Approved for Public Release



## Optical Atomic Clocks for Enhanced Timing Performance

## Judith Olson, PhD Atomic Clocks Portfolio Tech Lead

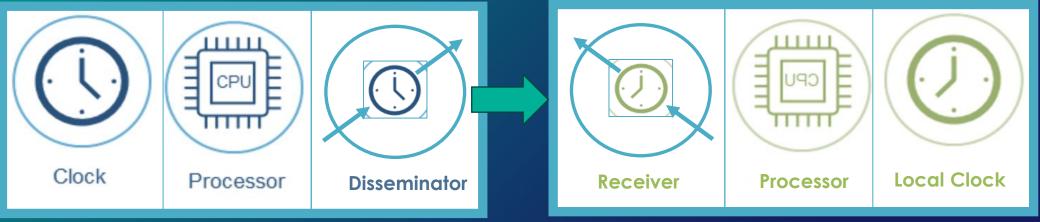
63rd Meeting of the Civil GPS Service Interface Committee , Timing Subcommittee, Denver, CO, September 11, 2023

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### Need more than just a clock...

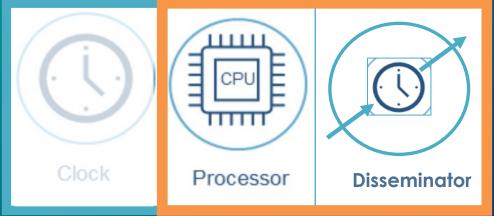
## Networked Timing Unit



# Toward an improved network timing unit

Network systems are rapidly enabling better timing at all levels

## Networked Timing Unit



Light travels  $\sim 1$  foot in 1 ns Intra-clock use Swabian instruments

- Sub-ns time tagging
- "Last centimeters" problem
  - PCIe PTM 0 getting time off the NIC

### Inter-clock use

- White Rabbit (WR)
  - Sub-ns timing over ethernet developed at CERN
  - For 10 Gigabit Ethernet





SAFRAN

- Entanglement



National Institute of Standards and Technology

- Haldar et al, Phys Rev A (2023) •
- Optical frequency comb
  - NIST Newbury group
- Wireless 2Way Interferometry (WiWi)
  - NICT Shiga group

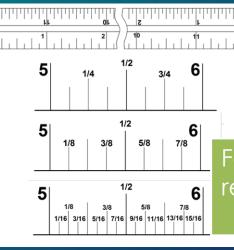


National Institute of Information and Communications Technology

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# Optical clocks: the future of timekeeping

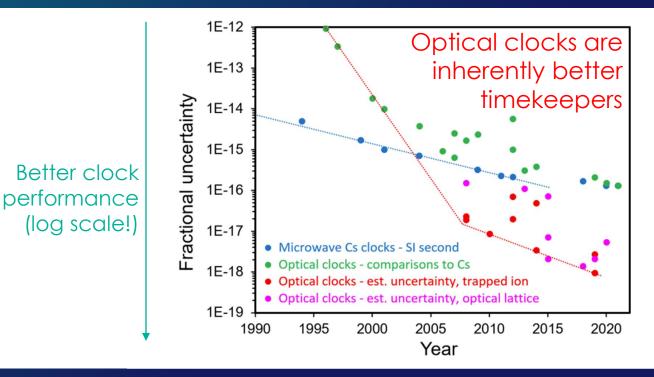


#### JUDITH OLSON, PHD

Faster 'ticking' clocks allow better timing resolution and measurement, like having more ticks on a ruler

- Performance 

   frequency instability
- Optical clocks (100's THz) tick ~10,000 x faster than microwave clocks (10's GHz)
- 10,000x improvement in timing and environmental susceptibility possible



(Plot from NASA Cold Atoms in Space Workshop 2022 publication)



# Optical clocks are coming to market

- Optical versus microwave clock performance and **fieldability** greatly improved
- Biggest technology barriers to commercial deployment are lowering (TRL and MRL)
- Emerging mission needs exceed current capabilities

#### Laboratory bench clocks



NIST comb lab

5



## Optical clocks are leaving the lab

Readiness Level

Ultra-ruggedized

SWaP-reduced

Commercial systems

Commercial subsystems

Lab-level

Component demos infleqtion tigker Prime

2025

#### First stage

- 2 lasers (clock+comb)
- Active maser-like

Maser-like performance, but more ruggedized and affordable clocks with lower SWaP. Coming to market now.

