A Space Based Timing Infrastructure using Frequency Combs

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Integrity ★ Service ★ Excellence

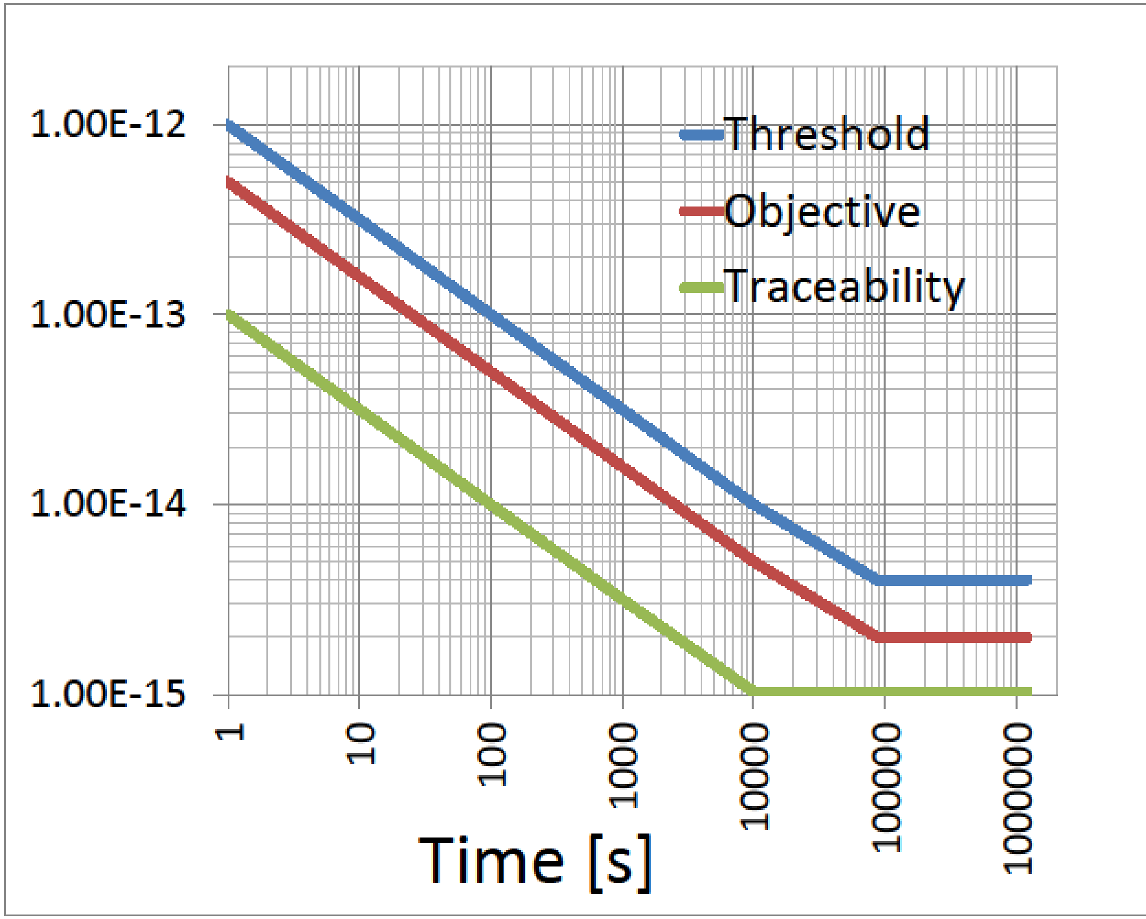
Clock Goals (from RFI's)

- Launch and space survivable clock

Size and Power

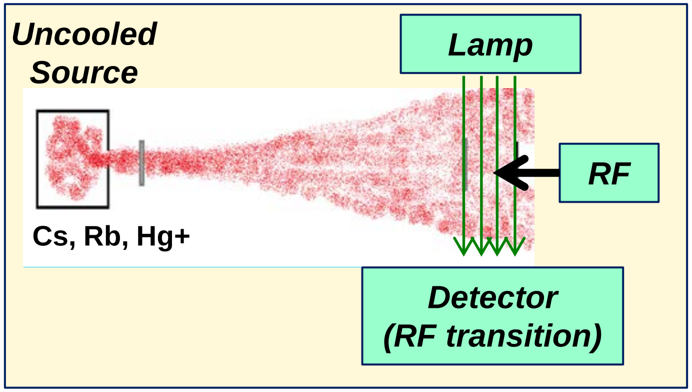
	Size [L]	Pow [W]
Thresh.	50	30
Object.	6	15

