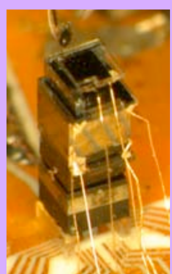
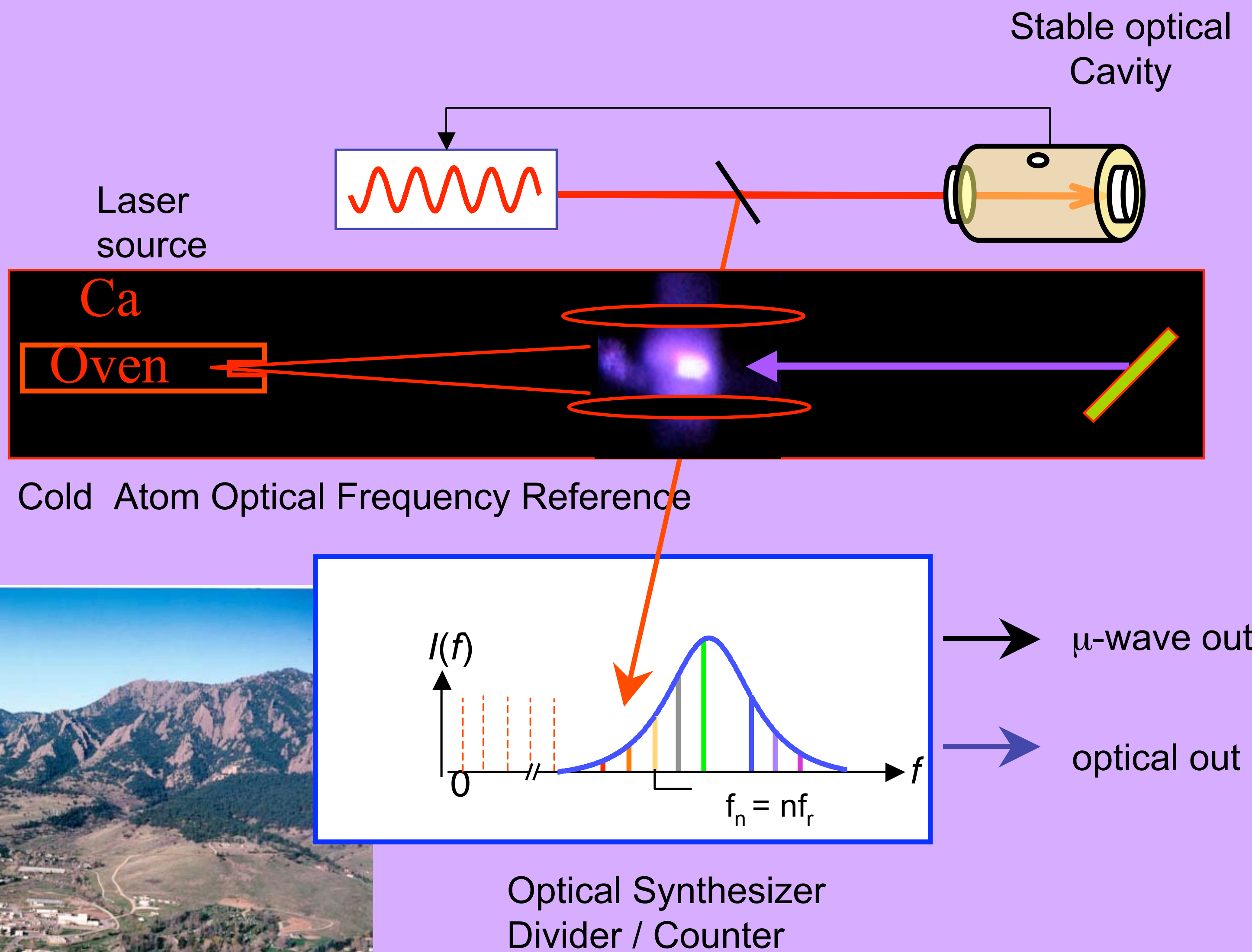
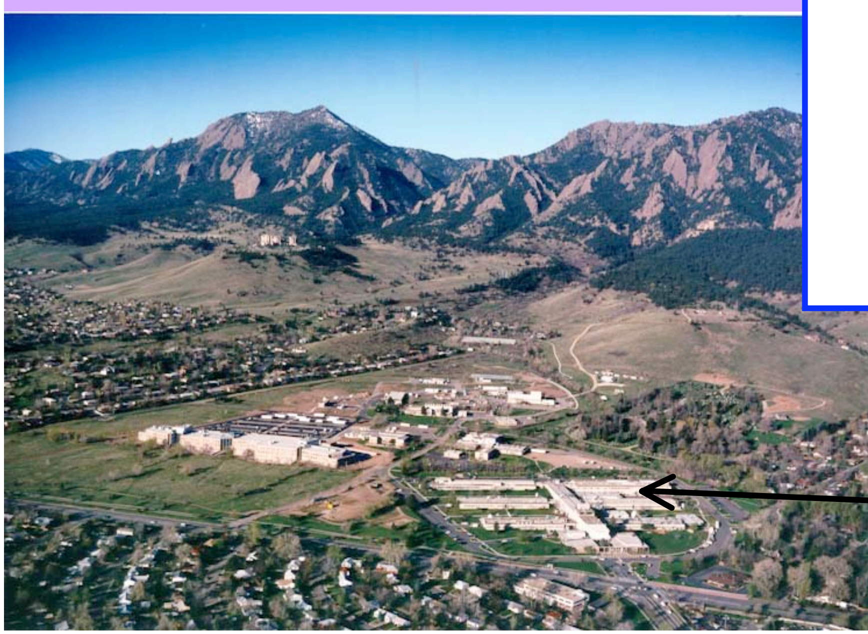
Atomic Clocks & Magnetometers for Navigation and Metrology

Leo Hollberg

CSAC







Time & Frequency Division

NIST

Optical Frequency Measurements Group
NIST, Boulder

http://tf.nist.gov/ofm/

Optical Clocks

Chris Oates

Cold Ca

Yann Le Coq → (SYRTE, Paris)
Jason Stalnaker → (Oberlin)
Guido Wilpers (Germany/NPL-UK)
Anne Curtis (CU → NPL-UK)
Kristin Beck (Rochester, SURF)

Cold Yb

Chad Hoyt (→ Bethel College)
Zeb Barber (CU)
Valeriey Yudin (Russia)
Aleksei Taichanachev (Russia)
Nathan Lemke (CU)
Nicola Poli (LENS, Italy)

Chip Scale Atomic Devices clocks, magnetometers …

John Kitching

Svenja Knappe (Germany)
Peter Schwindt (Sandia)
Vishal Shah → (Princeton)
Vladi Gerginov (Bulgaria, N.D....PTB)
Ying-Ju Wang (Taiwan)
Clark Griffith
Andy Geraci
Hugh Robinson
Liz Donley
Eleanor Hodby (England)
Alan Brannon (CU) → industry
Matt Eardley (CU)
Ricardo Jimenez (CU, Mexico)
Susan Schima
Lucas Willis (LSU, SURF)
Nicolas VanMeter (SURF)
Tara Cubel-Liebisch

fs Frequency Combs

Scott Diddams

Tara Fortier (LANL)
Jason Stalnaker → (Oberlin)
Qudsia Quraishi (CU)
Stephanie Meyer (CU)
Albrecht Bartels → (Konstance)
L-S Ma, Z. Bi, (ECNU-BIPM)
Y. Kobayashi (AIST Japan)
Vela Mbele (South Africa)
Matt Kirchner (CU)
Andy Weiner* (Purdue)
Danielle Braje
Vladi Gerginov (Bulgaria, N.D....PTB)

Optical Length Metrology

Richard Fox

& many others at NIST and JILA

Carol Tanner (Notre Dame)

•$$ NIST, DARPA-MTO, ONR-CU-MURI, NASA, LANL

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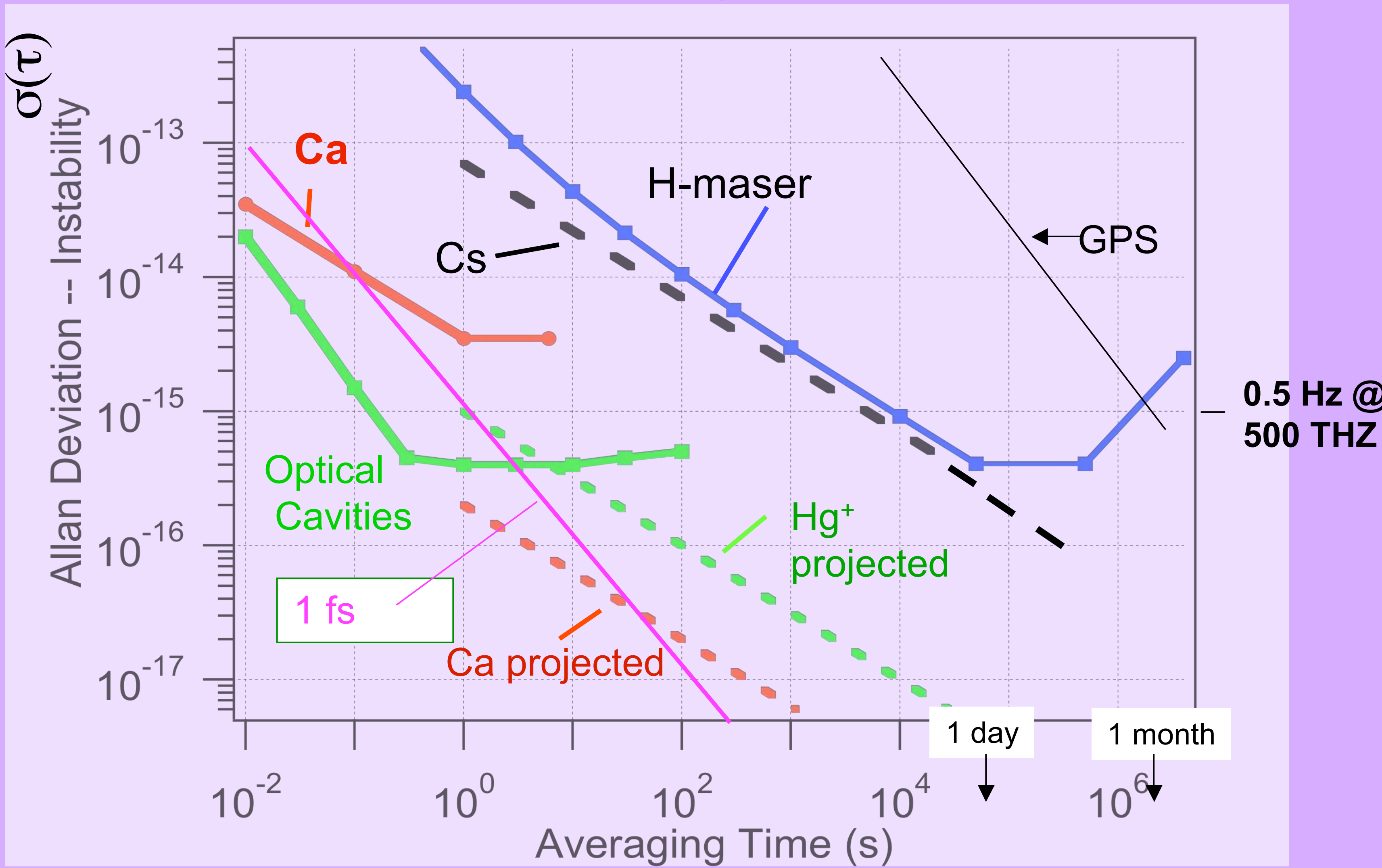
Oscillator Stability



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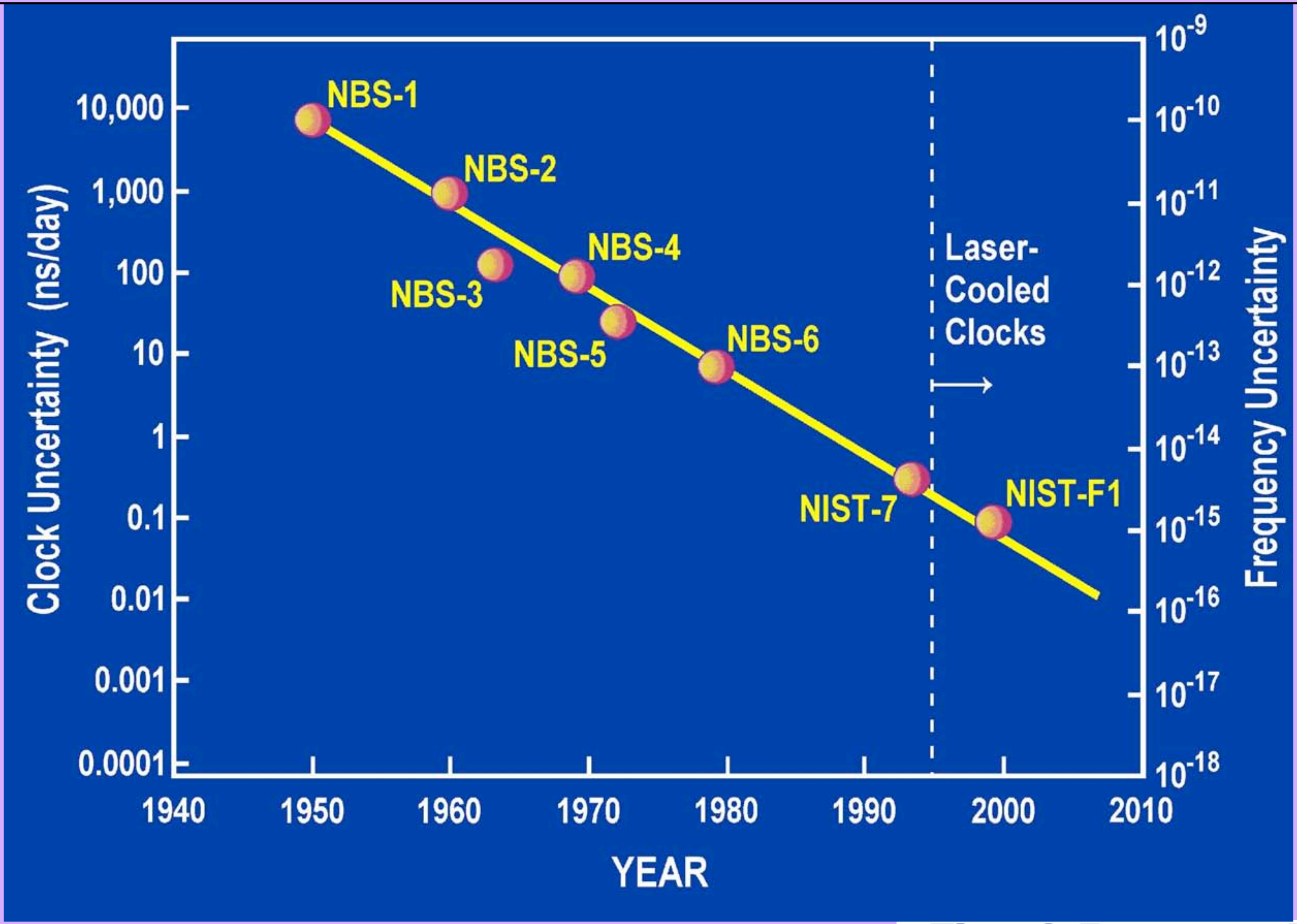
Highest Accuracy Atomic Clocks



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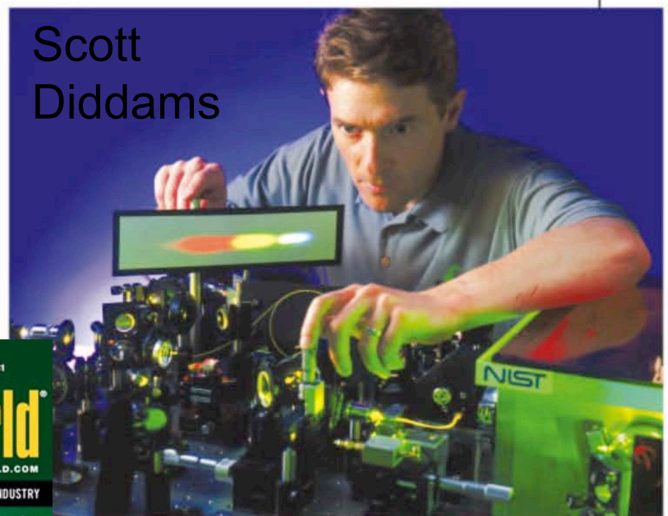
Enthusiasm for Optical Atomic Clocks and fs Combs


news feature

The times, they are a-changin'

More accurate timepieces could lead to better global positioning systems, insights into fundamental physics and a redefinition of the second. David Adam rates the runners in the race to build tomorrow's atomic clocks.

