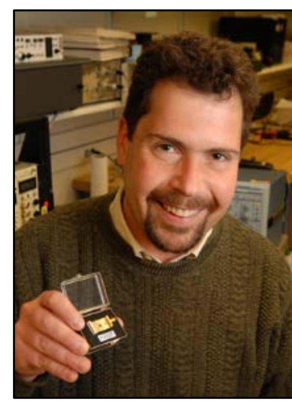
Dave Howe
IEEE Rabi Award
Oscillators



Dave Wineland
AAAS
Quantum state engineering



Tom O'Brian
DoC Gold Medal
Leadership of research and services

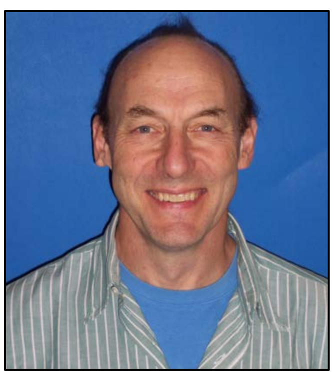


John Kitching, Svenja Knappe
Rank Foundation Prize in Optoelectronics (UK)
Chip-scale atomic devices

Scientific Awards in Time and Frequency Division

Mike Lombardi
NCSLI Best Paper
Remote measurement services

Liz Donley, John Kitching, Svenja Knappe
Colorado Governor's Award for High Impact Research
Chip-scale atomic devices



Marc Weiss
NIST Slichter Award
NIST measurements to telecom industry

Trudi Peppler, Jim Spicer, Susan Schima, Andrew Wilson
NIST Safety Award
Unique safety approach to PML Service Galley management

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

2. Scientific expertise.
   - Quality of technical staff compared to rest of world.
   - Is technical staff expertise adequate to achieve stated mission?

Quality of scientists reflected by:

- Best in the world capabilities in nearly all Division scientific areas reflects capabilities of the technical staff.

- Multiple awards for staff representing all Division main mission areas:

  - UTC realization, Dissemination (services), Research.

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

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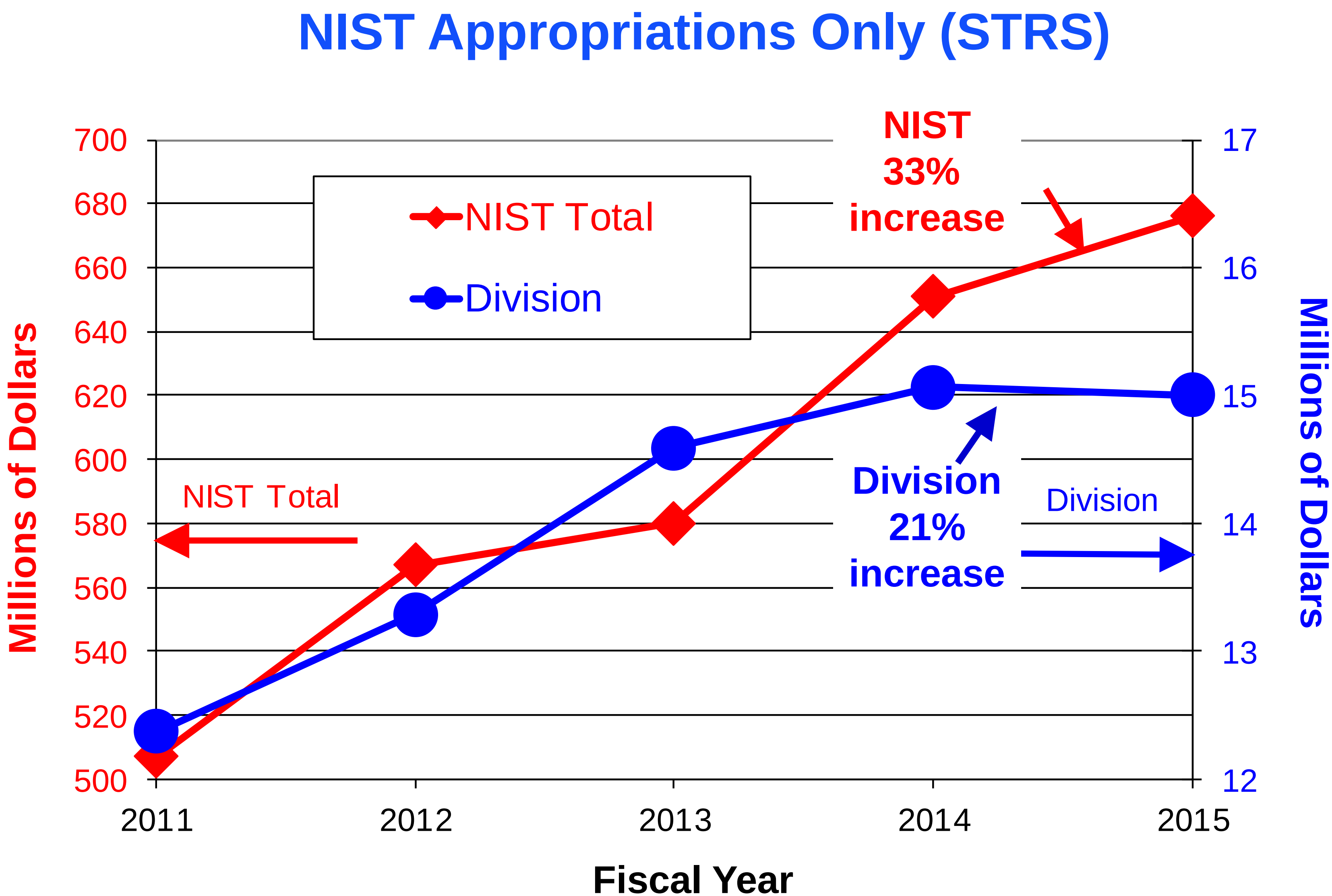
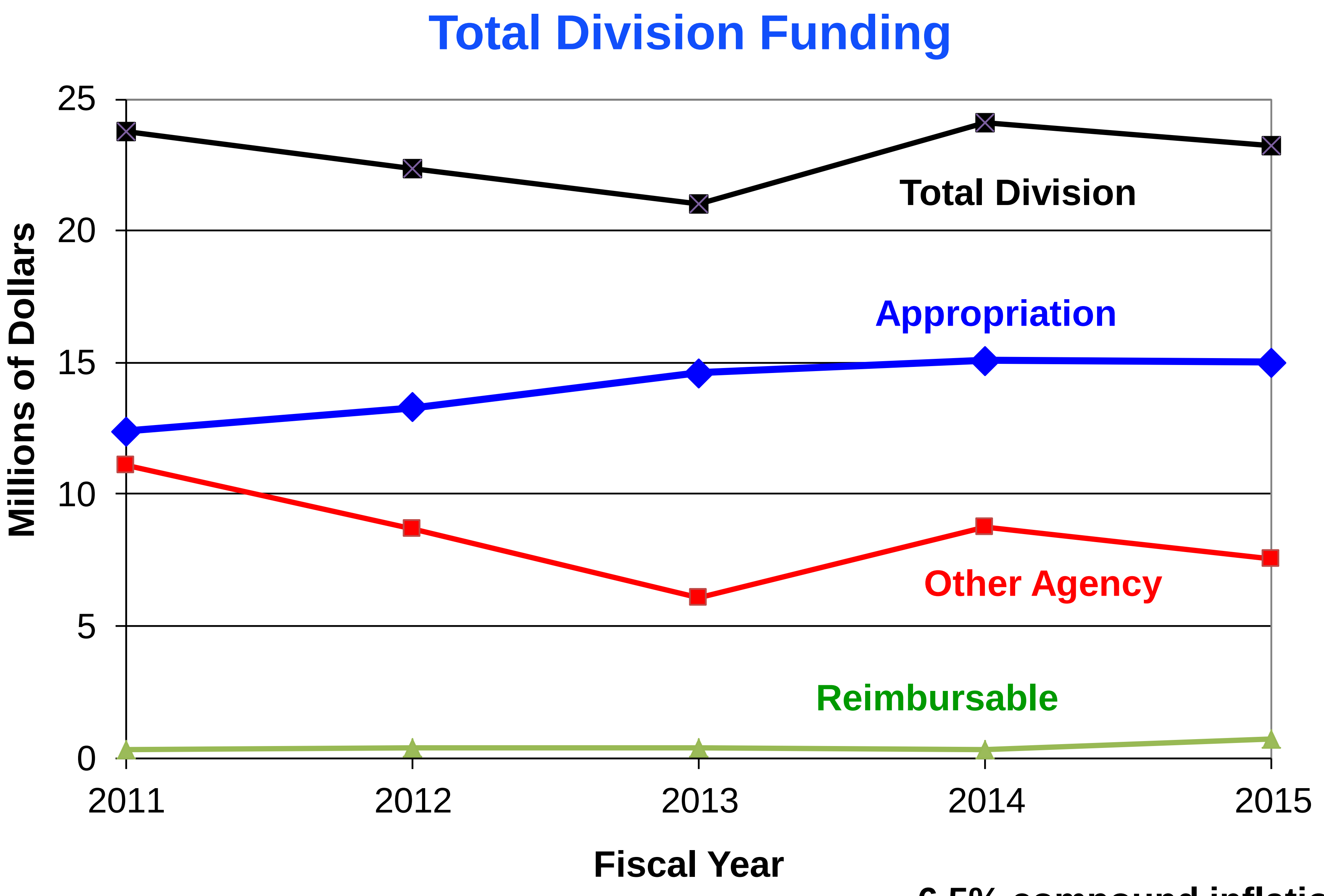
4. Dissemination of outputs.
   - How effectively does the organization disseminate/transfer its outputs?