Fractional Frequency Stability



Atomic Clocks Moving Forward

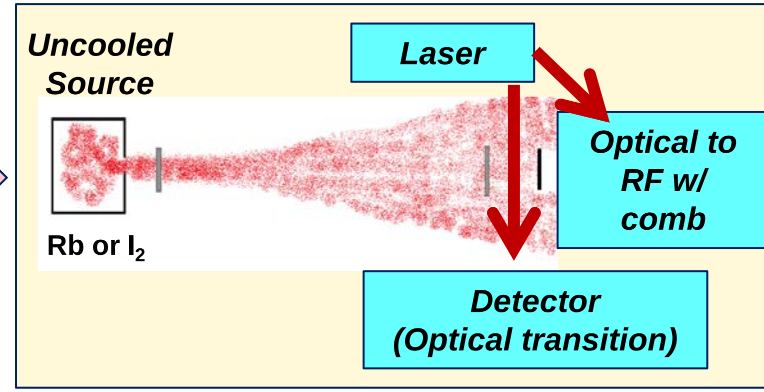
Current GPS clocks: "Warm Atom – RF"



- *Vacuum Tube technology*
- *At theoretical limit*
- *Complex manufacturing*

Optical Transition

Warm Atom - Optical (AFRL In-House)

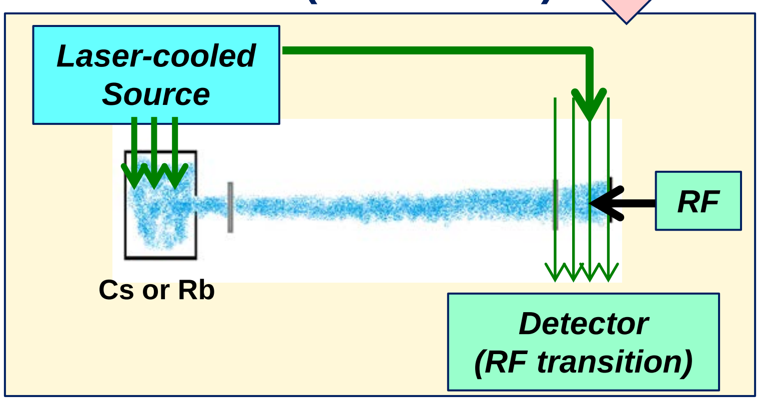


- *~10X Better performance*
- *Leverage COTS Telecom components*
- *Noble Prize in Frequency Comb*
- *Simpler Manufacturing*

Cold Source

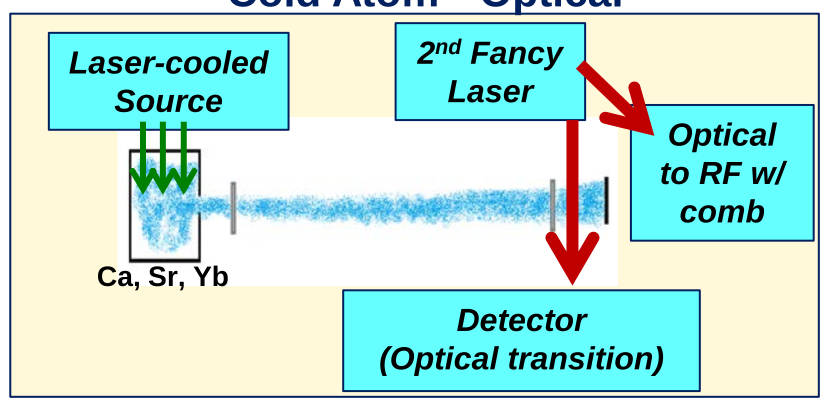
Both

Cold Atom - RF (AFRL-NIST)



