Past, Present, and Future of Space Clocks

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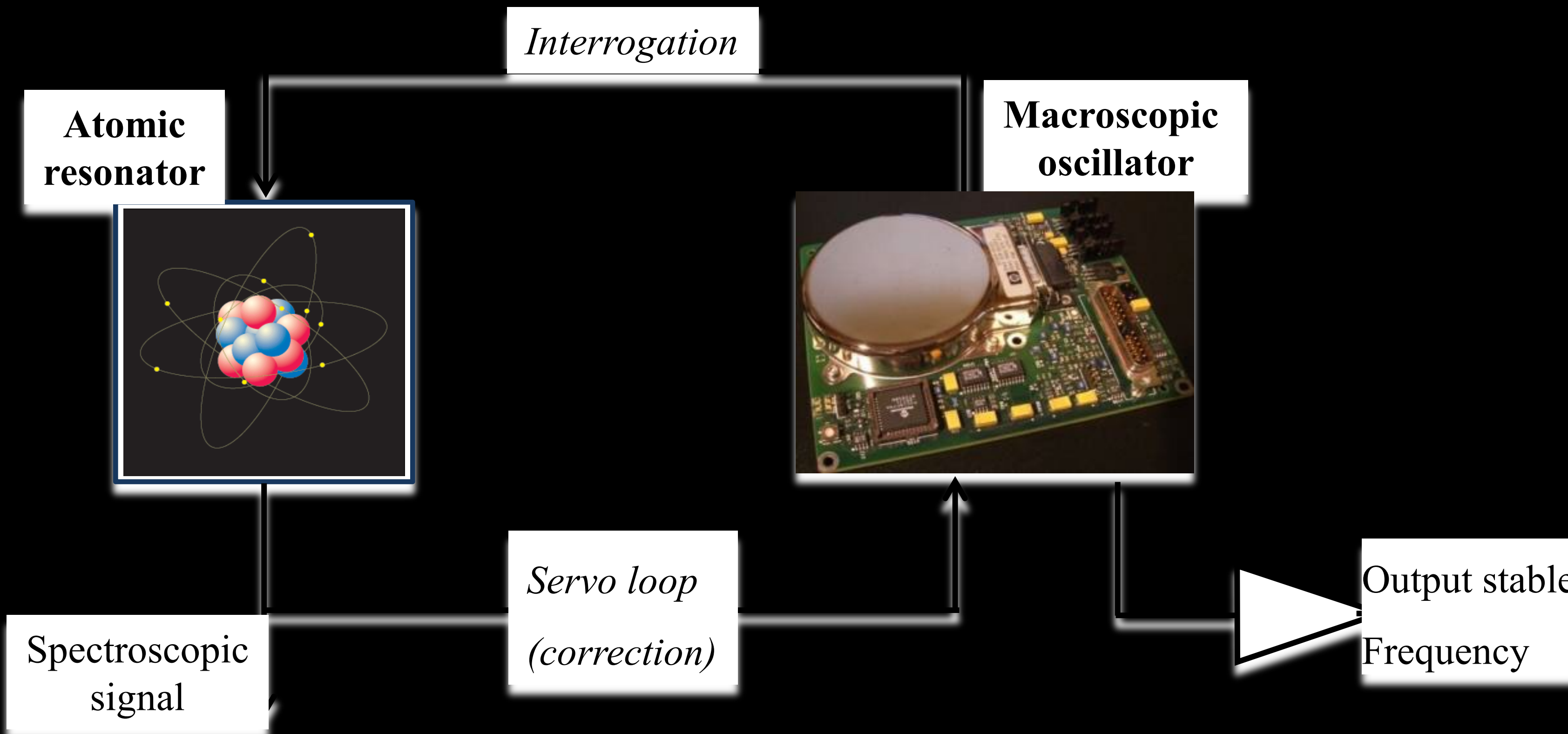
ROLL TIDE A ROLL TIME

OUTLINE

- ❑ Space clocks: overview, evolution and performances
- ❑ GNSS systems: space clocks and their applications
- ❑ Space clocks basics: how to build one?
- ❑ Quantime research overview

WHAT IS AN ATOMIC CLOCK?



"Adjust and maintain the frequency of an oscillator to a reference atomic transition frequency."

- T. Bandi, Invited Review, BEMS Reports. 9(1):1-10, 2023.

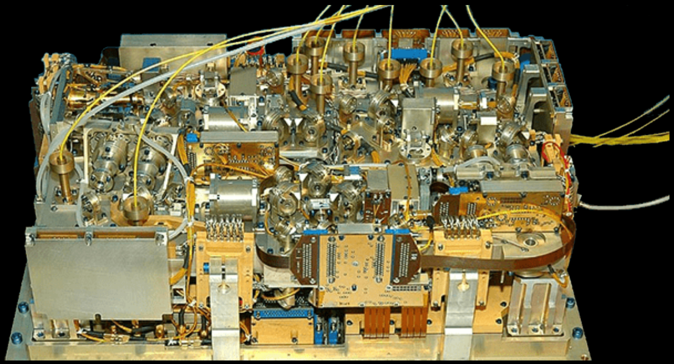
SPACE CLOCKS OVERVIEW

SWaP: Size, Weight, and Power

Rb cell clock (Excelitas)

Rb cell clock (Safran)

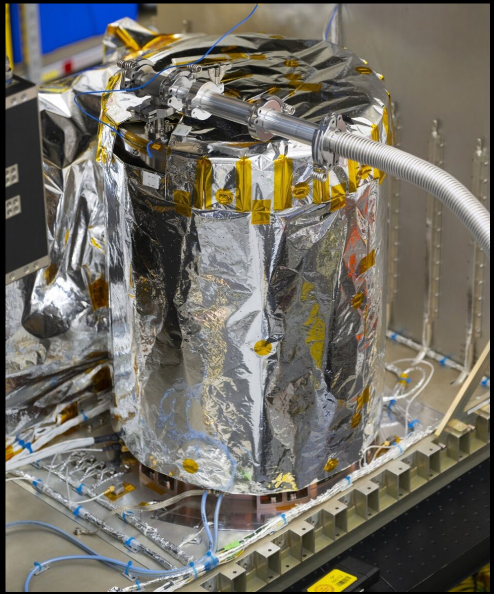
ACES (ESA):