Further SWaP-reduced and enhanced ruggedization versions to come.

2030

→ Time (approx.



## Optical clocks are leaving the lab

Second stage "clocks"

Just beyond maser, some

specialized performance attributes

(sensor-like instead of clock-like)

Industry/defense-led pursuits

2025

Active maser-like

3+ lasers

Readiness Level

Ultra-ruggedized

SWaP-reduced

Commercial systems

Commercial subsystems

Lab-level

Component demos Near-future clocks, sensors, and quantum communications will unlock new applications beyond existing GPScapabilities

2030

• Time (approx.)



## **Optical clocks are leaving the lab**

Second stage "clocks"

• 3+ lasers

Readiness Level

Ultra-ruggedized

SWaP-reduced

Commercial systems

Commercial subsystems

Lab-level

Component demos

2025



2030

Future tech unleashes new capabilities – geodesy, gravitational corrections, optical phase references

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CGSIC, Sept 11, 2023

performance attributes

be worth commercializing

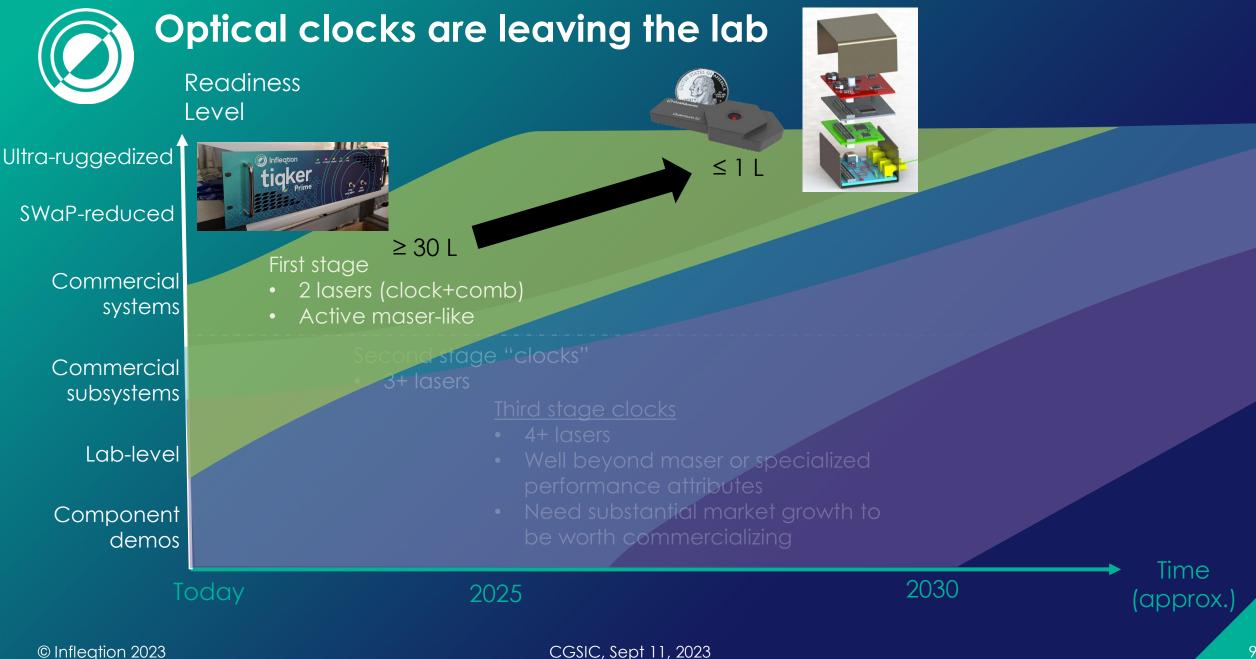
Need substantial market growth to

Third stage clocks

4+ lasers

Time

(approx.