It's perhaps not the ultimate race against time, but rather the race to keep ultimate time. In a handful of labs around the world, physicists are developing a new generation of clocks so accurate that they should lose just one second in 100 billion years. By taking the pulse of laser light synchronized to the beating of atoms or ions, the researchers are confident that they can create clocks up to 1,000 times more accurate than today's best timepieces.

Such precision won't make much difference in the everyday world — trains will still run late and eggs will still take around four minutes to boil. But with the proposed optical clocks, studies of fundamental physical constants could become much more powerful. Global positioning systems (GPS) should also see a boost in precision, allowing them to pin

Scott Diddams

...ner: Scott Diddams' prototype mercury clock was the first timepiece to use optical wavelengths.

...clock with a pendulum that swings ...second is more accurate than a sundial, ...repeats its cycle over 24 hours, so ...that can count transitions driven by ...her frequencies of optical radiation ...tentially much more accurate than ...wave systems. In theory, an optical ...could measure a second down to a ...ing 18 decimal places.

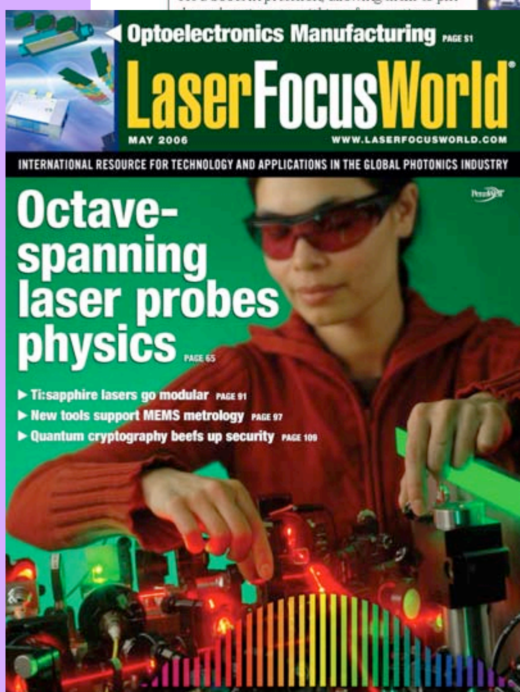
...current undisputed leaders in this ...re Scott Diddams and his colleagues ...National Institute of Standards and ...ology (NIST) in Boulder, Colorado. In

...theory, an optical ...ock could measure ...econd down to ...lecimal places.

August 2001, they demonstrated a prototype optical clock for the first time (S. A. Diddams *et al. Science* **293**, 825–828; 2001). Diddams' clock harnesses the 10^{15} oscillations per second made by a laser that is exciting a single mercury ion. The way in which the ion absorbs the laser light is monitored, and the laser is adjusted so that it resonates with the ion's movements between energy levels. The researchers are currently trying to establish how accurate the clock is. "There's still a long road ahead to make real devices that can function day-in and day-out," says Diddams.

To improve matters, the NIST team is studying the factors that control the accuracy and stability of their clock. These are two separate issues — accuracy defines how closely a clock's output matches the desired time interval, whereas stability is a measure of how steady that output is. A clock that loses precisely a second each day is inaccurate but stable, for example.

Tara Fortier



Nobel Prize 2005

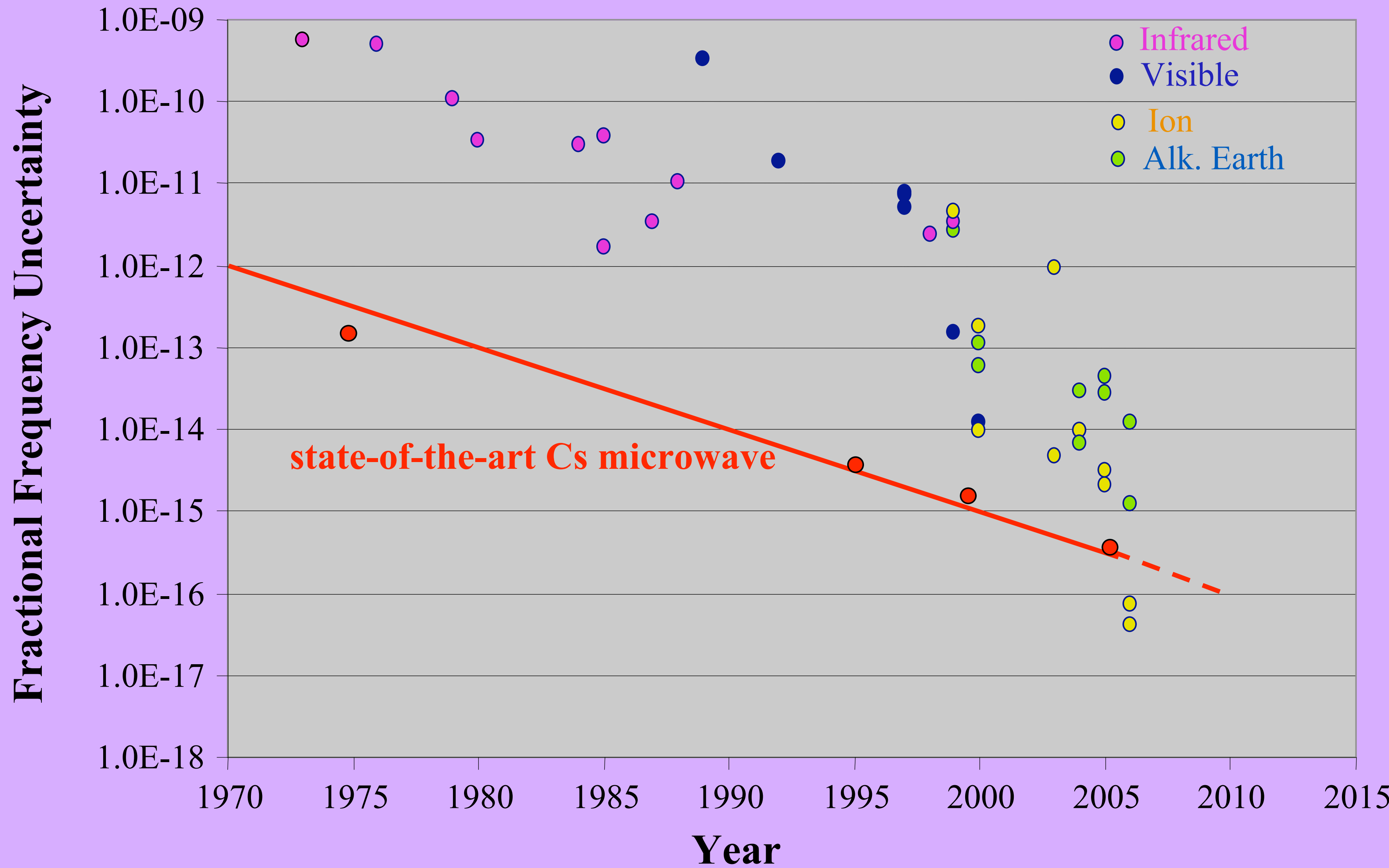
Jan Hall

Ted Hänsch

...ency Division

NIST

Accuracy of Atomic Frequency Standards - History



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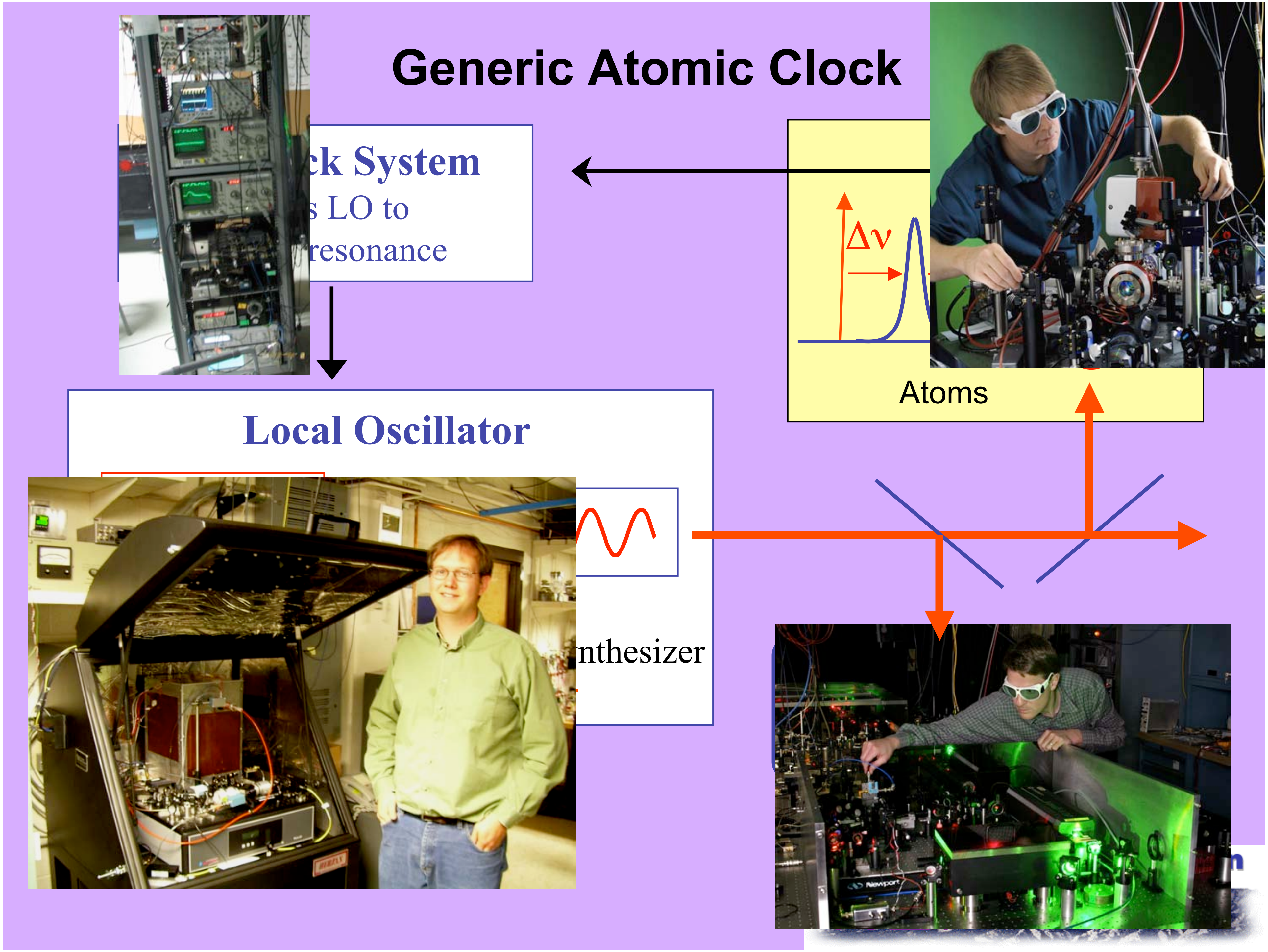
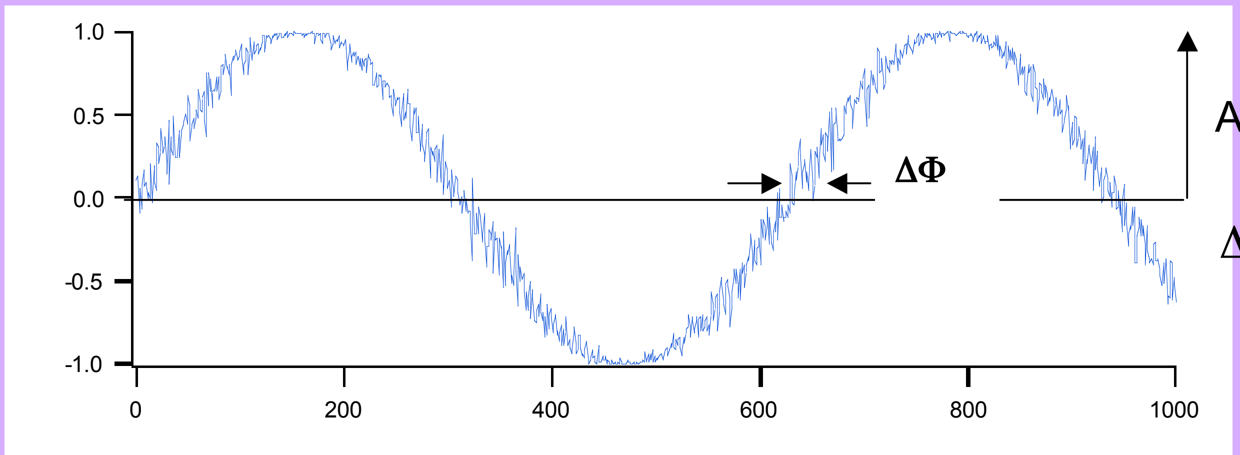
Generic Atomic Clock



Phase Noise on Oscillating Signals



Timing precision

$dS/dt \sim Af_0$ / noise

$\Delta\tau/\tau = \Delta\Phi/\Phi = \Delta\Phi/2\pi n = \Delta f/f_0$

Optical

- Shot-noise I = sqrt(2eIBW), technical AM noise
- ~ fs timing, (10^{-15} at 1s) ,… (with several caveats)

Electronics

- Thermal noise sqrt(4kTRBW), electronic phase-noise
- Timing precision in electronics is limited to ~ ps gate delay dispersion

Note! difference between residual fluctuations and absolute fluctuations, jitter with regard to same source vs. two independent sources.