Division Financial Resources



~6.5% compound inflation FY2011 to FY2015

Division Financial Resources



~6.5% compound inflation FY2011 to FY2015

Division Financial Resources

Some Division financial challenges:

- New NIST appropriations (STRS) directed mostly to current Administration priorities:
    - IT security.
    - Direct manufacturing support.
    - Support for legal forensics.
    - Etc.

- Fewer appropriations (STRS) directed to core NIST Labs measurement science research programs.

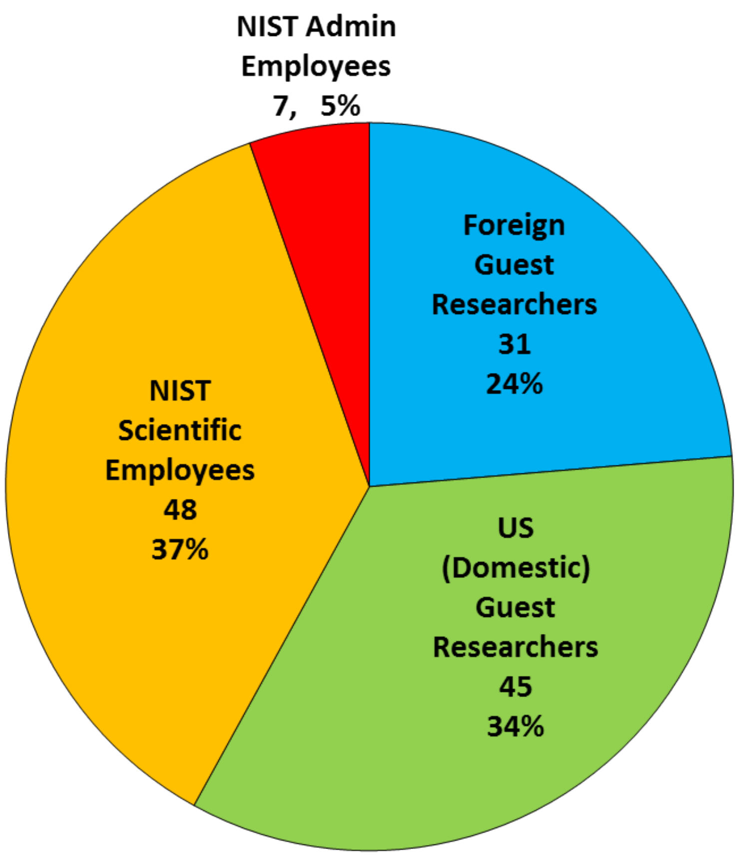
Division Financial Resources

Some Division financial challenges:

- Significant challenges with funding from Other Federal Agencies:
  - Other Agency funding has been key to highest impact Division programs:
    - Chip-scale atomic devices.
    - Quantum information processing.
    - Frequency comb development and applications.
    - Phase noise metrology and advances.
    - Etc.
  - These NIST programs have addressed key Other Agency needs.
  - Changes in NIST Other Agency administrative processing have made the process enormously more difficult.

Division Personnel

Time & Frequency Personnel
(snapshot 8/12/2015)



- 131 total people.
  - 58% guest researchers.
  - 42% NIST employees.

Guest researchers include:

- Grad students.
- Postdocs.
- Contractors.
- Foreign visitors.

- Division is right size for budget.
- Appropriate balance of senior NIST staff, early career staff and associates.
- Constantly refreshing skill set through postdocs, visitors, contractors.
  - All hires from that pool.
- Use of postdocs, students, visitors also broadens networks of contacts outside NIST.