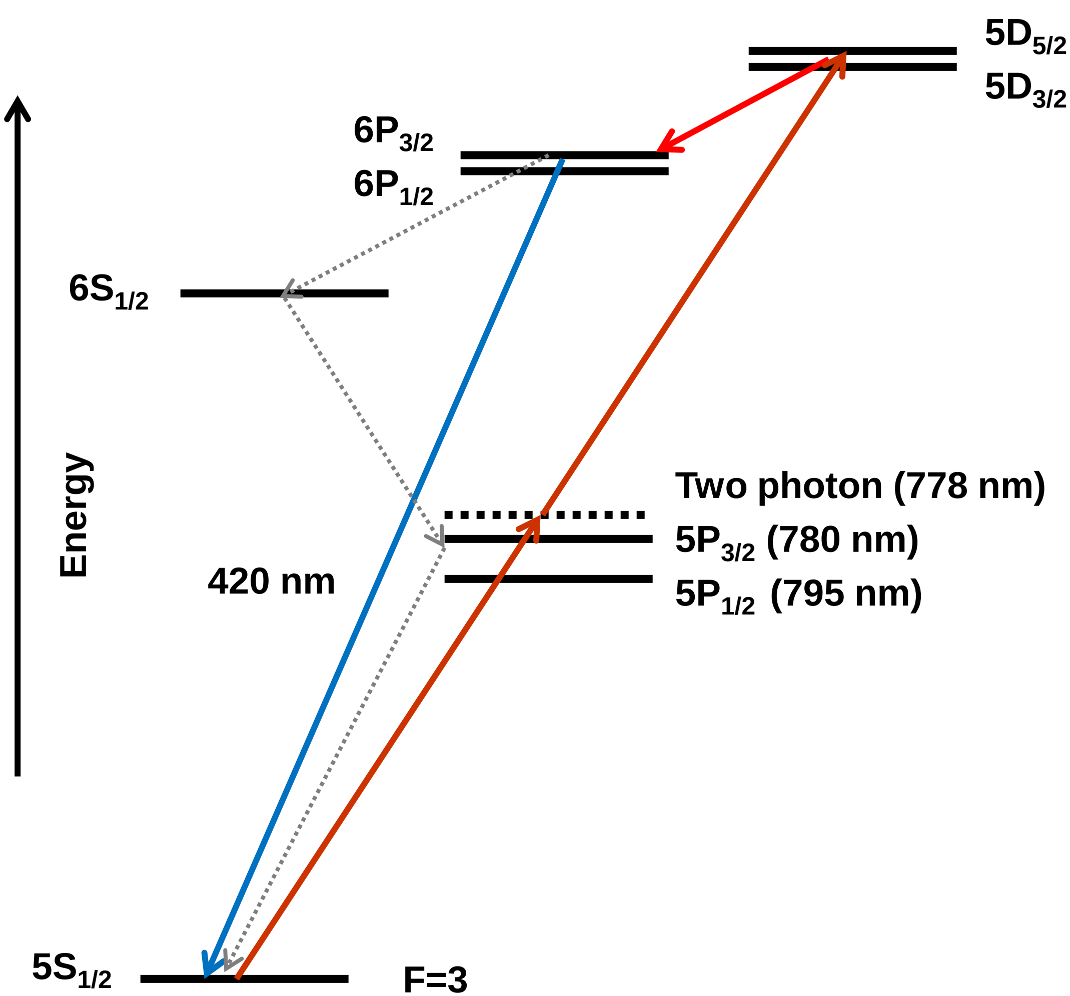
- *~10X Better performance*
- *Nobel Prize in Laser Cooling*