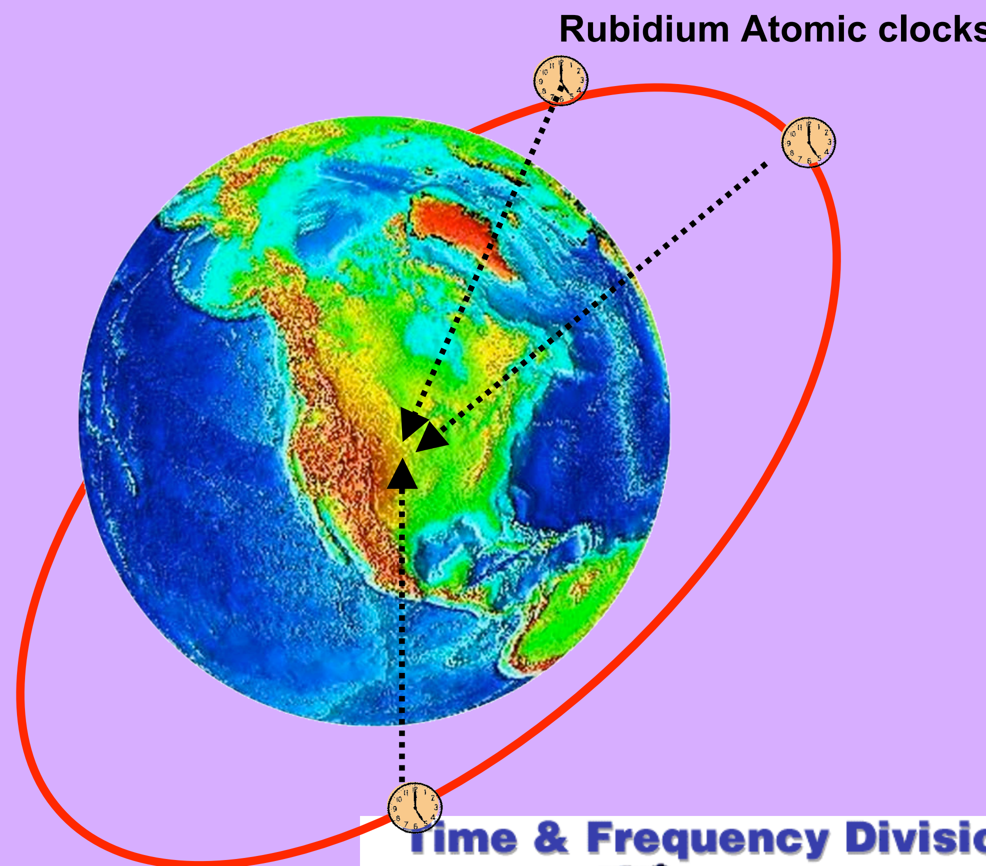
What is the most significant achievement resulting from Atomic Clocks ?

Clocks in Space !

GPS (Global Positioning System)

Array of 24 orbiting GPS satellites

≈ 4 Rb atomic clocks per satellite



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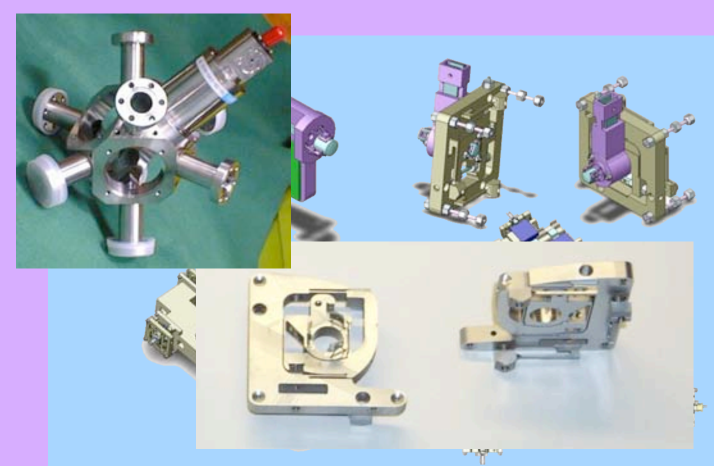
Myopic history of cold atom clocks for space

- ≈ 1989 several months at ENS-Paris & already found there discussions, proposal for cold Cs clock in space
- 19 years later, ACES-PHARAO a reality (but still on the ground)

- NASA microgravity program: 1997, PARCS, RACE
  - NIST-JPL … PARCS hardware built/tested,
  - SCR, PDR, RDR reviews….
  - uncert. ≈ 1×10^{-16}

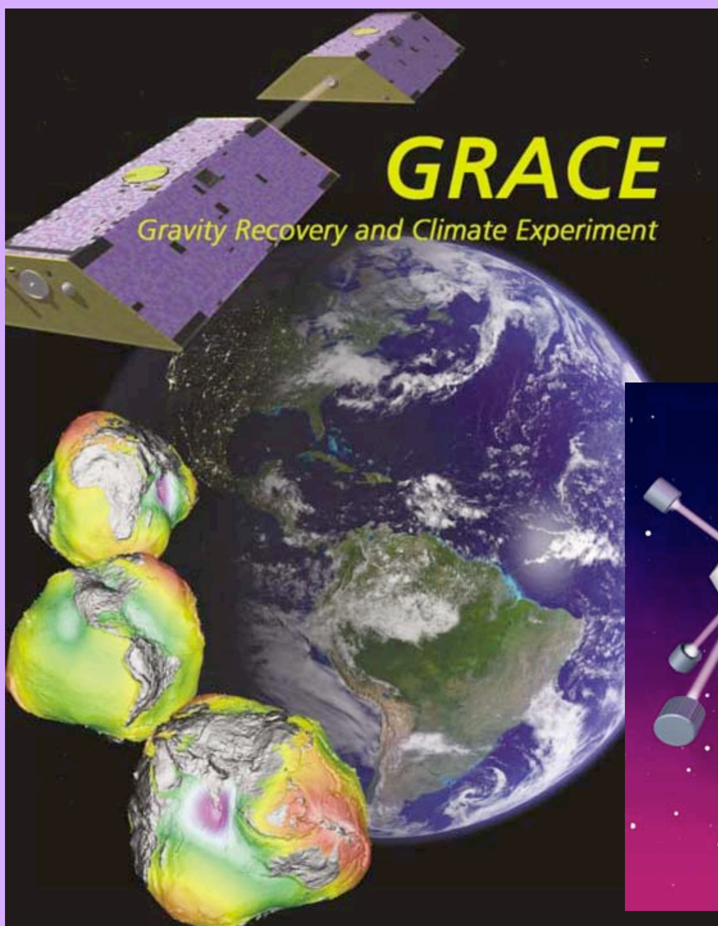
Optical Atomic Clocks – Prospects

- Improved stability and accuracy
- Increased complexity
- Optical and microwave connections
- uncert. ≈ 1×10^{-17} feasible?

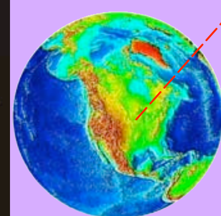


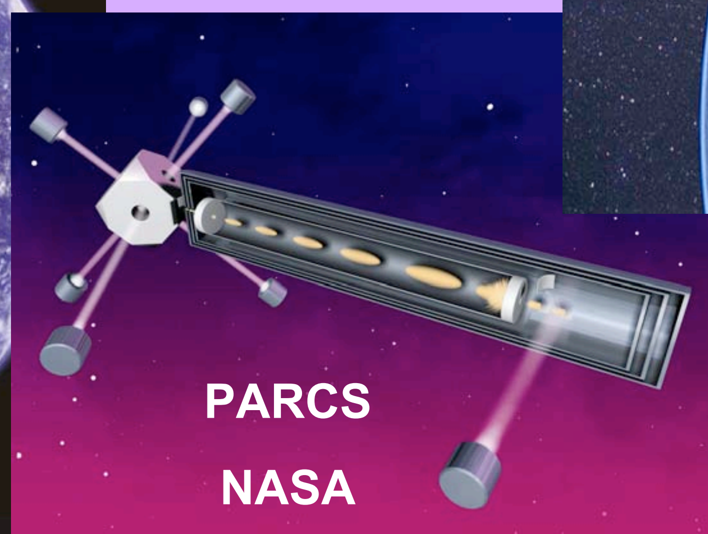
Advanced cold atom clocks or Laser ranging/imaging in/from Space

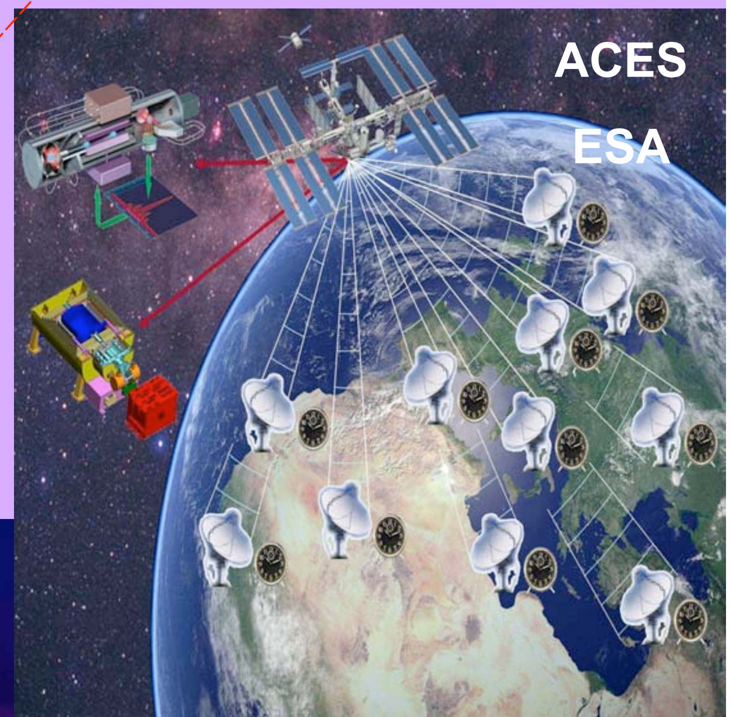
Next generation Grace laser ranging ?



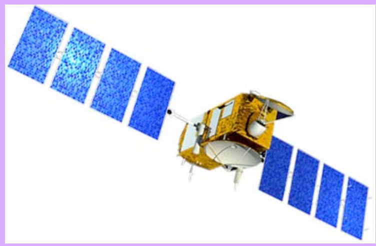
Lunar ranging w/ laser pulses







HYPER, …



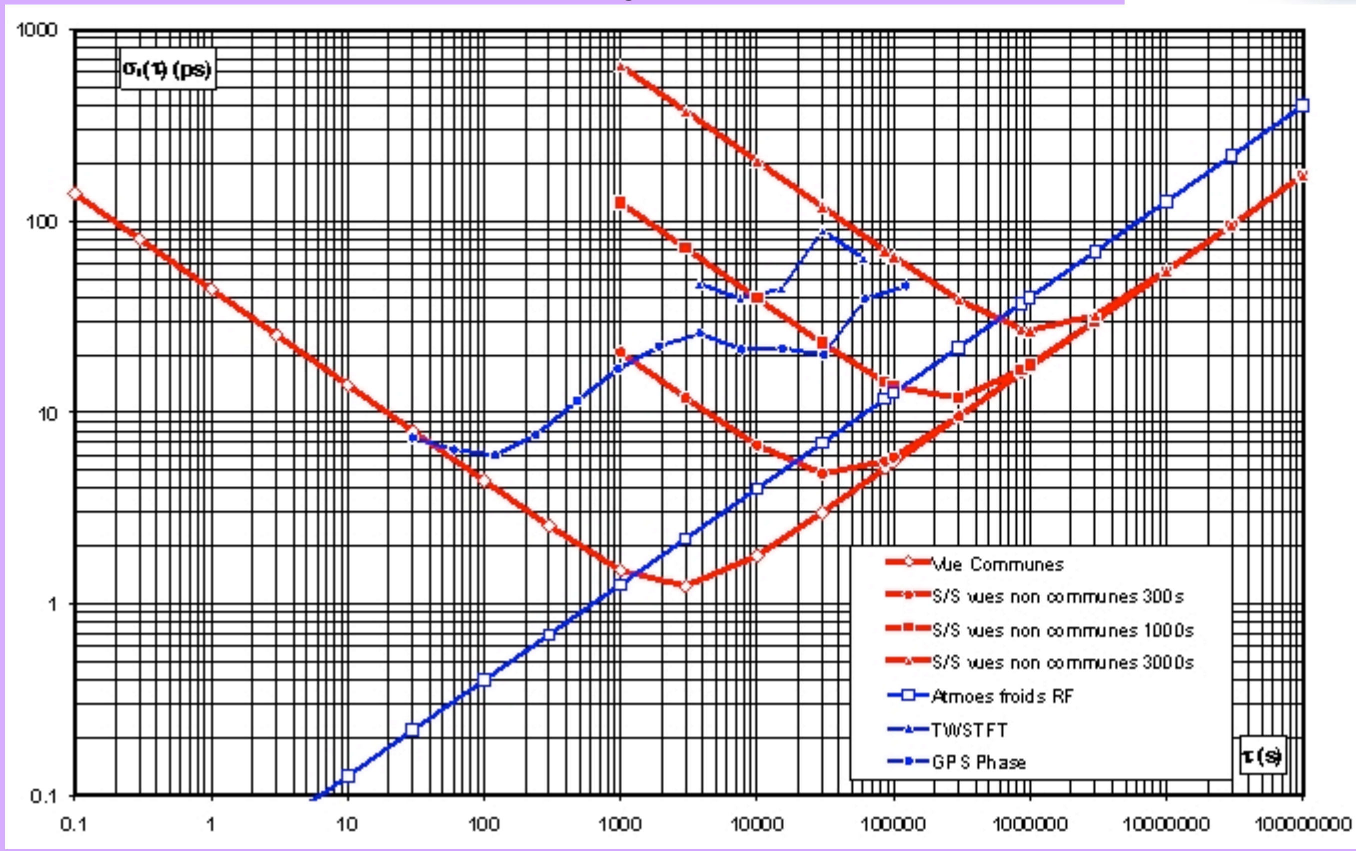
JASON–2

T2L2 (Time Transfer by Laser Link)

CNES

Projections

ps



Averaging time (s)

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Optical Atomic Clocks for Space

Claims

- Exceptionally performance
- Could provide exquisite timing and frequency reference for science missions (tests of relativity, precision probes of space-time, searches for new physics, temporal variation of fundamental constants…)
- Technological advances: improved time transfer, navigation reference, unprecedented imaging from space …

But NOT yet ready for space :

- Would require major investment of people-time and $$ to put optical clocks in space within 10 years
- Critical components missing (lasers and time transfer)
- Complexity, SWAP issues

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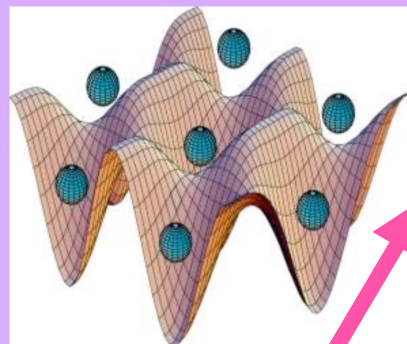
Ytterbium optical atomic clock

- Excellent prospects for high stability and small absolute uncertainty



$^1P_1$ (6s6p)

398.9 nm,
28 MHz

Lattice
759 nm

$^3P_{0,1,2}$ (6s6p)