Division Facilities

- Most NIST Boulder buildings almost 60 years old.

- Older buildings incapable of providing necessary environment for 21st century research and metrology.
  - Temperature stability.
  - Vibration isolation.
  - Air quality.
  - Etc.

- New advanced lab completed in 2012 significantly remedies lab performance problems.
  - Various names for the same building:
    - “Precision Measurement Lab” PML.
    - B1E.
    - Building 81.

- Selected renovations of Building 1 Wings also will help, but greatly delayed.

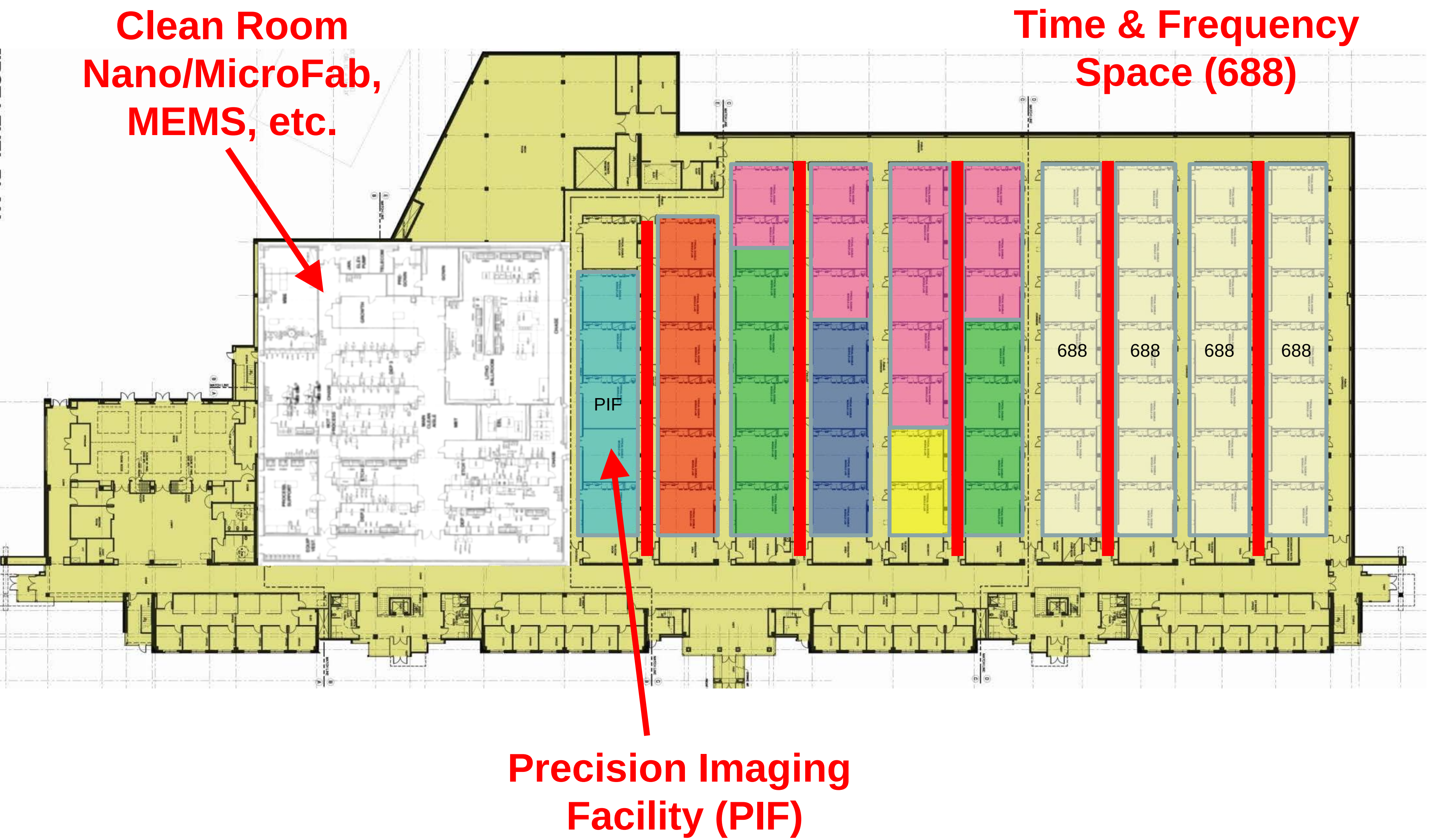
- Start up of new Communications Technology Laboratory (CTL) poses potential space crunch.

Division Facilities

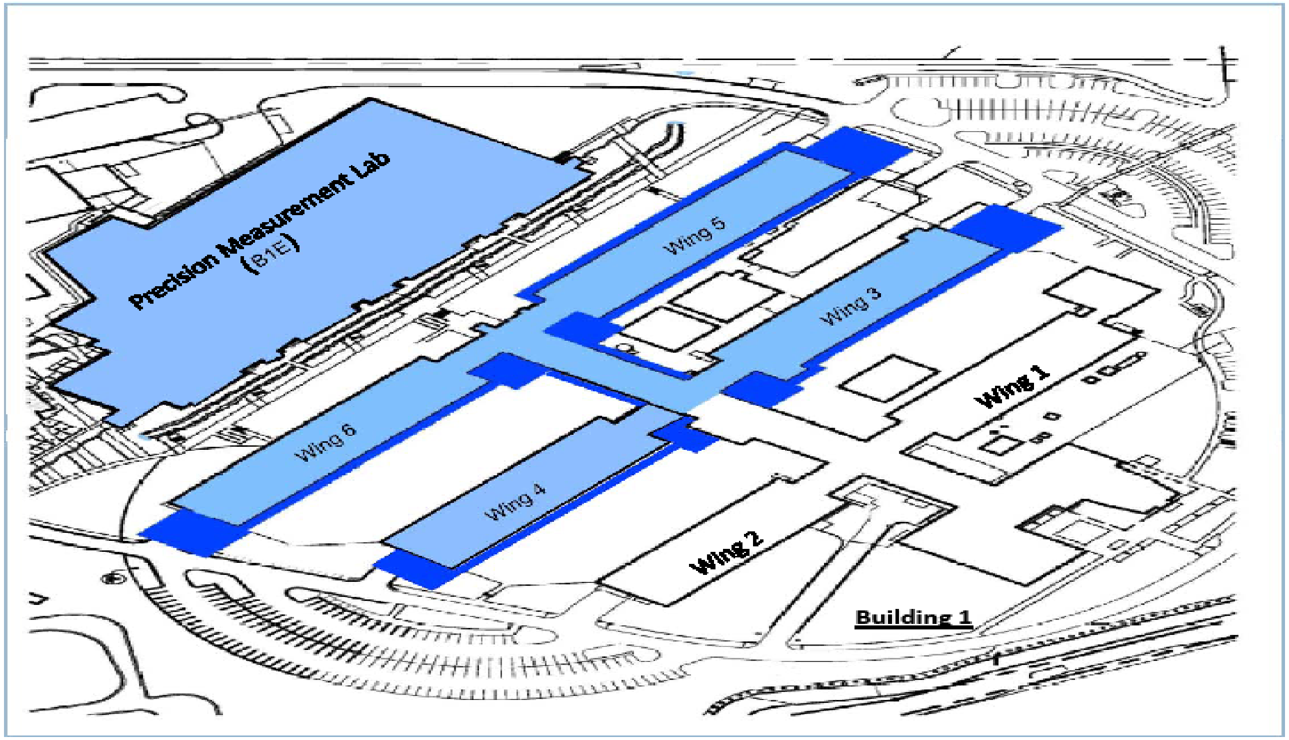
- $102 million Advanced Laboratory.
- High performance laboratory space.
- Advanced Clean Room and Precision Imaging Facility.
- Offices and conference space.