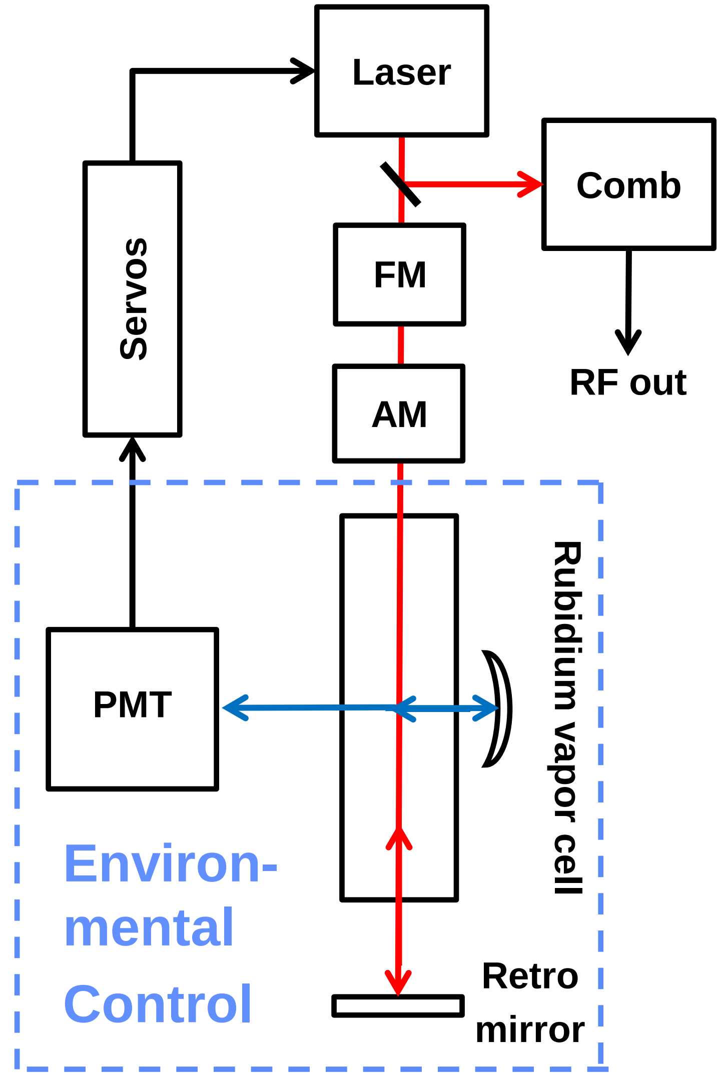
Cold Atom - Optical



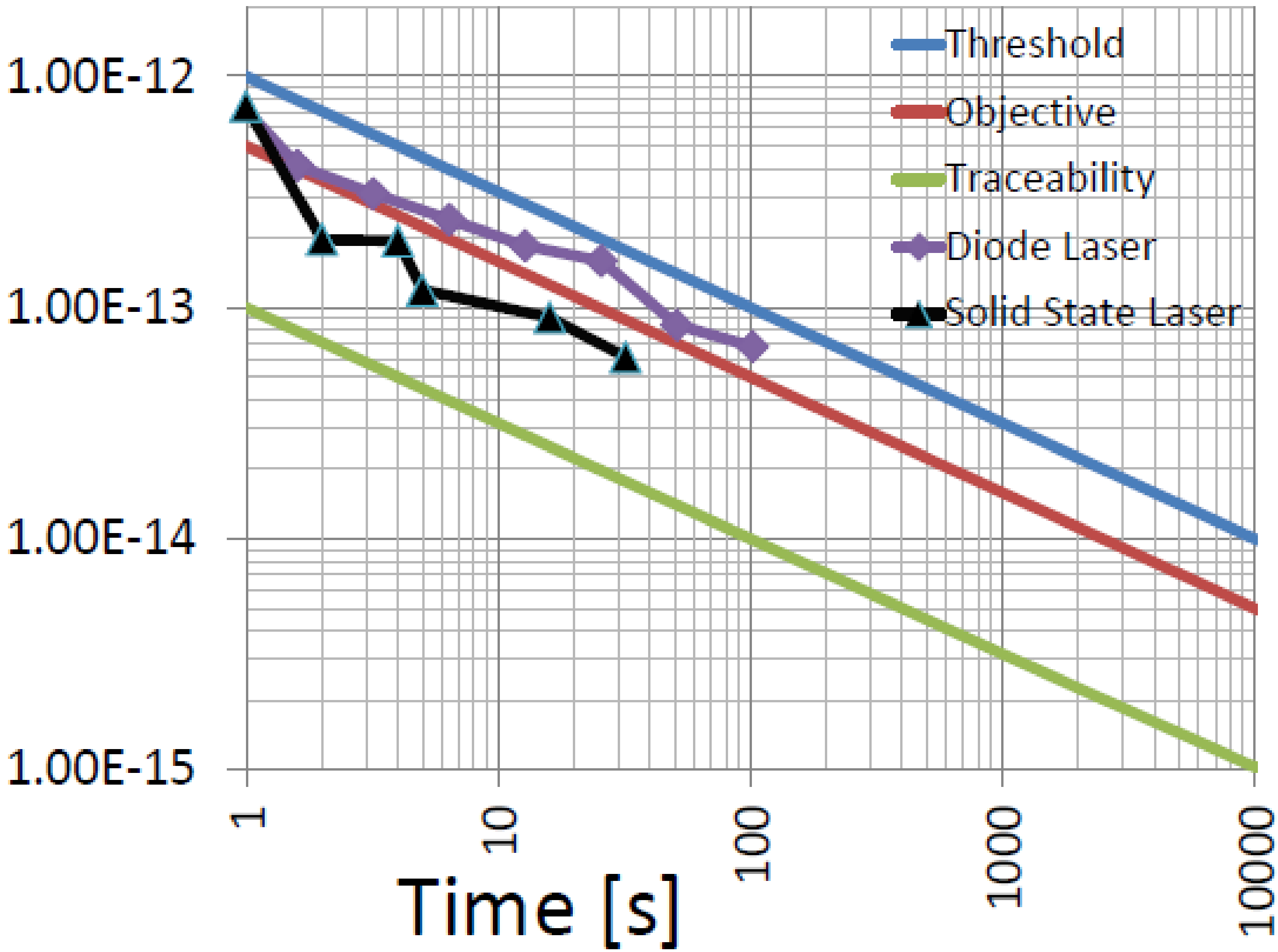
- *~1000X Better performance*
- *Most Complex, lowest TRL, highest SWaP*