Energy

$^3P_1$: 555.8 nm,
182 kHz

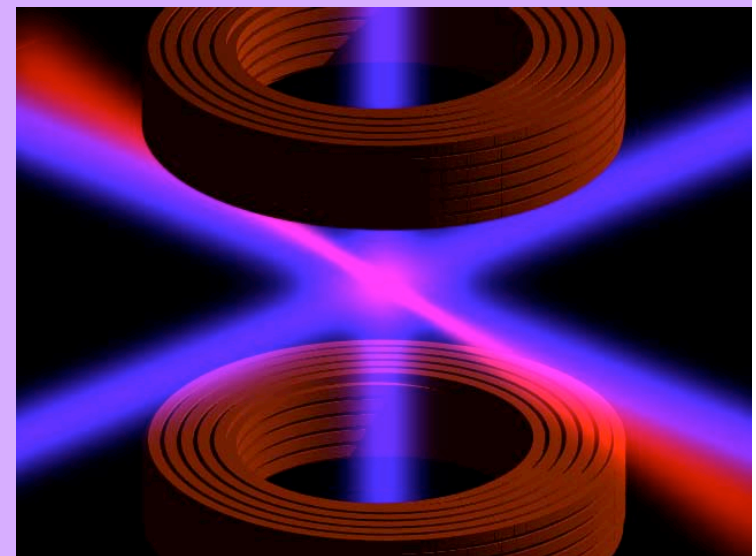
λ = 578 nm

Δv = ~0 ^{174}Yb

15 mHz ^{171}Yb, ^{173}Yb

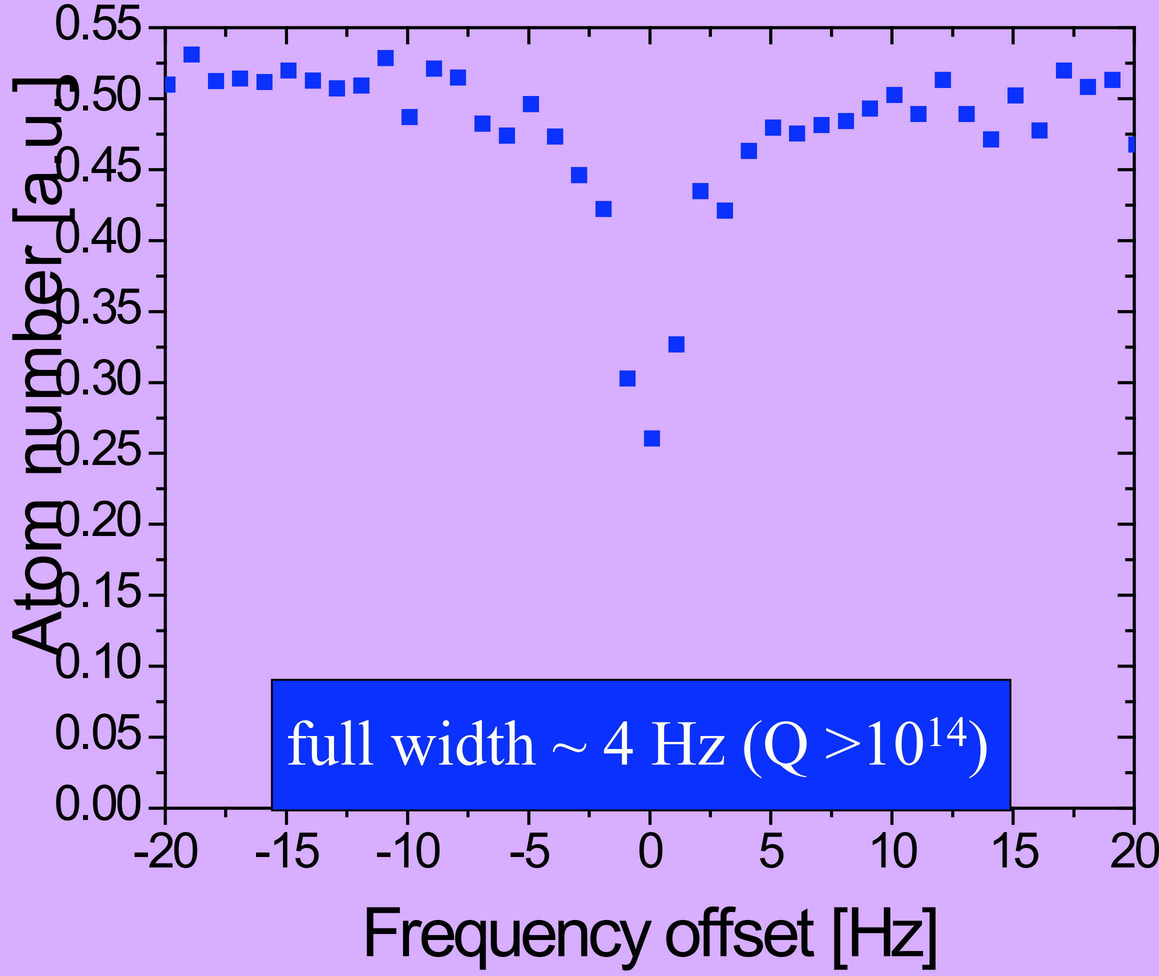
$^1S_0$

(^{171}Yb, ^{173}Yb I=1/2,5/2)



Chad Hoyt
Zeb Barber
Chris Oates
Jason Stalnaker
Nathan Lemke

High resolution specctroscopy with lattice-trapped Yb atoms



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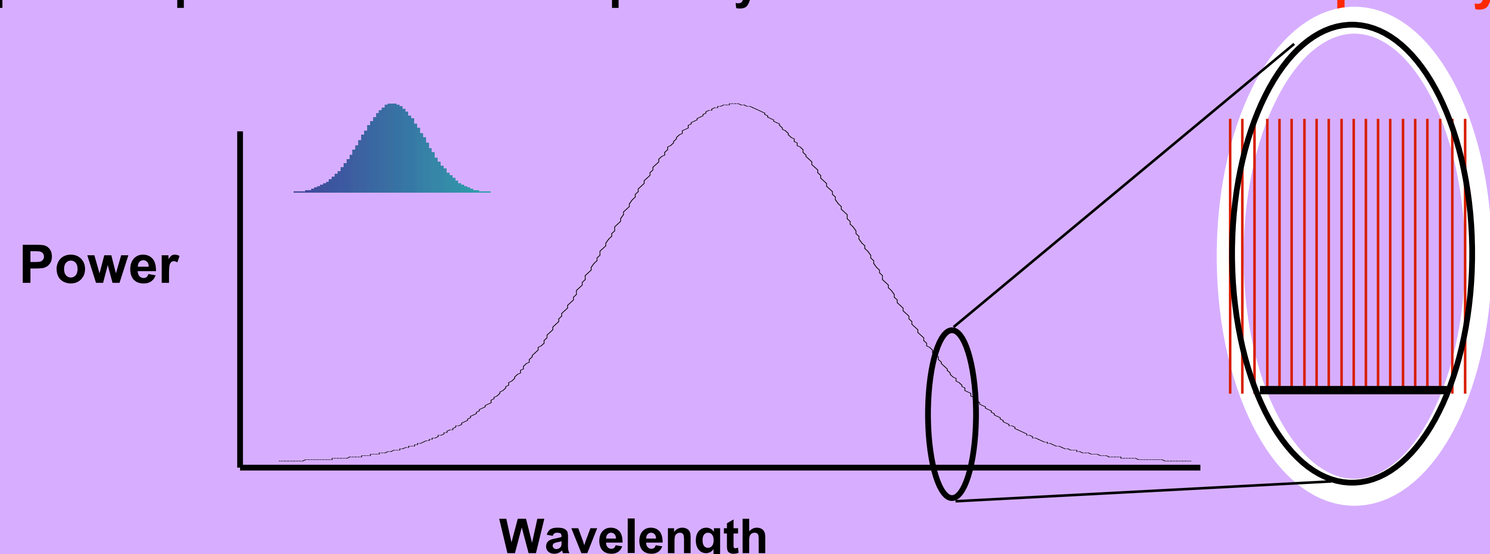
Count Optical Frequencies with Optical Frequency Combs
Ultra-short and repetitive pulses of light

Ultrashort optical pulse, plus nonlinear fiber → **Broad Spectum**

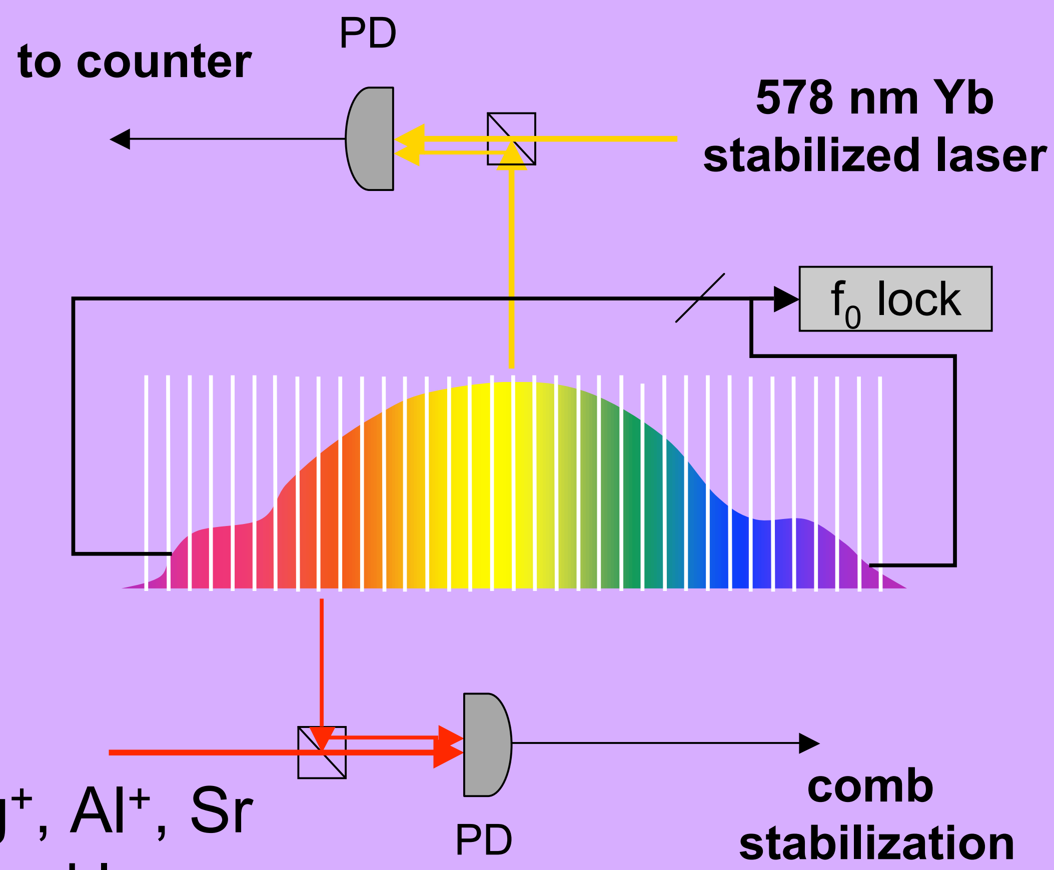
Repetitive pulse train → Frequency Comb → **"ruler for frequency/time"**



•Initial efforts/ideas: J. Eckstein, A. Ferguson & T. Hänsch (1978), V. P. Chebotayev (1988)

Optical clock comparisons via optical frequency combs

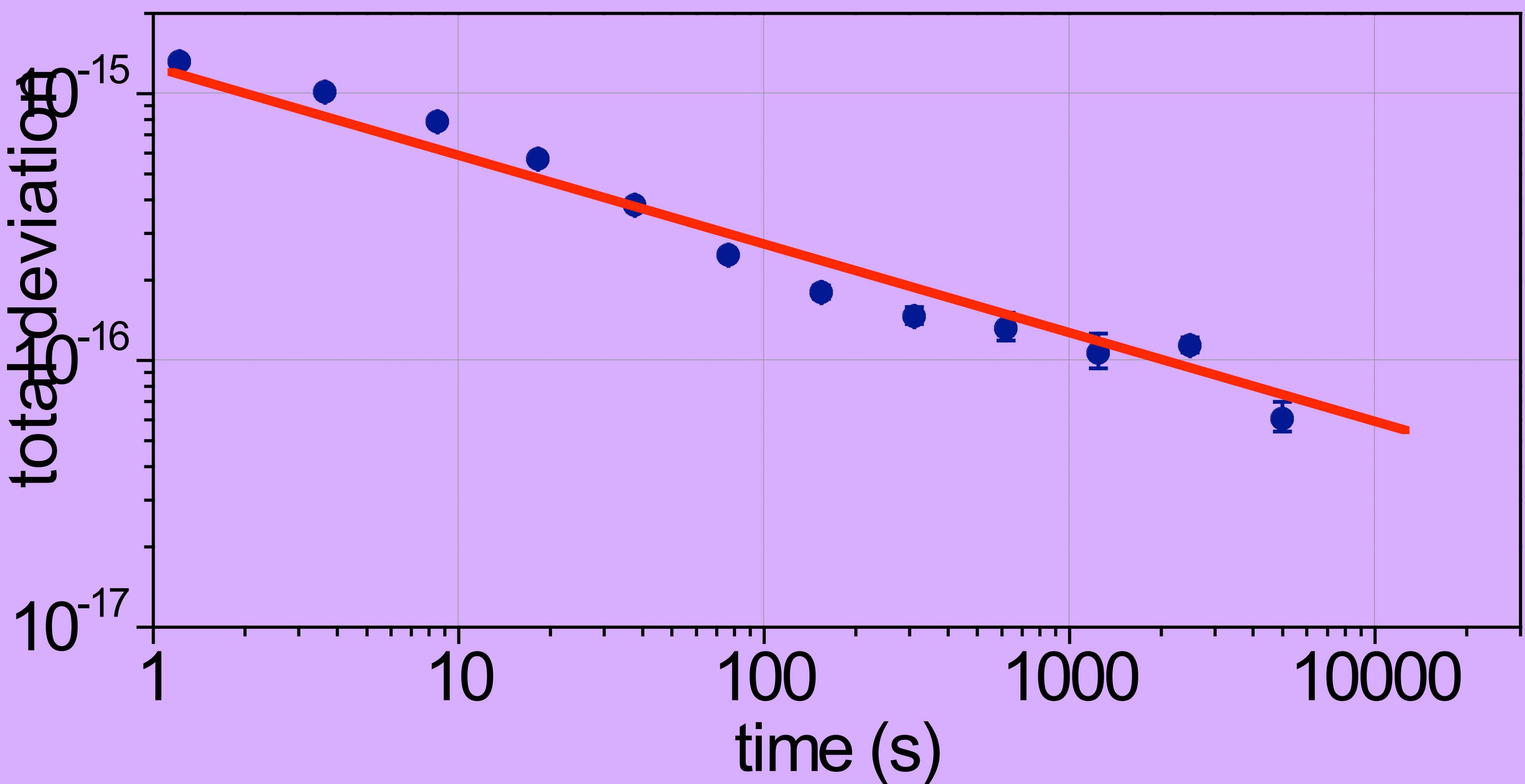
$$f = N \times f_{rep} + f_0$$



Ca, Hg^+, Al^+, Sr
stabilized laser

T. Fortier
S. Diddams …

Instability: Sr v. Yb



Sr at JILA, Ludlow, Ye et al.
vs. Yb at NIST via 3 km optical fiber

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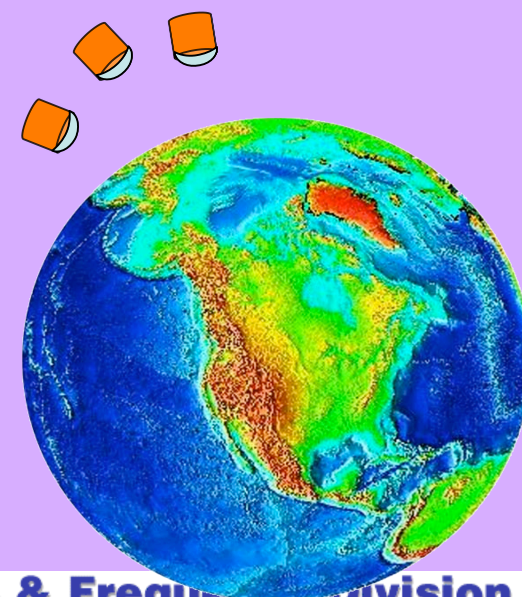
Applications of Optical Frequency References and Combs

- Advanced communication systems (security, autonomous synchronization)
- Advanced Navigation (position determination and control)
- Precise timing (moving into the fs range)
- Tests of fundamental physics (special and general relativity, time variation of fundamental constants)
- Sensors (strain, gravity, length metrology ……)
- Ultrahigh speed data, multi-channel parallel broadcast, or receivers, coherent communications
- Low noise microwaves, and electronic timing signals
- Scientific applications (precision spectroscopy, chemistry, trace gas detection…)
- Quantum information (Ivan Deutsch …)
- Fourier synthesized arbitrary waveform generation