- Commissioned February 2012.
- Phased move in.
- Increases available lab space by ~1/3, but main goal is improved performance.

Division Facilities



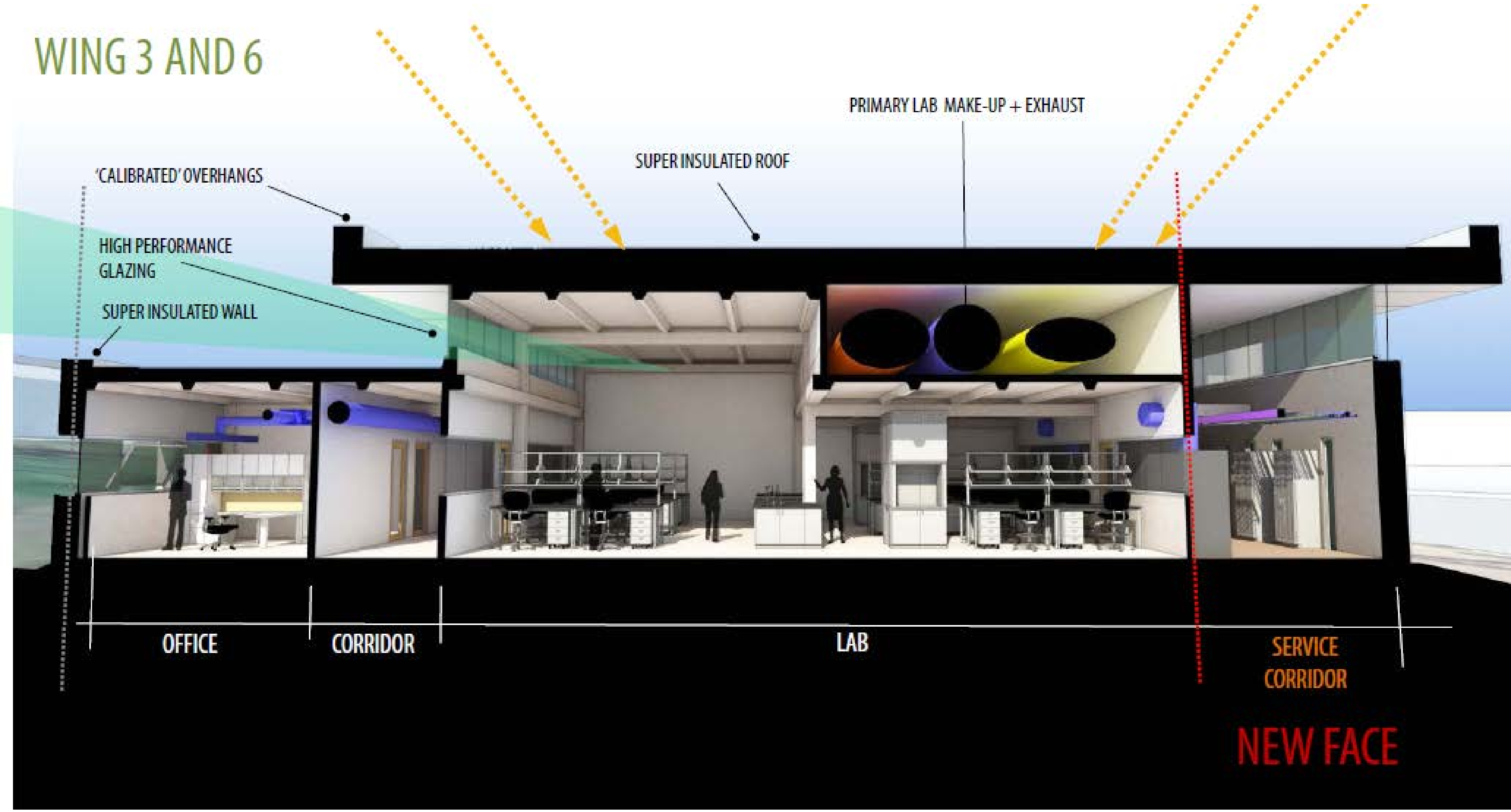
Division Facilities



- Renovation of 170,000 gsf lab and office space.
- Improved temperature, vibration, air quality control.
- Completion of entire project 2019??? (multiple delays, budget uncertainties).

Division Facilities

Building 1 Renovation



Division Facilities

Problem for Time and Frequency Division and all Divisions:

- Insufficient office space and collaboration space.
- Speculative plans underway to try to address the shortfall.

Assessment of the NIST Time and Frequency Division

3. Infrastructure.
    - Are quality of facilities, equipment, human resources adequate to achieve stated mission?

- Significant recent improvement in high performance lab facilities.
    - Arguably an existential requirement for continued scientific leadership.

- Financial resources are relatively flat:
    - Appropriated budget is relatively flat.
    - Major challenges with Other Agency funding.

- Need for significant additional office/collaboration space.
    - Some speculative solutions being explored.

- Pending loss of central instrument shop.

- Generally good access to equipment, but:
    - Procurement process is very onerous with substantial delays.
    - ~50% overhead on capital equipment makes purchase of expensive equipment very difficult.

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

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   - How effectively does the organization disseminate/transfer its outputs?

NIST Time and Frequency Mission

Dissemination

Radio broadcasts

Networks

Satellites

Noise metrology

- Remote broadcast services.
  - Best in the world
  - Used more than all other NIST measurement services combined.
  - Unique high performance services to industry users.