PHARAO (CNES)

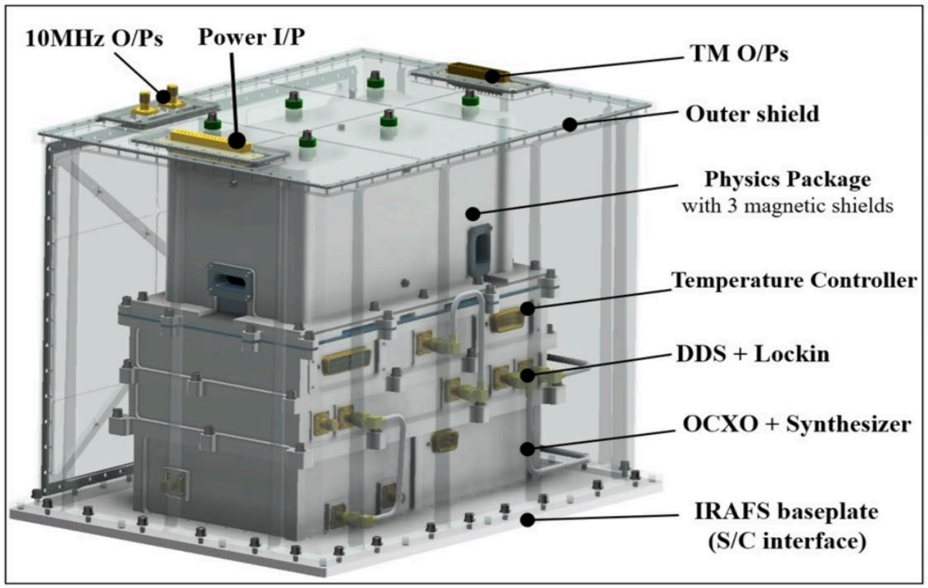
Passive H-maser (Galileo)

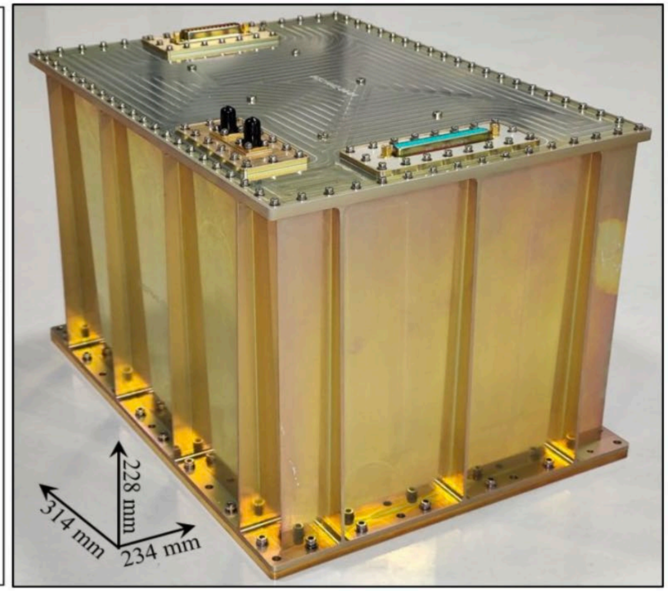
DSAC (NASA-JPL)



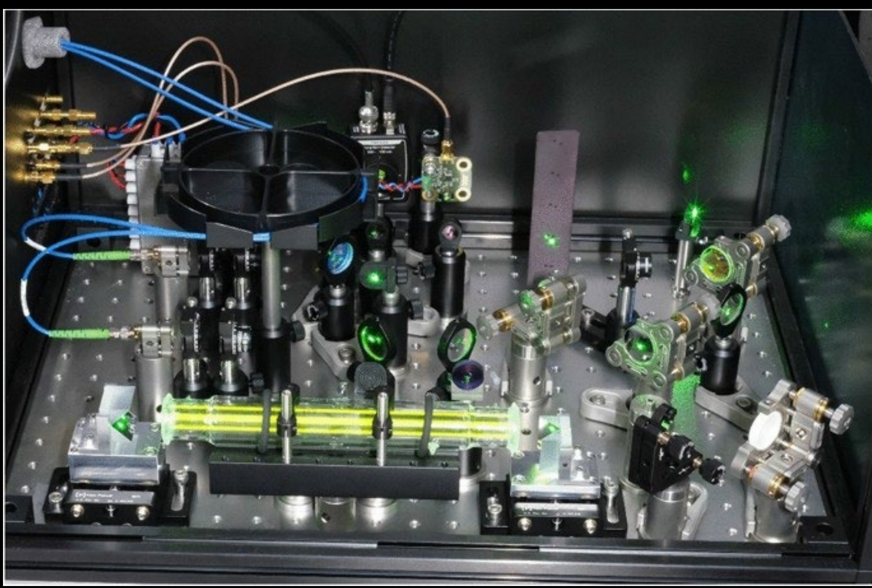
SHM (Safran)