Phase-coherent imaging from independent satellites



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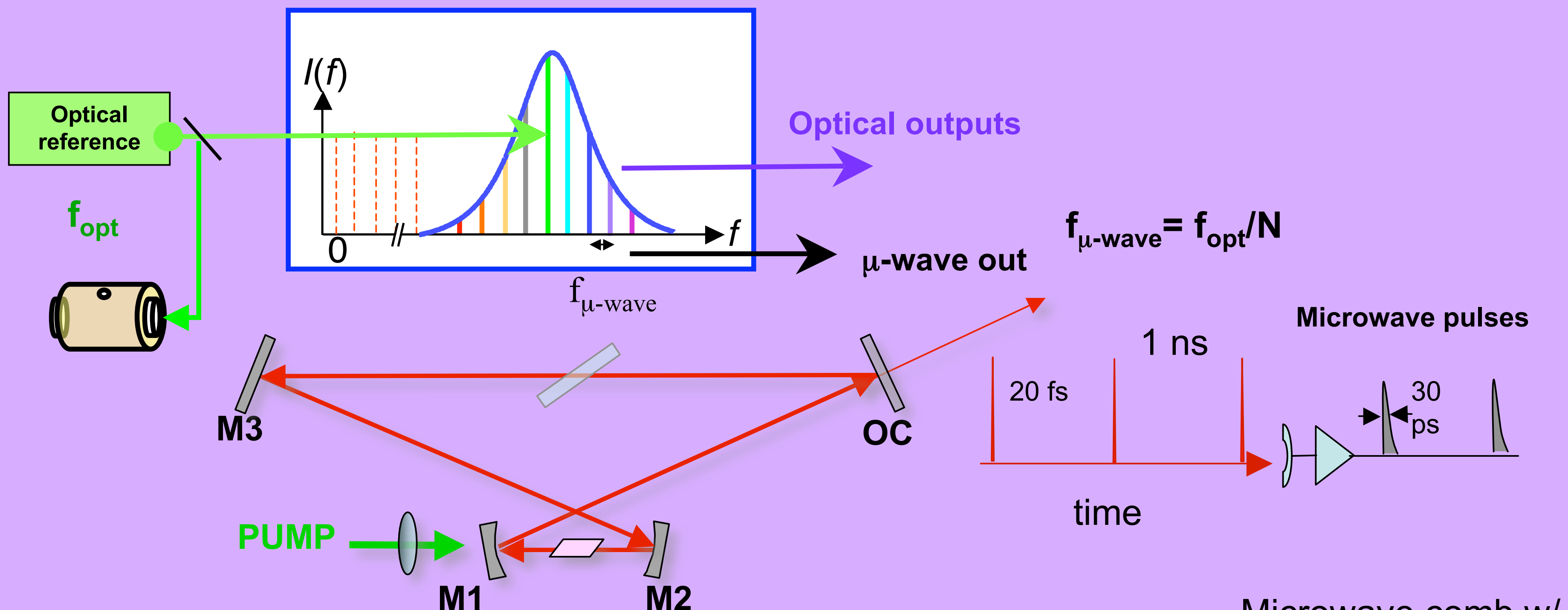
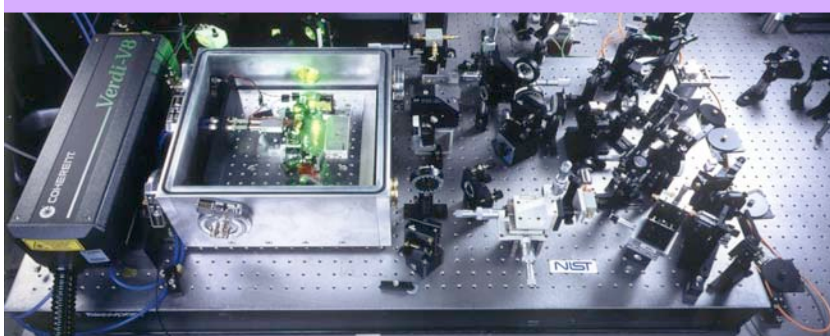
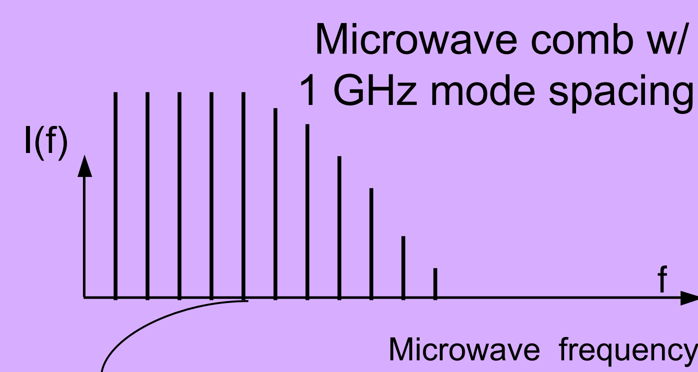
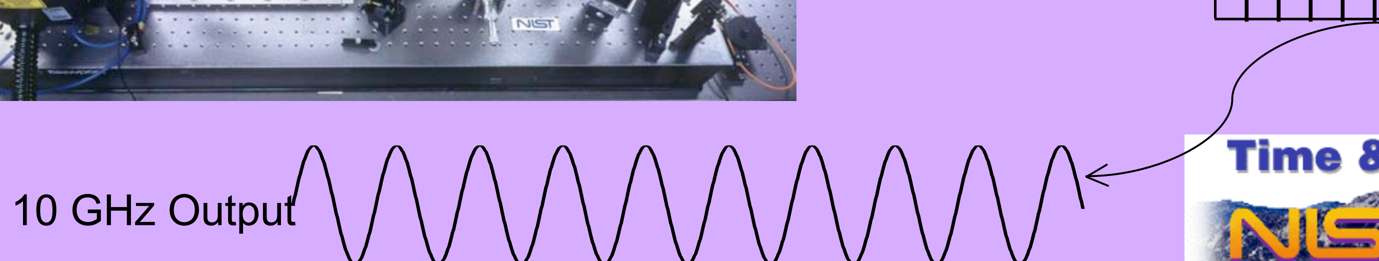
Optical Clock, fs frequency combs as Optical Frequency Divider
Generation of microwaves with low phase noise









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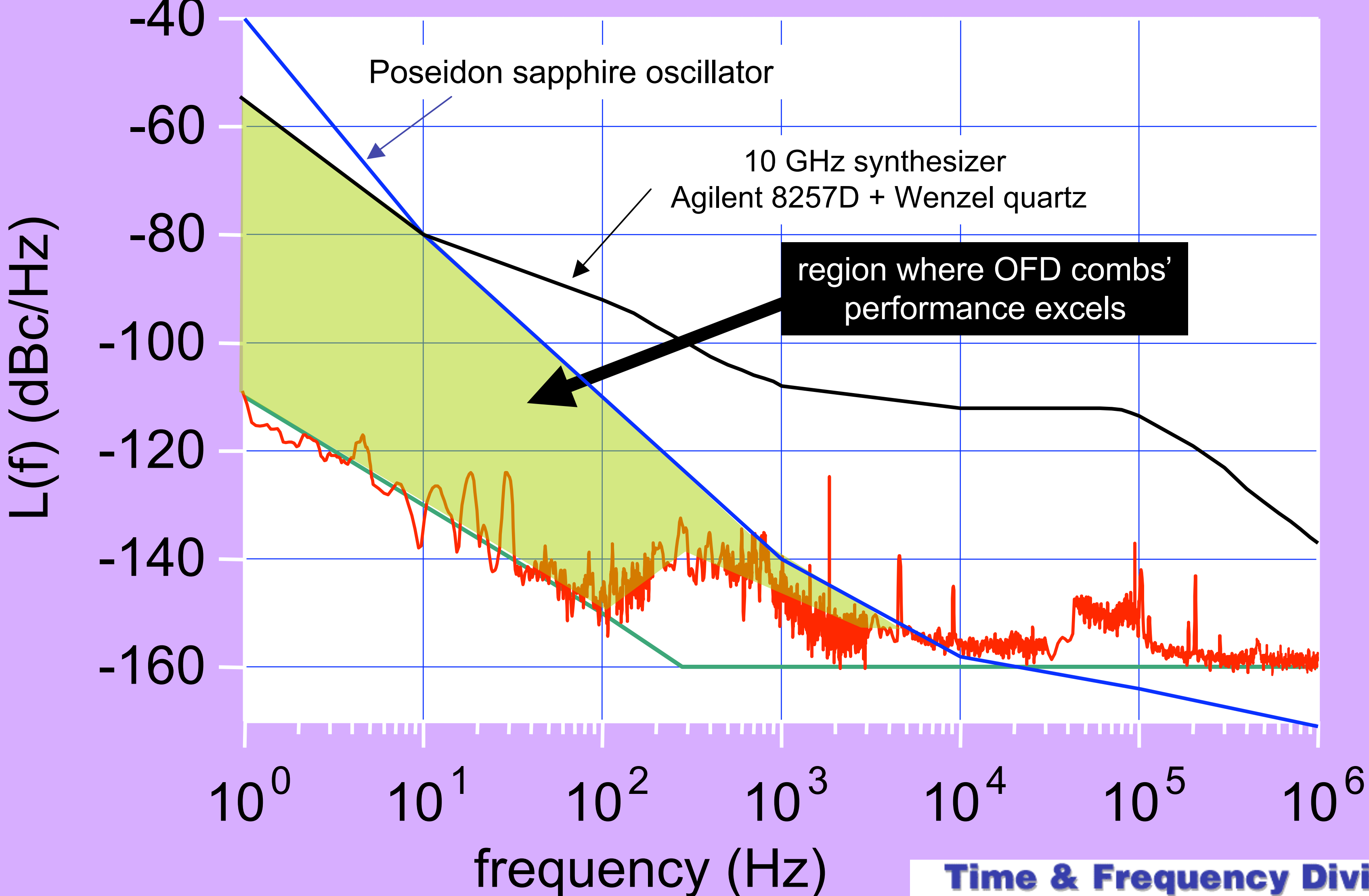
Two Optical Frequency Dividers

Phase noise for 10 GHz output



April 2008

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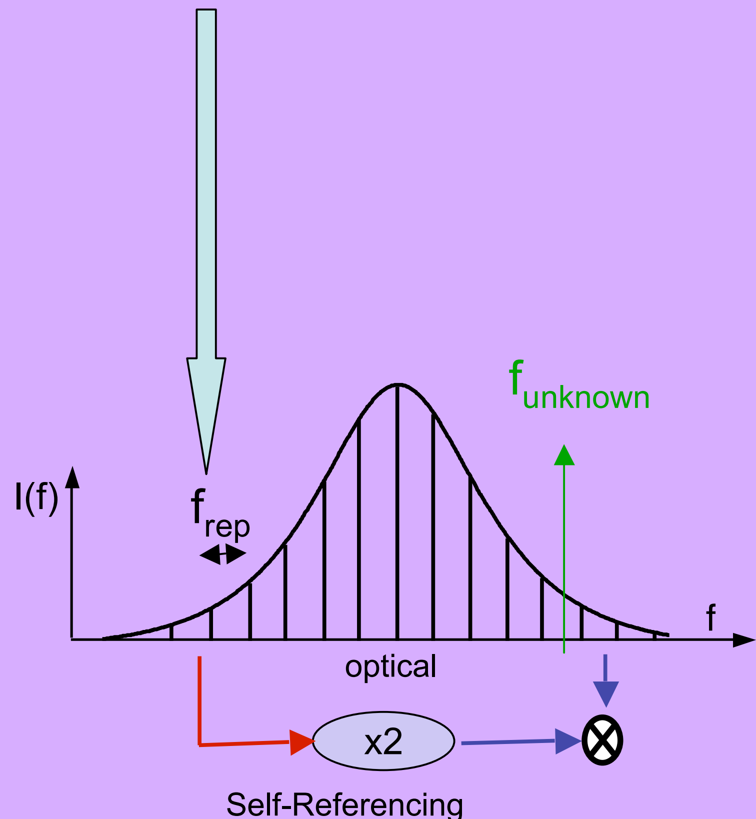
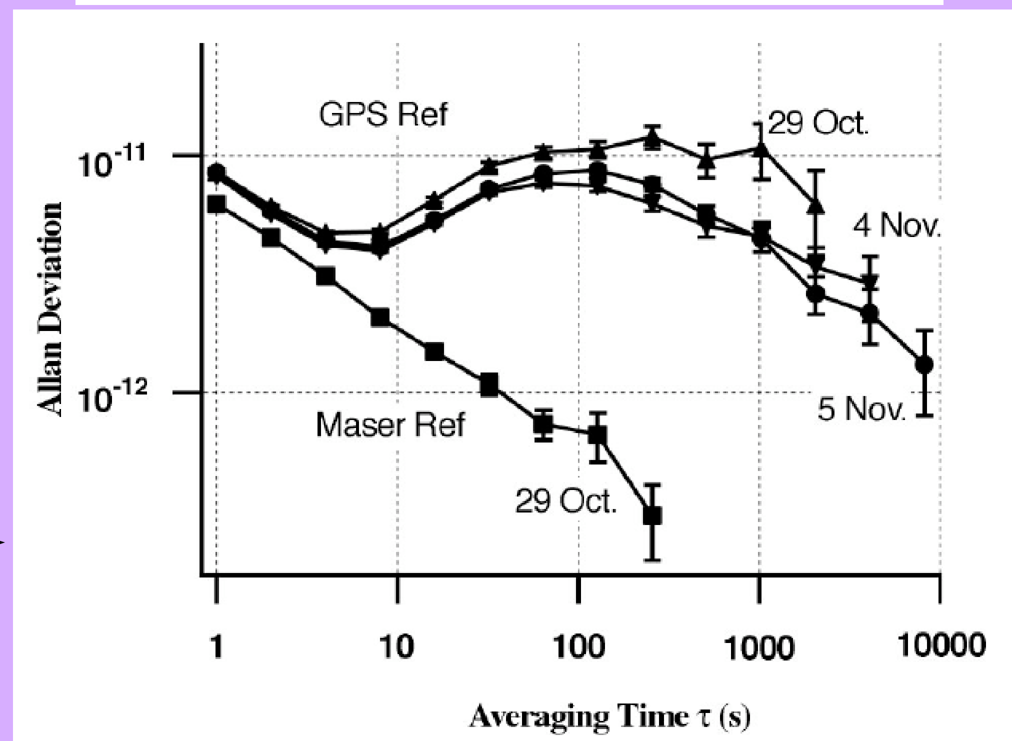
Optical Frequencies Measured via GPS