- Phase noise metrology.
  - Best in the world new ultralow noise measurement capabilities.

- Unique real-time SIM international time scale.
  - Setting standard for future of UTC.

Dissemination of Results: Publications

Dissemination of Results: Publications

Public, searchable database of Time & Frequency Division publications.
>2,700 PDFs posted.

tf.nist.gov

Physics Laboratory
Time & Frequency Division
NIST
National Institute of Standards and Technology

NIST Time and Frequency Publication Search Results

Number of items found: 2784

Return to publication search form

Authors	Title	Journal	Vol No.	Page Nos.	Pub. Date	Bin No.
W.M. Itano, J.C. Bergquist, and D.J. Wineland	Early observations of macroscopic quantum jumps in single atoms	Int. J. Mass Spectrom.		403-409	20150325	2723
N. Ashby, S. Barlow, T. Heavner, and S. Jefferts	Frequency shifts in NIST Cs primary frequency standards due to transverse RF field gradients	Phys. Rev. A	91	033624-13	20150323	2734
L. Nugent-Glandorf and S.A. Diddams	Open-air, broad-bandwidth trace gas sensing with a mid-infrared optical frequency comb	Appl. Phys. B-Lasers O.		12 p.	20150320	2748
W. Loh, A. Green, F. Baynes, D. Cole, F. Quinlan, H. Lee, K. Vahala, S. Papp, and S.A. Diddams	Dual-microcavity narrow-linewidth Brillouin laser	Optica	2	225-232	20150305	2754
F.N. Baynes, F. Quinlan, T.M. Fortier, Q. Zhou, A. Beling, J.C. Campbell, and S.A. Diddams	Attosecond timing in optical-to-electrical conversion	Optica	2	141-146	20150210	2755
S. Burd, D. Leibfried, A.C. Wilson, and D.J. Wineland	Optically pumped semiconductor lasers for atomic and molecular physics	Proc. 2015 SPIE Conf.	9349	93490p-8	20150207	2765
M. Weiss, J. Eidson, C. Barry, D. Broman, L. Goldin, B. Iannucci, E.A. Lee, and K. Stanton	Time-Aware Applications, Computers, and Communication Systems (TAACCS)	NIST Tech. Note 1867	1867	26 p.	20150201	2767
B.C. Sawyer, J.G. Bohnet, J.W. Britton, and J.J. Bollinger	Reversing hydride-ion formation in quantum-information experiments with Be+	Phys. Rev. A	91	011401-5	20150112	2759
P. Del'Haye, A. Coillet, W. Loh, K. Beha, S.B. Papp, and S.A. Diddams	Phase steps and resonator detuning measurements in microresonator frequency combs	Nature Communications	6	8 p.	20150107	2733
K. Beloy, N. Hinkley, N. Phillips, J. Sherman, M. Schioppo, J. Lehman, A. Feldman, L. Hanssen, C. Oates, and A. Ludlow	Atomic Clock with 1×10–18 Room-Temperature Blackbody Stark Uncertainty	Phys. Rev. Lett.	113	260801-5	20141231	2752
C.L. Holloway, J.A. Gordon, S. Jefferts, A. Schwarzkoph, D.A. Anderson, S.A. Miller, and G. Raithel	Broadband Rydberg Atom-Based Electric-Field Probe for SI-traceable Self-Calibrated Measurements	IEEE T. Antenn. Propag.	62	6169-6182	20141212	2763
A. Hati, C.W. Nelson, and D.A. Howe	PM Noise Measurement at W-Band	IEEE T. Ultrason. Ferr.	61	1961-1966	20141212	2732
M. Weiss, L. Cosart, and J. Hanssen	Ethernet Time Transfer through a U.S. Commercial Optical Telecommunications Network	Proc. 2014 PTTI Mtg.		214-220	20141204	2760
J. Yao and J. Levine	GPS Measurements Anomaly and Continuous GPS Carrier-Phase Time Transfer	Proc. 2014 PTTI Mtg.		164-169	20141204	2758
M.A. Lombardi, J. Levine, J. Mauricio Lopez, F. Jiménez, J. Bernard, M. Gertsvolf, H. Sanchez, O.G. Fallas, L.C. Hernández Forero, R. José de Carvalho, M.N. Fittipaldi R.F. Solis, and F. Espejo	International Comparisons of Network Time Protocol Servers	Proc. 2014 PTTI Mtg.		57-66	20141204	2757
V. Zhang and Z. Li	Measured Ionosphere Delay Correction for Code-Based GPS Time Transfer	Proc. 2014 PTTI Mtg.		144-148	20141204	2756
T. Zanon-Willette, S. Almonacil, E. de Clercq, A.D. Ludlow, and E. Arimondo	Quantum engineering of atomic phase shifts in optical clocks	Phys. Rev. A	90	053427-8	20141124	2741
W. Sun, F. Quinlan, T.M. Fortier, J.-D. Deschenes, Y. Fu, S.A. Diddams, and J.C. Campbell	Broadband Noise Limit in the Photodetection of Ultralow Jitter Optical Pulses	Phys. Rev. Lett.	113	203901-5	20141114	2746
A. Klose, G. Ycas, D.L. Maser, and S.A. Diddams	Tunable, stable source of femtosecond pulses near 2 μm via supercontinuum of Erbium mode-locked laser	Opt. Express	22	28400-28411	20141107	2753
M.A. Lombardi, A.N. Novick, and V.S. Zhang	A Low-Cost Time Transfer Receiver for Contributions to Coordinated Universal Time	J. Res. Natl. Inst. Stan.	119	583-601	20141106	2742
M. Palmero, R. Bowler, J.P. Gaebler, D. Leibfried, and J.G. Muga	Fast transport of mixed-species ion chains within a Paul trap	Phys. Rev. A	90	053408-5	20141106	2739
R. P. Erickson, M. R. Vissers, M. Sandberg, S. R. Jefferts, and D. P. Pappas	Frequency Comb Generation in Superconducting Resonators	Phys. Rev. Lett.	113	187002-5	20141031	2762
O. Alem, A.M. Benison, D.S. Barth, S. Knappe, and J. Kitching	Magnetoencephalography of Epilepsy with a Microfabricated Atomic Magnetrode	J. Neurosci.	34	14324-14327	20141022	2736
W. Loh, S. Papp, and S. Diddams	Noise and Dynamics of Stimulated Brillouin Scattering Microresonator Laser Oscillators	Proc. 2014 Photonics Conf. IEEE		528-529	20141016	2750
E. Rouvalis, F.N. Baynes, X. Xie, K. Li, Q. Zhou, F. Quinlan, T.M. Fortier, S.A. Diddams, A.G. Steffan, A.	High-Power and High-Linearity Photodetector Modules for Microwave Photonic	J. Lightwave Technol.	32	3810-3816	20141015	2726