SPACE CLOCKS OVERVIEW





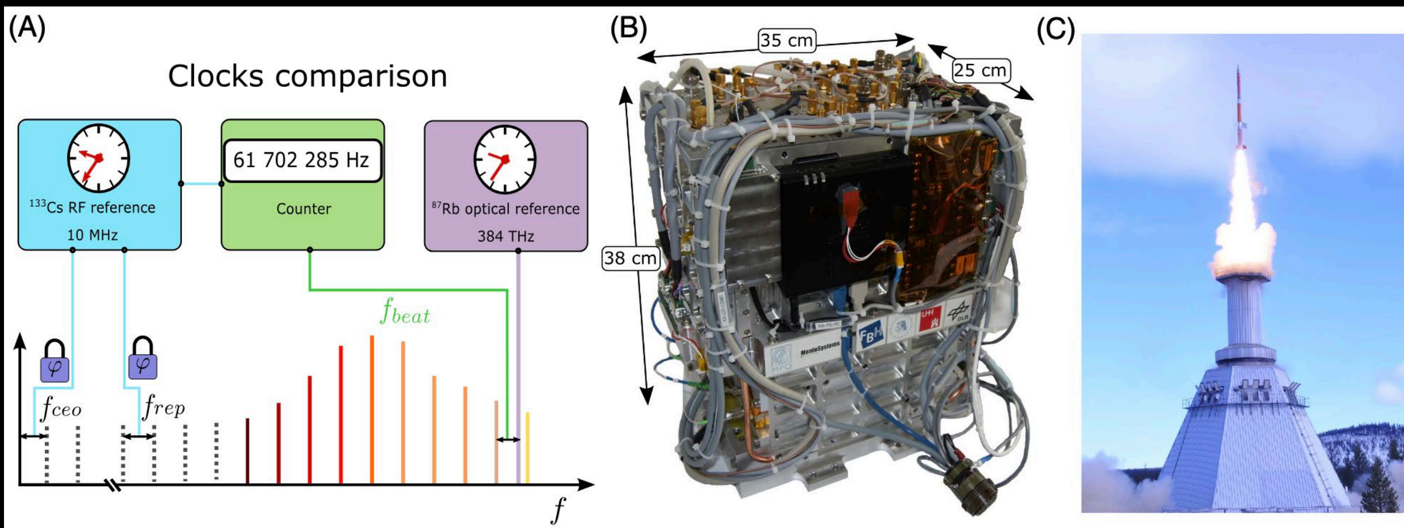
IRAFS
(NavIC, ISRO)



COMPASSO
(DLR)

Space CSAC (Microchip)

Optical Frequency Comb + Clocks in Space

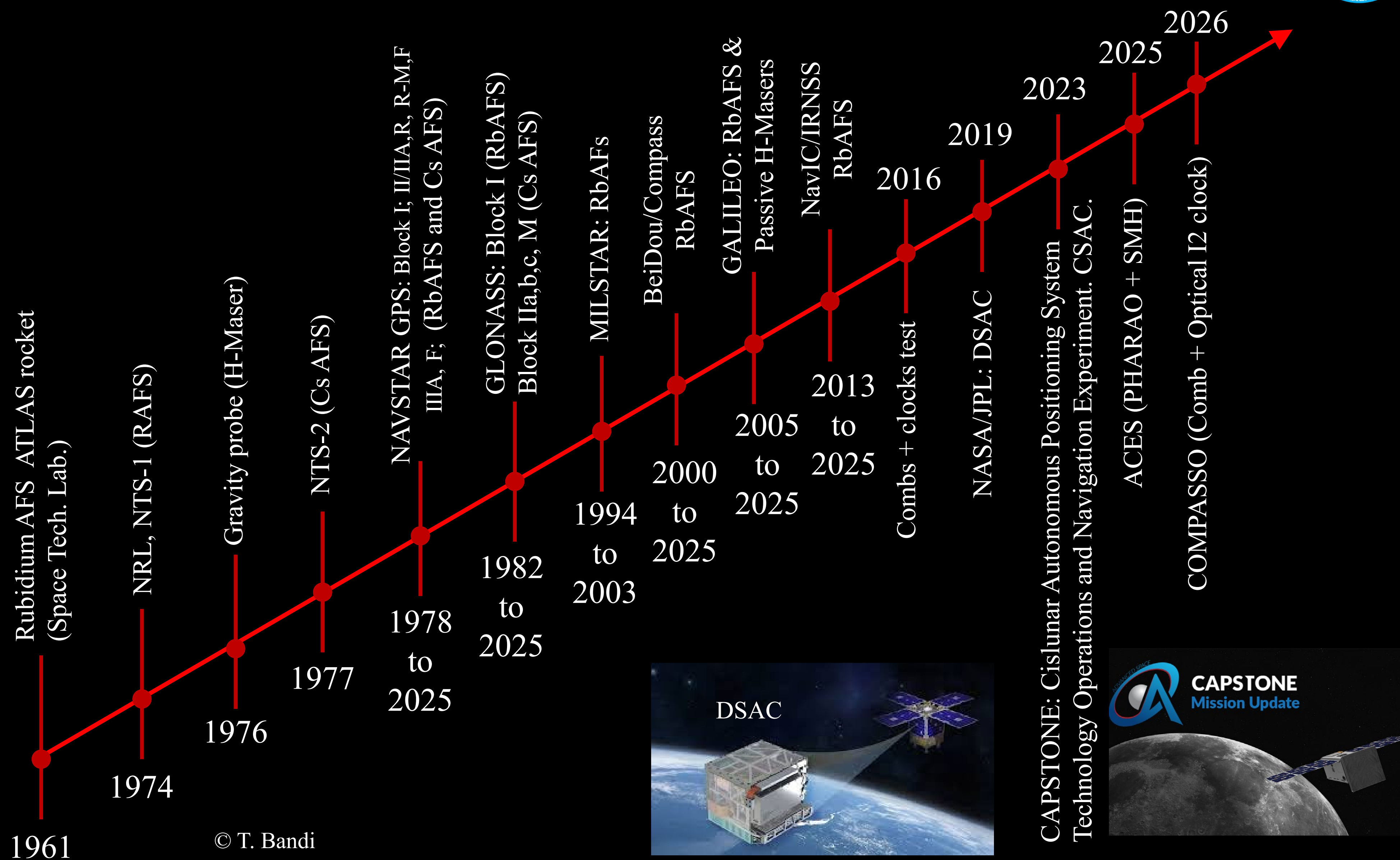


M. Lezius et al., Optica, vol. **3**, no. 12, 2016.

- Onboard sounding rocket (12.5g), range ~77 km.
- Tested in microgravity for 360 s.
- Two atomic clocks – optical D2 transition in Rb, and CSAC (^{133}Cs) clock, referenced to comb teeth, measuring 1e-11 at 100s.