R. Fox, S. Diddams NIST,
also similar work at NPL …



Red, 633nm I_2 – Stabilized HeNe laser



Fox et al. Applied Optics, 05,

Even commercial systems now available – CLEO/QELS trade show

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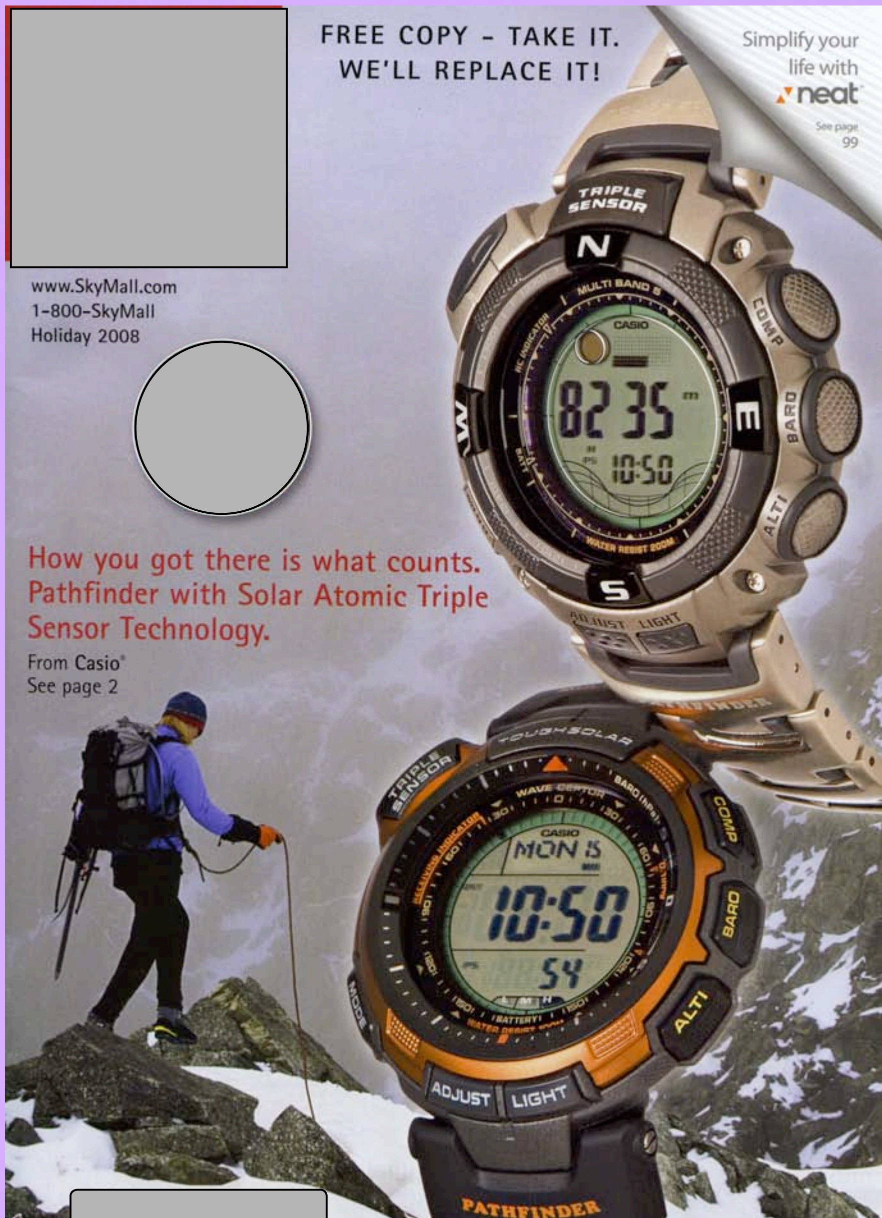

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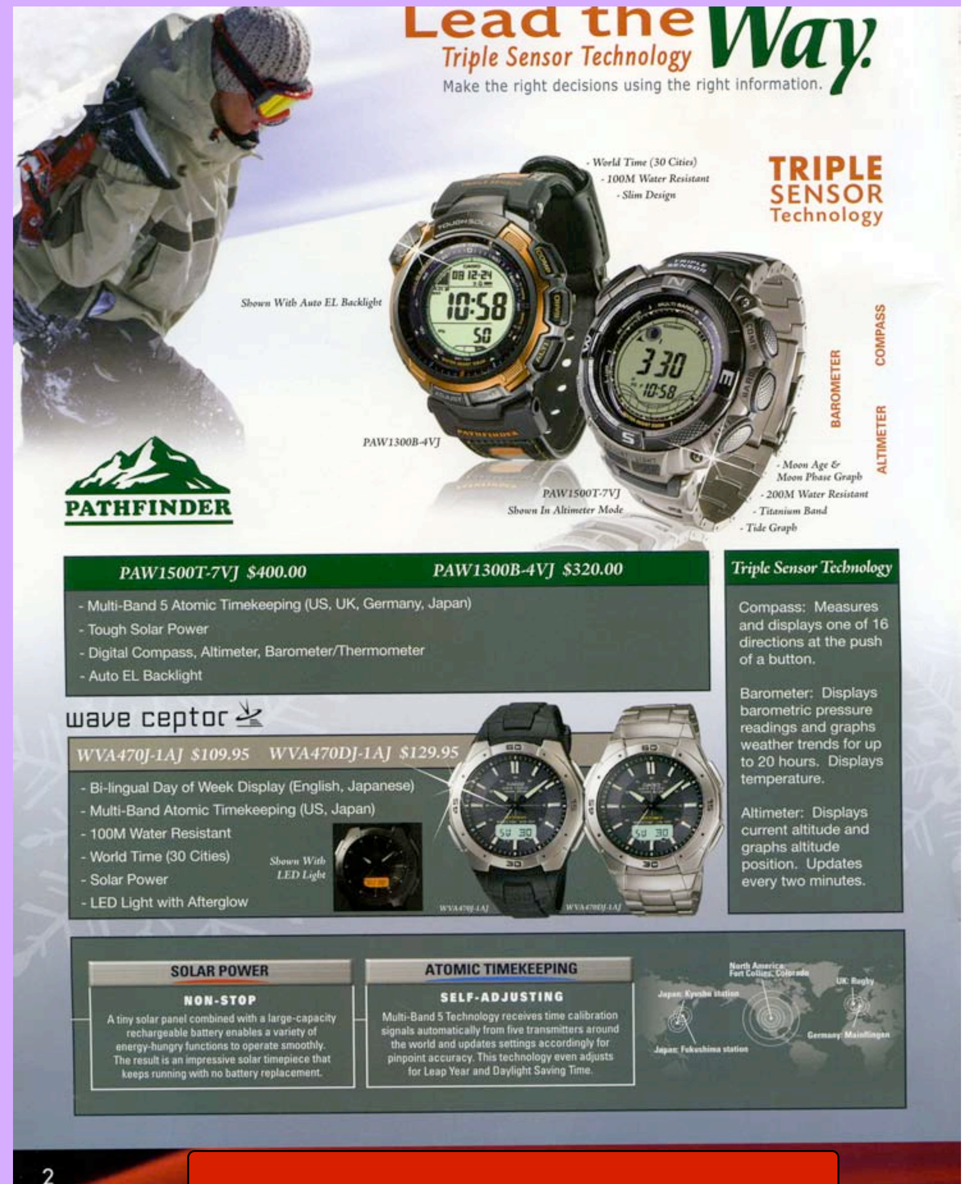

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TRIPLE SENSOR Technology
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- 100M Water Resistant
- Slim Design
Shown With Auto EL Backlight
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PAW1500T-7VJ Shown In Altimeter Mode
- Moon Age & Moon Phase Graph
- 200M Water Resistant
- Titanium Band
- Tide Graph
BAROMETER
COMPASS
ALTIMETER
PATHFINDER
PAW1500T-7VJ $400.00
PAW1300B-4VJ $320.00
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- Tough Solar Power
- Digital Compass, Altimeter, Barometer/Thermometer
- Auto EL Backlight
Triple Sensor Technology
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Barometer: Displays barometric pressure readings and graphs weather trends for up to 20 hours. Displays temperature.
Altimeter: Displays current altitude and graphs altitude position. Updates every two minutes.
wave ceptor
WVA470J-1AJ $109.95
WVA470DJ-1AJ $129.95
- Bi-lingual Day of Week Display (English, Japanese)
- Multi-Band Atomic Timekeeping (US, Japan)
- 100M Water Resistant
- World Time (30 Cities)
- Solar Power
- LED Light with Afterglow
Shown With LED Light
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A tiny solar panel combined with a large-capacity rechargeable battery enables a variety of energy-hungry functions to operate smoothly. The result is an impressive solar timepiece that keeps running with no battery replacement.
ATOMIC TIMEKEEPING
SELF-ADJUSTING
Multi-Band 5 Technology receives time calibration signals automatically from five transmitters around the world and updates settings accordingly for pinpoint accuracy. This technology even adjusts for Leap Year and Daylight Saving Time.
North America: Fort Collins, Colorado
UK: Rugby
Japan: Kyushu station
Germany: Mainflingen
Japan: Fukushima station
2

NIST

CSADs Team

NIST Time and Frequency

John Kitching

- Svenja Knappe
- Vladislav Gerginov
- Vishal Shah
- Susan Schima
- Peter Schwindt

} CSAC

- Clark Griffith
- Brad Lindseth
- Ying-Ju Wang

} CSAM

- Ying-Ju Wang
- Matt Eardley
- Andy Geraci

} Dir. Coup.

- Elizabeth Donley
- Eleanor Hodby
- Hugh G. Robinson

} Gyro

NIST Electromagnetics } MEMS

- John Moreland
- Li-Anne Liew

University of Colorado

- Z. Popović
- A. Brannon
- J. Breitbarth

} LO

- J. Maclennan
- Y. Li

} Wall coatings

DARPA

SERDP

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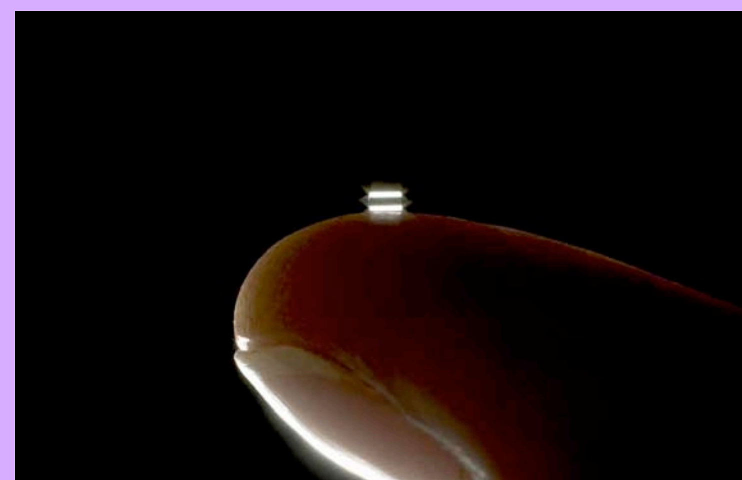
Chip Scale Atomic Devices

CSAC (clock), CSAM (magnetometer), CSAG (gyro)

Optical excitation, atoms, MEMS, VCSEL lasers, low power

Battery powered devices, connect to application requirements



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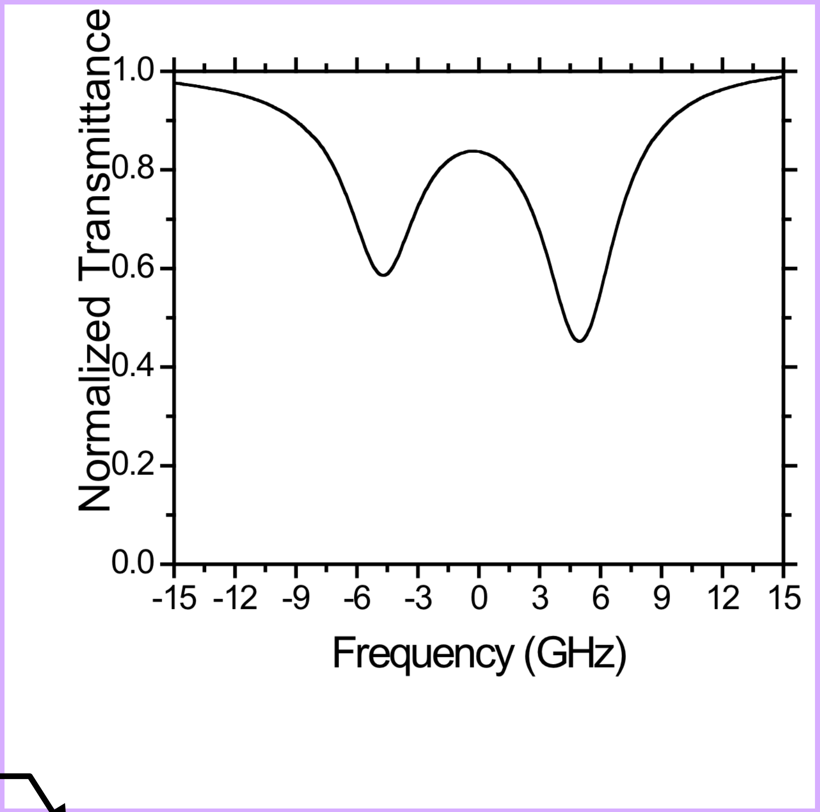
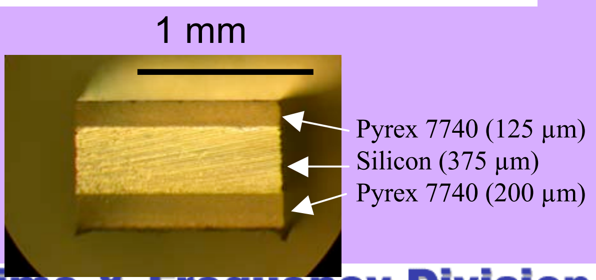
Cell Fabrication: Anodic Bonding

- Preform created by KOH etching or DRIE of Si
- Pyrex bonded on one side with anodic bonding
- Cell preform filled with Cs or Rb
  - And buffer gases
- Diced cells made at NIST using the anodic bonding technique
  - Interior: 1 mm x ∅ 0.9 mm
  - Exterior: 1.33 mm x (1.45 mm)^2





L. Liew, et al., Appl. Phys. Lett., ***84****, 2694, 2004.*

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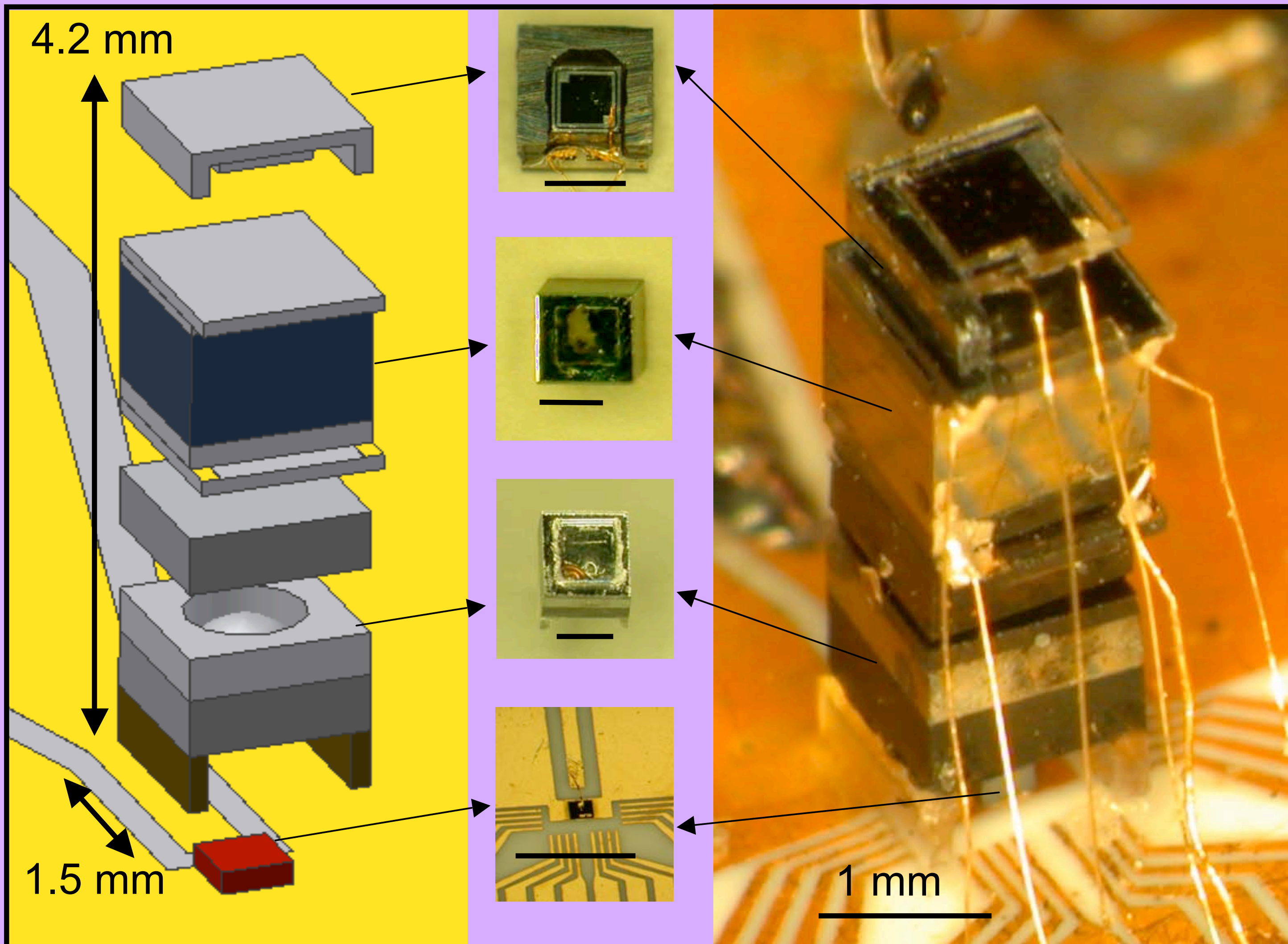
NIST Chip-Scale Atomic Clock: 2004



