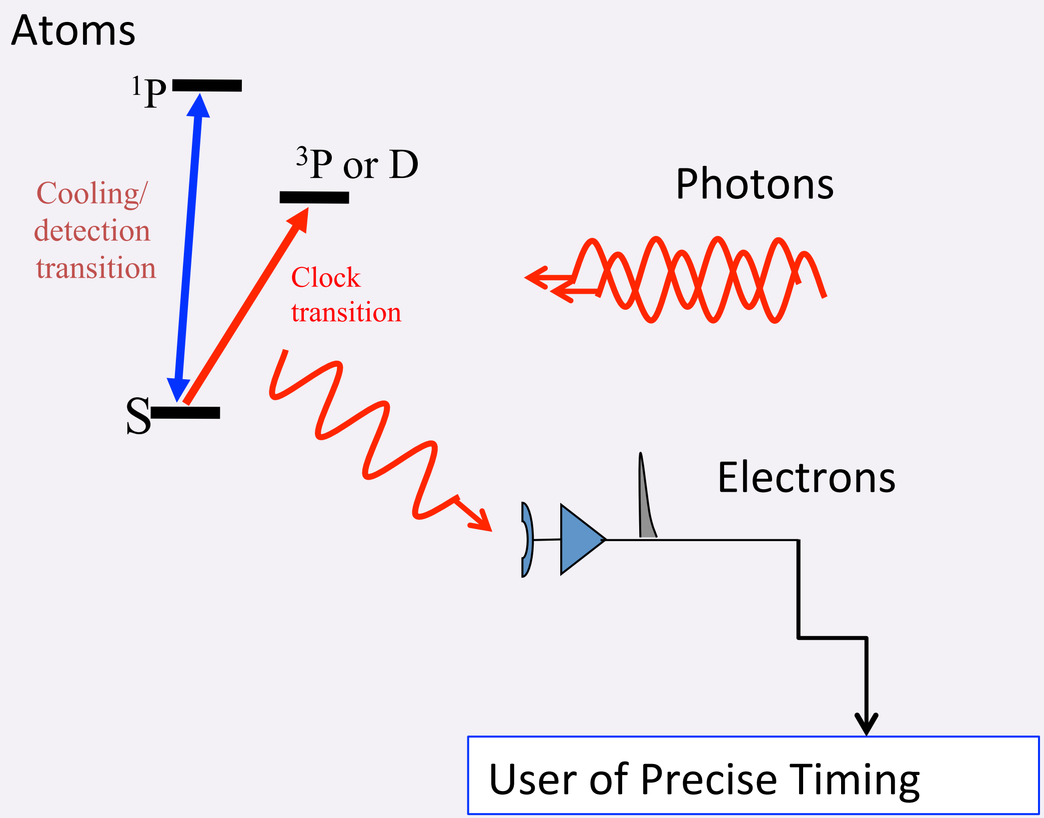
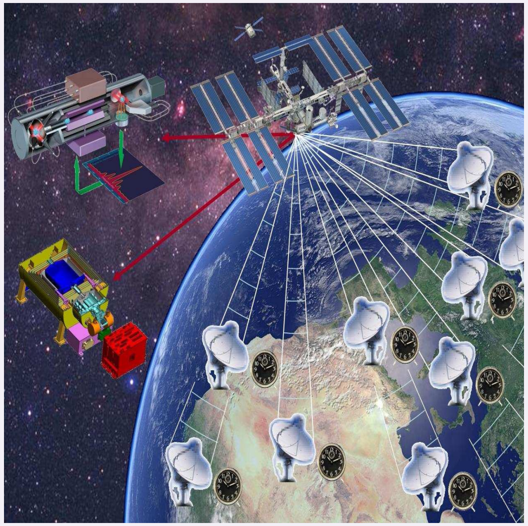
Atoms ➔ Quantum transitions probed with lasers, for real world applications?

Leo Hollberg, Stanford Univ.
Dept. of Physics, and Stanford Center on Position Navigation and Time



Motivated by:

- Fundamental Science
  of Time, Frequency and Coordinate Space
- Applications
  -- Navigation ...
  -- Earth science
  -- ultrafast timing, elect.



Support: NASA Fundamental Physics, DARPA "seedling?

Glasgow Feb. 2014

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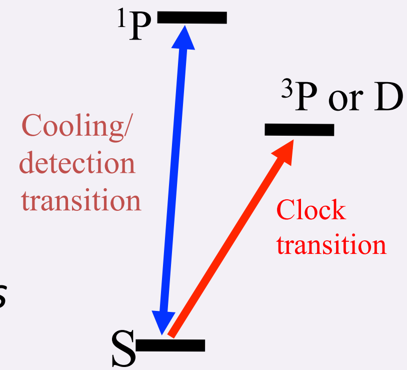
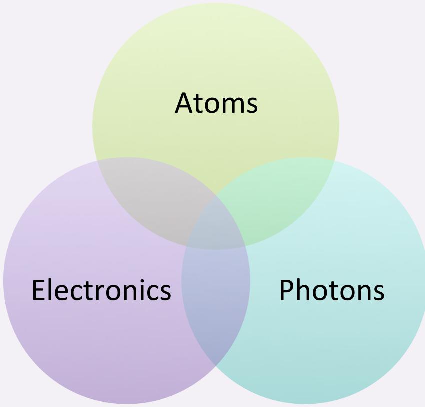
Leo Hollberg, Stanford Physics & HEPL

- *Experimental Atomic/Laser Physics*
- *laser cooling of "interesting" atoms*
- *Ultrafast Opto-electronics*
- *Optical Time transfer*
- *optical atomic clocks & precision measurements*
- *fundamental physics with view to applications*
- *small is good: Chip Scale Atomic Devices*
- *stable cw and ultra-fast lasers*



Experiments exploring overlap regions of atoms, lasers and fast electronics



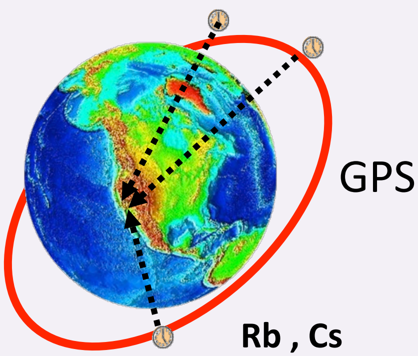
Career archeology

AOSense Inc, atom interferometric inertial sensors, applications

NIST, Time and Frequency Division; laser physics quantum meas.

Chip Scale Atomic Clocks (CSAC)..., Optical Atomic Clocks

AT&T Bell labs, laser cooling and trapping of atoms, squeezed light



many many contributors, collaborators through the years

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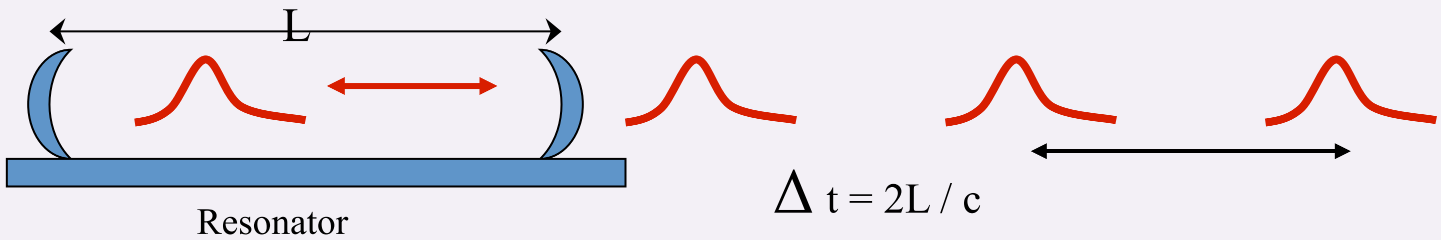
Types of Clocks

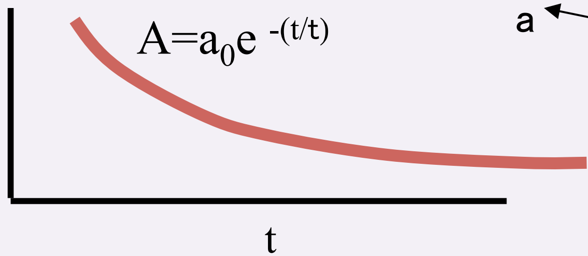
• require something predictable vs. time and measurable

Ruler Clock

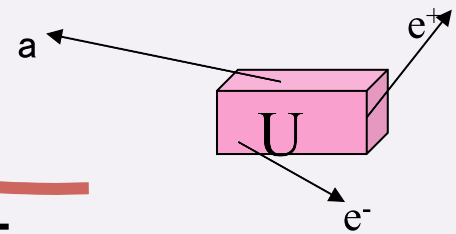


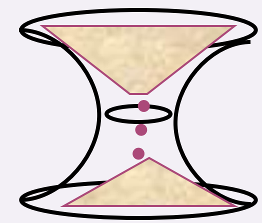
$\Delta t = 2L / c$

Decay

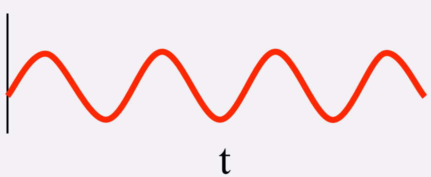


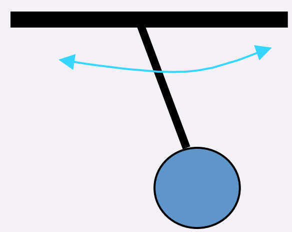
$A = a_0 e^{-(t/t)}$

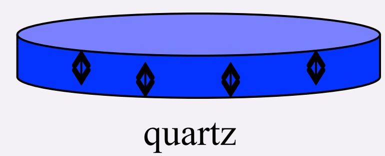




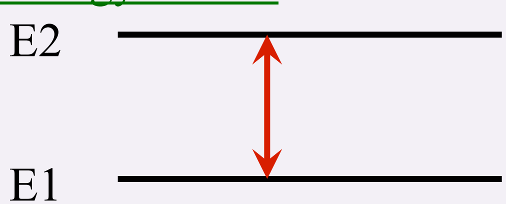
Stable Oscillator







Atomic Energy Levels



$\Delta E = h \cdot f$ $\Delta t = n / f$

h = Planck's constant
f = frequency (number of oscillations /second), Hertz (Hz)

Idea for atomic time reference documented as early as 1879 Lord Kelvin, Treatise on Natural Philosophy **

NBS director Ed Condon and Harold Lyons w/ 1st ? Atomic clock ; Ammonia spectroscopy steering the frequency of a quartz crystal , 1949

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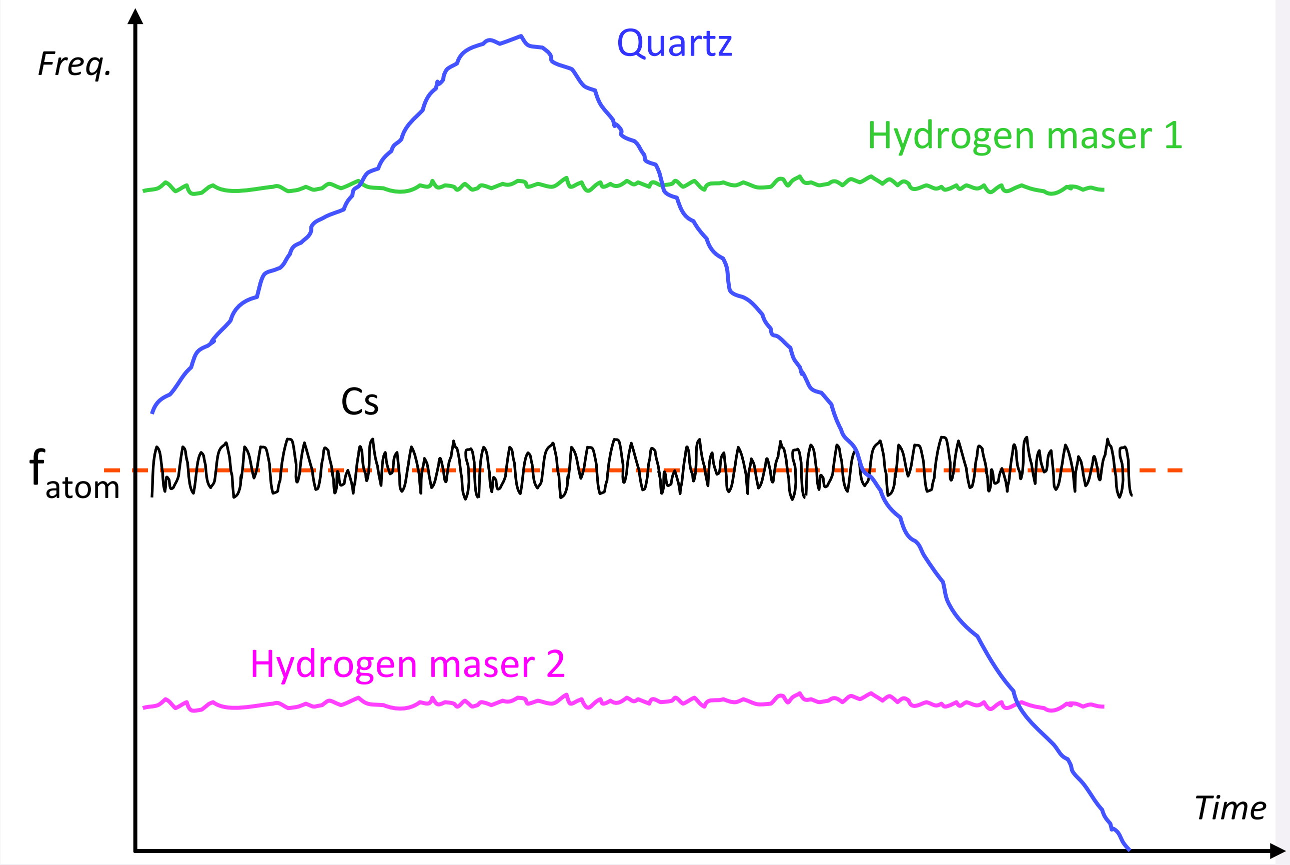
Attributes of Clocks / Frequency Standards

Accuracy: Same average frequency $f_{clock} = f_{atom}$

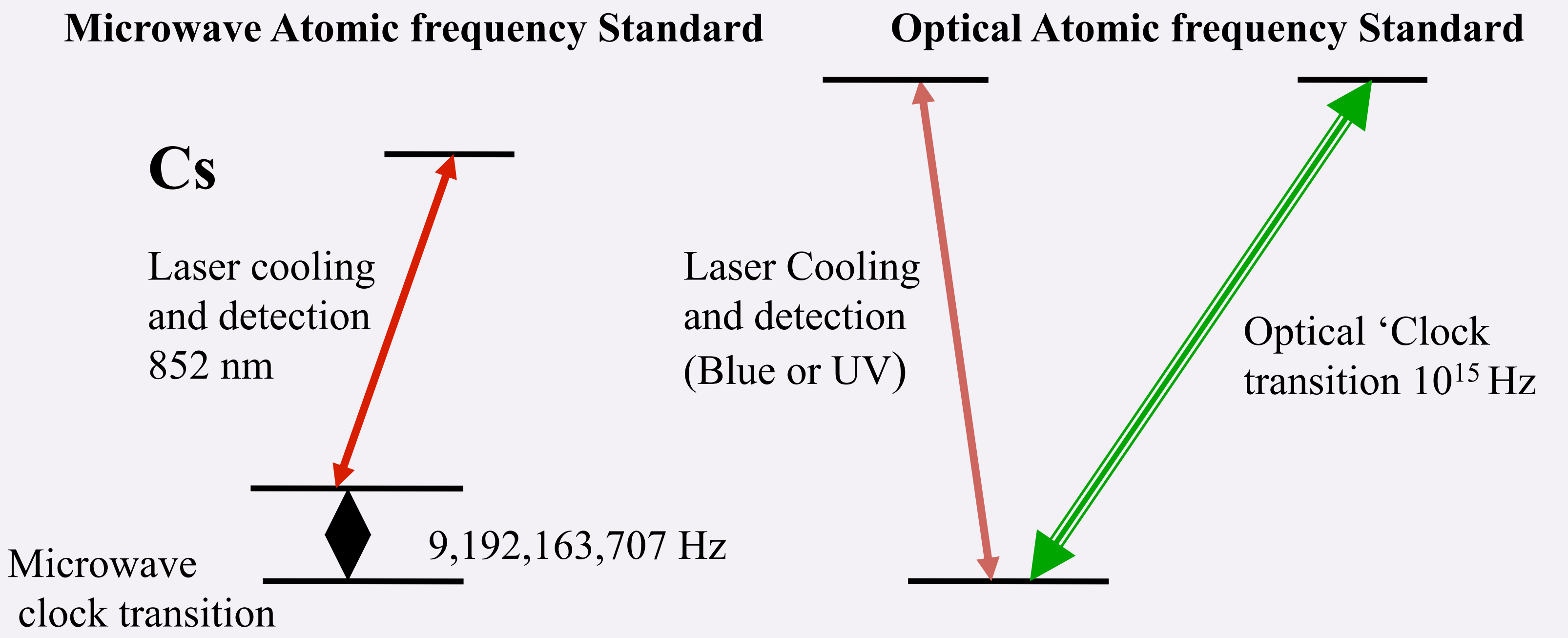
Reproducibility: Different clocks give same frequency.

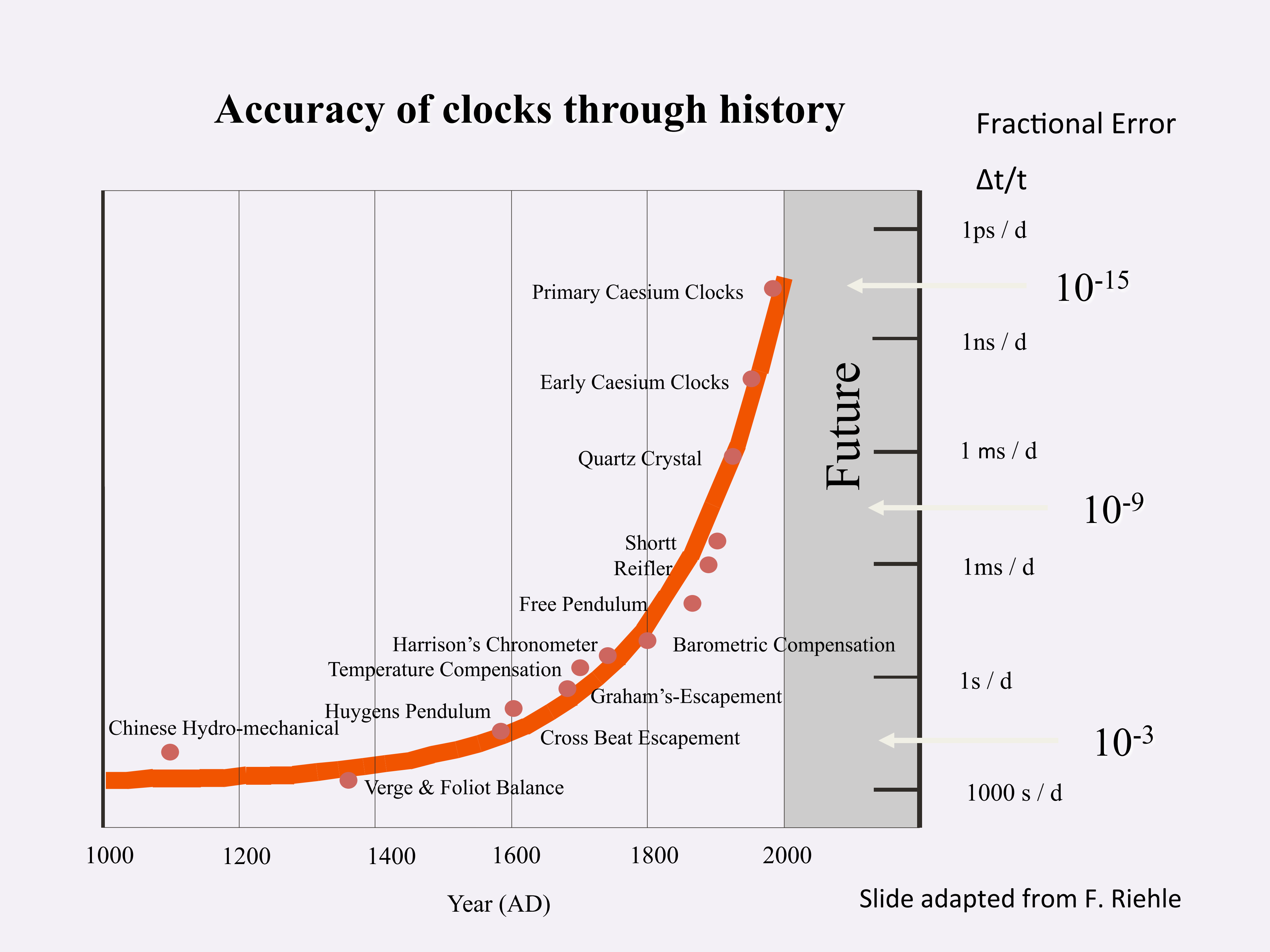
Stability: Frequency does not change with time. → $\frac{\Delta f_{rms}(\tau)}{f_o}$



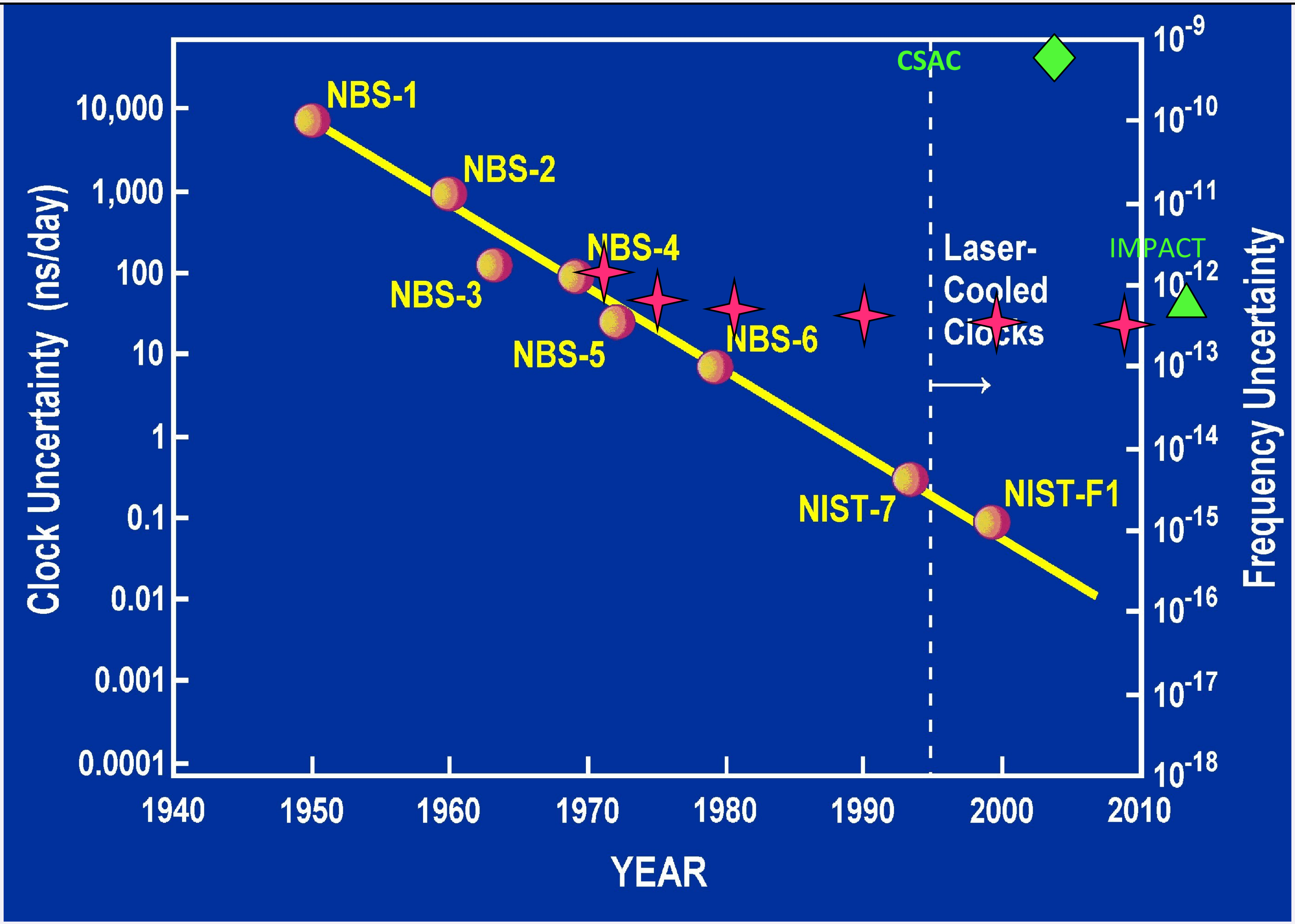
Examples of Atomic Frequency Standards “Clocks”