2-Photon Optical Rubidium Atomic Frequency Standard (O-RAFS)





Current Status w/ Menlo comb



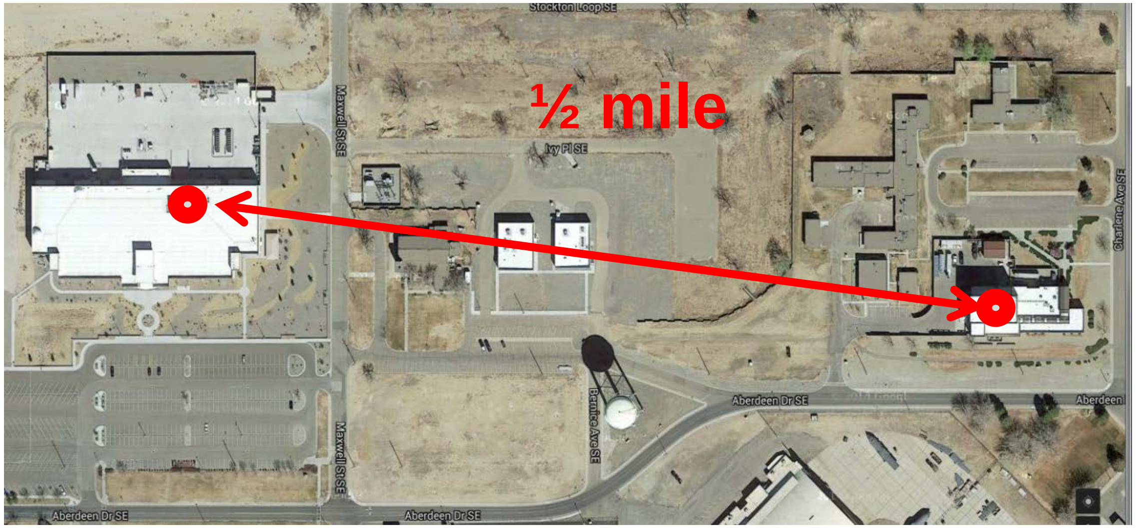
Cagnac et al Laser Physics Vol 6 No 2 (1996)

Millerioux et al. Optics Comm. 108 pg 91-96 (1994)

Network of two way optical time transfer (2TT)

- Measure position and time of entire constellation without any atomic clocks in space
  - Satellite sets measure relative range and time
  - Propagate sync and map to constellation
  - Doppler?
- Optical atomic clocks on ground compare via network, update constellation
  - Optical clock comparisons across globe

AFRL starting 2TT ½ mile link



Eventually want to try balloon test:

Small sat – sat test

Payload Size: about 10 cu ft

Giorgetta et al. Vol. 7 pg. 434-438, Nature Photonics (2013)

Fundamental physics with space clocks – Nathan Lemke

Absolute gravitational redshift

Expected redshift, to 1st order:

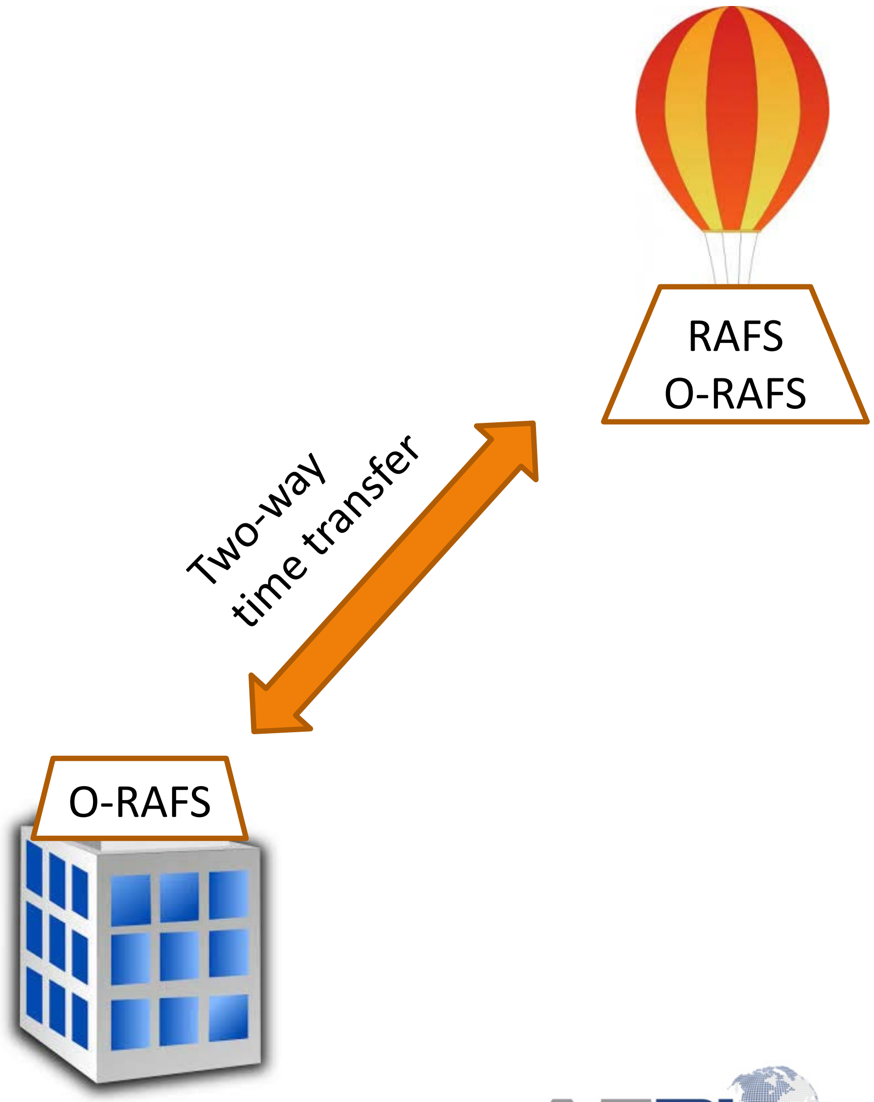
$$\frac{\nu_1 - \nu_2}{\nu} = \frac{U(r_2) - U(r_1)}{c^2}$$