## **Commercial optical** clocks today

- Optical clocks coming to market now, pre-production units available
- Maser-like performance with added benefits of:
  - More fieldable, ruggedized
  - Lower cost
  - Shorter lead times
  - Much smaller size
  - Better holdover/drift performance

#### **Pre-Production**

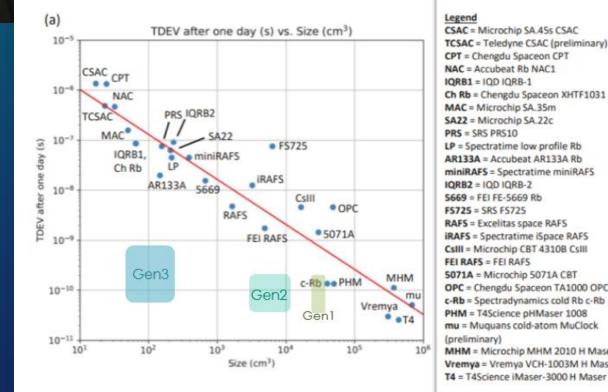
100



(Gen1)



Tiqker HD (Gen2)



Legend CSAC = Microchip SA.45s CSAC TCSAC = Teledyne CSAC (preliminary) CPT = Chengdu Spaceon CPT NAC = Accubeat Rb NAC1 IORB1 = IOD IORB-1 Ch Rb = Chengdu Spaceon XHTF1031 MAC = Microchip SA.35m SA22 = Microchip SA 22c PRS = SRS PRS10 LP = Spectratime low profile Rb AR133A = Accubeat AR133A Rb miniRAFS = Spectratime miniRAFS IORB2 = IQD IQRB-2 5669 = FEI FE-5669 Rb FS725 = SRS FS725 RAFS = Excelitas space RAFS iRAFS = Spectratime iSpace RAFS CsIII = Microchip CBT 4310B CsIII FEI RAFS = FEI RAFS 5071A = Microchip 5071A CBT OPC = Chengdu Spaceon TA1000 OPC c-Rb = Spectradynamics cold Rb c-Rb PHM = T4Science pHMaser 1008 mu = Muguans cold-atom MuClock (preliminary) MHM = Microchip MHM 2010 H Maser Vremya = Vremya VCH-1003M H Maser

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## Areas of interest for near-term clocks

#### Pre-Production



Early adopters and those wanting to ensure future compatibility with optical clocks

- Pilot Program underway
- Field demos

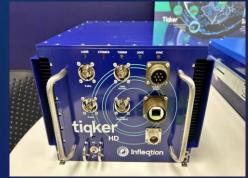
<u>Contact for Pilot Program information:</u> Too Vira, Director of Product Engagement too.vira@infleqtion.com Tiqker Prime (Gen1)



"Office-use" version for

- Data networks
  - Meshed, distributed
- 6G infrastructure
- National timescales
- Science and research
- IoT and local networks
- Tests and demos of new capabilities for GPS security, hyper-accurate positioning, backup networks

Tiqker HD (Gen2)



Ruggedized version for deployed and mounted scenarios

- Intelligent surveillance and reconnaissance
- Autonomy
- Radar



- 0
  - Incorporate local timing, eLoran, cellular, 4G+, and wifi 0 information
    - Koelemeij et al in *Nature*, 2022 Eindhoven, Netherlands
    - SuperGPS, Point One Nav, TRXSystems, OPNT, Hellen Systems, 0 PassTime, Hoptroff, Safran, TrustPoint... there are many!









We'd love to hear from you: judith.olson@infleqtion.com

NDIA Conf. Aug 29, 2023