- Optical Atomic clocks – use lasers rather than microwaves to probe atoms
- CSAC (Chip Scale Atomic Clocks) for hand held portable systems



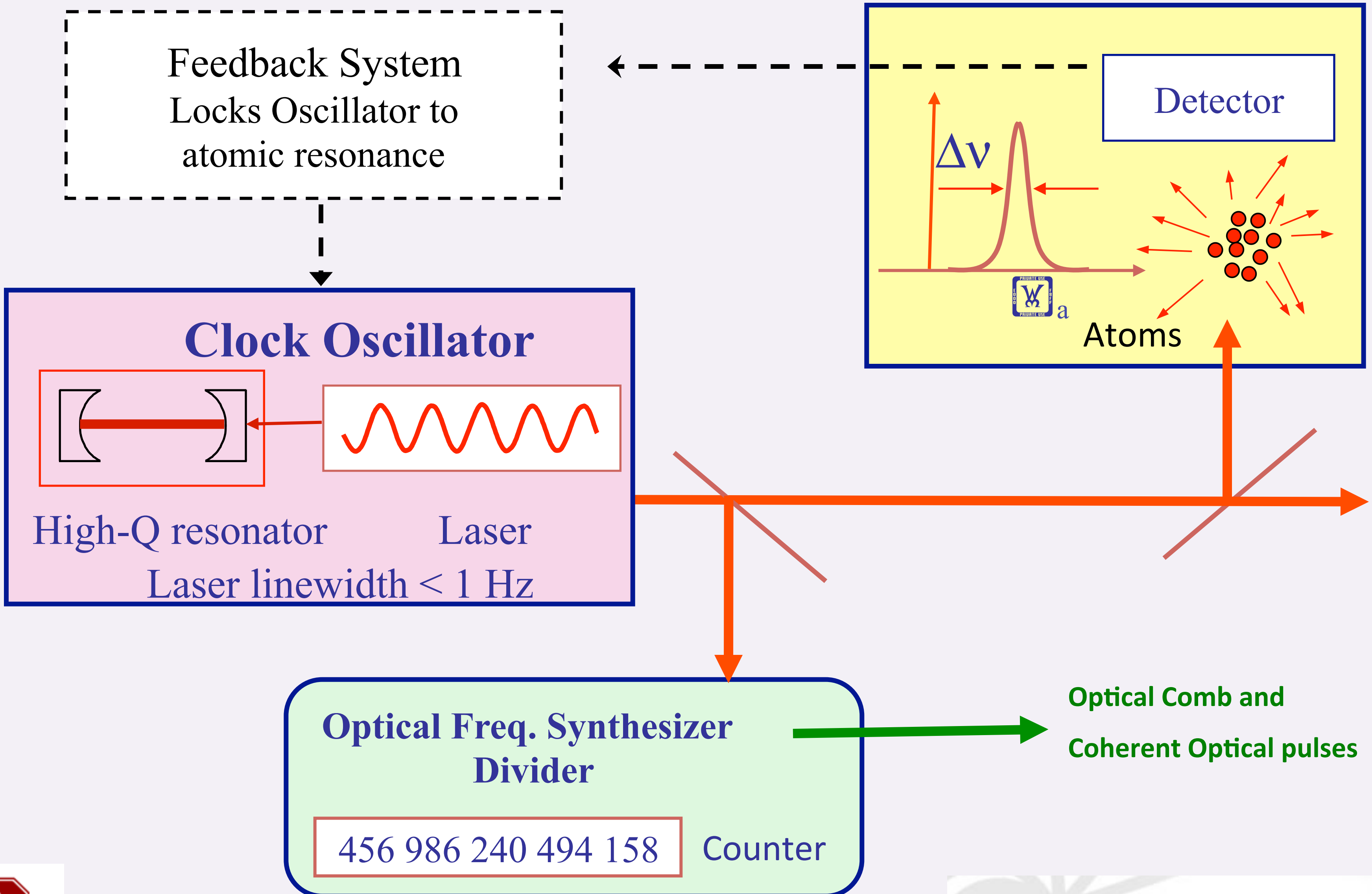

Accuracy of clocks through history
Fractional Error
Δt/t
1ps / d
10-15
1ns / d
1 ms / d
10-9
1ms / d
1s / d
10-3
1000 s / d
Future
Primary Caesium Clocks
Early Caesium Clocks
Quartz Crystal
Shortt
Reifler
Free Pendulum
Harrison's Chronometer
Barometric Compensation
Temperature Compensation
Graham's-Escapement
Huygens Pendulum
Chinese Hydro-mechanical
Cross Beat Escapement
Verge & Foliot Balance
1000
1200
1400
1600
1800
2000
Year (AD)
Slide adapted from F. Riehle

High Accuracy Atomic Primary Frequency Standards



Commercial Cs, Ref: L. Cutler HP, Symmetricom.com, Micro-Semi ?

Generic Atomic Clock



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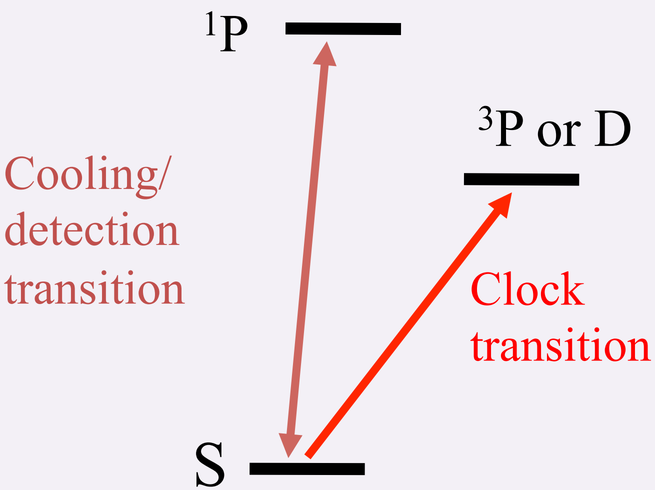
Advantages of Optical Clocks



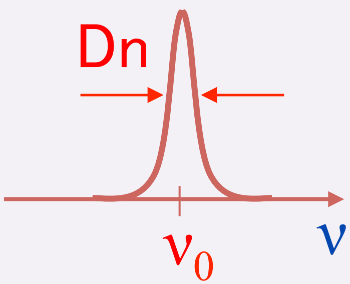
Quantum Projection Noise

Fractional Frequency instability ~

$$\sigma_y = K \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_{cycle}}{N_{atoms}\tau}}$$

τ = observation time

N = number of atoms



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

- Large number of atoms — 10^6 or more
- High signal/noise
- Possibility of lattices

Candidate neutral atoms

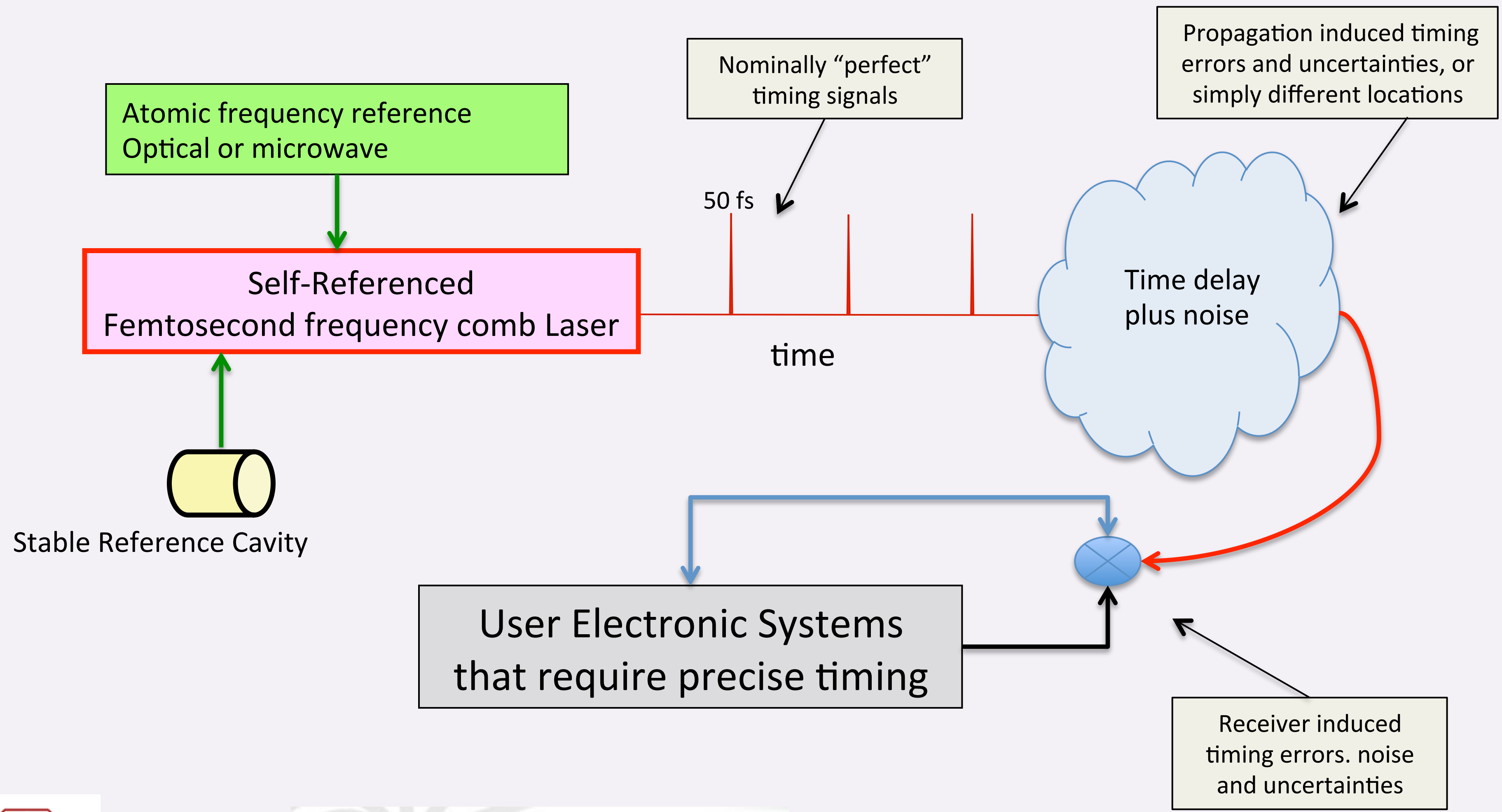
Ca, Sr, Yb, Mg, H, Ag, Hg…

One atomic clock is always "perfect"

Two similar clocks -- hard to detect systematic errors

Different types of clocks can determine most accurate and stable

Notional "Time" transfer problem:
Short distance (mm, on chip) or long distance (100s km, free space or to space)



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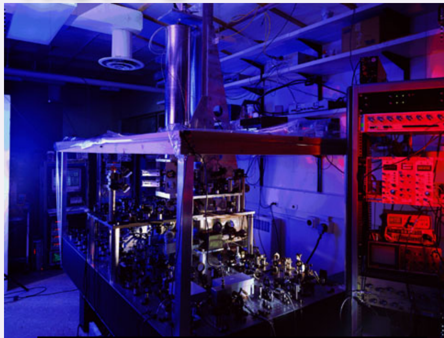
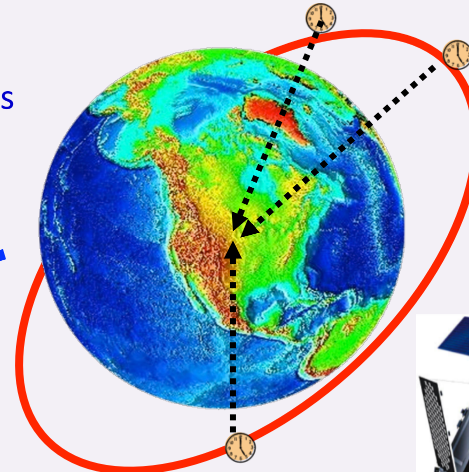
Time and Frequency Standards & Distribution

NIST-F1

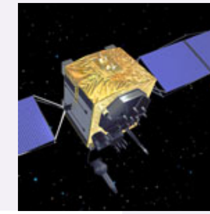


Hydrogen masers and
Cesium beam clocks for time scales
Calibrated by Cs Fountain clocks



Rb and/or Cs

GPS



Measurement Systems

Signal Out = internet time, radio broadcasts

Communications satellites

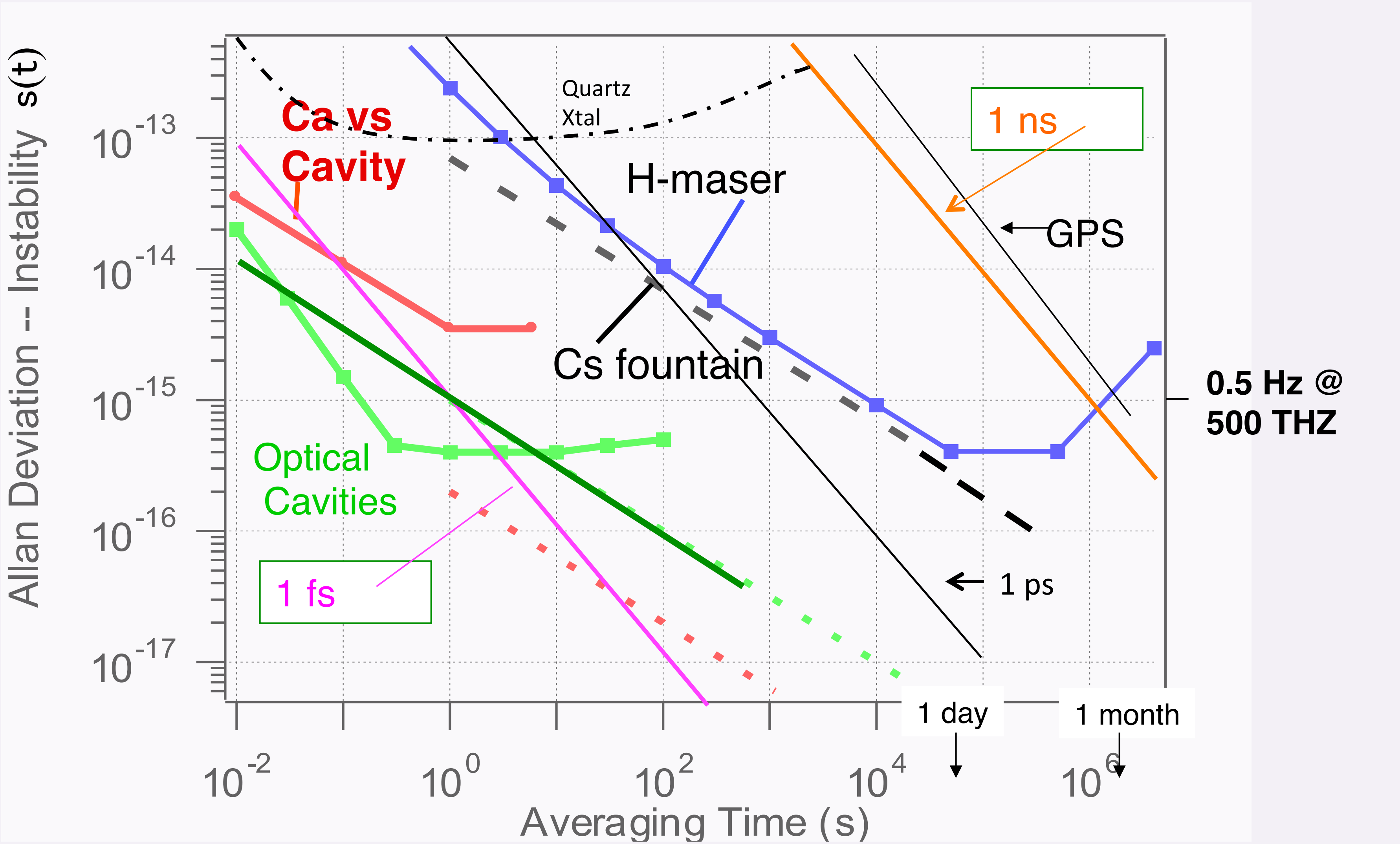
NIST, USNO, AMC JPL

$\Delta f/f \sim 1\mathrm{x}10^{-15}$
for best primary standards and distribution

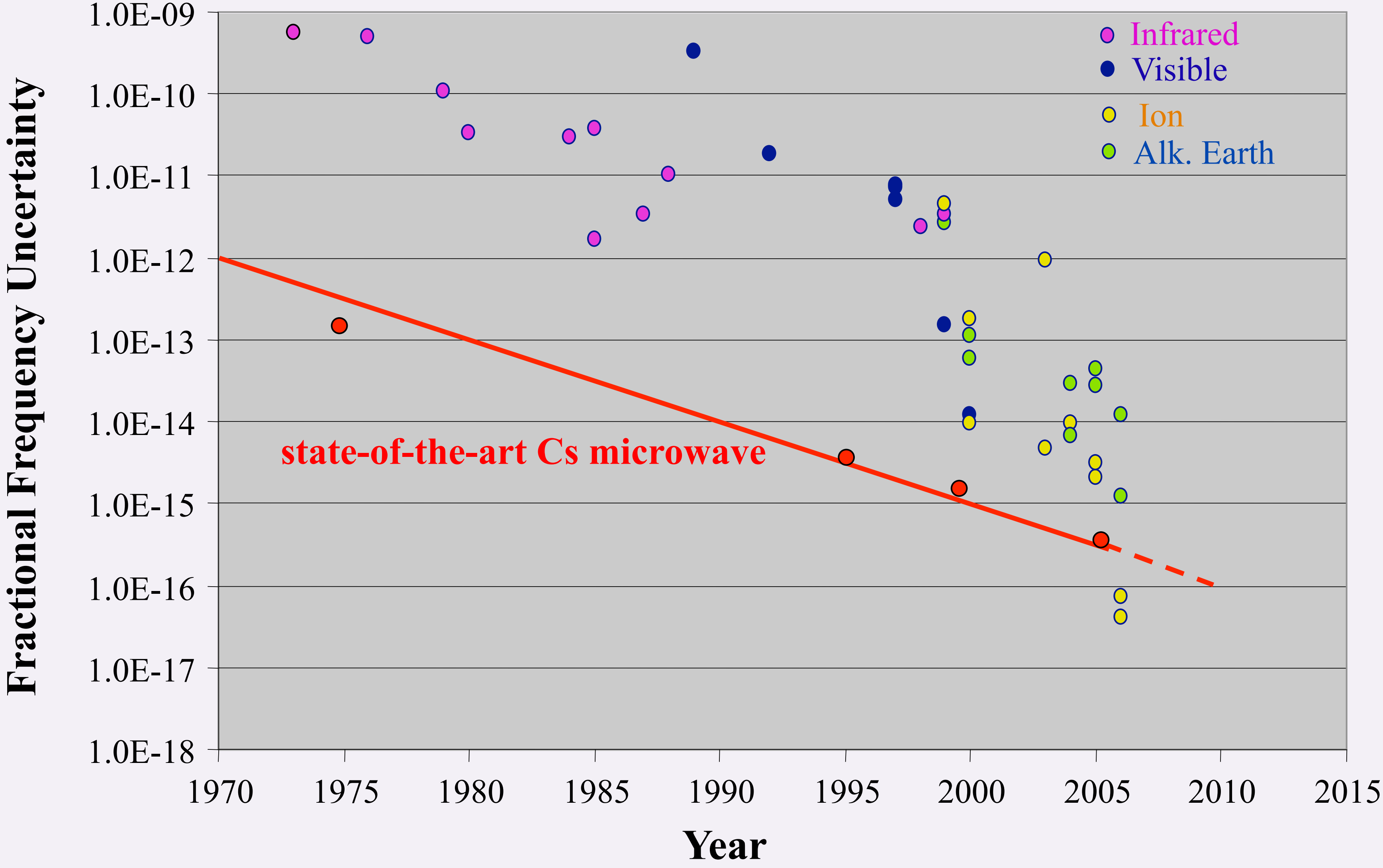
USNO

Time . Gov ; services
Performance vs. type; radio, internet, GPS

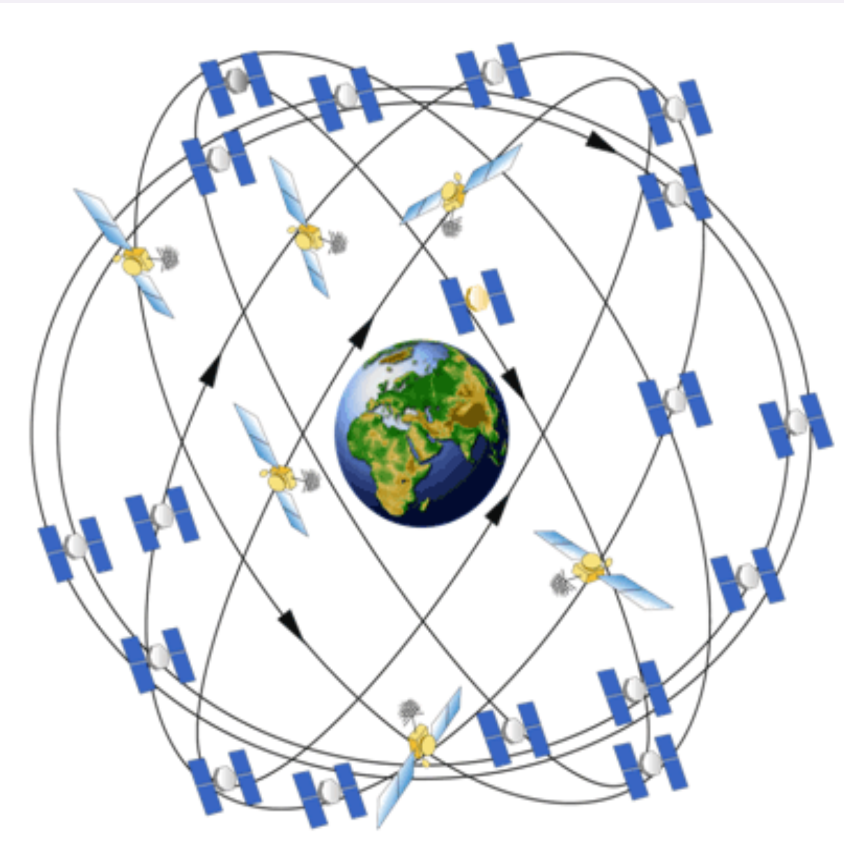
Frequency instability vs. time interval

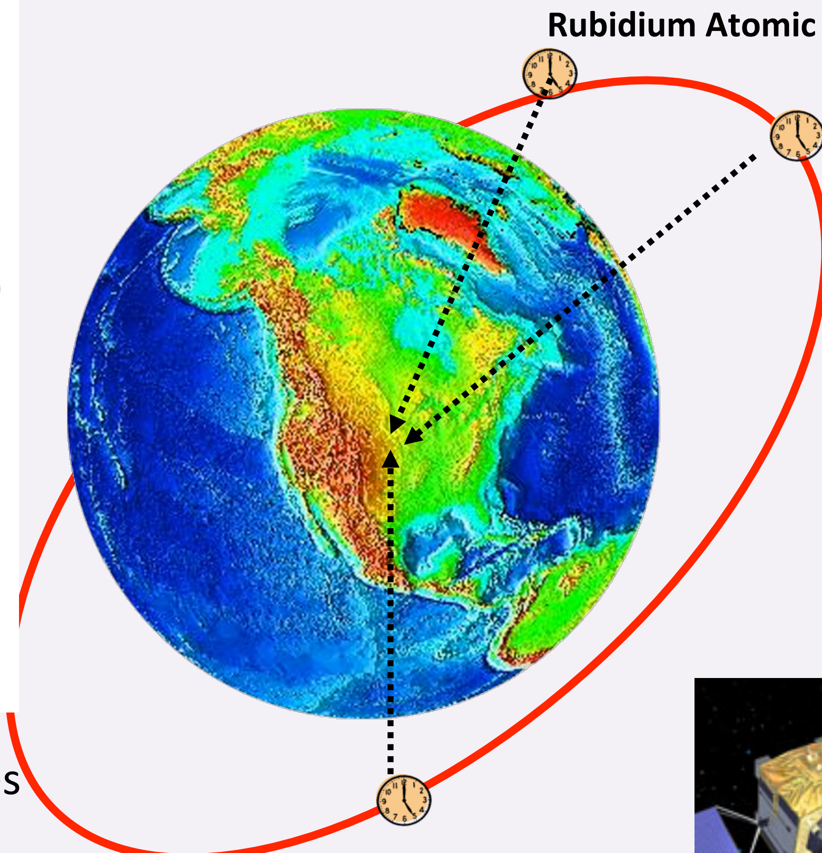


Accuracy of Atomic Frequency Standards - History



For world wide Position, Navigation and Time, We need a suitable coordinate reference system