Dissemination of Results: Publications

Downloads of PDFs from Division public database

Calendar Year	Number of Publications Posted	Number of PDF downloads
2008	2,369	955,648
2010	2,472	2,325,012
2012	2,603	2,574,838

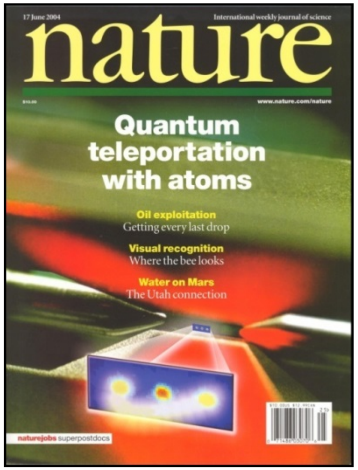
NIST discontinued its web statistics program after 2012, so no more recent data…

Dissemination of Results: Publications

From 2010 through 2014:

- 289 publications.
    - Average of ~58 per year.

- Average of 24% are in “highest impact” journals:
    - Science, Nature family, Physical Review Letters, Optics Express, Optics Letters, Applied Physics Letters.



Dissemination of Results: Patents (Granted or Applications)

Frequency comb technologies:

Broadband ultrashort pulse measuring device using non-linear electronics.

Comb-generating optical cavity that includes an optical amplifier and optical modulator.

Microresonator frequency combs:

Laser machining and mechanical control of optical resonators.

Frequency synthesis with frequency combs:

Direct optical frequency synthesis and phase stabilization of ultrashort optical pulses.

Agile electronic frequency synthesis based on the detection of optical pulses and direct digital tuning.

Ultralow phase noise:

Reduction of oscillator PM noise from AM-PM noise correlation.

High Spectral Purity Microwave Oscillator Using Air-Dielectric Cavity.

Chip-scale atomic devices:

Miniature frequency standard based on all-optical excitation and a micromachined containment vessel.

Method of minimizing the short-term frequency instability of laser-pumped atomic clocks.

Integrated microchip incorporating atomic magnetometers and microfluidic channels for detection of NMR and MRI.

Compact atomic magnetometer and gyroscope based on a diverging laser beam.

Atomic magnetometer and method of sensing magnetic fields.

A remote sensor head for chip-scale atomic devices.

Network time services:

Time-Stamp Service for the National Information Network.

Dissemination of Results: Training

Formal training provided by Division experts:

- Annual Time and Frequency Metrology Seminar (40th annual seminar in 2015).
    - 4 day intensive training with lectures, labs, discussions.
    - ~50 participants from industry, universities, other agencies.

- ATIS-T1X1 Synchronization Workshop.
    - ~200 participants primarily from industry.

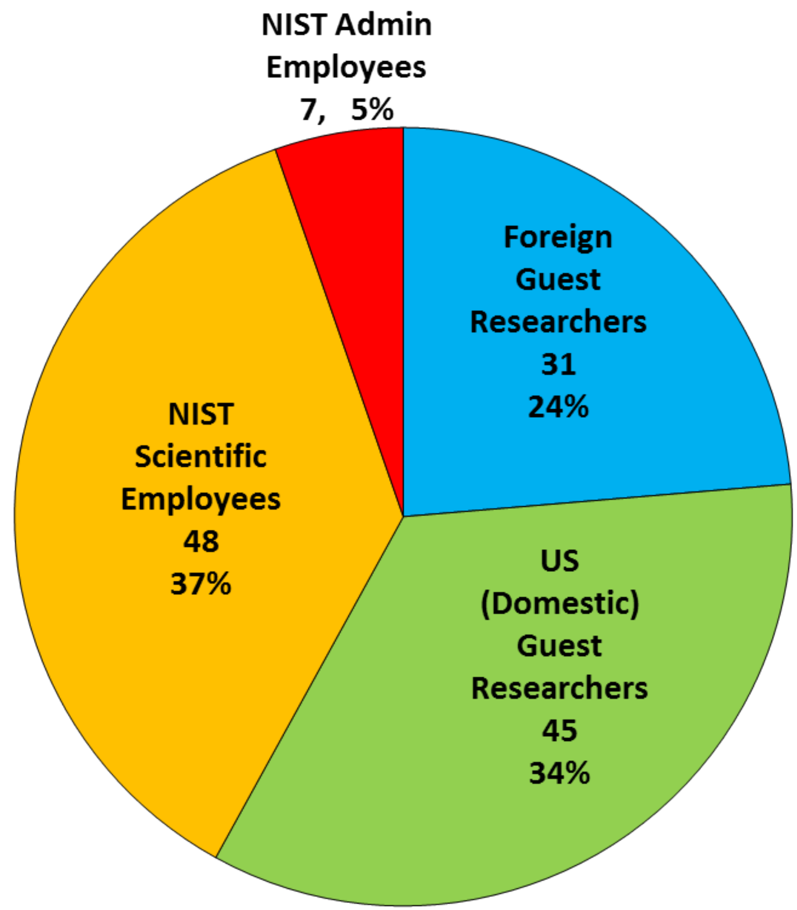
- Tutorials and Short Courses at conferences.
    - Broad variations in participants depending on course, conference, etc.
        - Handful of participants to dozens.
        - Companies, universities, other agencies, metrology labs, etc.

Dissemination of Results: Training

"On-the-job" training provided by Division:

At any given time (typical numbers):

- ~30 postdocs.
- ~10 grad students.
- ~20 senior scientist visitors.



Exchange of highly trained people is arguably the most effective form of tech transfer.

Dissemination of Results: Innovation

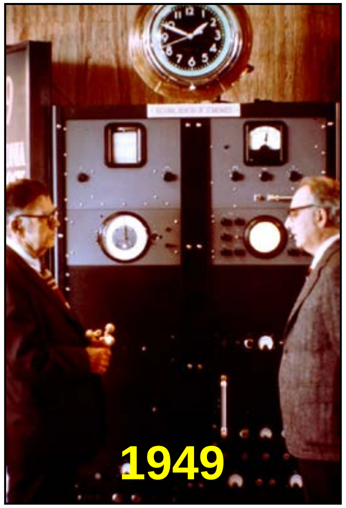
Time and Frequency research is an innovation engine.

A less formal dissemination mechanism, and difficult to measure.