Volume:
9.5 mm^3

Cell volume:
0.81 mm^3

Cell temp:
85 ºC

Heating power:
75 mW

Stability:
σ_y(1 sec.) = 2.5×10^{-10}

S. Knappe, et al., Appl. Phys. Lett. ***85****, 1460 (2004).*

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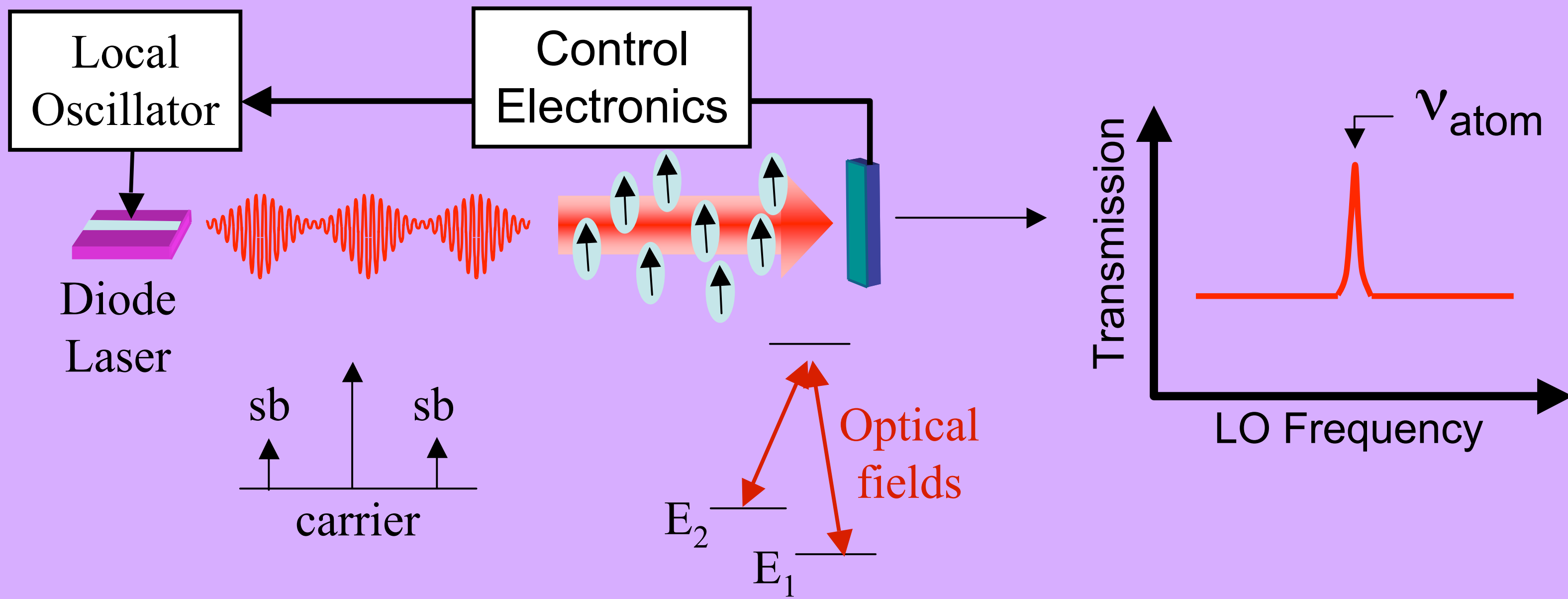
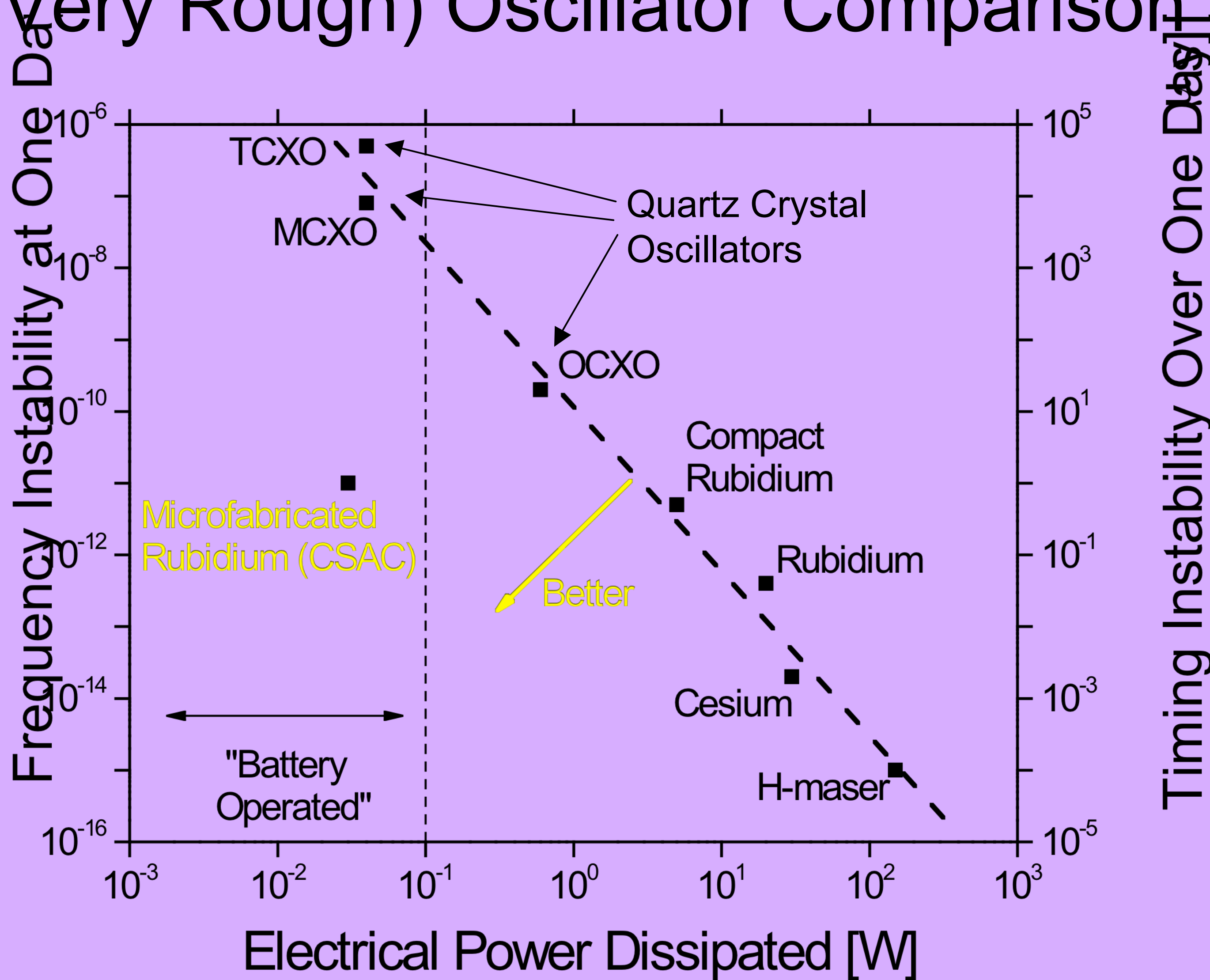
All-Optical (CPT) Excitation



- Non-linear process in atoms drives hyperfine oscillation at difference frequency between optical fields
- Absorption of light changes when modulation frequency equals hyperfine splitting
- Can be very small !

Time & Frequency Division

(A Very Rough) Oscillator Comparison



Adapted from figure by R. Lutwak, Symmetricom

Applications of Microfabricated Atomic Clocks

- Size (1 cm^3)
- Power (30 mW)

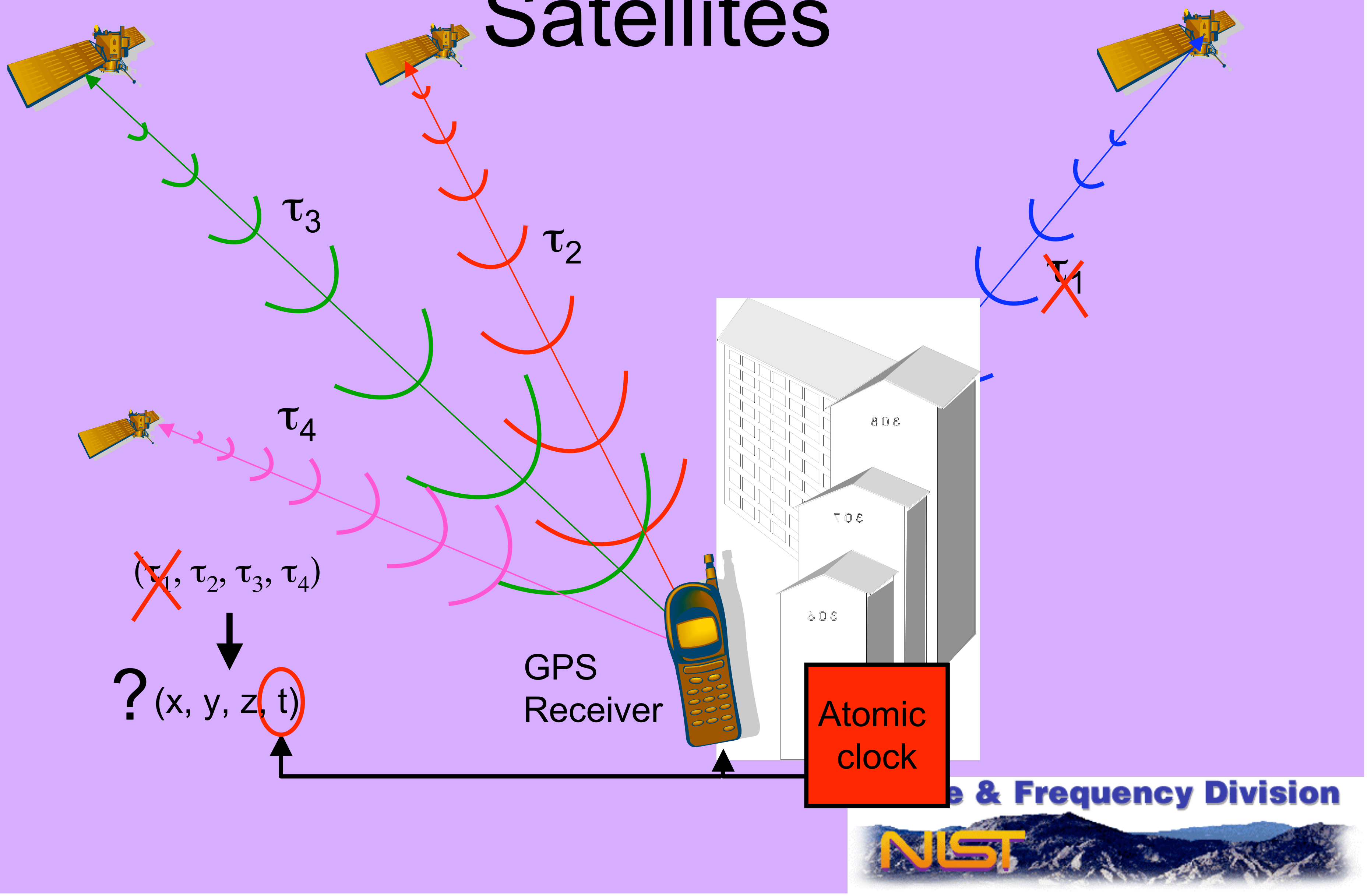
} Integration in portable, battery-operated devices

- Precise timing: higher-performance, more reliable operation

<u>Key application areas:</u>

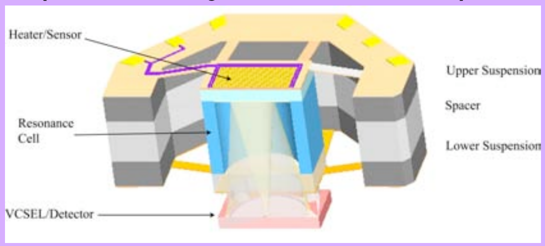
- Global positioning and navigation (GPS)
  - Faster acquisition time
  - More precise altitude determination
  - Direct P(Y)/M code acquisition → anti-jam capability
  - Position solution with < 4 satellites visible
- Wireless communications, network synchronization
  - Secure communications
  - Avoidance of data accumulation, more information capacity
- Data logging, seismology, remote sensors…
- Others …

GPS Positioning with < 4 Satellites

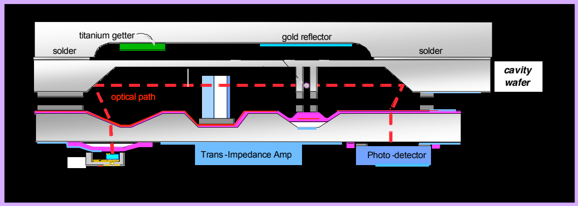


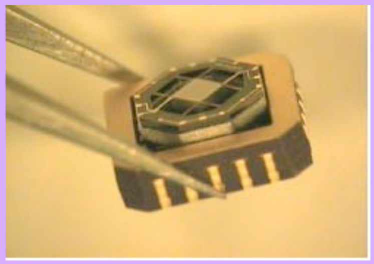
Commercialization of Chip-Scale Atomic Clocks

Symmetricom/Draper/Sandia
(courtesy R. Lutwak)



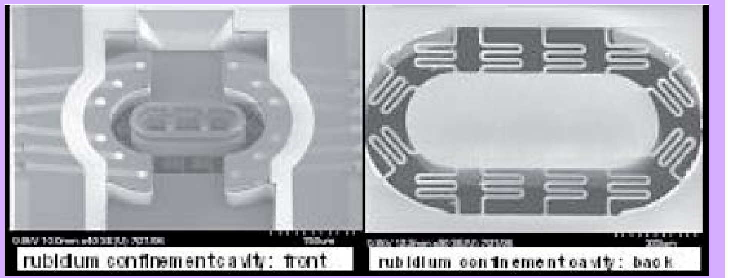
Honeywell
(courtesy D. Youngner)