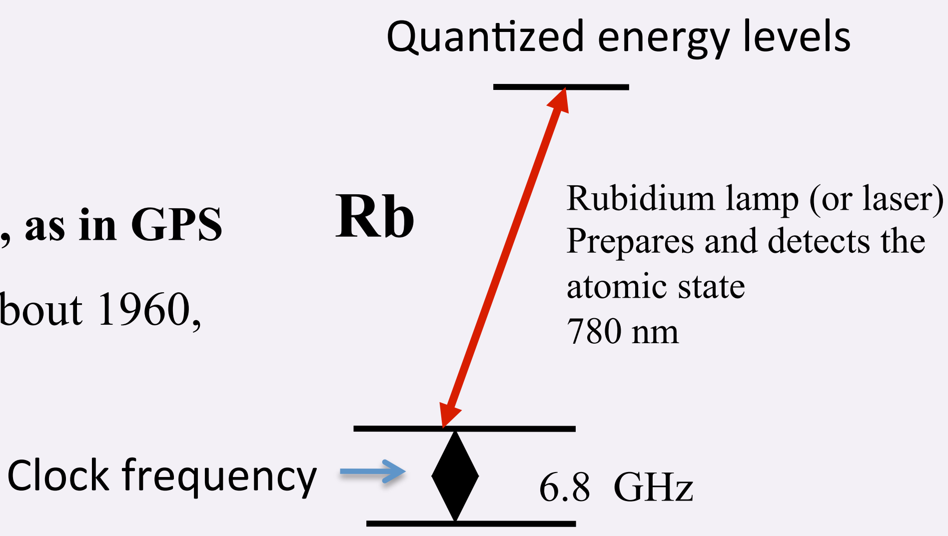
Array of approx. 24+ orbiting GPS satellites

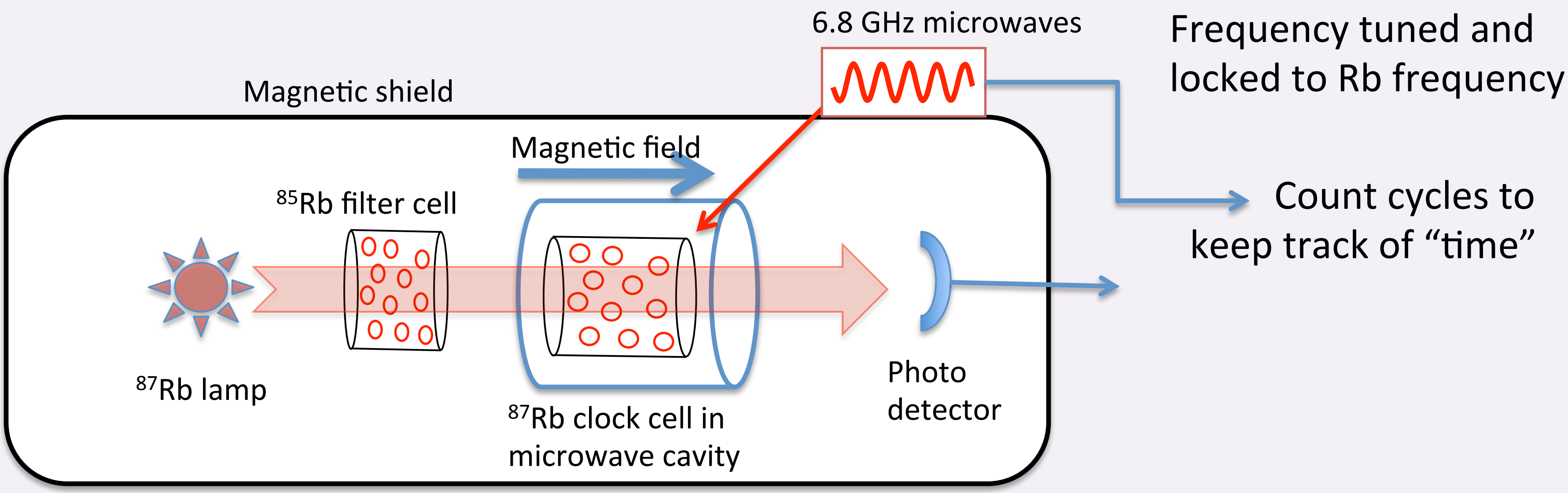
≈ 4 Rb atomic clocks per satellite

A side note :

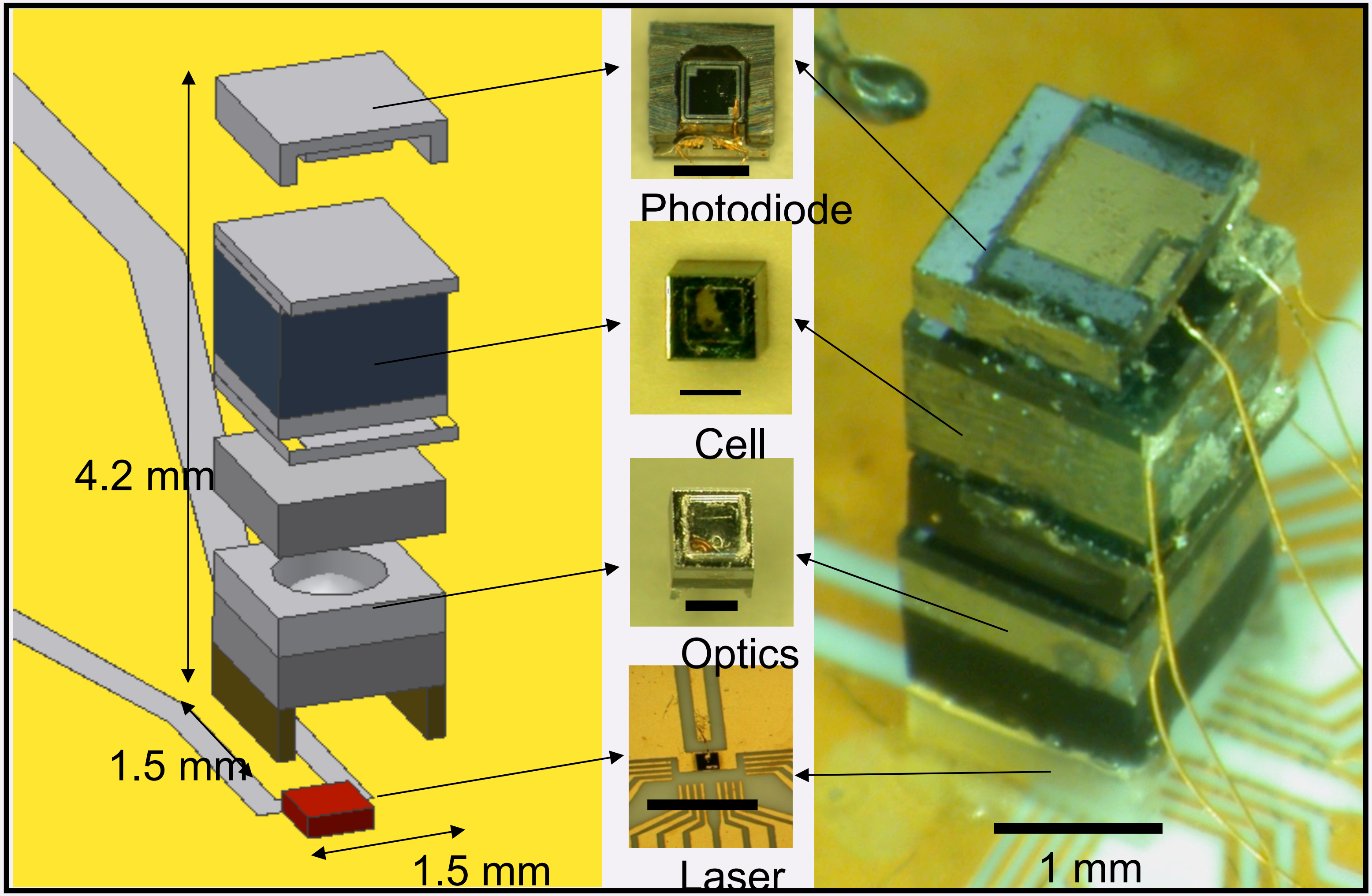
Rubidium Atomic frequency Standard, as in GPS

Really very simple concept, ideas from about 1960, but now highly refined.



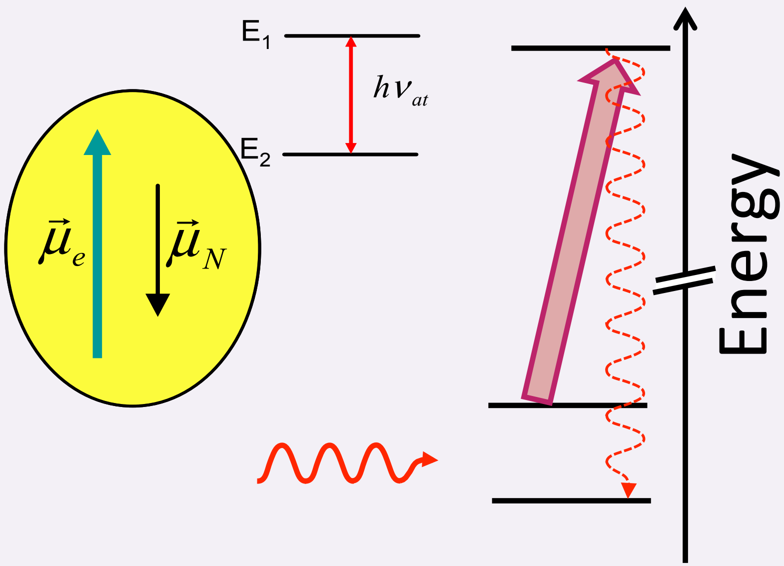


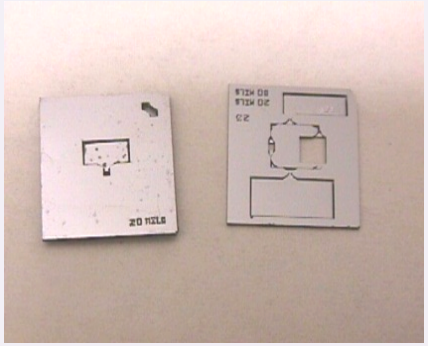
Chip Scale Atomic Clock (CSAC)

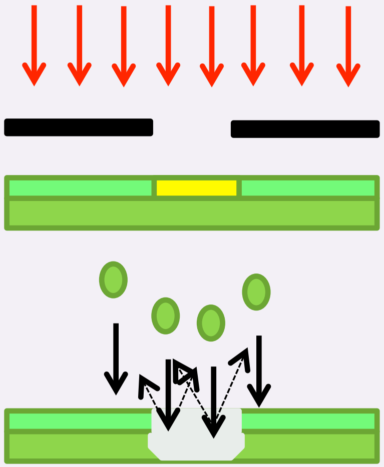


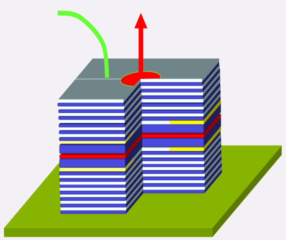
NIST, Kitching, Knappe, LH 2001--

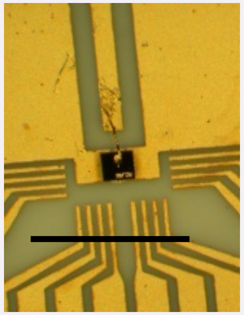
Chip Scale Atomic Devices

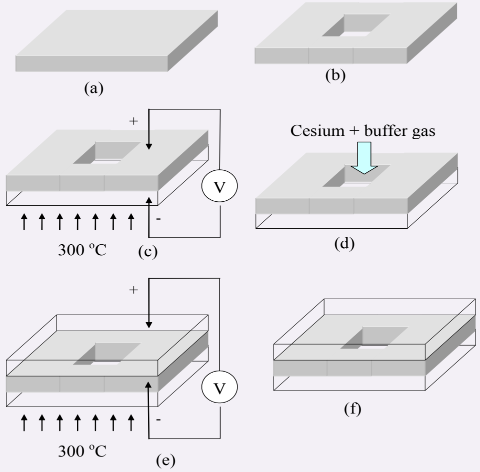


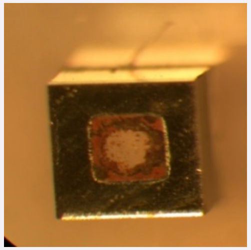


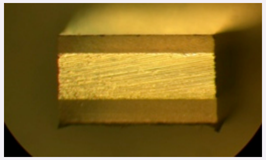








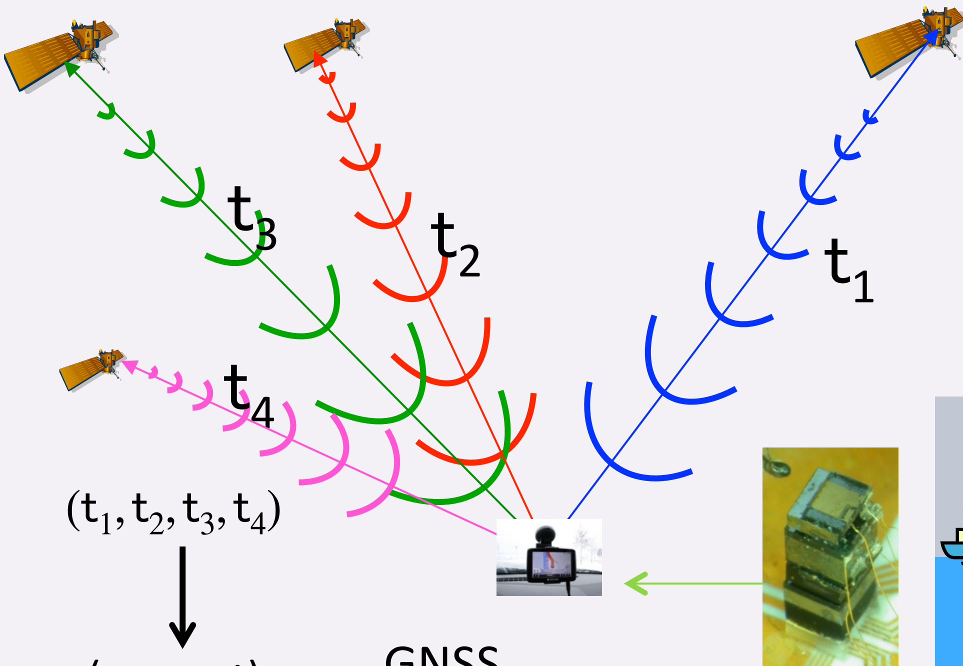




NIST, Kitching, Knappe, LH ....

- symmetricom device

CSAC PNT applications

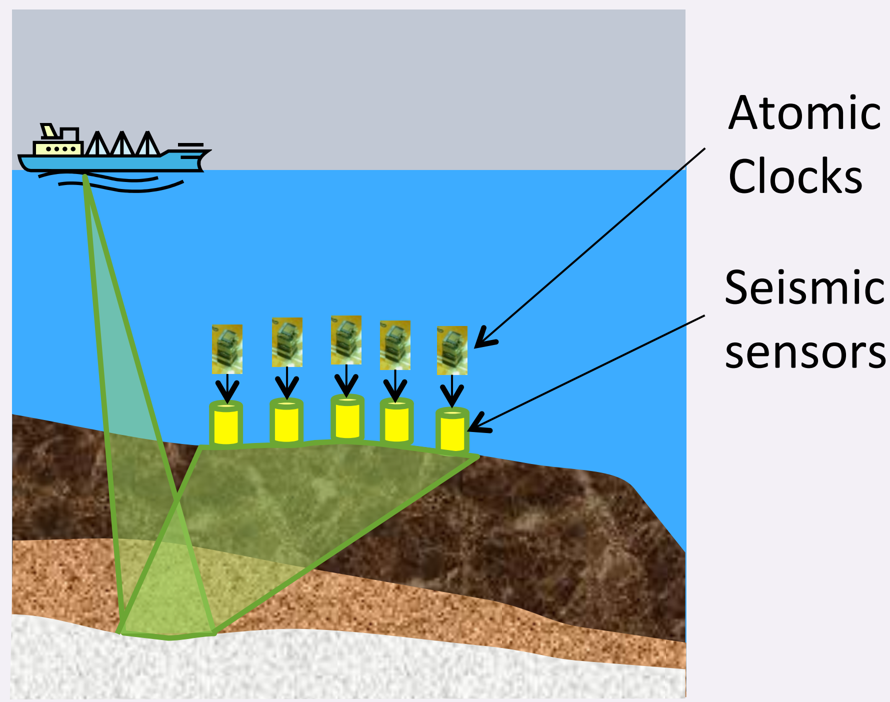


(t_1, t_2, t_3, t_4)

↓

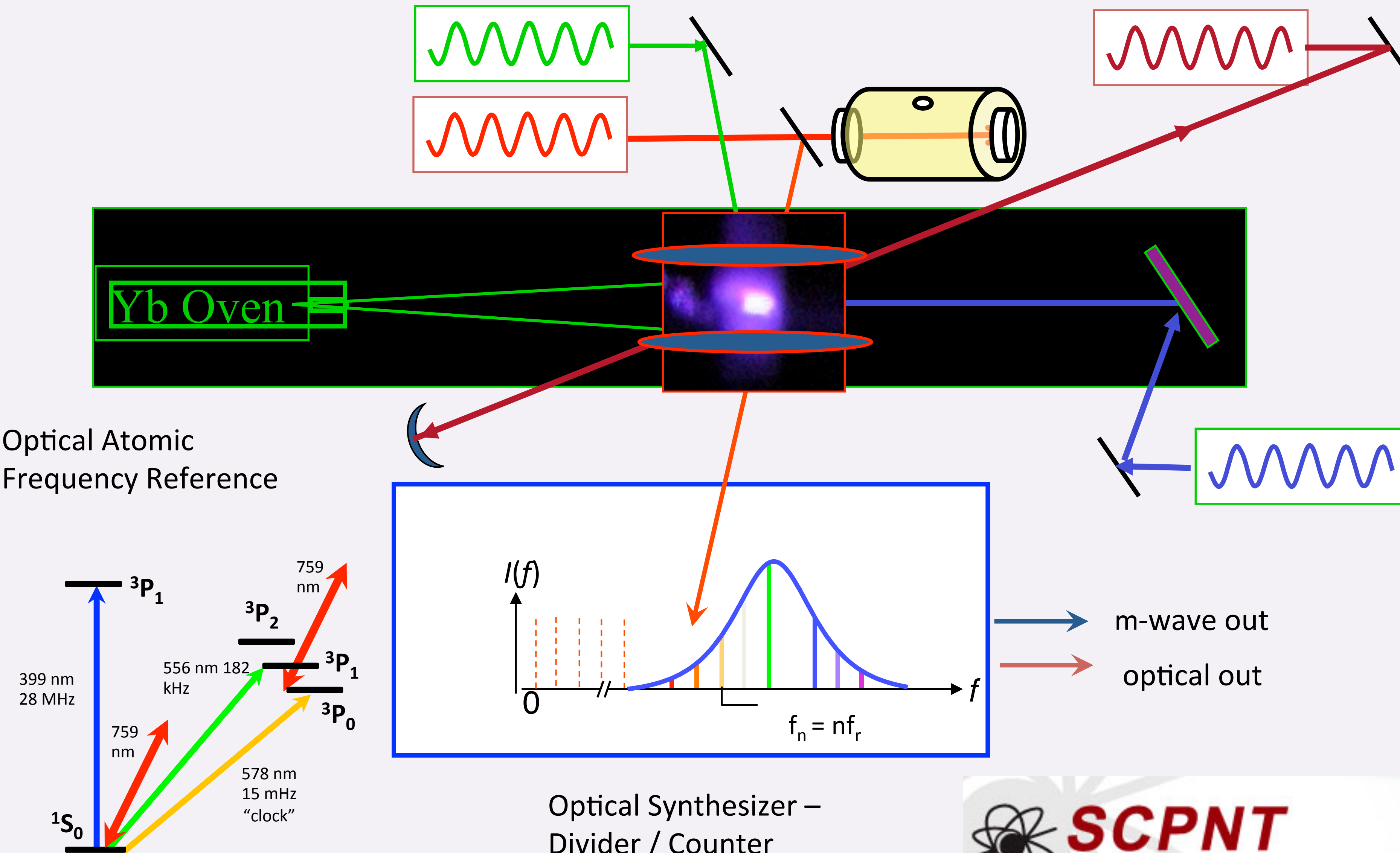
(x, y, z, t)

GNSS
Receiver



NIST, Kitching, Knappe, LH ....