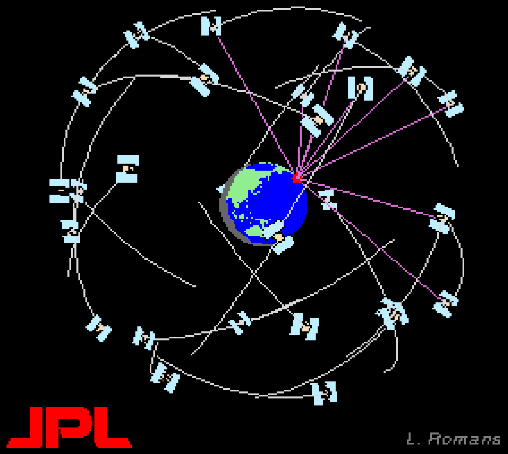
- Next planned Menlo comb launch in 2026, onboard COMPASSO mission (target 1e-18 levels) to MEO.
- 6.5 L, 7.5 kg, 35-55 W, rad hard 1kGy (>10 y life).

SPACE CLOCKS EVOLUTION



GNSS SYSTEMS & ONBOARD CLOCKS

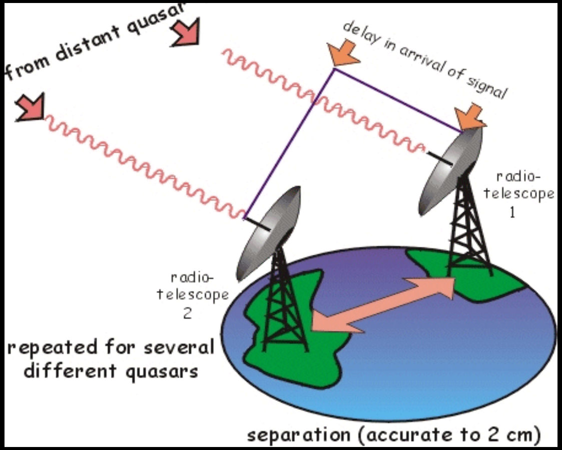
GNSS	Countries involved	Onboard Clocks
Global Positioning System (GPS)		Cesium beam clock, **Rubidium clock**
Galileo		**Rubidium clock,** Passive Hydrogen Maser (PHM)
Global Navigation Satellite System (GLONASS)		Cesium beam clock, Rubidium clock
BeiDou Navigation System (BDS)		**Rubidium clock**, PHM
IRNSS/NavIC Navigation with Indian Constellation		**Rubidium clocks**
Quazi-Zenith Satellite System (QZSS)		**Rubidium clock,** Quartz Oscillator