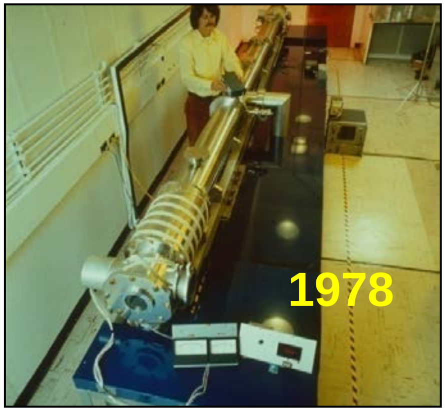
Enormous impacts.

Time & Frequency Research = Innovation Engine

- Atomic clock invented by NIST (NBS) in 1949.
- Factor of 10^8 improvement over six decades, rate of improvement accelerating in last decade.

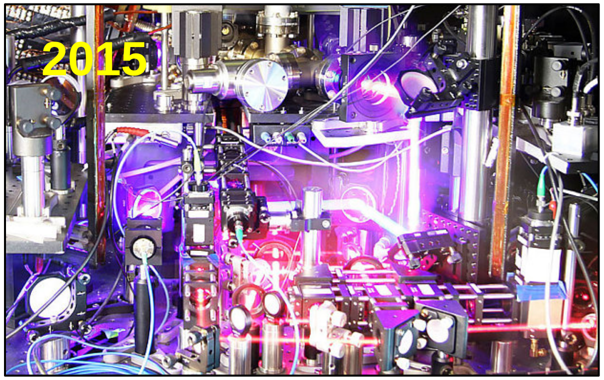


Ammonia clock



NBS-6

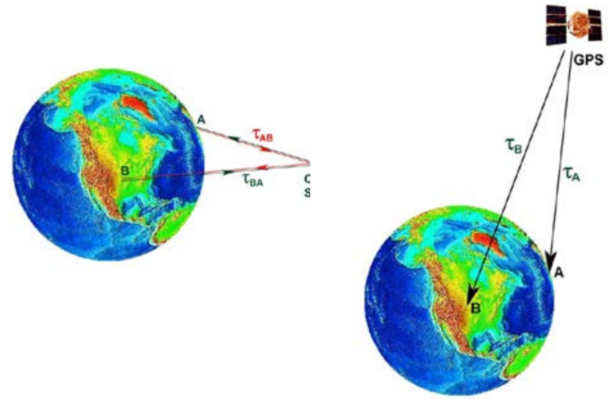
NIST-F1



Sr optical lattice clock

Time & Frequency Research = Innovation Engine

- **Invention of satellite-based time and frequency transfer.**
  - International time coordination.
  - GPS.
  - Etc.



- **Invention of laser cooling.**
  - Broad range of NIST metrology and research directly dependent on laser cooling.

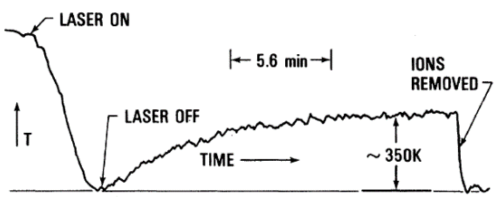
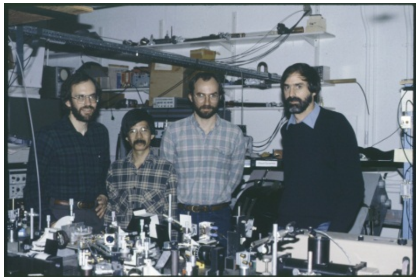
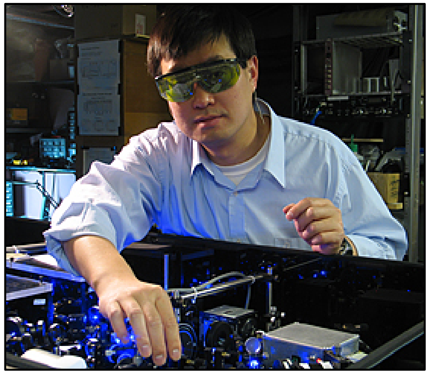


FIG. 2. Ion temperature vs time when laser cooling is applied for fixed $\nu_L - \nu_0$. The ions were initially heated above equilibrium temperature with the laser.

1978

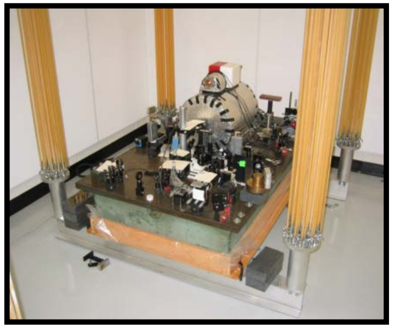


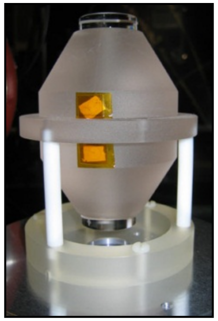
- **Pioneering optical atomic clocks**.
  - 1,000 times better than today's best atomic clocks.



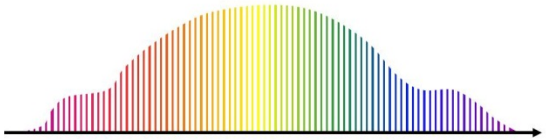
Time & Frequency Research = Innovation Engine

- **Ultrastable laser = ultraprecise measurements and new technologies.**

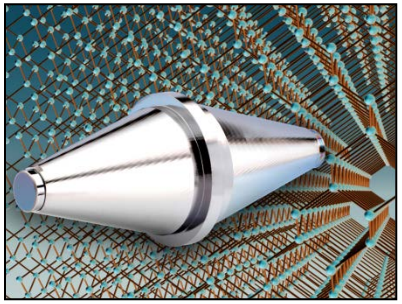


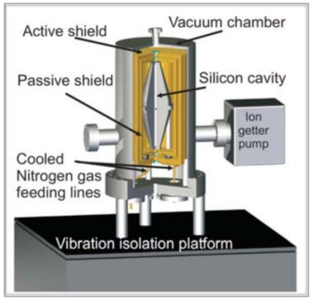


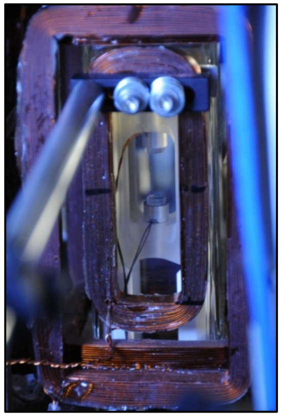
- World's most stable laser cavities (several generations).