Precision timing, frequency and Optical Atomic "clocks"



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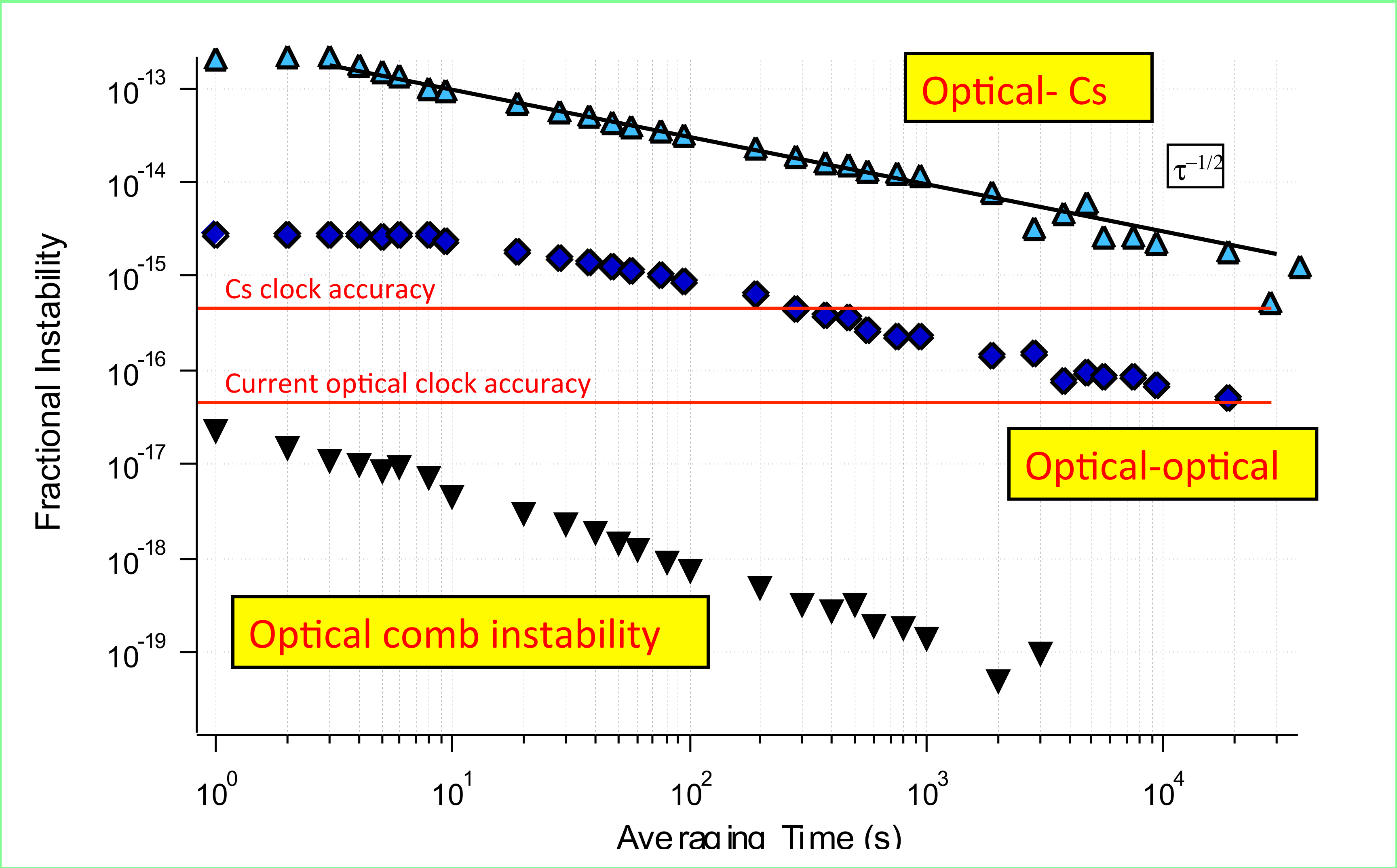
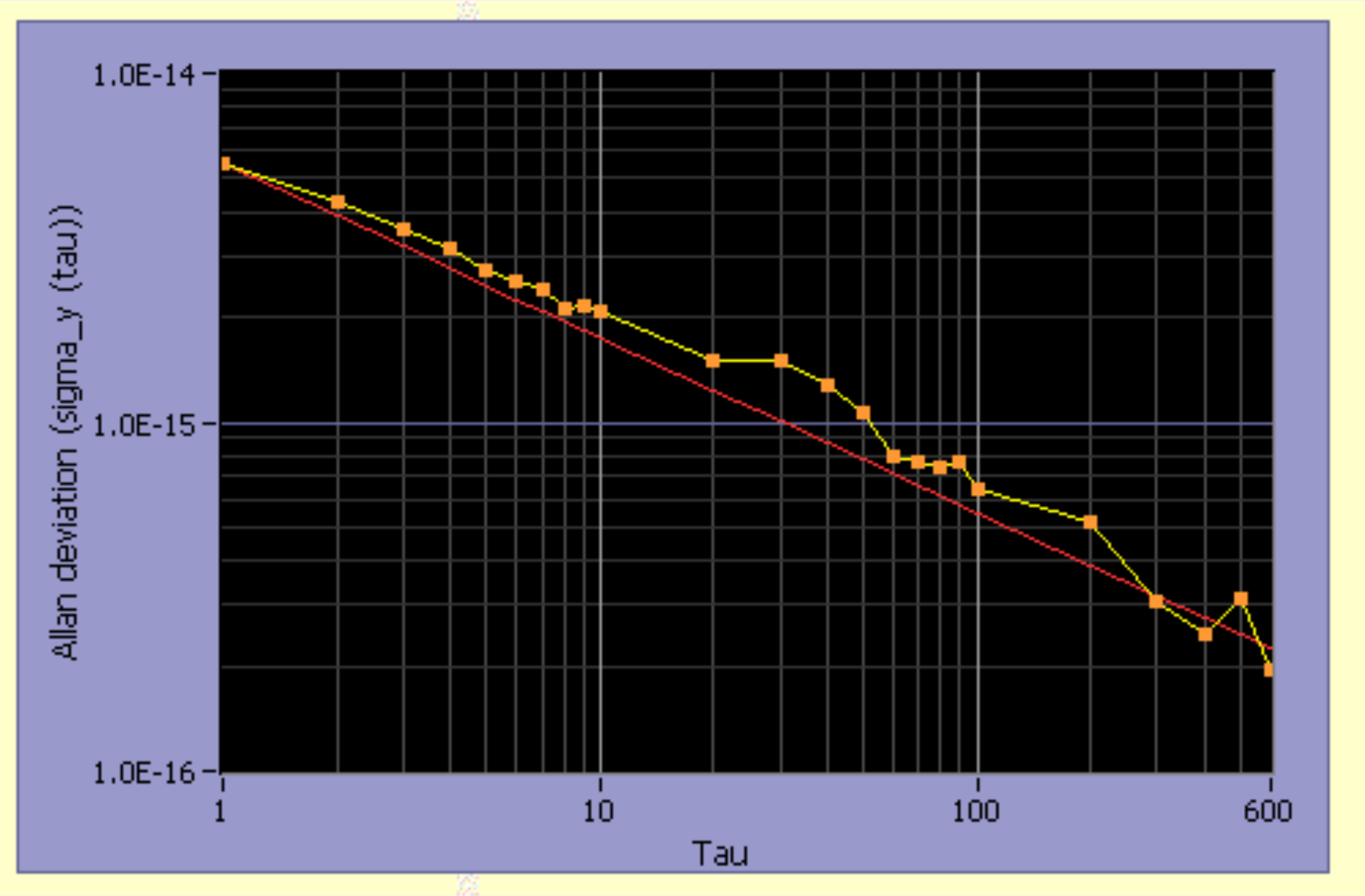
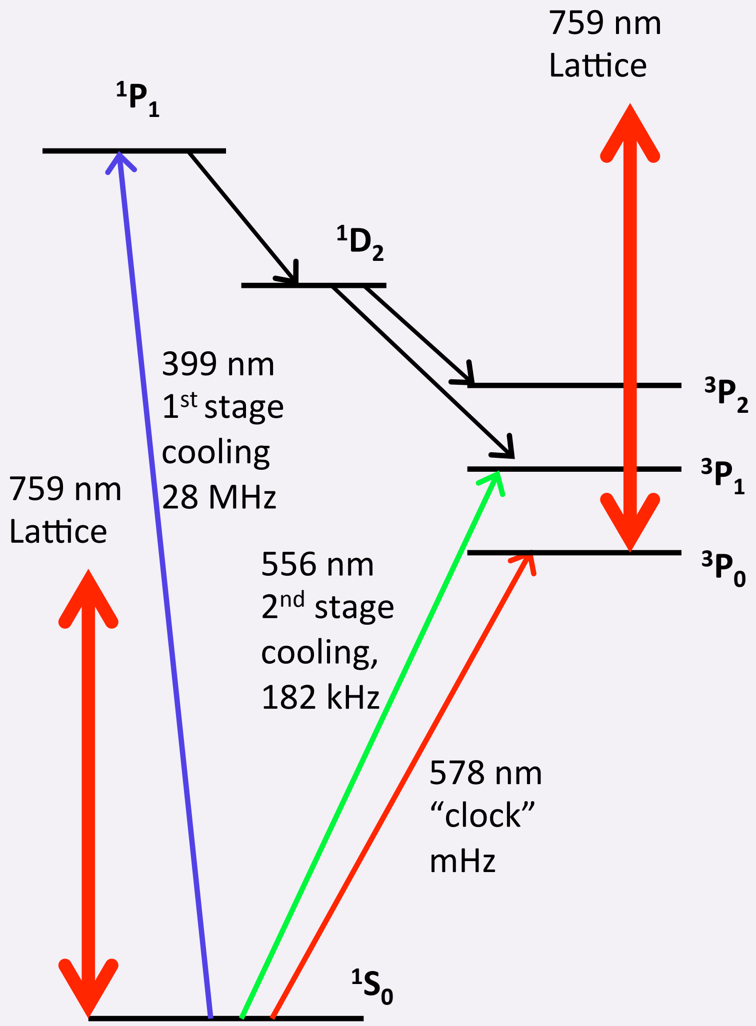
Example instabilities of clock comparisons with NIST frequency comb



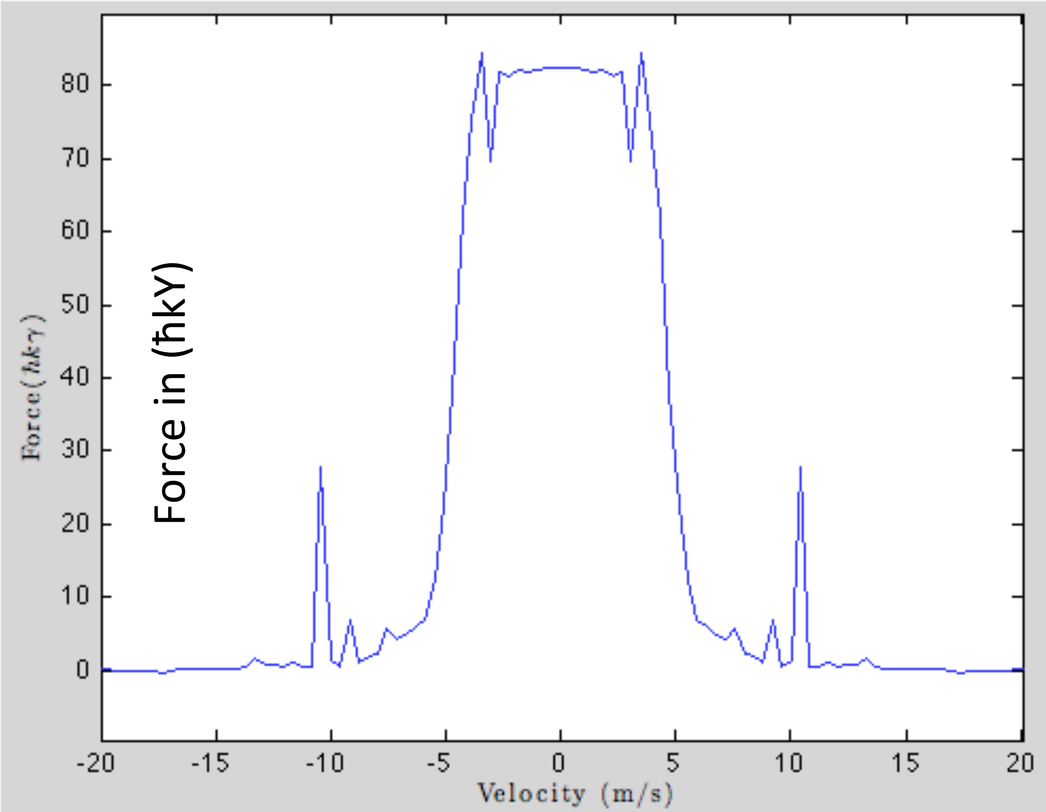
^{171}Yb vs Ca


1.0E-14
1.0E-15
1.0E-16
Allan deviation (sigma_y (tau))
1
10
100
600
Tau

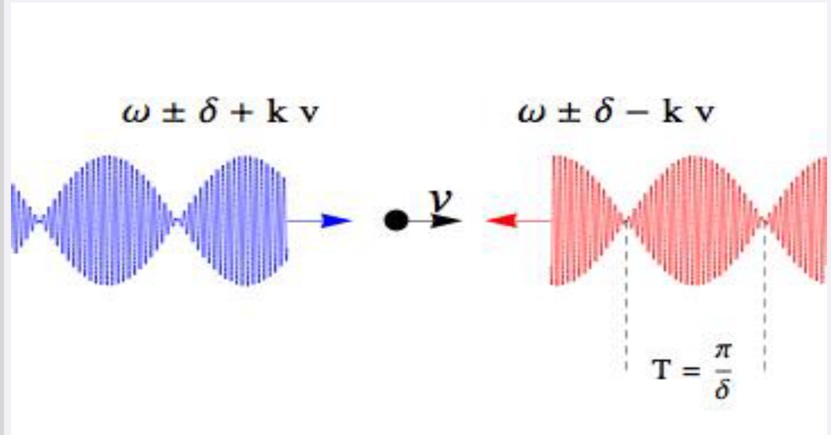
Can we simplify the Yb optical clock ???



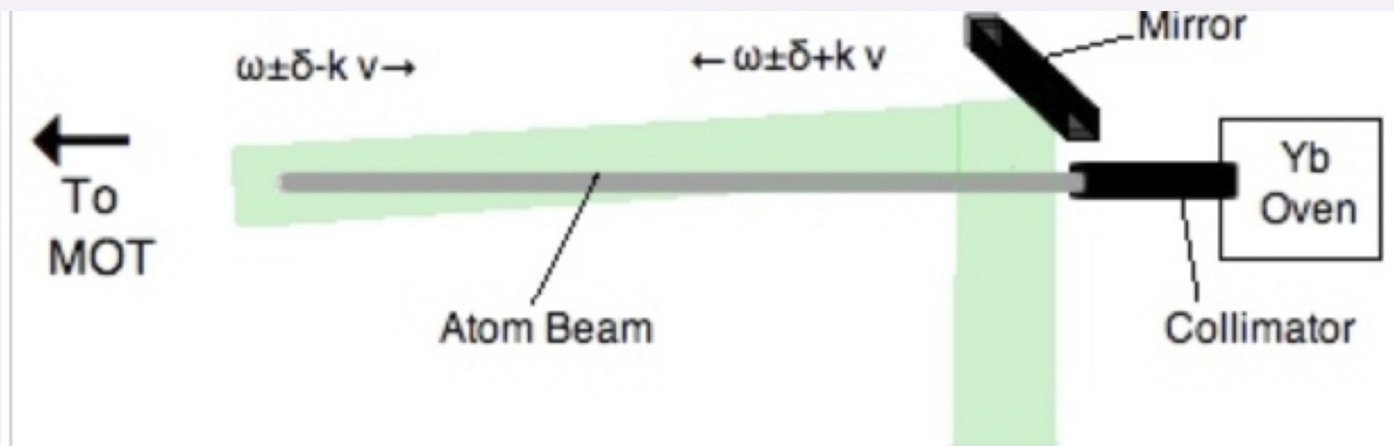
- No Lattice, free-falling cold atoms
- No 1st-stage cooling
- Faster 2nd-stage cooling ?



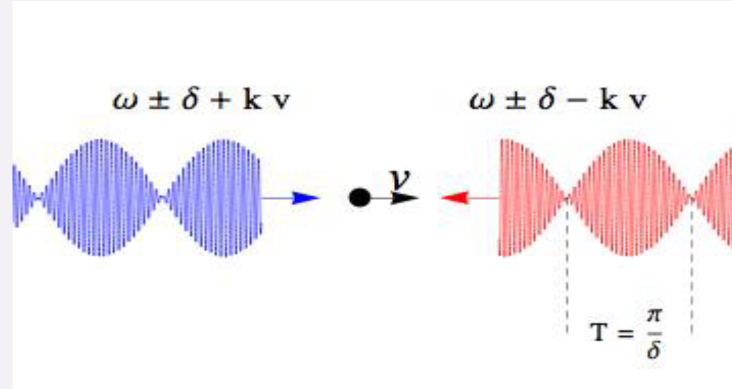
Atom Velocity m/s



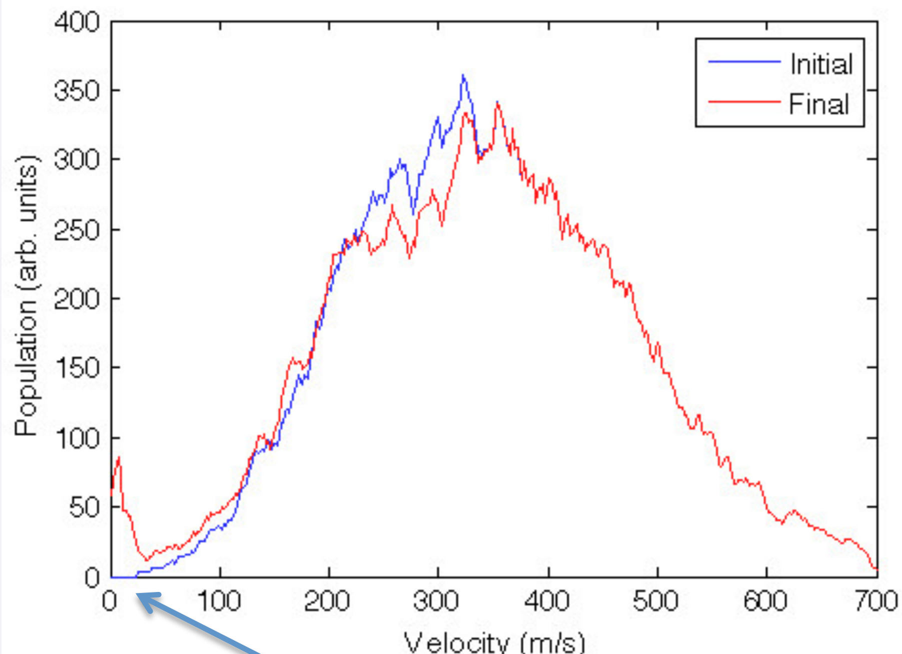
Analysis
by TianMin Liu and Nikhil Bordia



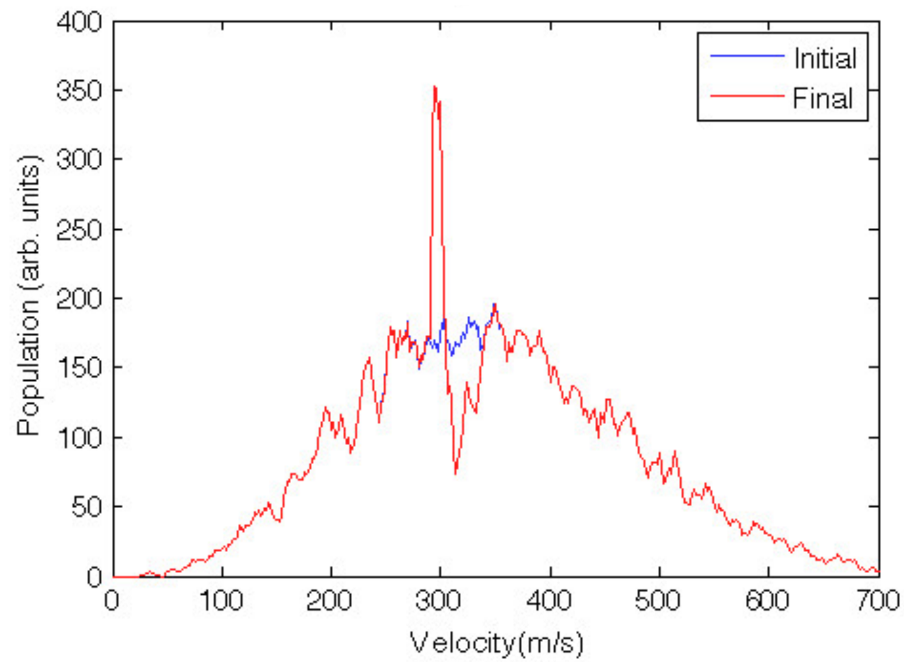
Stimulated slowing of Yb atoms
(556 nm intercombination transition)
Numerical model results
by TianMin Liu and Nikhil Bordia