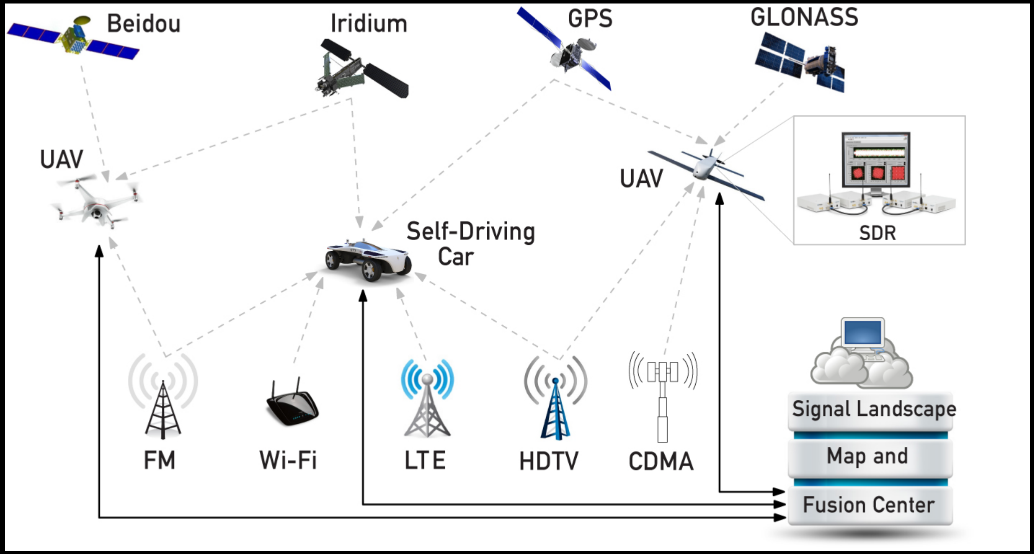
❖ GNSS

❖ Telecommunication synchronization

❖ Power grids synchronization



❖VLBI

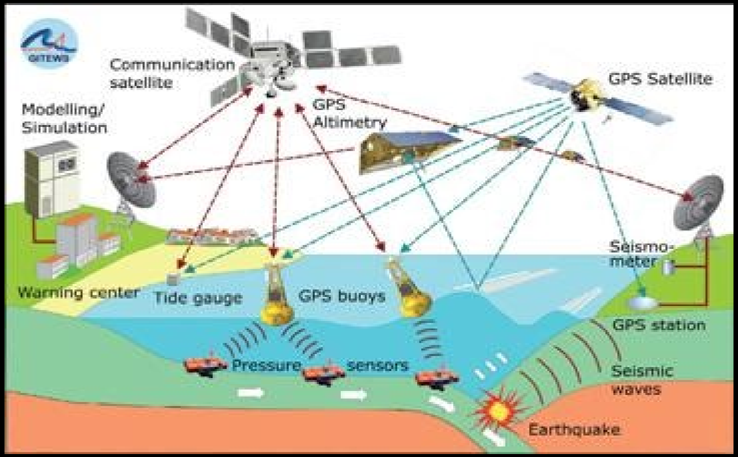


Credit: ASPIN Laboratory at UC Riverside

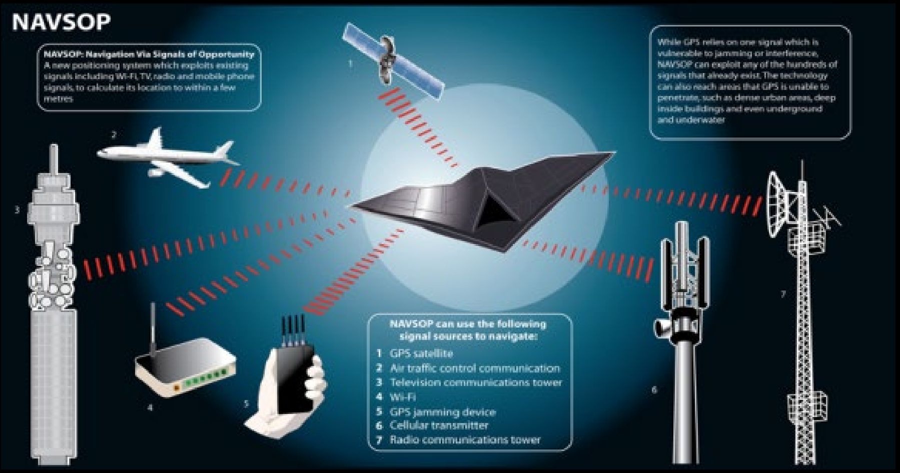
Images credit: Internet

APPLICATIONS OF SPACE CLOCKS

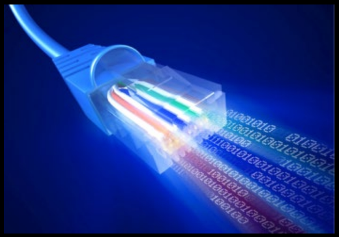
❖ Aviation



❖ Accurate predictions
- o Weather
- o Earth quake real-time monitoring
- o Cyclones
- o Atmospheric humidity analysis



❖ Military uses



❖ Precise science experiments on ground and space

❖And….
MANY MORE !!

Images credit: Internet, various sources

SPACE CLOCK BASICS: HOW TO BUILD ONE?

Space Clock requirements & specifications

Parameter Name	Parameter Definition/Remarks	Specification
Output Frequency	Two outputs with 50 dB isolation between them	10 MHz
Output Power	Two identical outputs	+10 ±1 dBm
Frequency Accuracy	Maximum frequency offset after 6 hours of warmup under vacuum conditions	Less than $\pm 1\times10^{-9}$
Frequency Drift	After 6 weeks of continuous operation under operating environmental conditions	Less than $\pm 5\times10^{-13}$ / day
Frequency Stability	At any fixed temperature in operating temperature range of -5 °C to +15 °C	τ in seconds — $\sigma_y(\tau)$ 1 — $\leq 5\times10^{-12}$ 10 — $\leq 1.5\times10^{-12}$ 100 — $\leq 5\times10^{-13}$ 1000 — $\leq 1.5\times10^{-13}$ 10000 — $\leq 5\times10^{-14}$ (drift removed)
Phase Noise	Maximum allowed Single Sideband spectral density induced on carrier shall not exceed the mentioned values	Offset from F_0 (Hz) — dBc/ Hz 1 — -85 10 — -100 100 — -125 1000 — -135 10000 — -145 100000 — -145

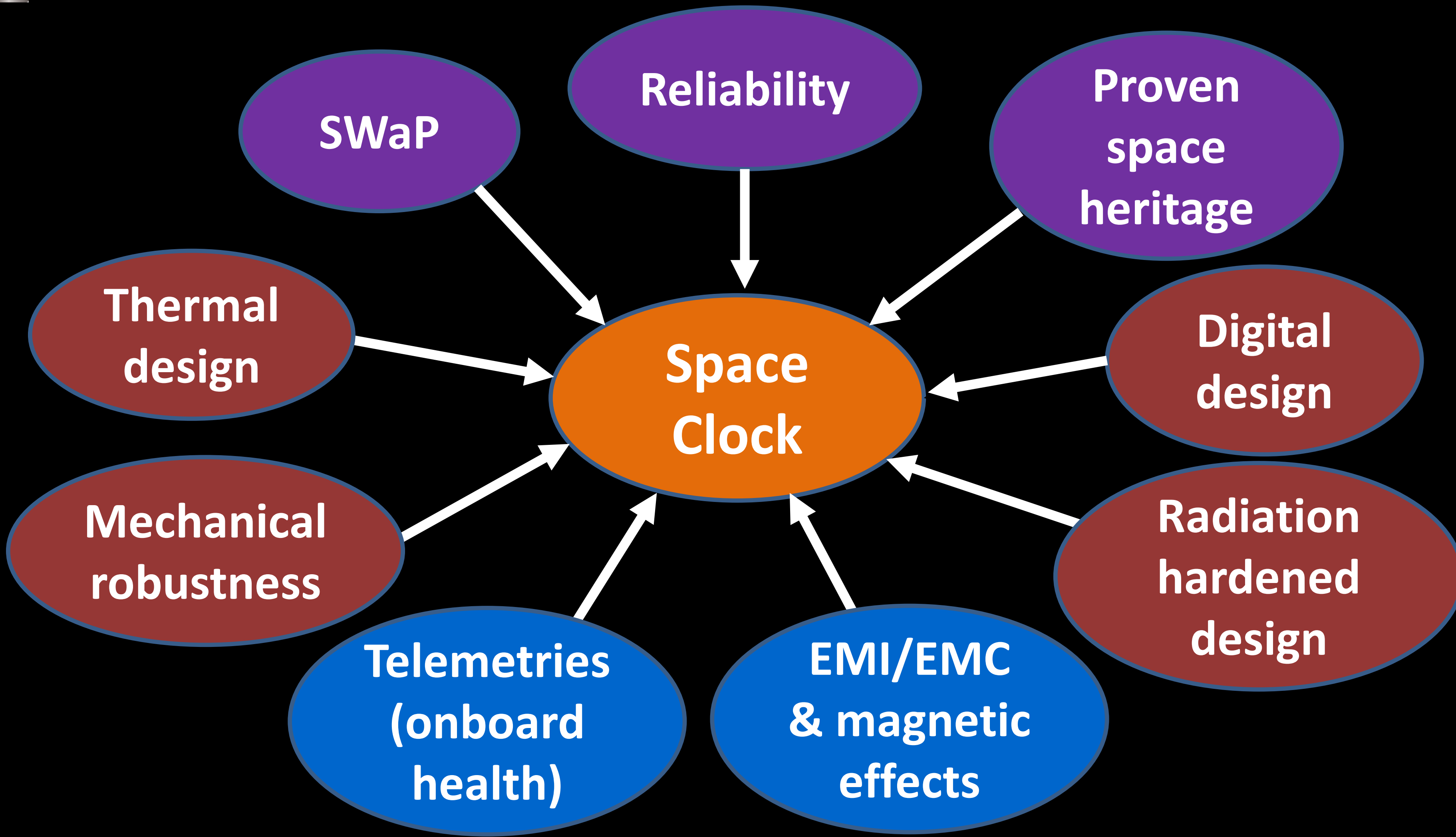
Bandi et al. GPS Solutions. 26:54, 2022.