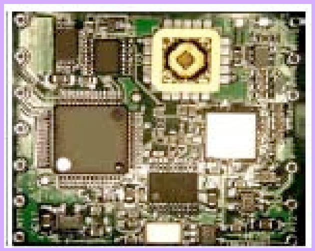


RF output

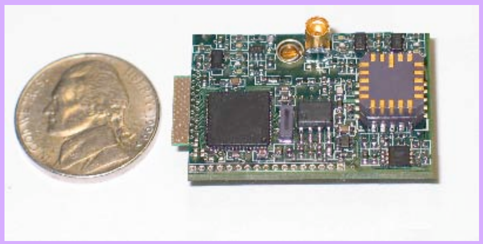
< 10 mW
power requirement



Complete functioning CSACs



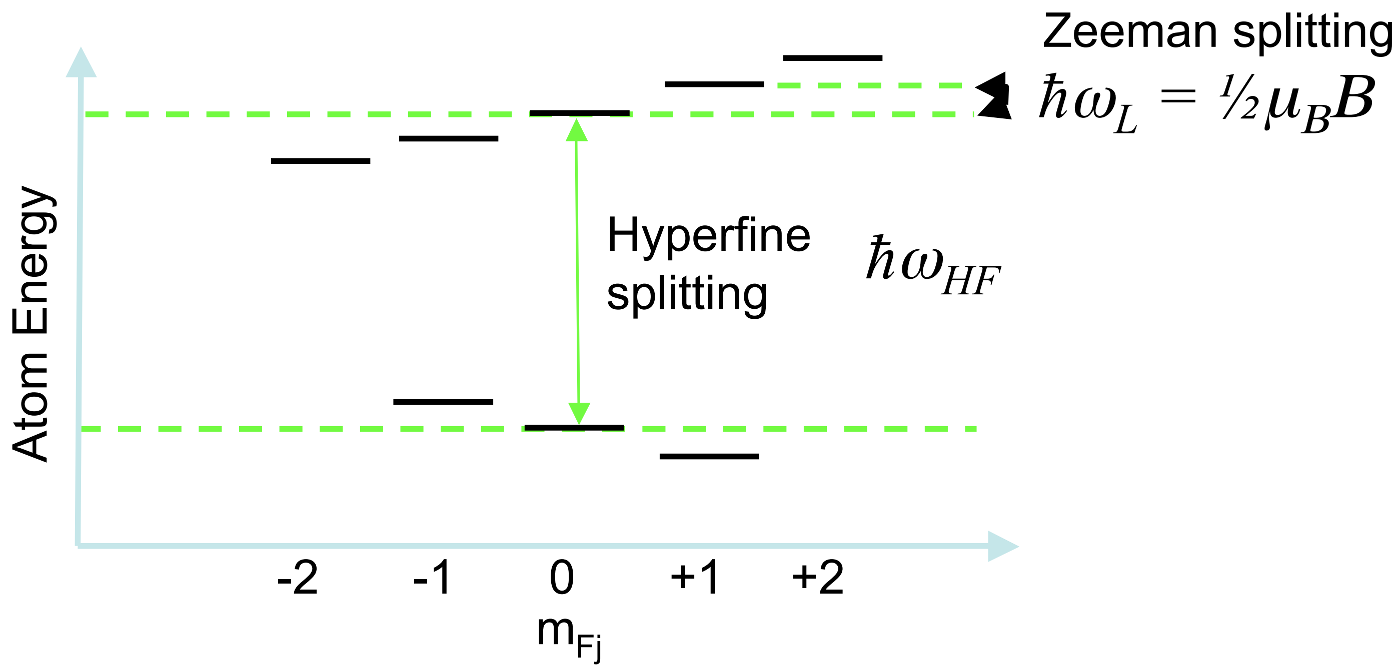
10 cm^3
108 mW
5×10^{-11}
@ 100 s



1.7 cm^3
57 mW
4×10^{-12}
@ 1 hr

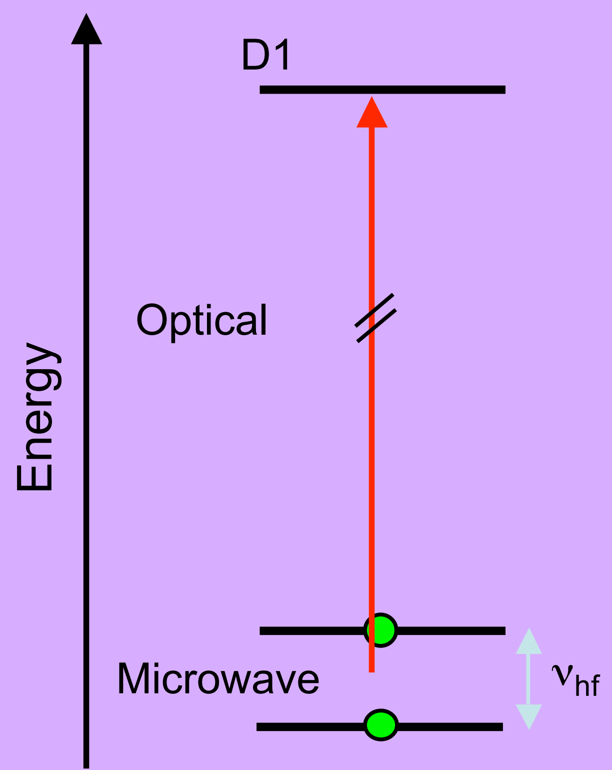
Time & Frequency Division
NIST

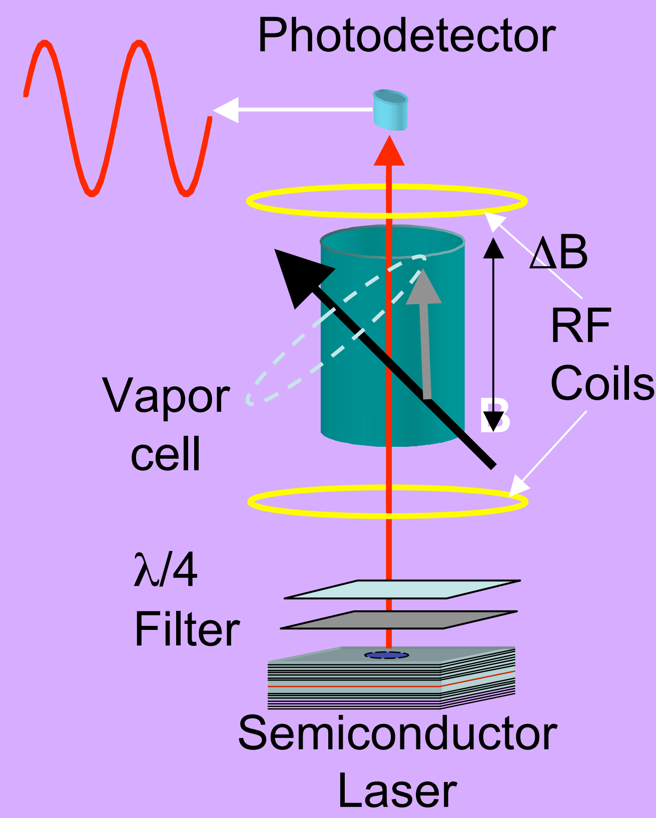
Magnetometry with Chip-Scale Devices



M_X Magnetometer

- Improved sensitivity; no GHz oscillator

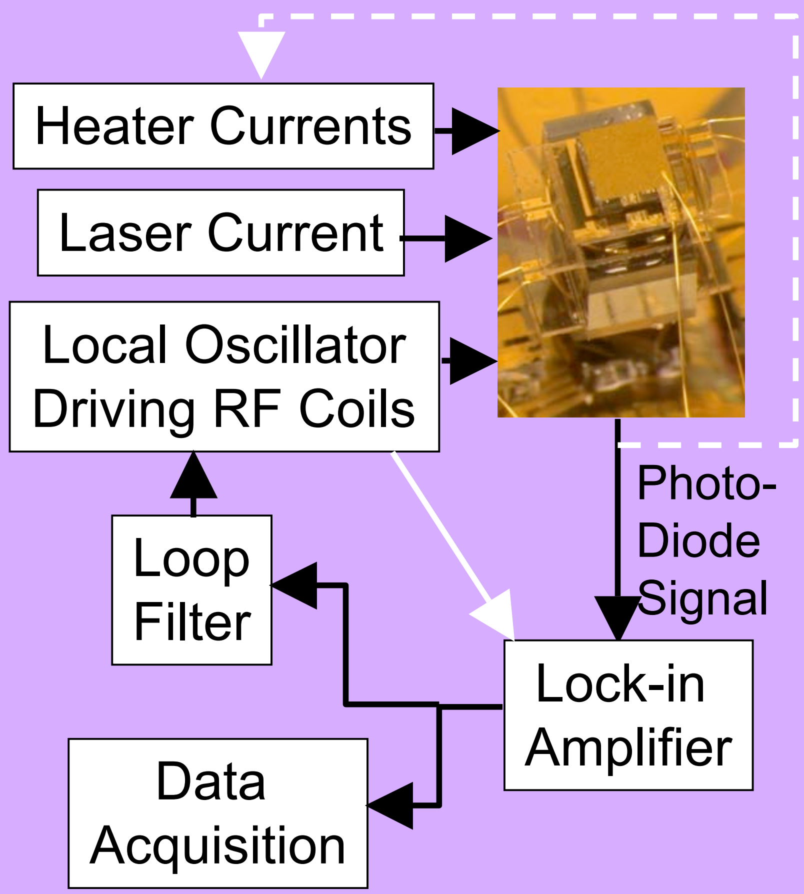


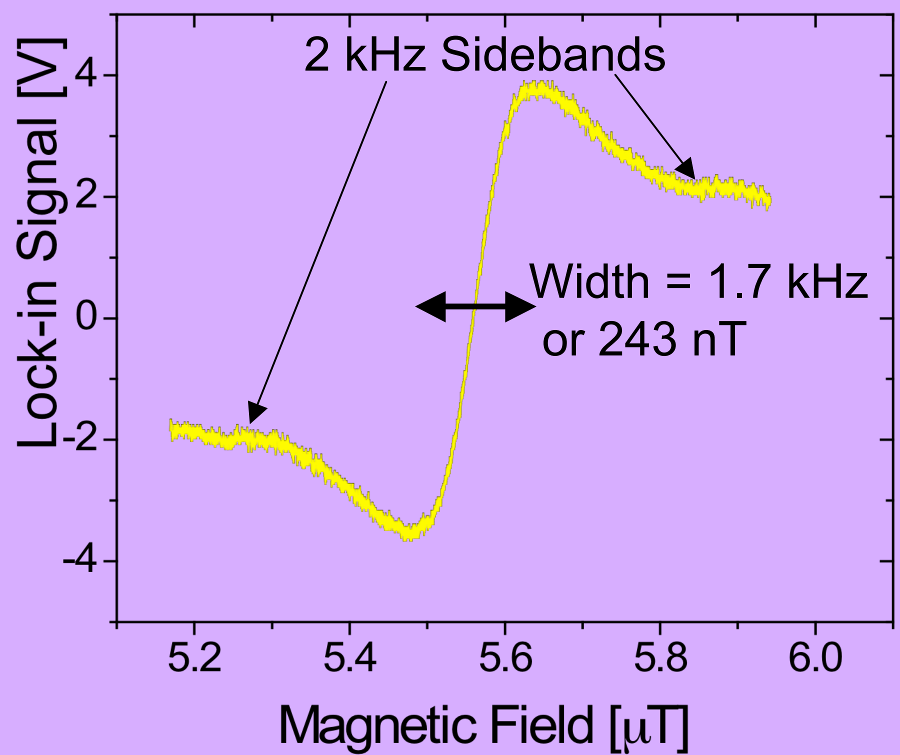


A. Bloom, E. Alexandrov, H. Dehmelt, H.G. Robinson, A. Weis, and many others

Time & Frequency Division

CSAM Operation

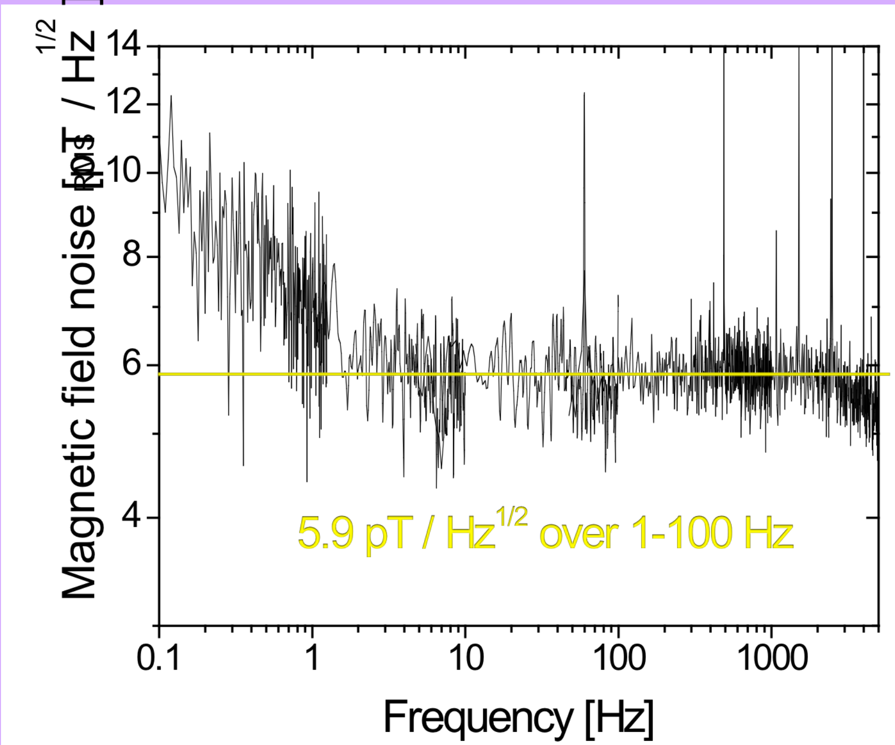




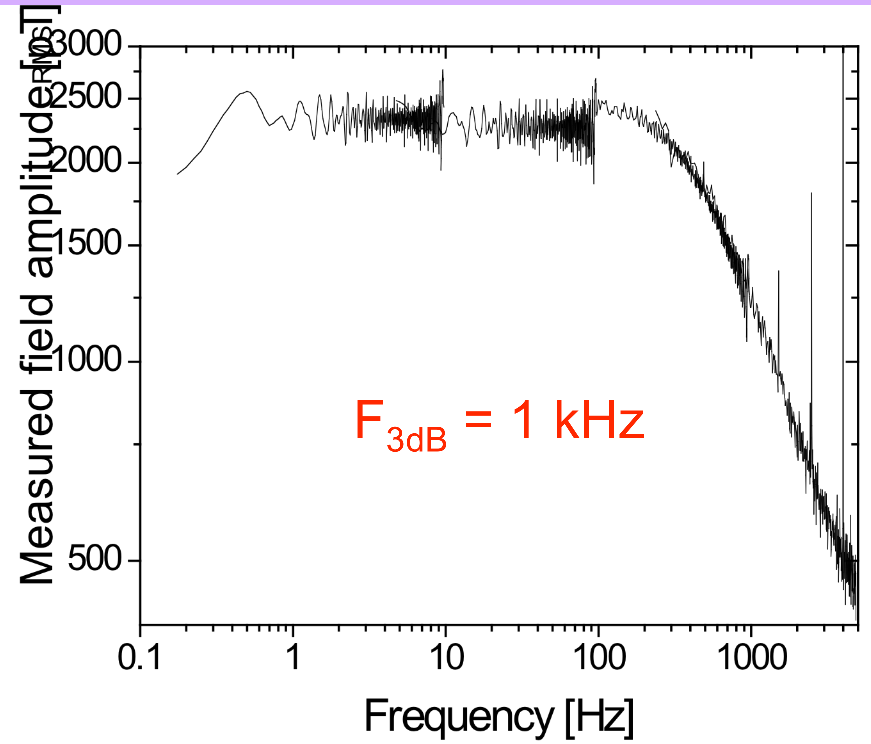
Time & Frequency Division
NIST

M_X CSAM Performance

Sensitivity



Frequency Response



Kitching, Knappe et al.

Time & Frequency Division

Time & Frequency Division