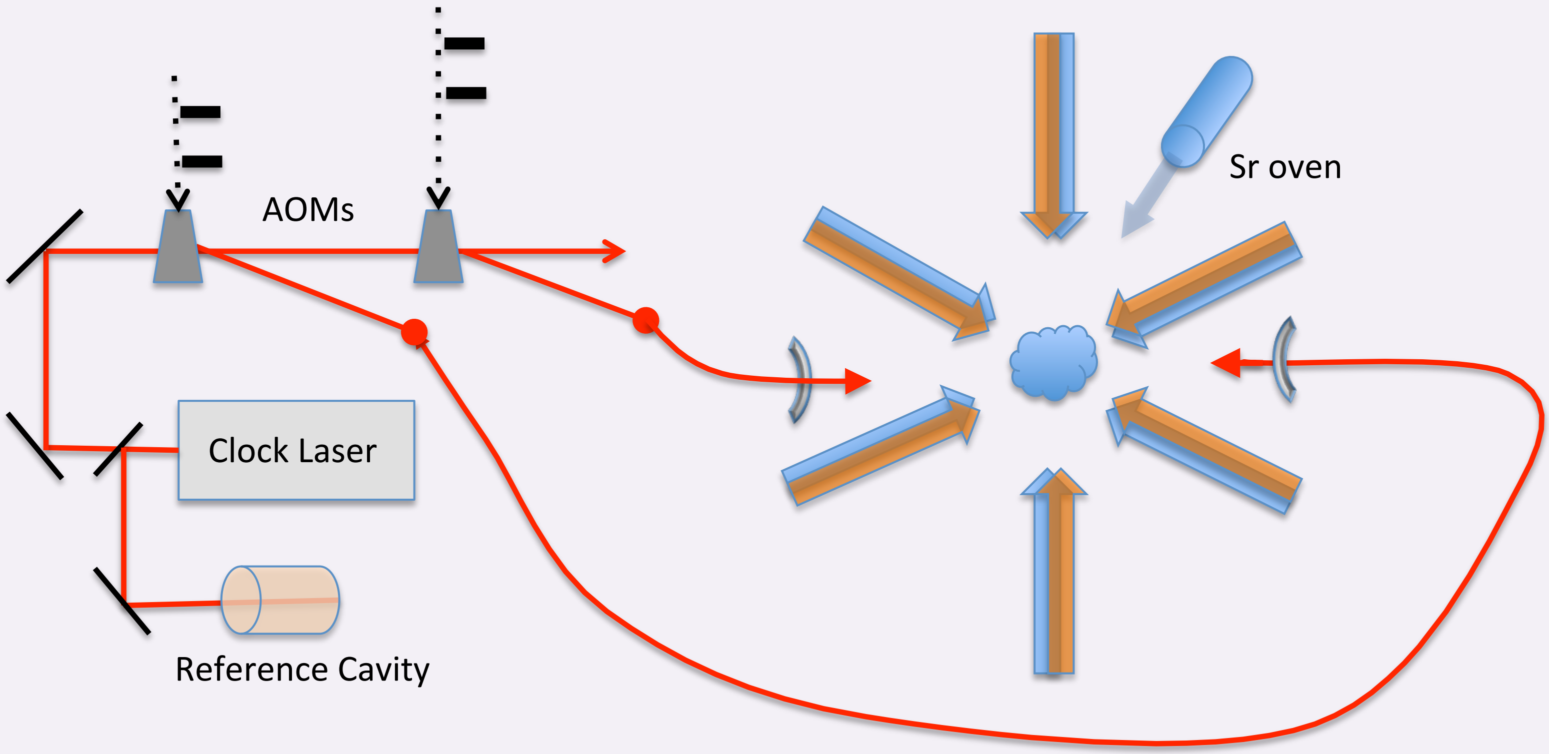
w/ laser frequency chirp



Fixed laser frequencies



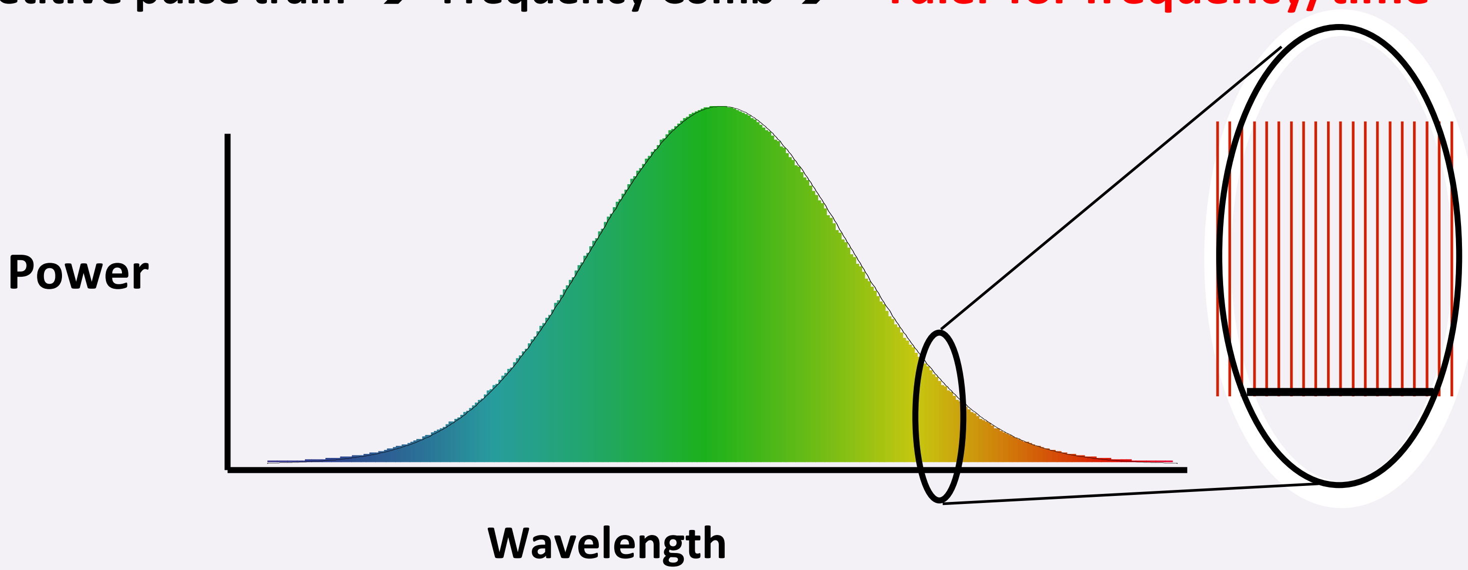
Atoms near zero velocity


AOMs
Sr oven
Clock Laser
Reference Cavity

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

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

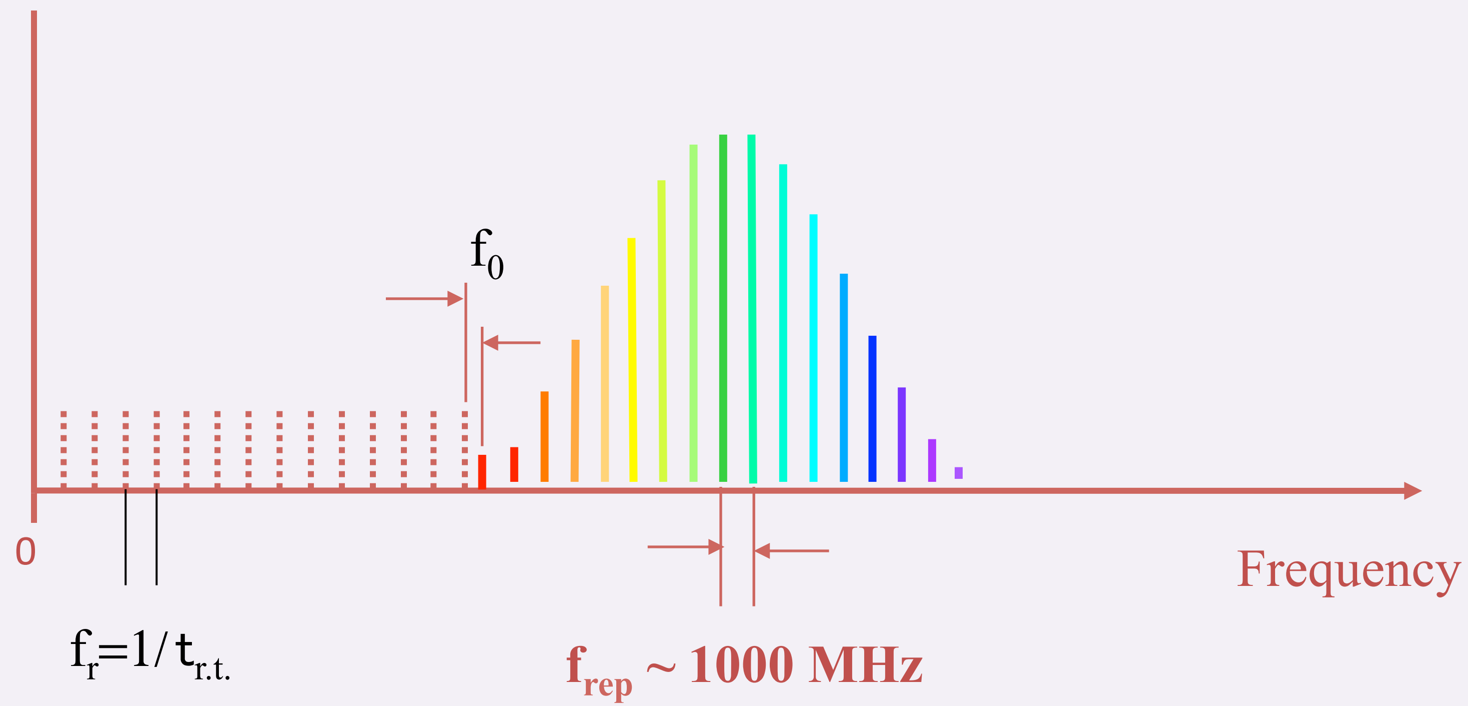
Repetitive pulse train ➔ Frequency Comb ➔ **"ruler for frequency/time"**



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

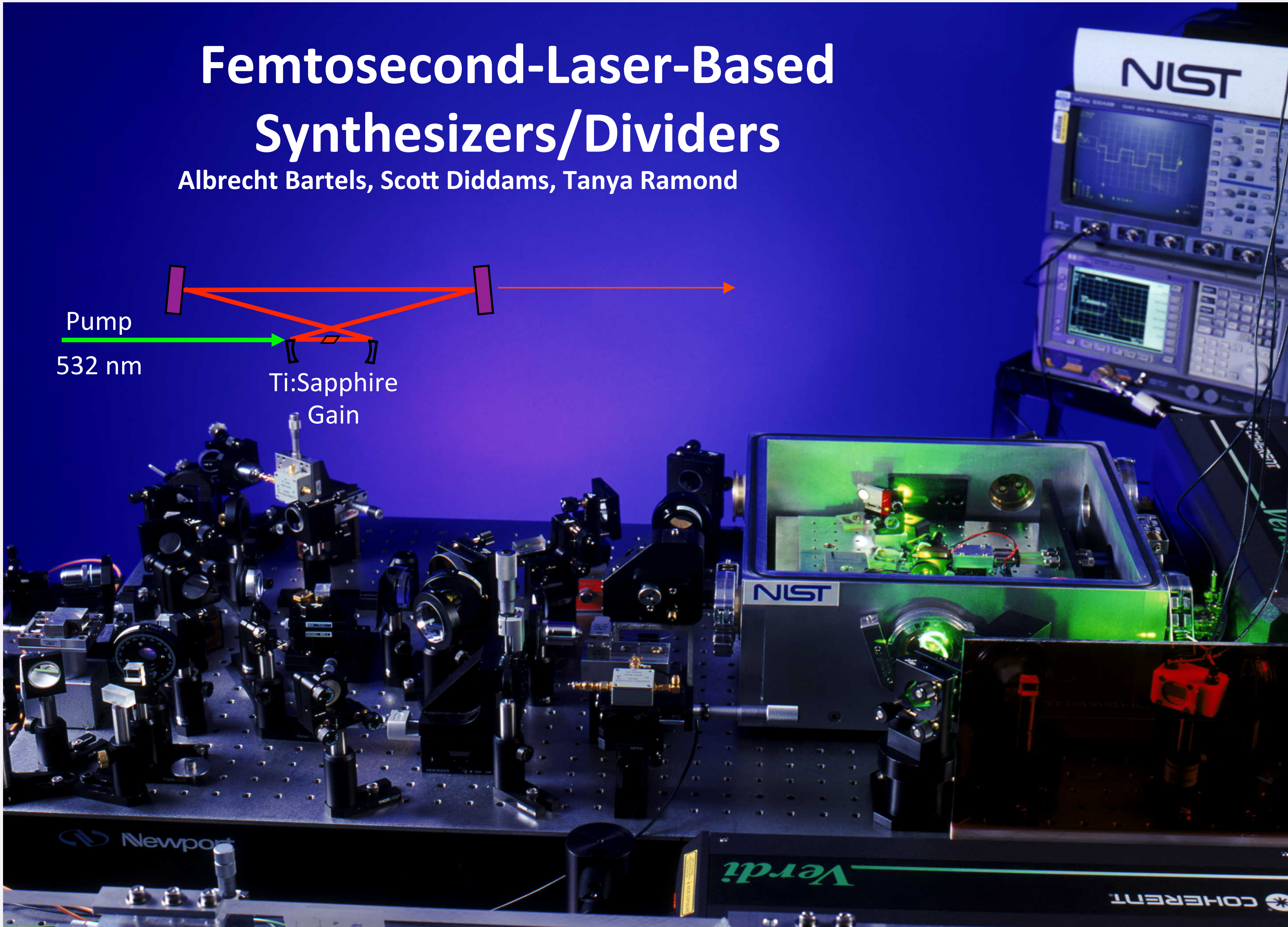
The frequency of a mode is simply $F_N = N * f_{rep} - f_0$ (0)

Where N is and integer ~ 10^6



Femtosecond-Laser-Based Synthesizers/Dividers

Albrecht Bartels, Scott Diddams, Tanya Ramond



Optical Time, timing ?

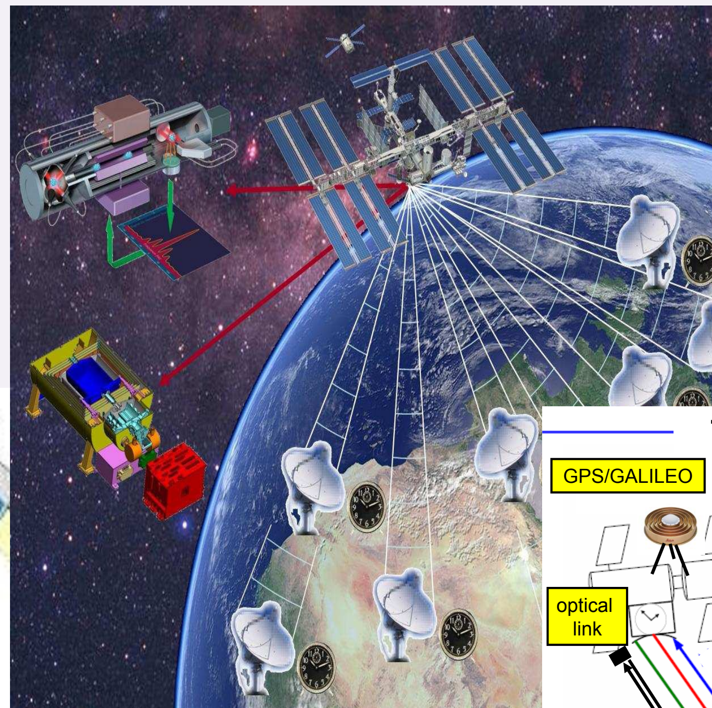
- Can the fantastic optical atomic clocks and fs combs make significant impacts for real-world applications or users of precise “time”?
- Can lasers and optics have significant advantages over exiting technologies or enable something not otherwise possible ?
- Where is “better” timing needed ?
- What is “better” ?

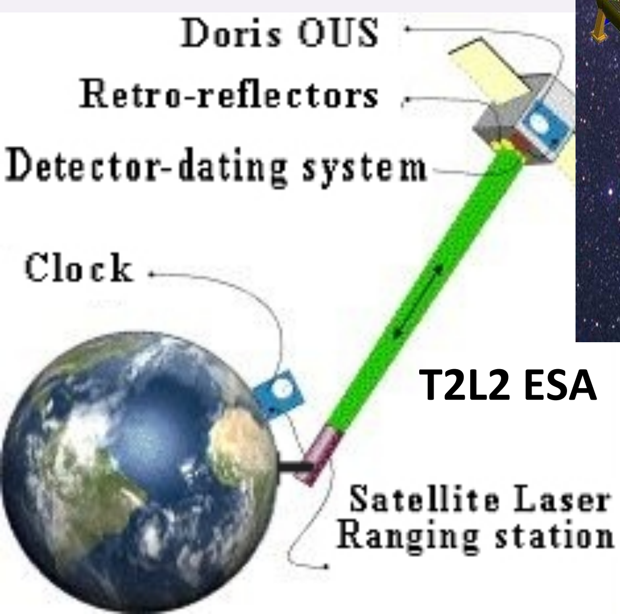
  accuracy, stability, robustness, size, weight power, reliability, lifetime, cost, epoch, jitter, phase noise... ?
- How do we get it to the user ?
- High value when precise Time and be transferred to everyone

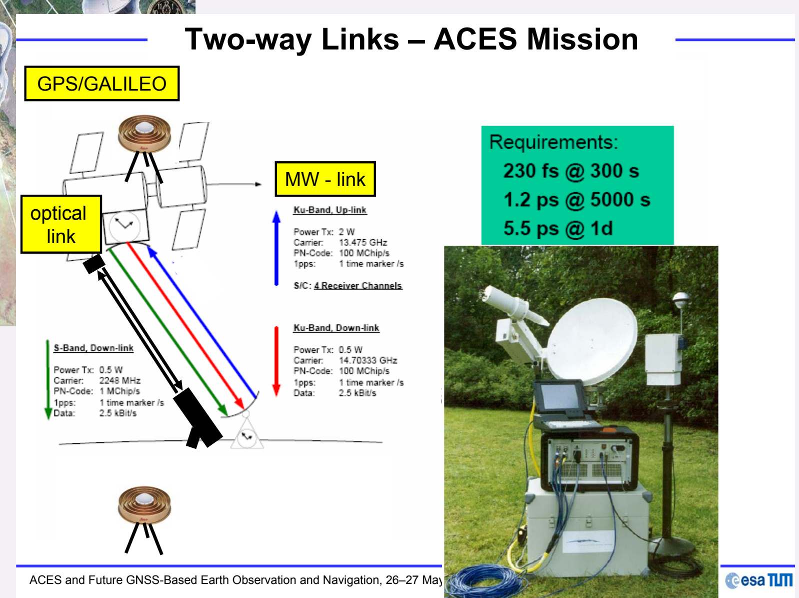
  (e.g. GPS from space)

Issues of Time-Frequency Transfer

• GPS, TWSTT, limited to about (note 1 day ≈ 10^5 seconds)	1 ns
• Via telecom optical fiber networks, possible, not generally avail.	few ps
• Dark optical fibers, two-way, not generally avail.	fs
• T2L2 ESA expectations (laser pulses ground to space)	10 ps ?
• ACES two-way microwave link	3 ps ?







Laser Link and Space–Time Reference for Earth

1. Improve knowledge of GNSS clocks and ephemeris
    - GNSS (GPS, GLONASS, GALILEO, COMPASS-BEIDOU)
    - Remove troposphere and ionosphere delays
    - More stable T(ime) & freq, accurate position reference: T, **R**
2. Precision Geodesy
    - mm position on Earth ?, water movement, ice, atmosphere…
    - Geodetic reference frames
3. Time, frequency transfer worldwide
4. Physics experiments
    - Precision measurements of Space-time (GR, KT, MM, LPI, c (t,r) ?
    - Searches for new physics (fields, ...)
    - Enabling for earth based measurements that need precise T, **Rs**

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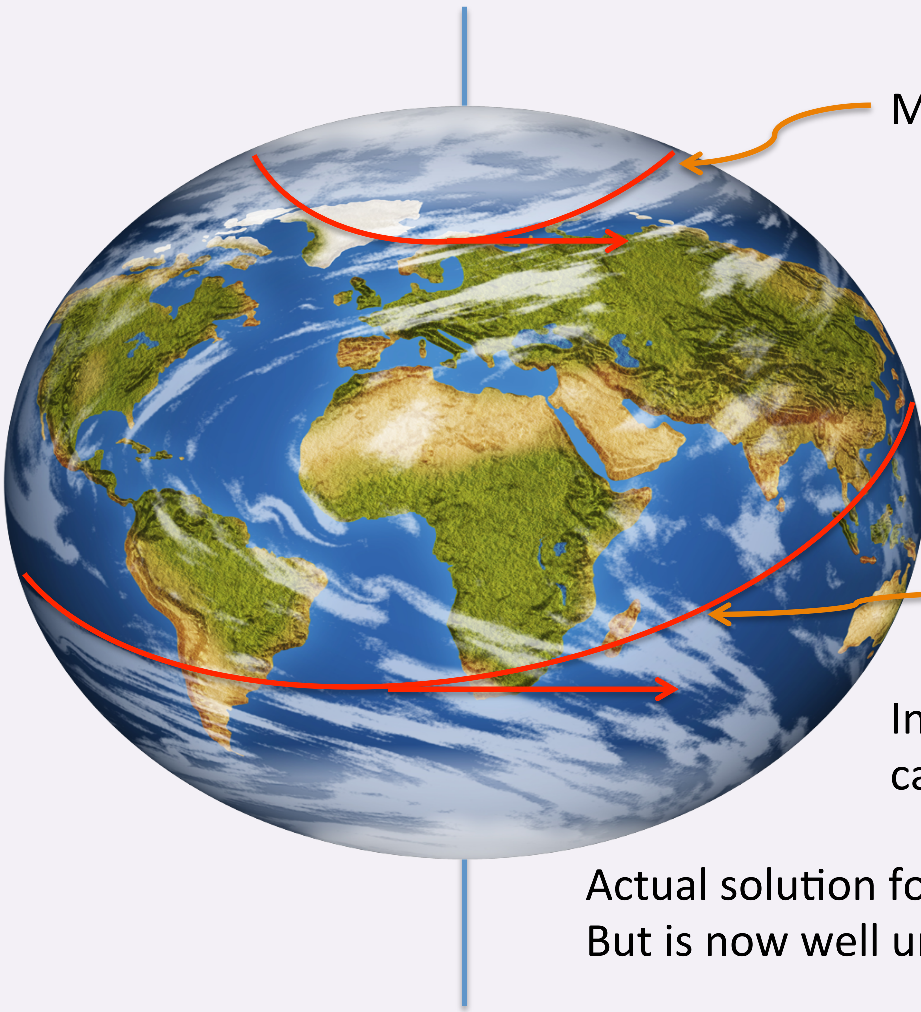
Yes but we are on a rotating earth, which is a non-inertial frame



More gravity due to oblates

$$(cd\tau)^2 = \left(1+\frac{2\Phi}{c^2}\right)(cdt)^2 - \left(1-\frac{2\Phi}{c^2}\right)\left(dx^2+dy^2+dz^2\right)$$

$$\Phi = -\frac{GM_{Earth}}{r}(1+\cdots)$$

$$\Delta t = \oint_{path} d\tau\left(1+\frac{V^2}{2c^2}-\frac{\Phi}{c^2}\right)$$

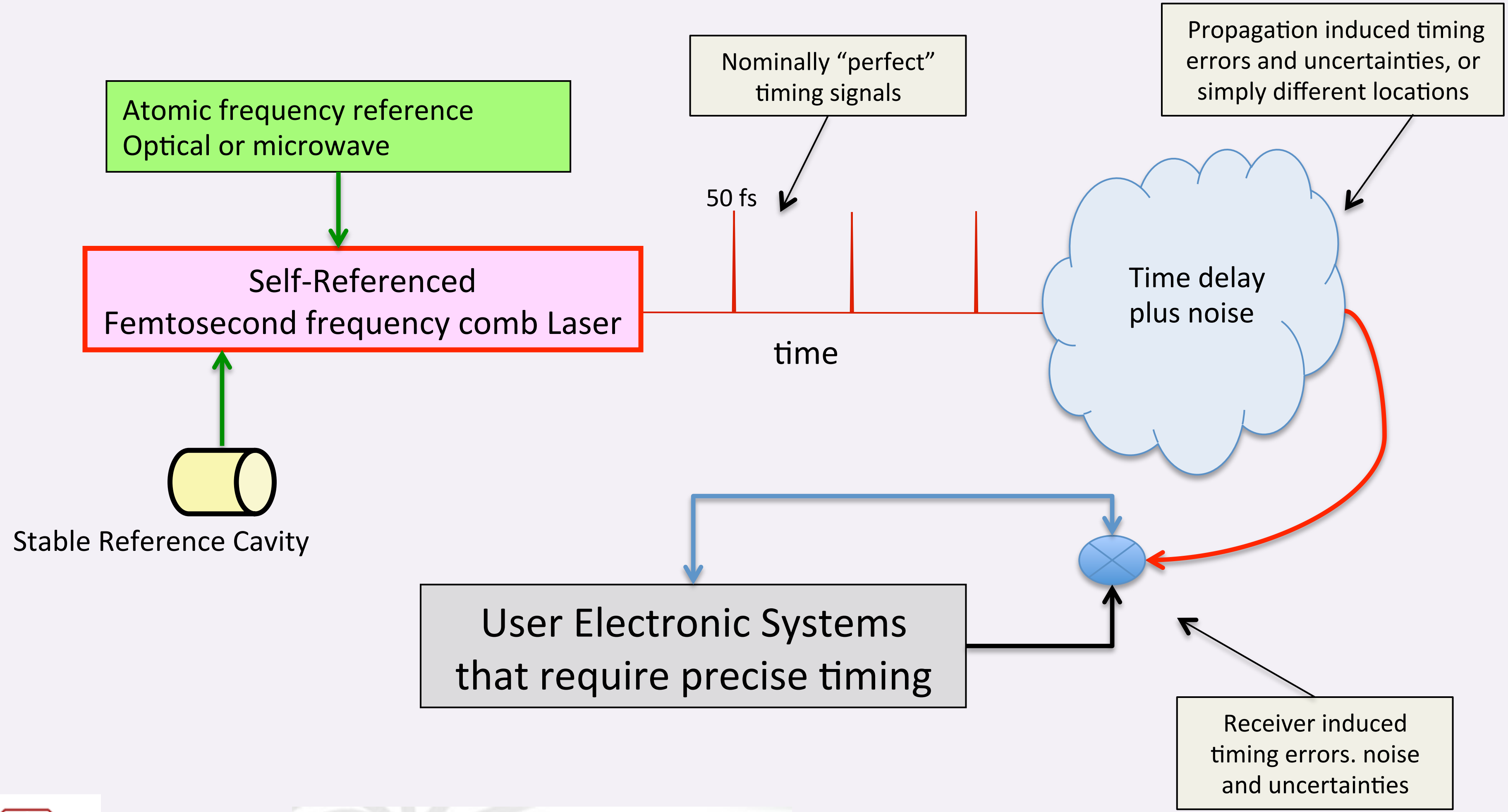
More time dilation due to larger ωR

In the end the various terms tend to cancel out on the equipotential Geoid

Actual solution for position and time is rather involved. But is now well understood and carefully implemented