Space Clock requirements & specifications

Frequency Temperature Stability	Frequency variation due to base plate temperature variation	Temperature coefficient less than $\pm 1 \times 10^{-13}$/°C.
Operating Temperature Range	Measured at the Satellite base plate	Satellite base plate operating temperature shall be in the range of -5 ^{0}C to +15 ^{0}C
Frequency Magnetic Sensitivity	Magnetic sensitivity is measured at the physics package level or at the complete clock level	Frequency variation due to magnetic field variations should be less than $\pm 1 \times 10^{-13}$/Gauss The static magnetic field up to ±2.5 Gauss shall also be permissible as long as the sum of static and dynamic magnetic fields shall not exceed 2.5 Gauss
Power consumption	Required power output of the EPC	<80 W (Warm up) <40 W (Steady State)
Power Supply Stability	Frequency variation due to power supply variation	Less than $\pm 3 \times 10^{-14}$/V.
Target mass and volume	Includes core RAFS and EPC	<10 kg <20 liters
Input rawbus voltage	from spacecraft bus	28V to 42V
Onboard Telemetries (TM)	Continuous output of TMs required to monitor onboard clock health	Clock ON/OFF; Light voltage; Signal voltage; Lock/Unlock; Base-plate temperature; Lamp inner temperature; Cavity outer temperature; Lamp input current; OCXO control voltage

Bandi et al. GPS Solutions. 26:54, 2022.