Lorentz Position Invariance

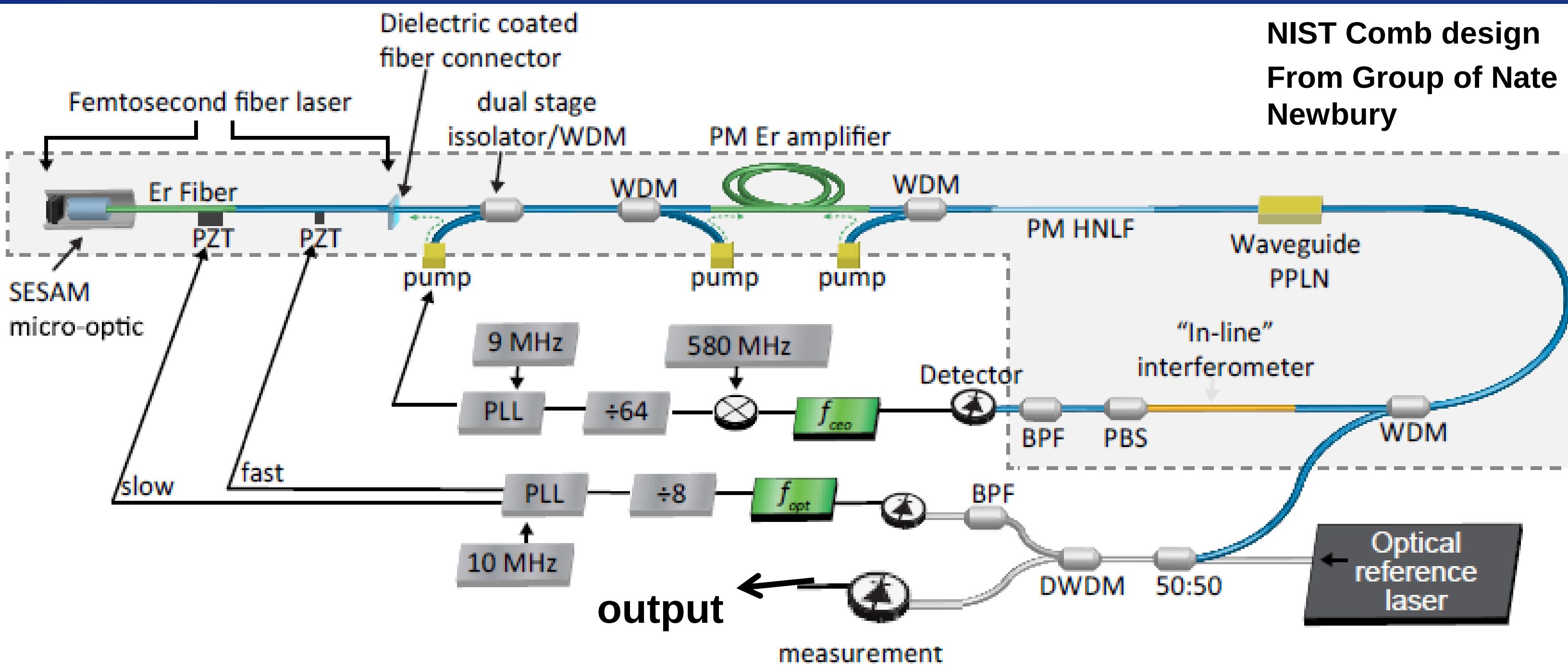
Use clocks to see if fundamental constants are coupled to gravity

$$\frac{\delta\nu}{\nu} = K\frac{\delta\alpha}{\alpha}$$

Doppler?