As per N. Ashby, relativity.livingreviews.org and elsewhere

Notional "Time" transfer problem:
Short distance (mm, on chip) or long distance (100s km, free space or to space)



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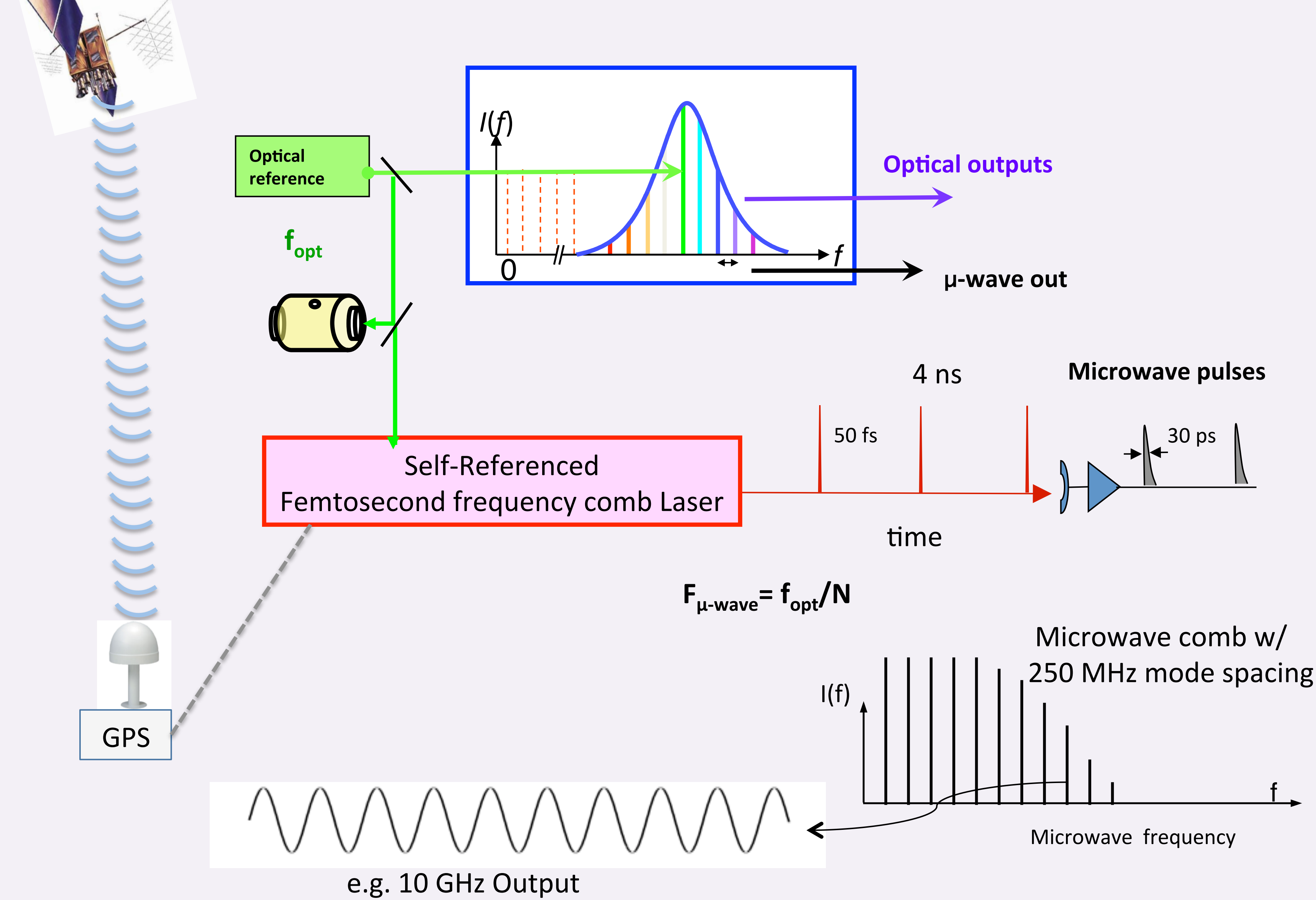
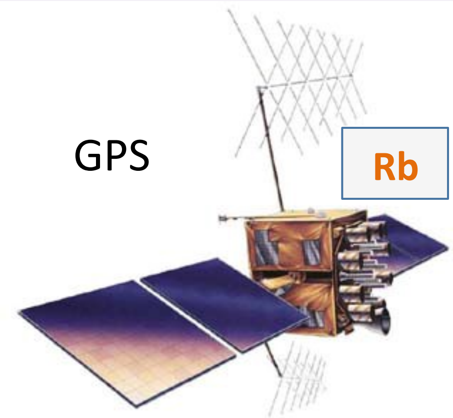
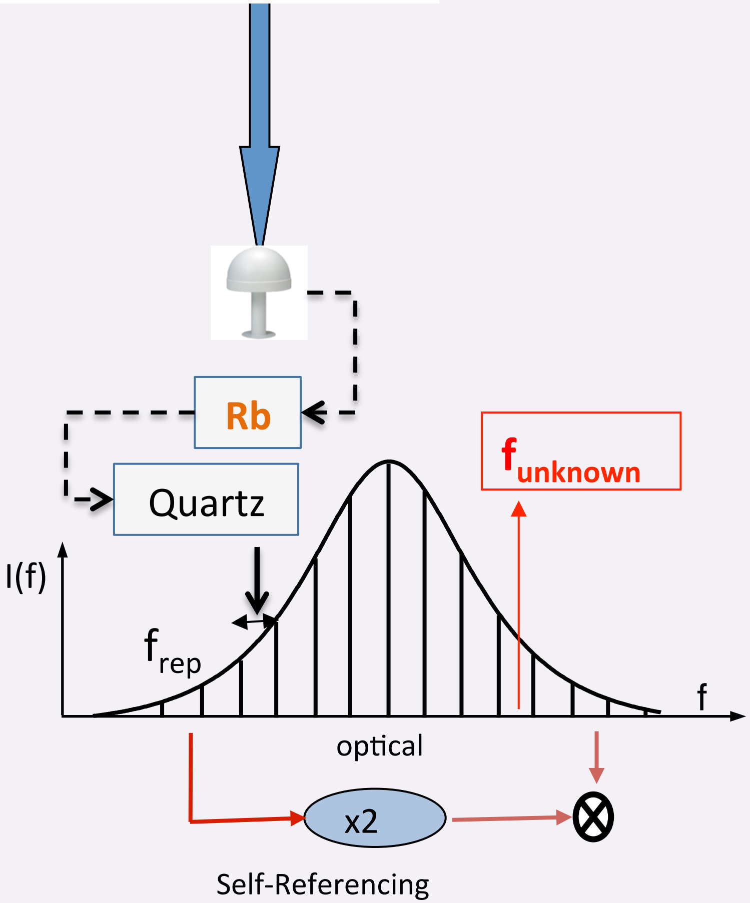
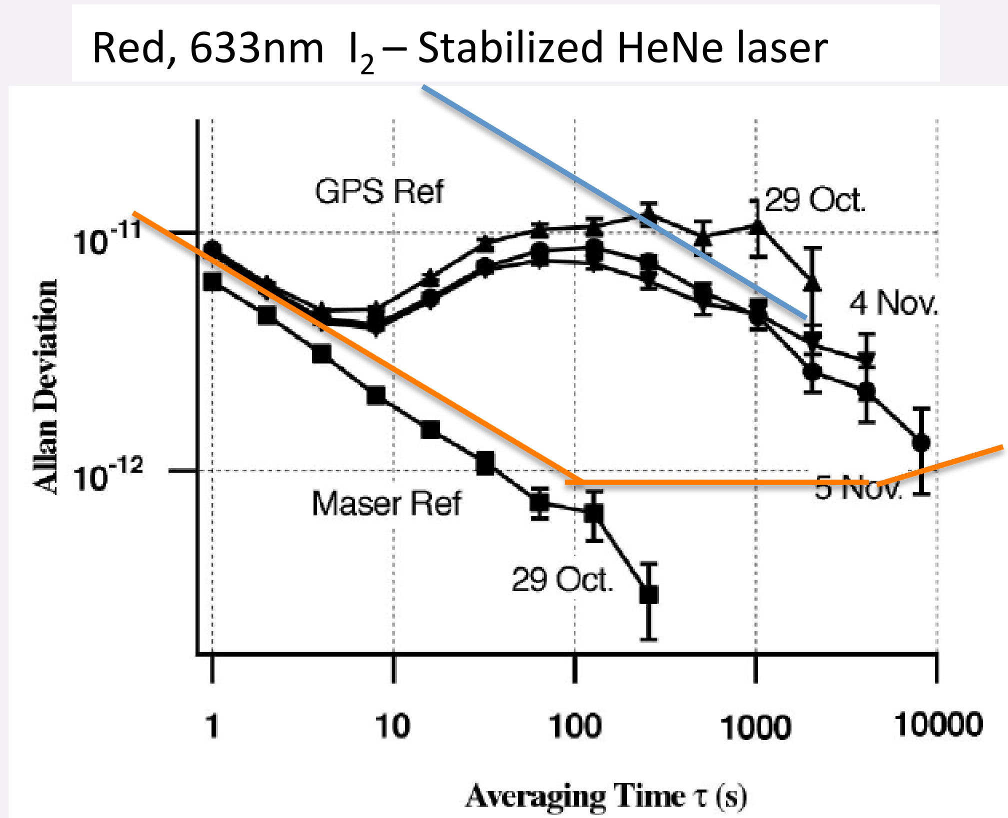
requency combs as perfect timing reference
eration of microwaves with low phase noise



Optical Frequencies Measured via GPS



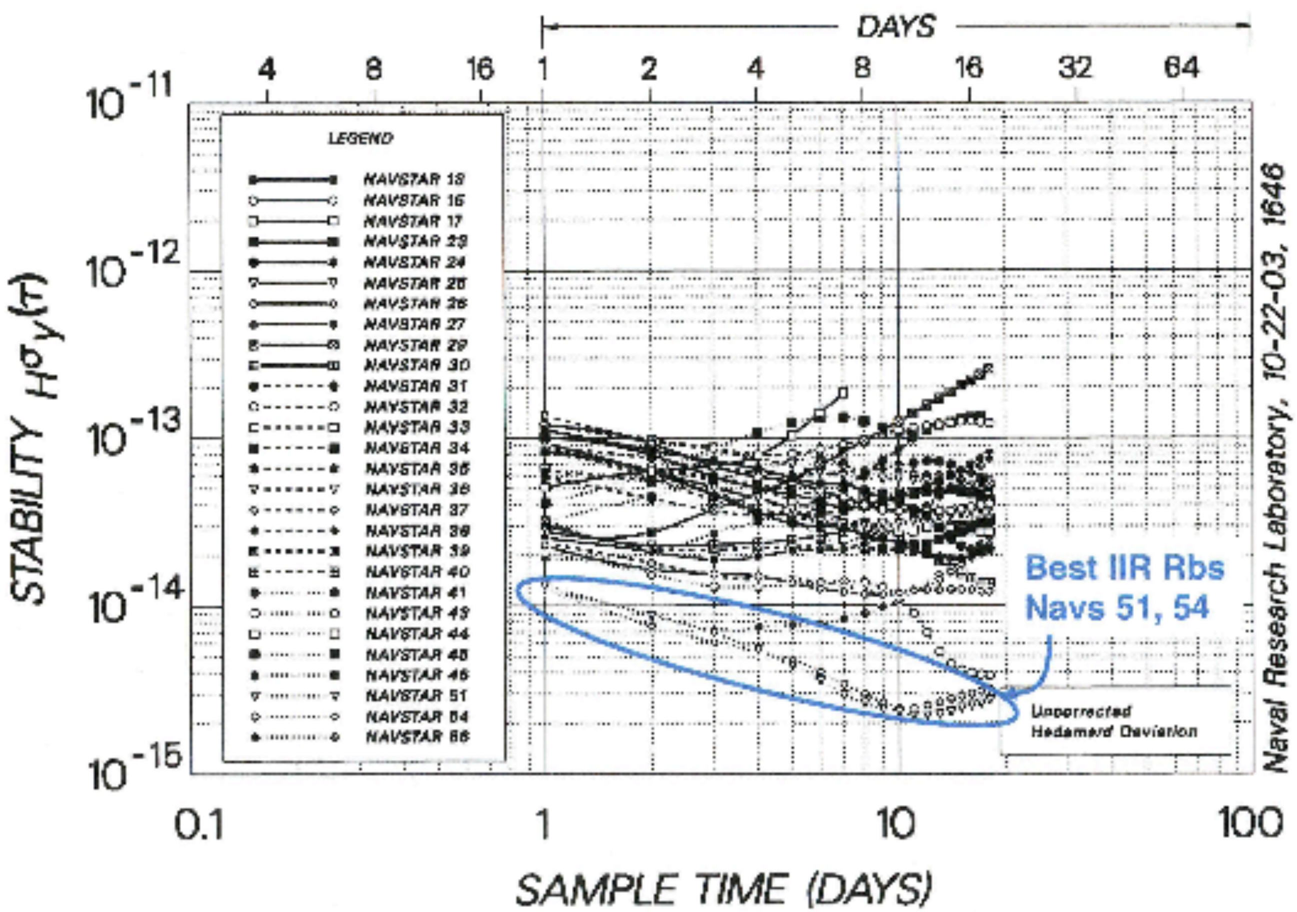




Fox et al. Applied Optics, 05,

Commercial systems now available, Menlo Systems

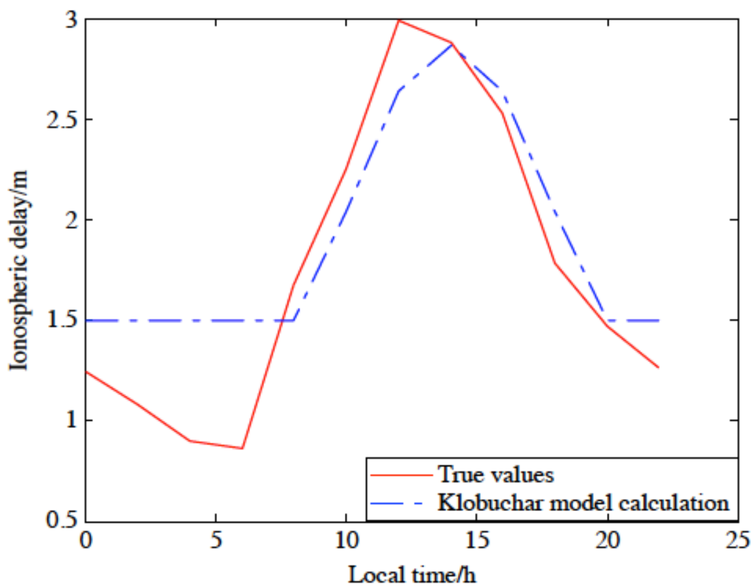
FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock
1-APR-03 to 1-OCT-03



Ionospheric delays, temporal and spatial fluctuations are significant

Wang Xinlong and Li Yafeng

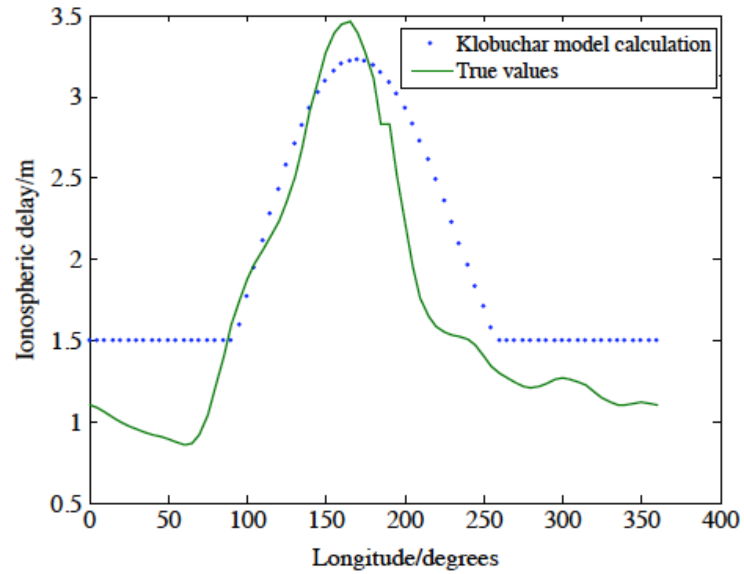
Figure 6 Curve of the relationship between ionospheric delay and local time



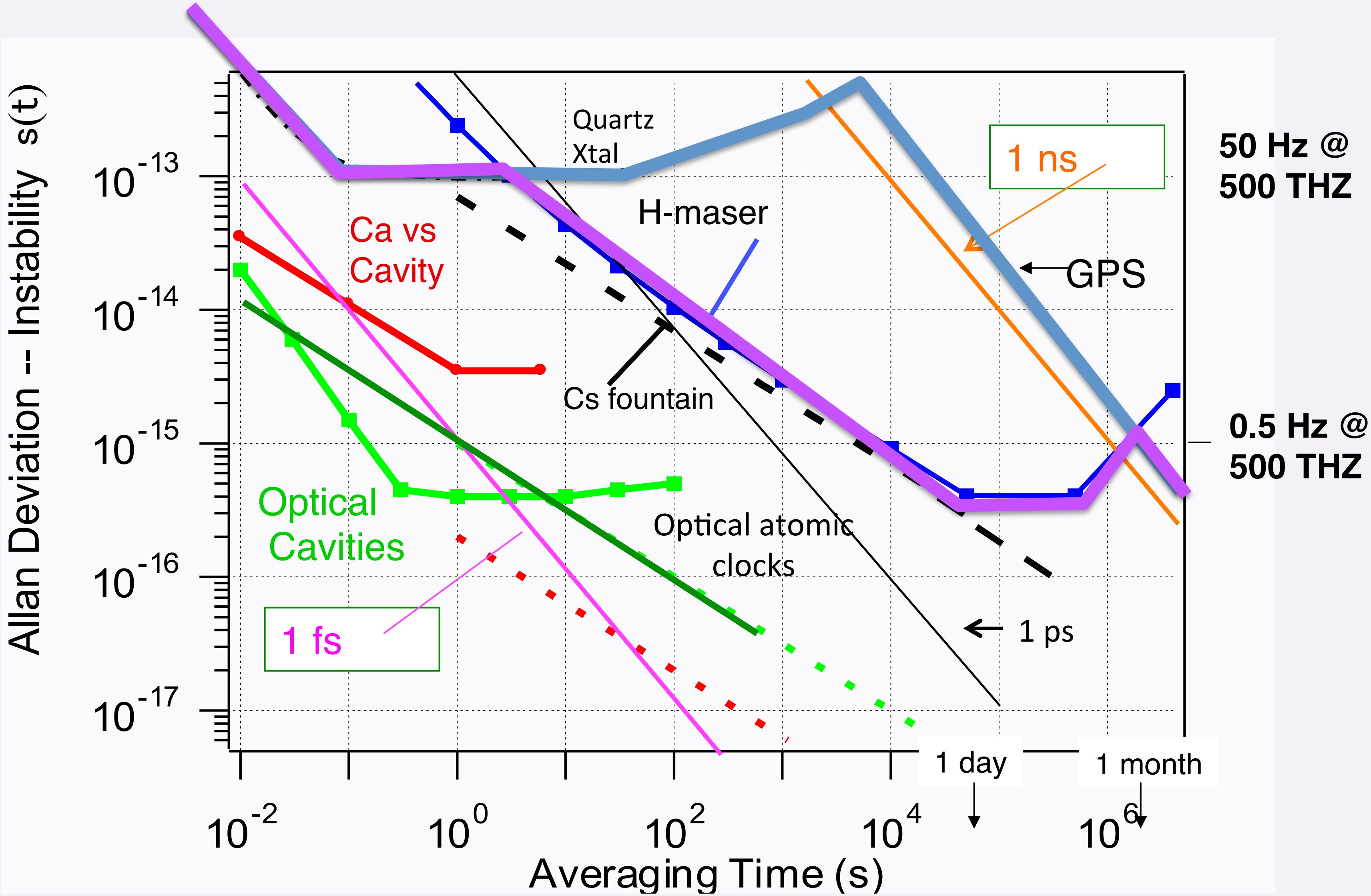
Aircraft Engineering and Aerospace Technology: An International Journal

Volume 81 · Number 4 · 2009 · 316–322

Figure 8 Curve of the relationship between ionospheric delay and longitude



"Clock" Frequency instability vs. time interval



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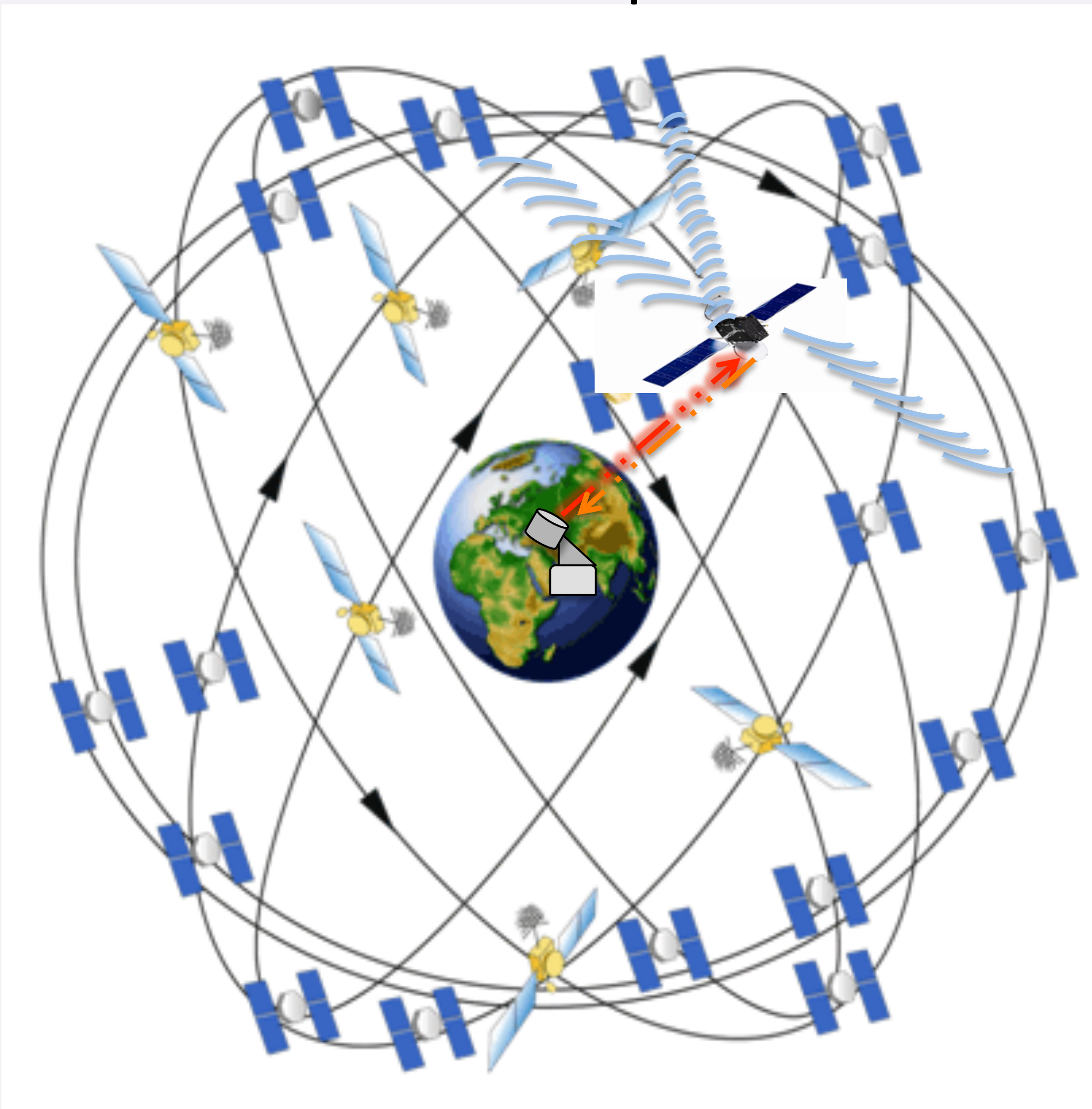
Time Transfer: *Optical*

- **Advantages**
  - Better timing precision, and accuracy
  - Ultra-short optical pulses, fs-optical frequency combs
  - fs timing precision achieved in labs, and some dedicated fiber networks
  - Less atmospheric dispersion, delay than microwaves
- **Limitations:**
  - Line of sight, reflection or via fiber
  - Dedicated system requirements
  - Clouds …

- **Questions & Opportunities**
  - Free space vs. fiber links ?
  - Highest performance TT that is robust, reliable, practical
  - Leverage and enhance other GNSS systems
  - Laser ranging systems to space show promise, demo projects underway in Europe T2L2, ESA-ACES mission – cold atom clock on space ISS 2016 ?