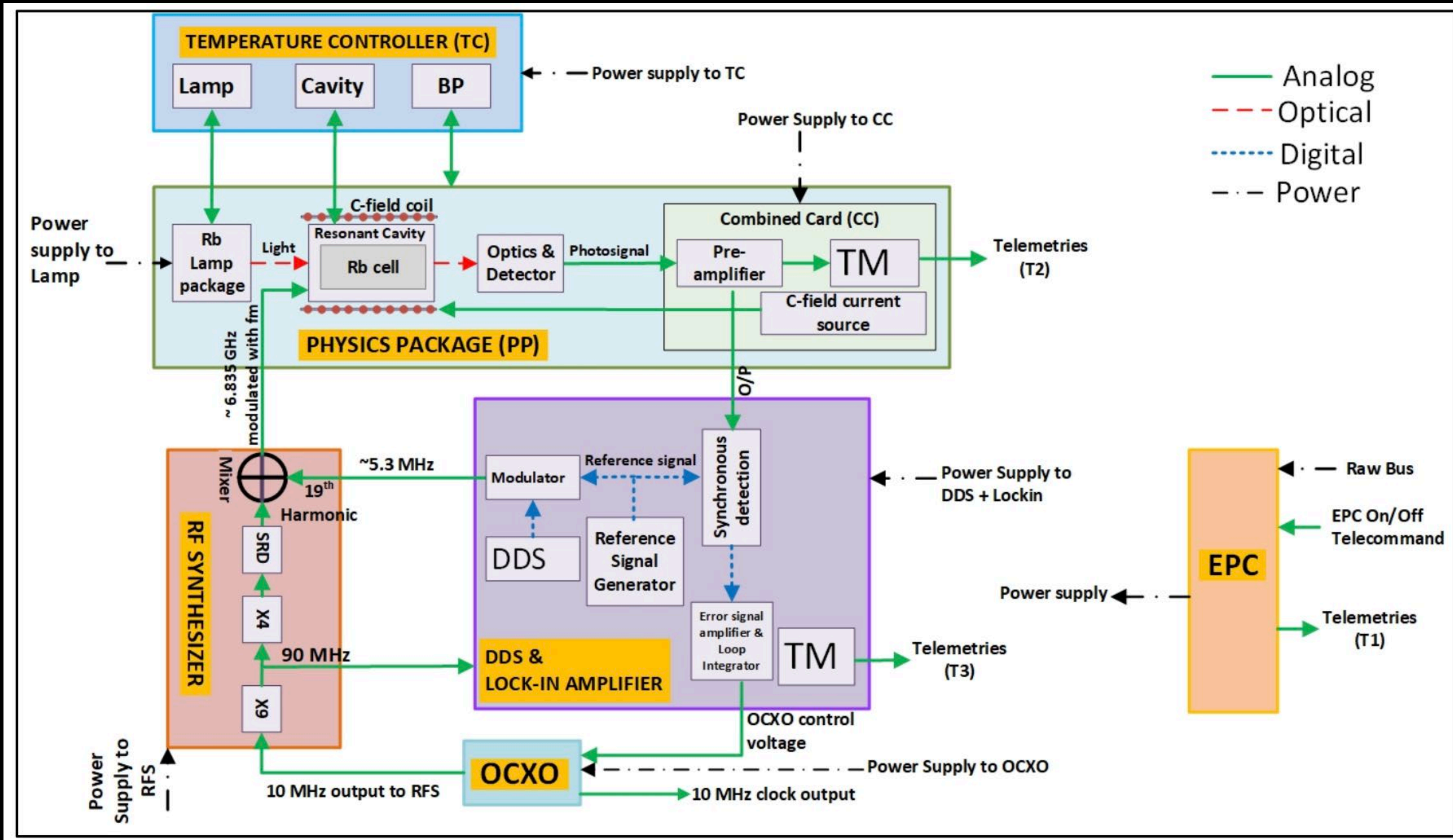
SPACE CLOCK BASICS: CONSIDERATIONS



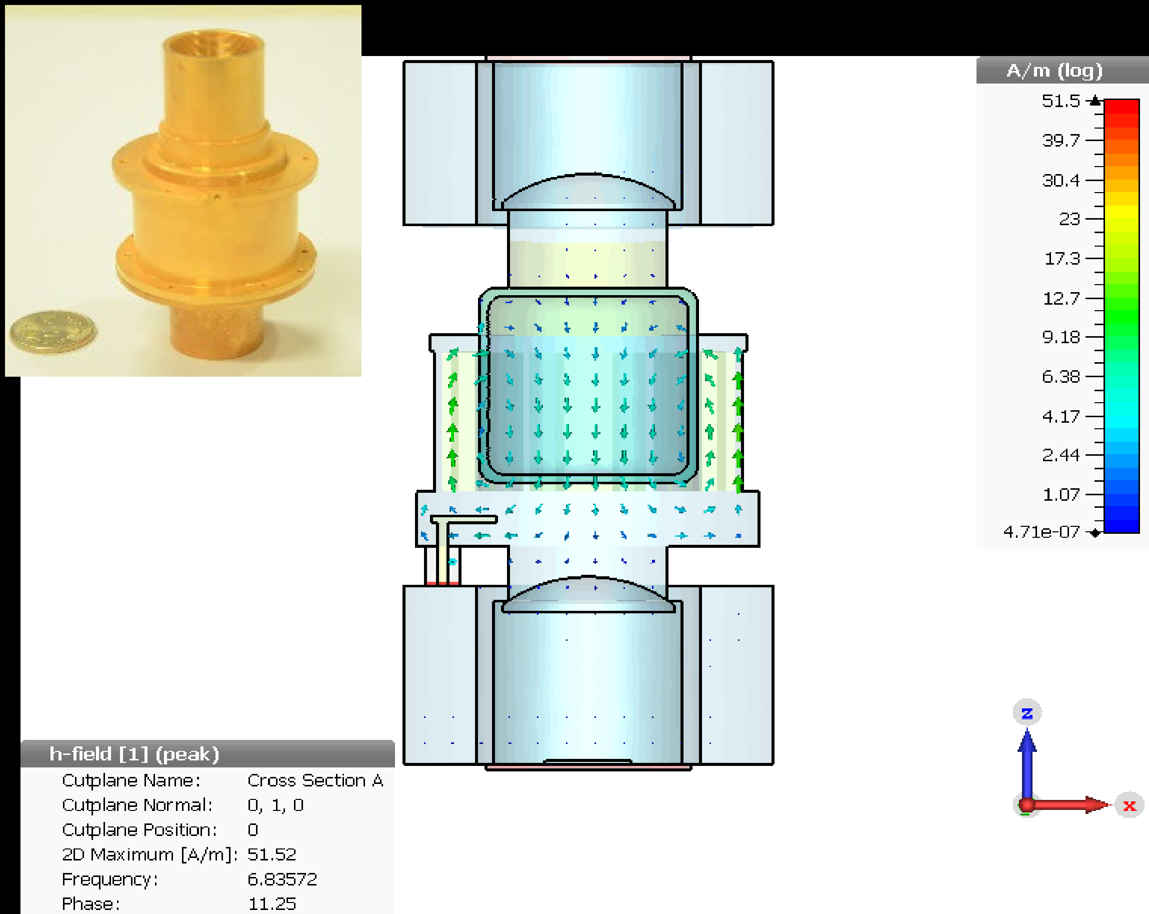
- Thorough characterization of the clock parameters
- Long-term ground tests (independent, stand-alone and integrated, w/ spacecraft)!