NIST comb



NIST Comb design

From Group of Nate Newbury

Awarded ~$2.6M in SBIR contracts to transition Er based PM fiber comb

-NP Photonics

-Stable Laser Systems

-Vescent Photonics

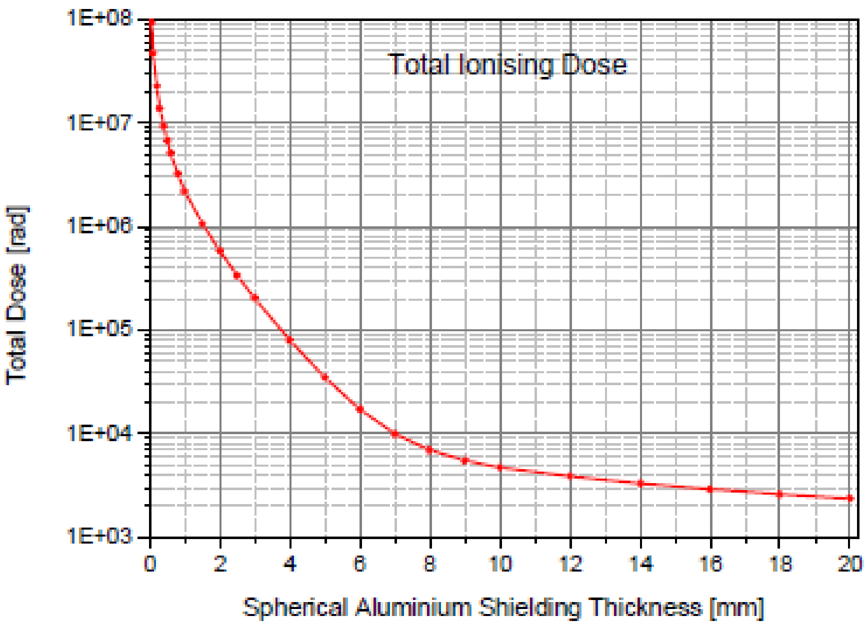
Outstanding Issues/unknowns

- Power Draw
  - Would like <30 Watt for whole system
  - Comb uses up the whole power budget
    - >20 Watts for pump diodes based on datasheets
    - FPGA Power?
- Radiation Effects in ***PM*** fiber
  - Need to take ~100's of krad (~10 krad/yr)

Thesis of B. Taylor, Radiation monitoring in the MEO environment with GIOVE-A

Radiation caveats

- Dose rate is highly variable
- Shielding can mitigate
- Radiation Spectrum
  - Most tests are with Co60, but there is large spectrum
- Detectors have different sensitivity than comb fiber



Buchs et al. Optics Express, vol 23, #8 (2015)

What do we know?

- Korean's tested SM Er fiber comb (20 Watt)
  - Weak link was Liekki Er80-4/125 SM gain fiber.
  - Around 30 krad TID
- Also they tested SESAM's to 120 krad
- CSEM group tested Yb based DPSS comb to 170 krad(H2O)

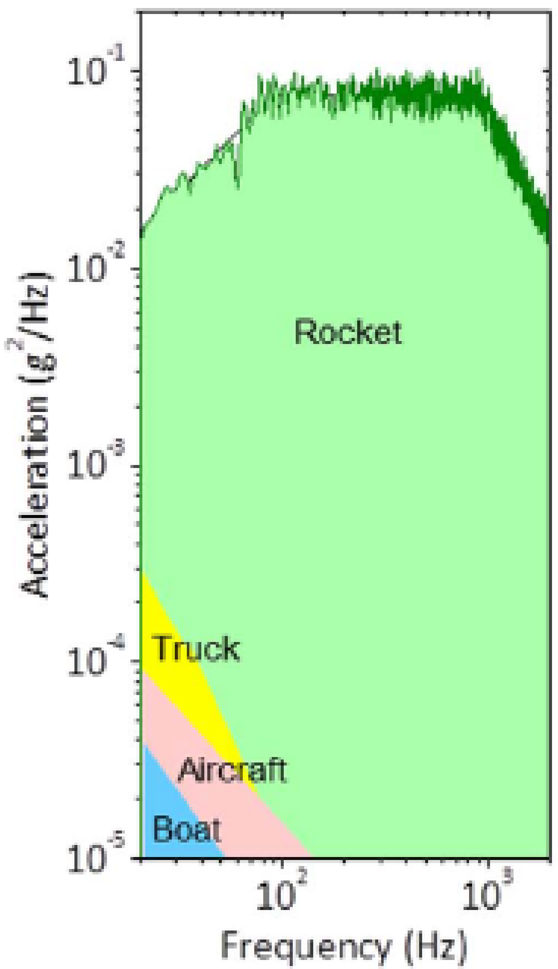
- Infer that pump diodes aren't serious problem

J Lee et al., "Testing of a femtosecond pulse laser in outer space", Scientific Reports 4:5134, (2014)

What do we not know?

- PM fiber rumored to be more sensitive.
  - If true, worry about PM Liekki fiber
  - What about PM-HNLF?
- Will radiation cause PP-LN(KTP) waveguide degradation?

- Shake and vib?
- Need to survive 0.1 g^2/Hz from 100 to 1000 Hz?



Summary

- Frequency combs can enable new space clocks, improved GPS
- Can enable 2TT networks
  - global optical atomic clock comparison
  - Alternate GPS architectures
- We need lower power and higher radiation tolerance with certainty