- Laser frequency combs.
- Radical new laser cavity technology.
- World's first "cavity-free" laser (super-radiant laser).



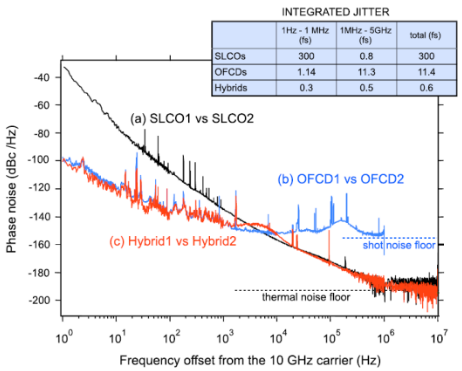




- Potential for improvement by 1,000x in laser stability and coherence.

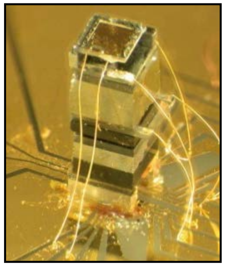
Time & Frequency Research = Innovation Engine

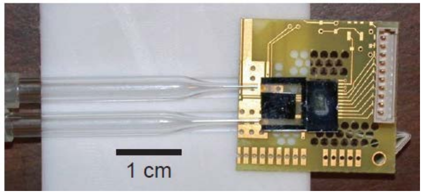
- **Phase noise:** New metrology to improve performance, enable new technologies.



	1Hz - 1 MHz (fs)	1MHz - 5GHz (fs)	total (fs)
SLCOs	300	0.8	300
OFCDs	1.14	11.3	11.4
Hybrids	0.3	0.5	0.6

- **Chip-scale atomic devices:** Greatest impact likely to be not timing but much broader metrology and applications.

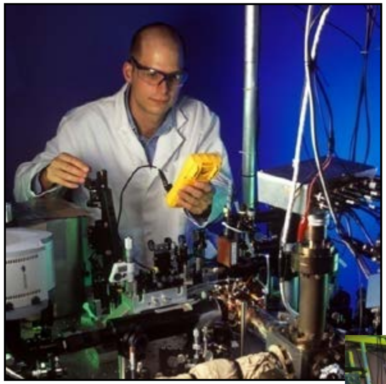




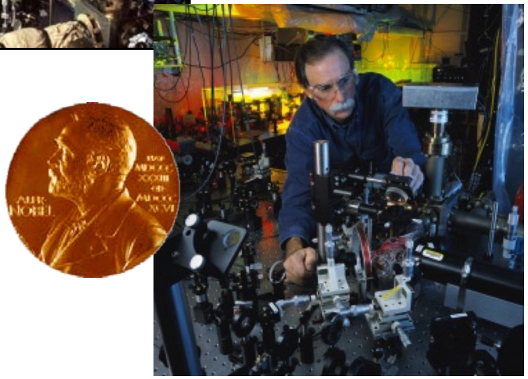
Time & Frequency Research = Innovation Engine

- **NIST on a Chip.**
  - Time, magnetic fields, electrical quantities, temperature, motion, force, etc. etc.
  - Small, low-cost, robust systems.
  - Revolution in delivery and impact of precision measurements.

- **Ultraprecise sensors based on optical atomic clocks.**
  - Gravity, magnetic field, motion, etc. etc.
  - Surpassing today's best measurement technologies.



- **Quantum information and new quantum-based measurements.**



Assessment of the NIST Time and Frequency Division

4. Dissemination of outputs.
    - How effectively does the organization disseminate/transfer its outputs?

- Remote broadcast services.
    - Best in the world, most heavily used of all NIST measurement services.
    - Unique high performance services to industry users.
- Phase noise metrology.
    - Best in the world new ultralow noise measurement capabilities.
- Unique real-time SIM international time scale.
    - Setting standard for future of UTC.

- Highly effective publication program, including heavily used public access.

- Use of patents where appropriate.

- Very strong training programs, formal classes and on the job. Exchange of highly trained people is arguably best form of tech transfer.

- Time and Frequency is particularly strong in innovations that become widely disseminated.

Assessment of the NIST Time and Frequency Division

Charge to the NRC Board on Assessment of NIST Programs from the NIST Director through contract with NRC (*paraphrased*):

1. Technical programs.
   - Quality of research compared to rest of world.
   - Are technical programs adequate to achieve stated mission?

2. Scientific expertise.
   - Quality of technical staff compared to rest of world.
   - Is technical staff expertise adequate to achieve stated mission?

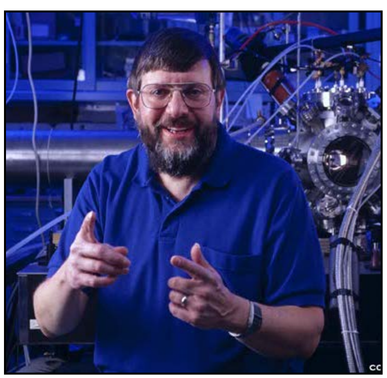
3. Infrastructure.
   - Are quality of facilities, equipment, human resources adequate to achieve stated mission?

4. Dissemination of outputs.
   - How effectively does the organization disseminate/transfer its outputs?

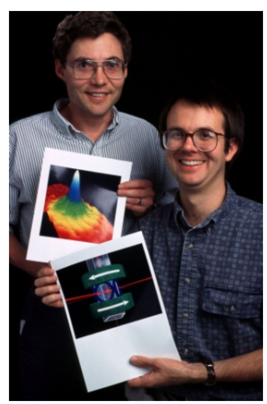
Time and Frequency Research and Metrology is Exciting and High Impact!

Some Nobel Prizes related to 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	**Bill Phillips,** Steven Chu, Claude Cohen-Tannoudji	Laser cooling of neutral atoms.
2001	**Eric Cornell,** Carl Wieman, Wolfgang Ketterle	Bose-Einstein condensate.
2005	**Jan Hall,** Ted Hansch, Roy Glauber	Femtosecond laser frequency combs.
2012	**Dave Wineland,** Serge Haroche	Quantum state measurement and manipulation.

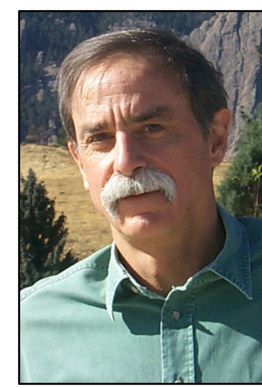


Bill Phillips
NIST



Carl Wieman
Eric Cornell
NIST/JILA

Jan Hall
NIST/JILA



Dave Wineland
NIST

Questions?

Comments?

Discussion?