Big Vision is: Optical Time transfer can enhance performance of GPS and enable space-science and earth-geo science applications



- ps vs. ns Time transfer
- A satellite below GPS orbits but above most of ionosphere
- Optical link to state-of-the-art clock on the ground
- Monitor GPS system clocks
- Requires pretty good atomic clock on MEO satellite but can measure to best ground clocks each orbit
- Time/freq transfer between best clocks around the world

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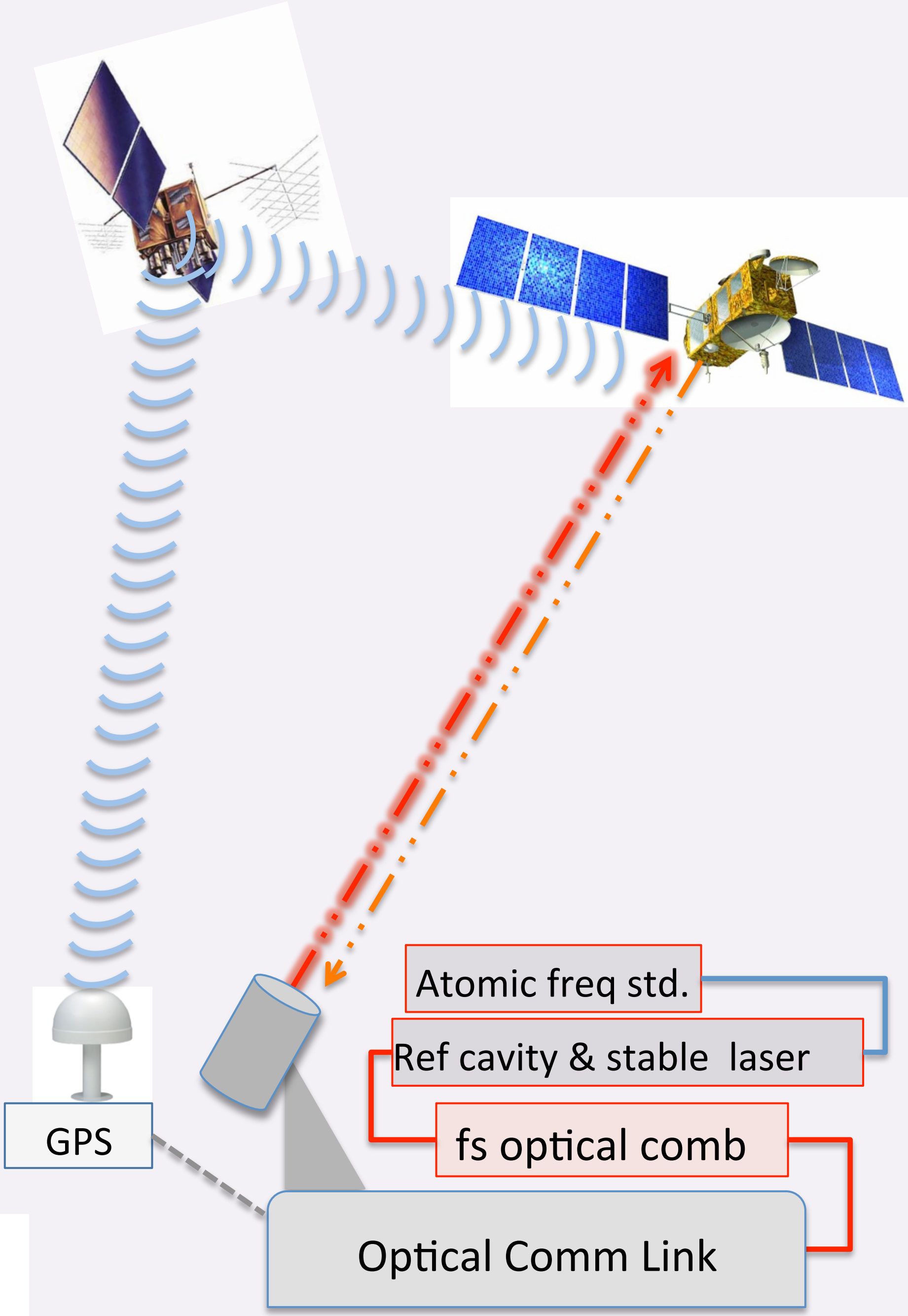
Laser Link and Space-Time Reference



- Basic idea :
  - With a high performance laser Time-transfer link from great clocks on ground to MEO satellite that has space clock (e.g. GPS – Rb, GALILEO H-Maser, JPL – Hg+ ion)
    - could upgrade in future to optical atomic clocks if/when ready plus fs-comb.
  - Mitigates:
    - Errors due to atmospheric delays of GPS signals to ground
    - Separates clock errors from tropo-ionospheric delay uncertainties
    - hence better knowledge of GNSS clocks and ephemeris from
    - stable orbit reference with good clock.
  - Goal 1 ps Time-transfer
  - Goal mm ranging to space
  - Goal of stable and predictable orbit with 1 mm precision

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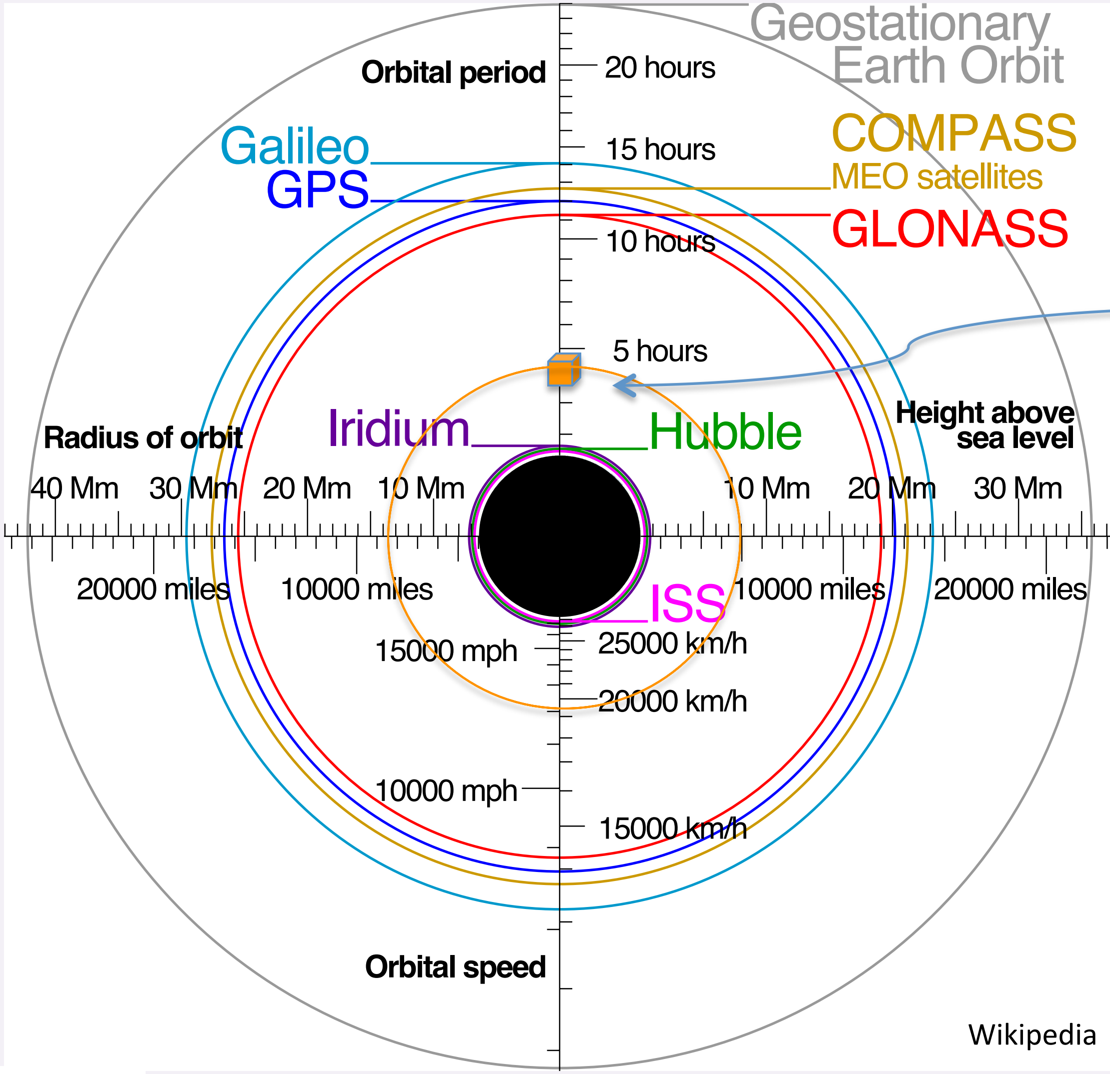
Space Time Reference in Mid-Earth Orbit (low-MEO)



- Well above ionosphere
- Well below GNSS orbits
- Low drag
- Monitor GNSS satellite clocks from above the troposphere and ionosphere
- Optical link transfers high performance clocks to space

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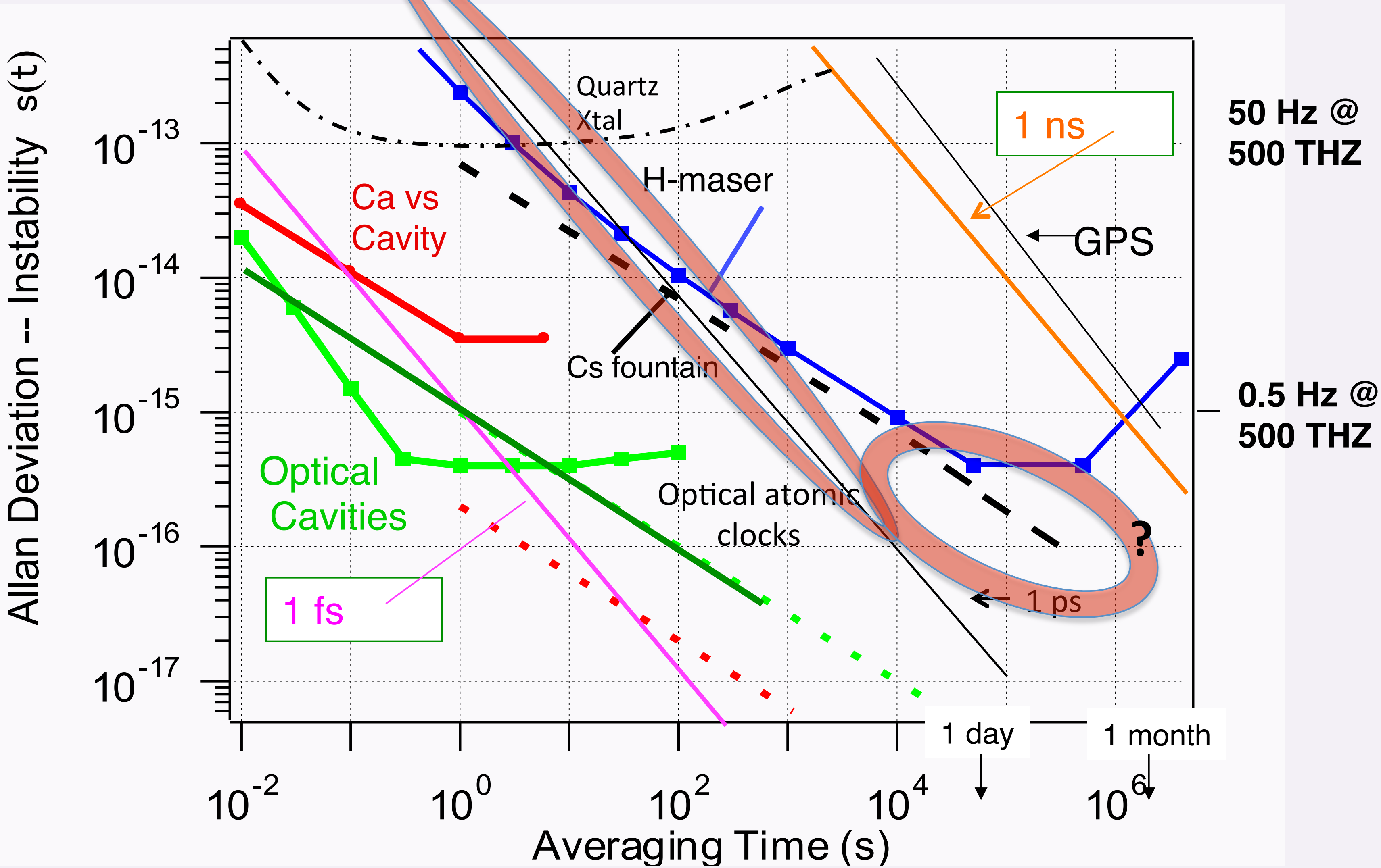
“Clock” Frequency instability vs. time interval



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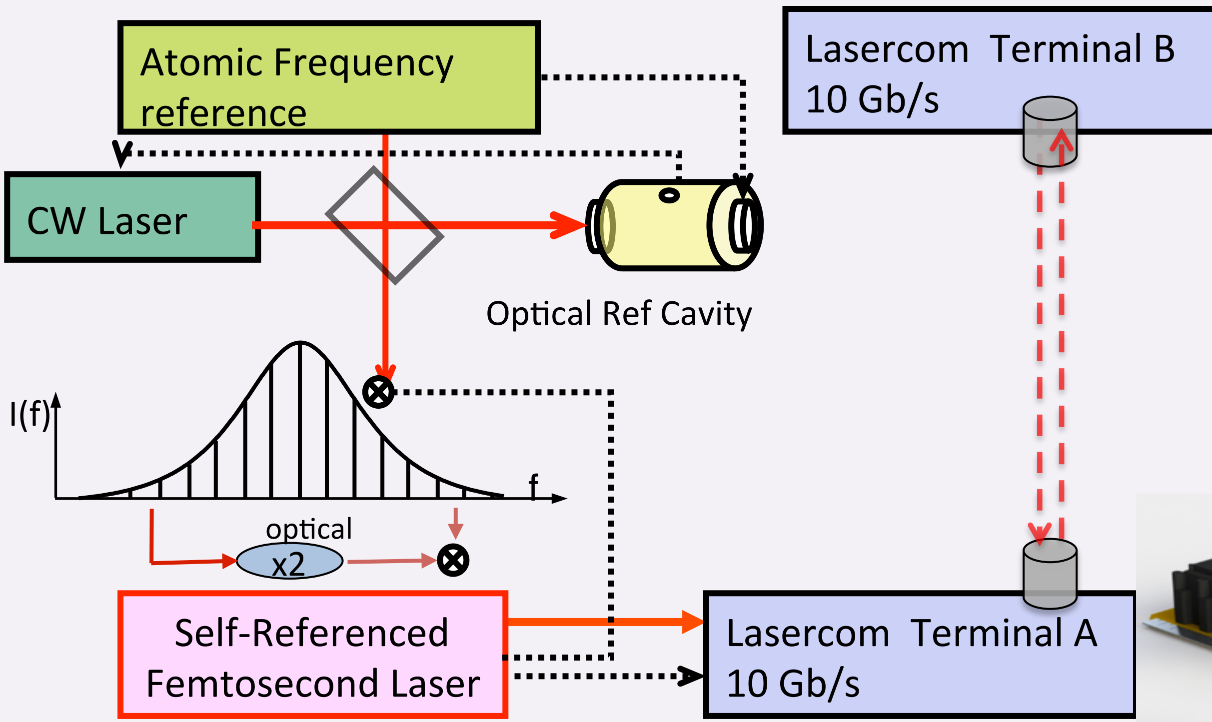
Free-space Laser Link with precise Atomic Time

High accuracy atomic clocks on the ground

- Link provides high speed data plus TIME / Range
- Validate In lab, between buildings via optical fiber, or free-space



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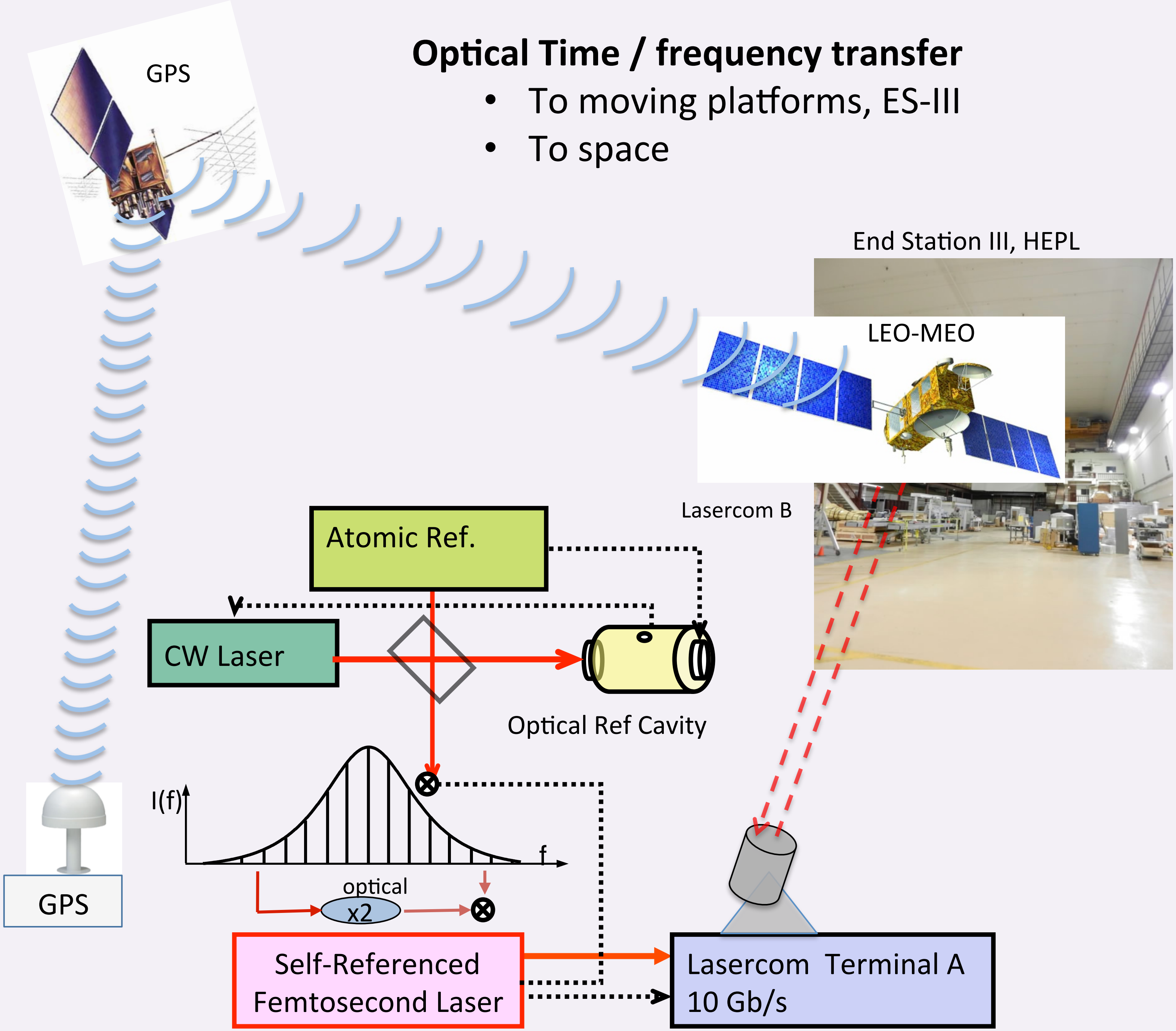
Optical Time / frequency transfer

- To moving platforms, ES-III
- To space



Leverage Existing

1. Great cold-atom microwave and optical atomic clocks on the ground (NIST, PTB, BNM-SYRTE, NPL, AIST…)
2. fs optical frequency combs – precise timing
3. Laser Communication links to space, two-way (JPL, MIT-LL,…)
   100s Mbts/s to 10 Gbts/s
4. Incredible GNSS infrastructure (GPS, GLONASS, BEIDOU, GALILEO…)
5. Other satellite and navigation system aids
   [WAAS, EGNOS, Satellite Laser Ranging (SLR), VLBI, DORIS]

Basically all of the required capabilities ALREADY exist within NASA, and other agencies; space tested or near space qualifiable

- LaserCom links
- Good ground clocks
- Compact Hg+ ion clock for space (soon)
- Geodetic applications and expertise

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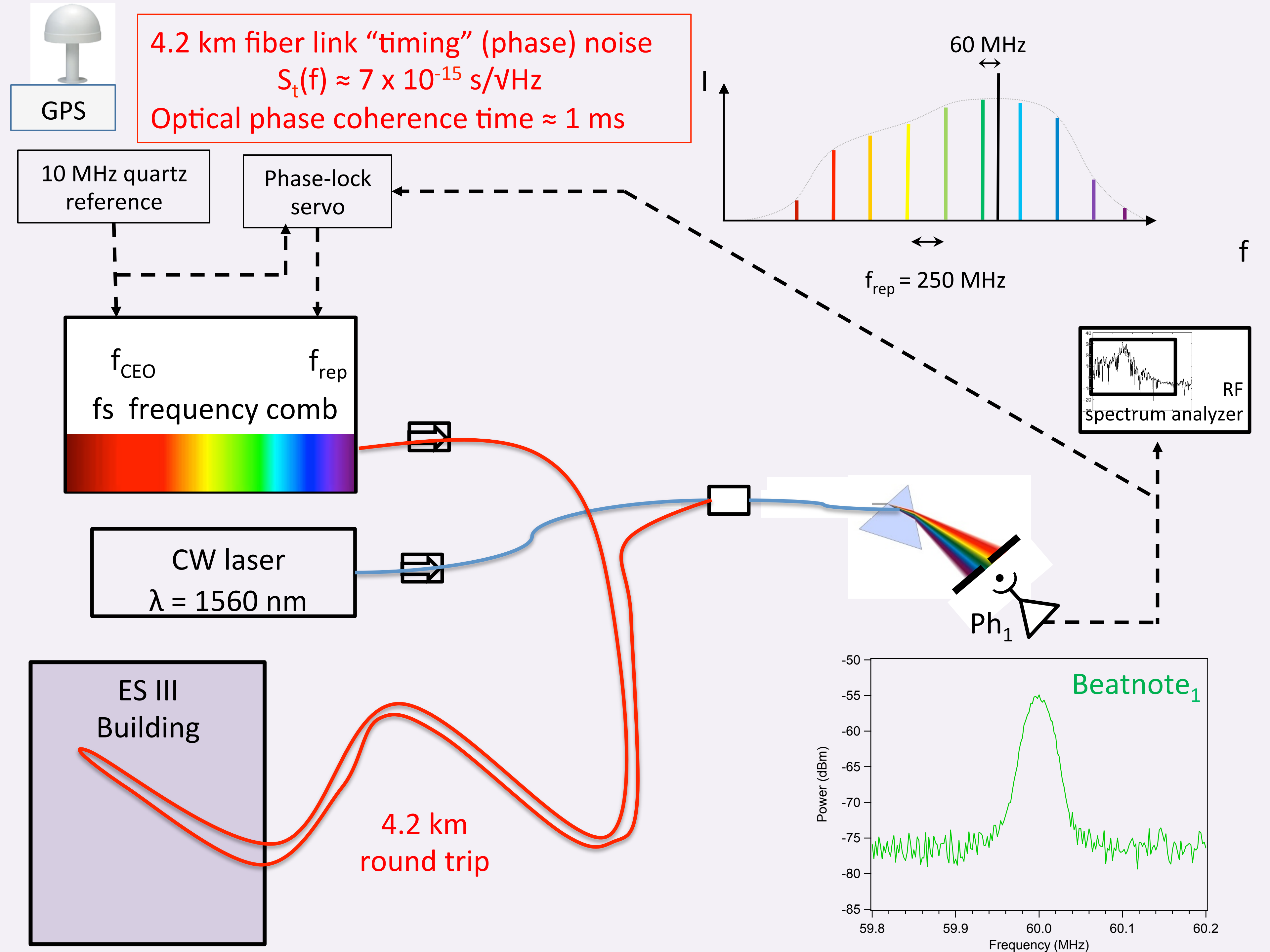
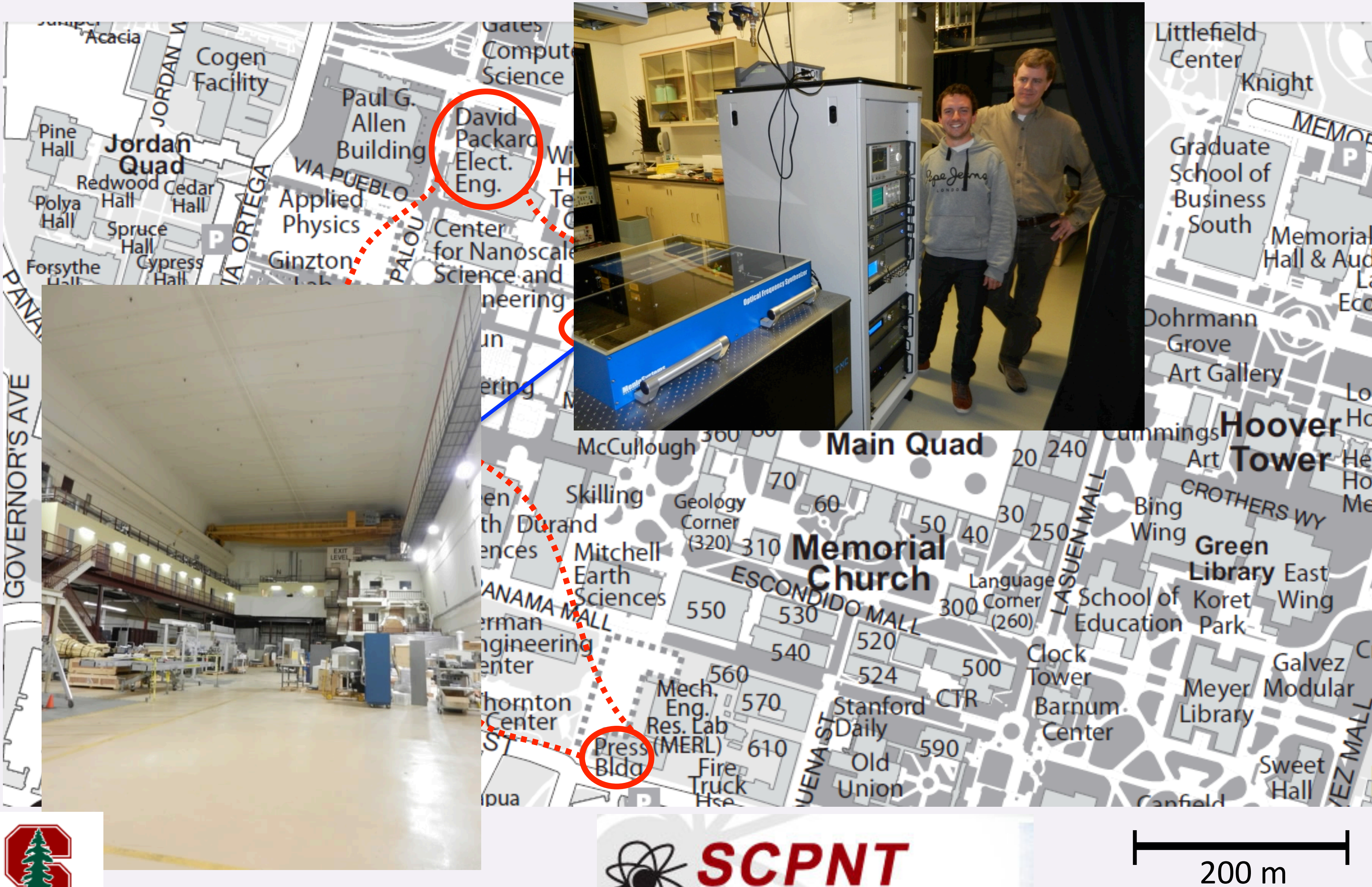

GPS
4.2 km fiber link "timing" (phase) noise
$S_t(f) \approx 7 \times 10^{-15}$ s/√Hz
Optical phase coherence time ≈ 1 ms
60 MHz
I
f
f_{rep} = 250 MHz
10 MHz quartz reference
Phase-lock servo
f_{CEO}
f_{rep}
fs frequency comb
RF spectrum analyzer
CW laser
λ = 1560 nm
Ph_1
ES III Building
4.2 km round trip
$Beatnote_1$
Power (dBm)
-50
-55
-60
-65
-70
-75
-80
-85
59.8
59.9
60.0
60.1
60.2
Frequency (MHz)

Optical "Time" transfer demo experiments on campus



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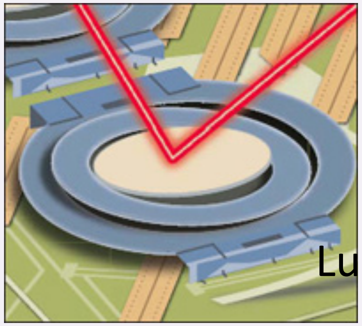
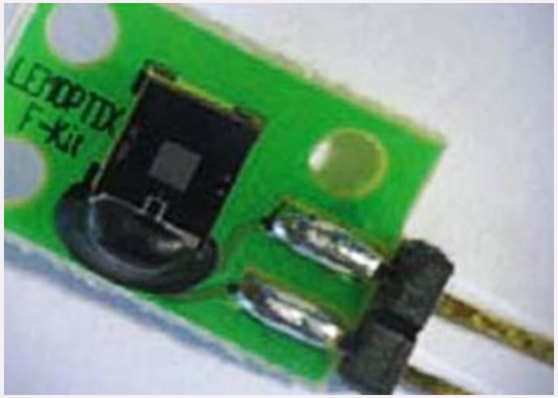
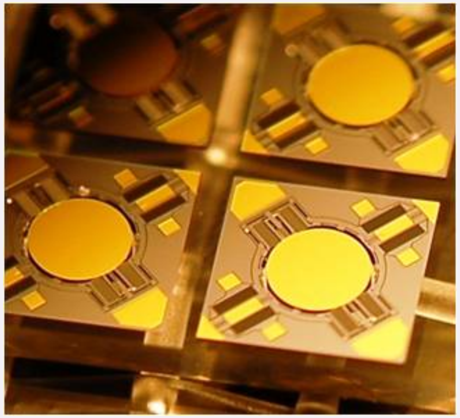
MEMS, MOEMS for laser atomic devices ?

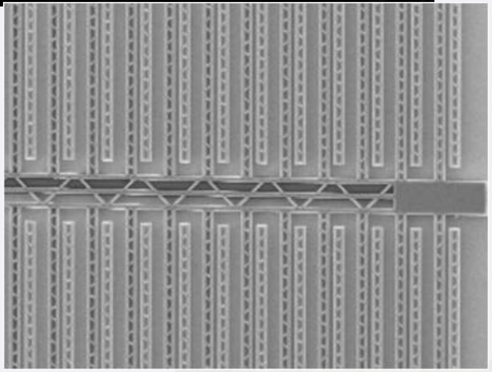


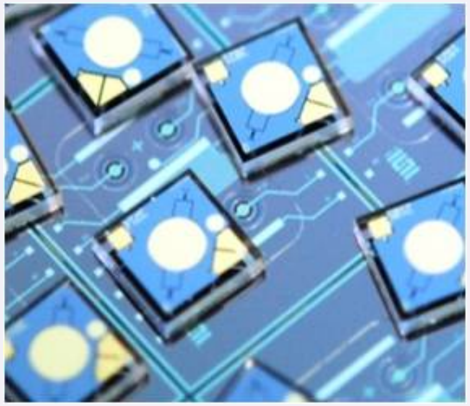
Lucent

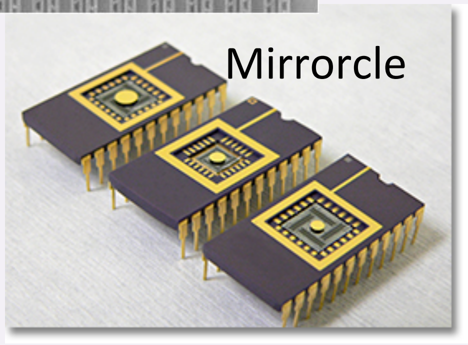




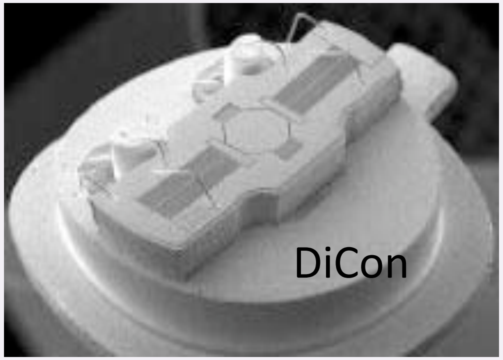
Preciseley







Mirrorcle



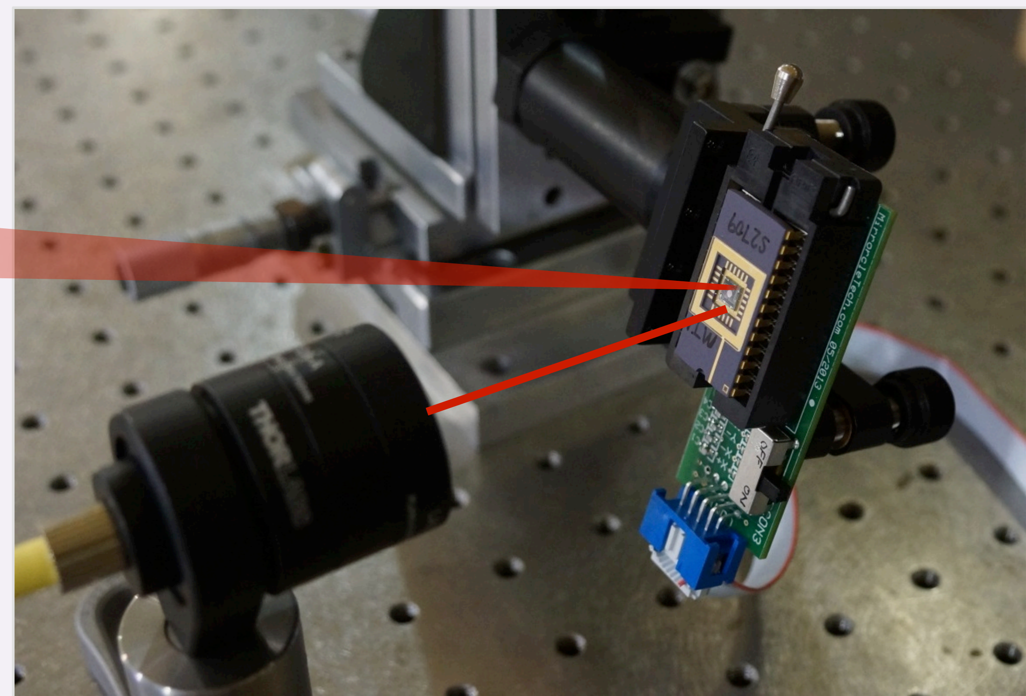
DiCon

MEMS Mirrors for Optical Tracking

Andrey Sushko, Leo Hollberg, Department of Physics, Stanford University

Facilitates optical communication between satellites for high speed data and precision time transfer

Gratefully acknowledge support from NASA Fundamental Physics and DARPA seedling



Robust, Low-power tracking demonstrated

Overview of concept of Space-Time Reference Satellite

- pretty good clock(s) in orbit (high stability for 5+ hrs)
  - Currently "avail" GPS Rb & Cs, GLONASS Cs, GALILEO H-Maser & Rb, JPL – Hg+ ion, PHARAO cold Cs)
- 2-way optical Laser-Comm link; with time markers 1 ps timing
- High performance GPS receivers in space
- Precise orbit determination at mm level
- Space clocks would get updated via laser link from super clocks on ground

Options:

-- upgrade to optical atomic clock (ESA SOC, AOSense SBOC, other ?)
and fs comb in space (Menlo – FOKUS)

-- Inertial test mass for drag free operation (GPB heritage)

-- laser ranging corner cube reflector (ISLR)

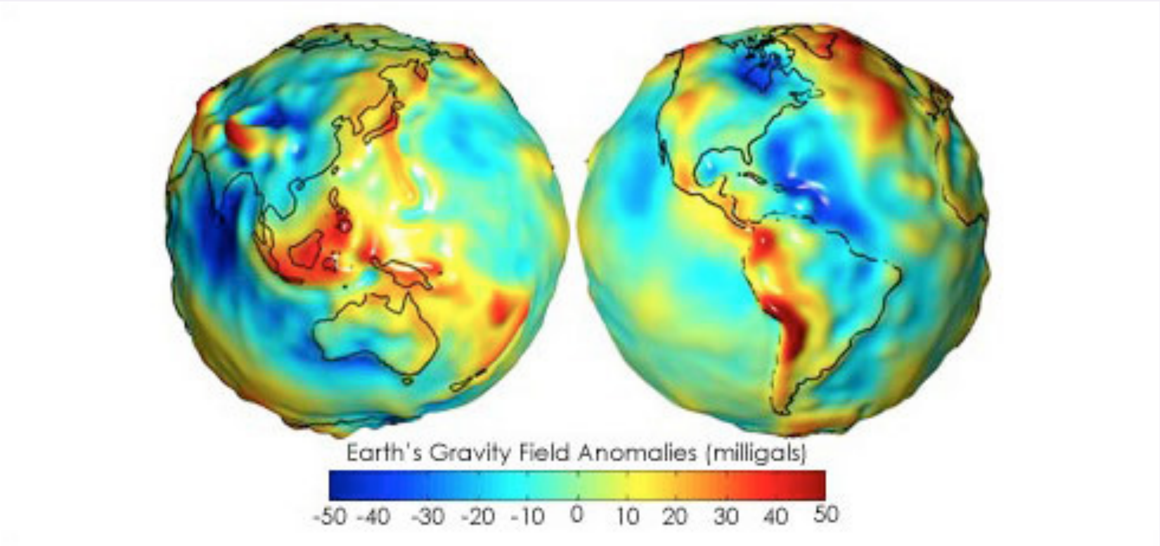
-- VLBI, DORIS

-- Physics experiments as payload

-- Install Laser TT link on geoscience missions, telecom GEO, …

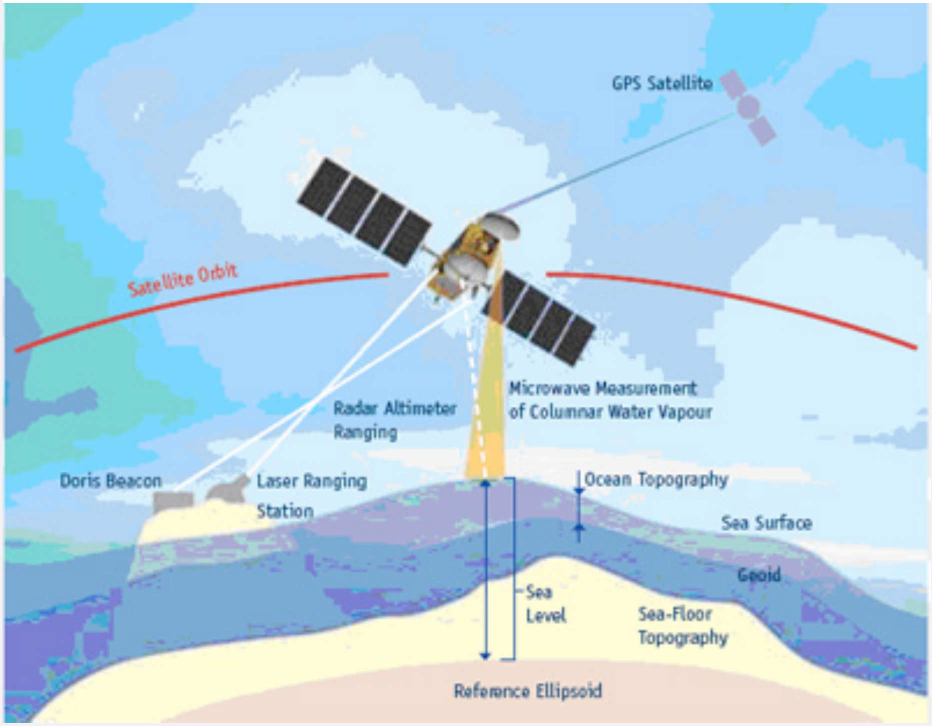
Note: synergistic ideas in Geodetics community, ; e.g. proposed GRASP, Y. Bar-Sever JPL,
(but no clock or laser link …)

Geodesy and Earth Sciences – via precise distance measurements



Gravity, Geoid maps
by gravity gradiometry

NASA	GRACE
ESA	GOCI



NASA, CNES
TOPEX/Poiseidon
JASON-1
JASON-2
JASON-3

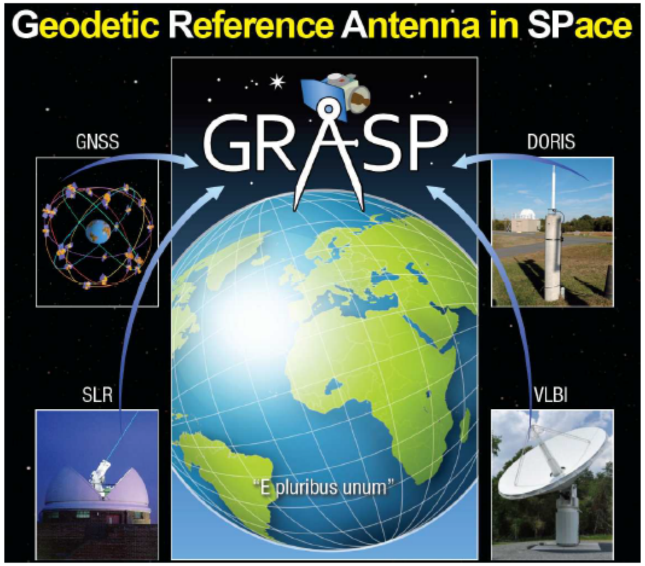
Very Simplified picture:
Typical vertical offsets 10 cm +
vertical rms fluct 1 mm

images credit NASA

The Geodetic Reference Antenna in Space (GRASP): A Mission to Enhance the Terrestrial Reference Frame

Yoaz Bar-Sever[1], R. Steven Nerem[2], and the GRASP Team

[1] Jet Propulsion Laboratory
[2] University of Colorado, Boulder

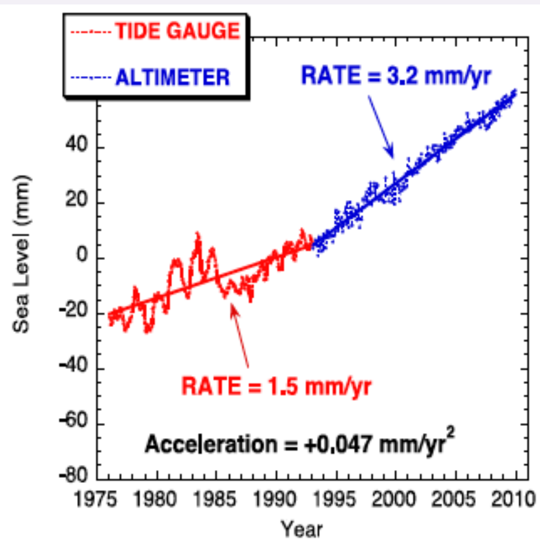


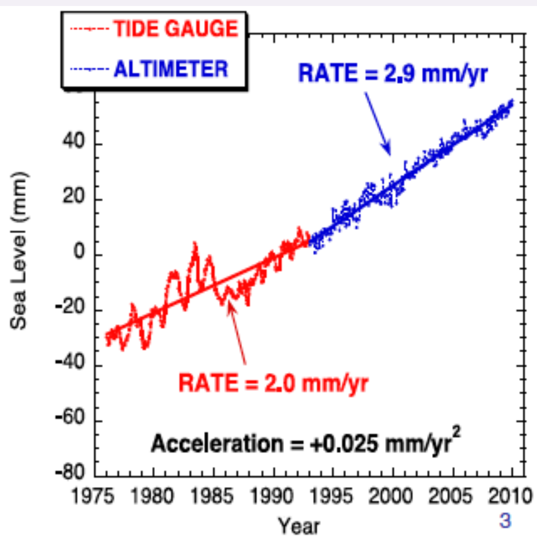
Proposed mission for precision geodesy, earth sciences

Bar-Sever et al

TRF errors readily manifest as spurious sea level rise accelerations

Left: ITRF2005
(based on Church and White, 2011)
Right: ITRF2000
(simulated into the Church and White records)





Broader impact ? Need general method to achieve high performance time and range info ground to space.

1. Time, frequency transfer worldwide, at 1 ps level
   - 1000 x better than GPS (which is about 1 to 30 ns) .... (recall the neutrinos and c ?)
   - "Lift" high precision ground clock performance into orbit, world wide distribution
2. Higher accuracy information of GNSS clocks and ephemeris
   - GNSS (GPS, GLONASS, GALILEO, COMPASS-BEIDOU)
   - Reduce troposphere and ionosphere delay uncertainties
   - Decouple clock/orbit uncertainties from troposphere and ionosphere uncertainties
   - More stable T(ime) & freq, accurate Position reference: T, **R**
3. Precision Geodesy, Geodetic reference frame
   - reliable mm position on Earth ?, water movement, ice, atmosphere…
4. Time reference when GPS not available
   - Natural disasters, secure environments
5. Precise: Time, laser ranging, precise orbit determination at the 1 mm level
   - Geodesy, Terrestrial Reference Frames, sea-level, ice motion
6. Physics experiments
   - Precision measurements of Space-time (GR, KT, MM, LPI, c (t,r) ?
   - We have big problems with Gravity, GR , astrophysics meas., or ???
   - Searches for new physics (fields, CPT variations)
   - Enabling for earth-based measurements that require T, **R** vector

HEPL

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Looking to the Future:
How will laser-cooled atoms & Precision laser measurements contribute?

--- Space-Time References ?
--- PNT (Position, Navigation, Time) systems
--- Ultrafast electronic timing ?
--- Information security ?
--- Communication systems ?
--- Other ?