IRAFS : ARCHITECTURE

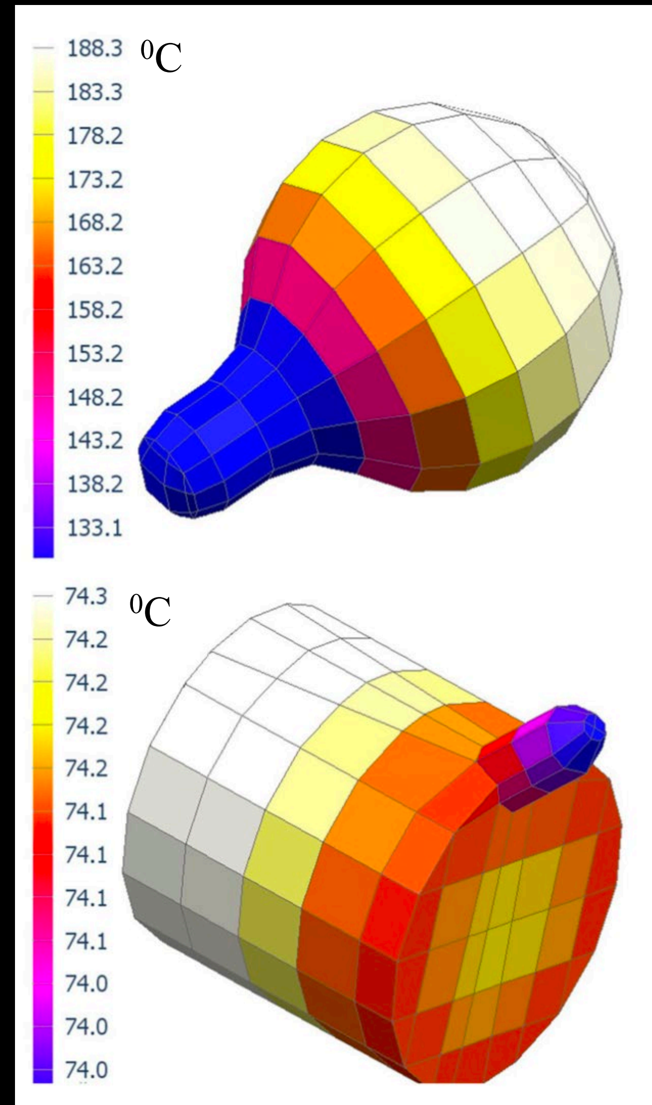
IRAFS: Indian Rubidium Atomic Frequency Standard



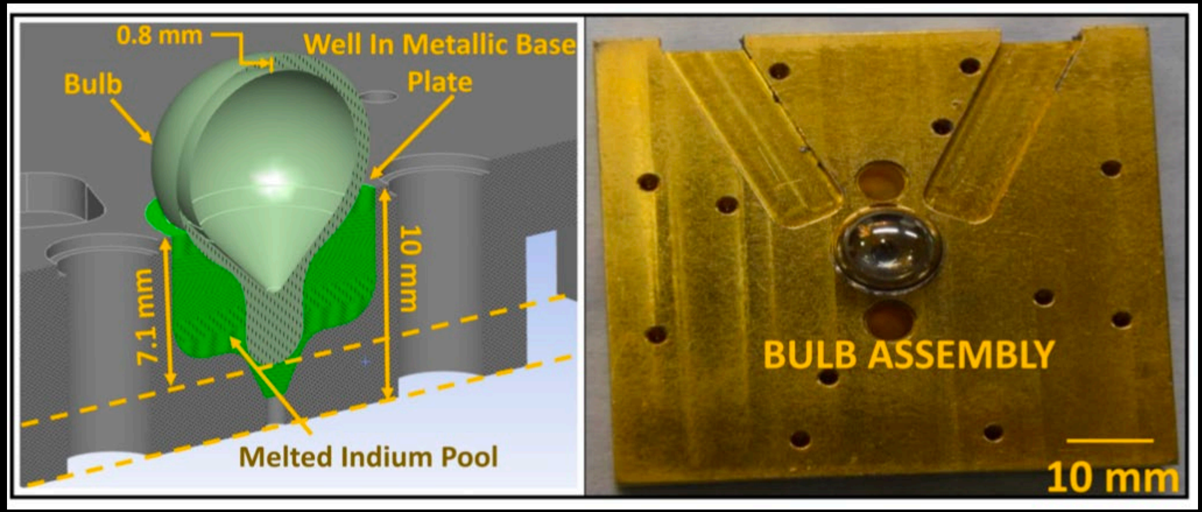
Bandi et al. GPS Solutions. 26:54, 2022.

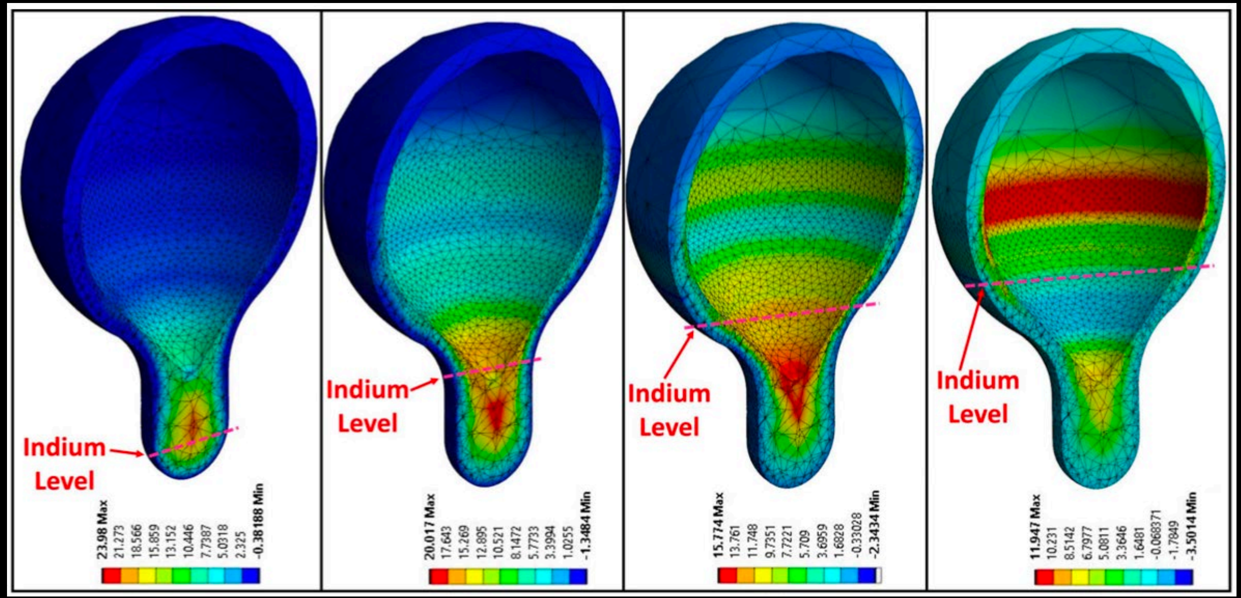


Kaintura et al. Rev. Sci. Instrum. 90 (084701), 2019.



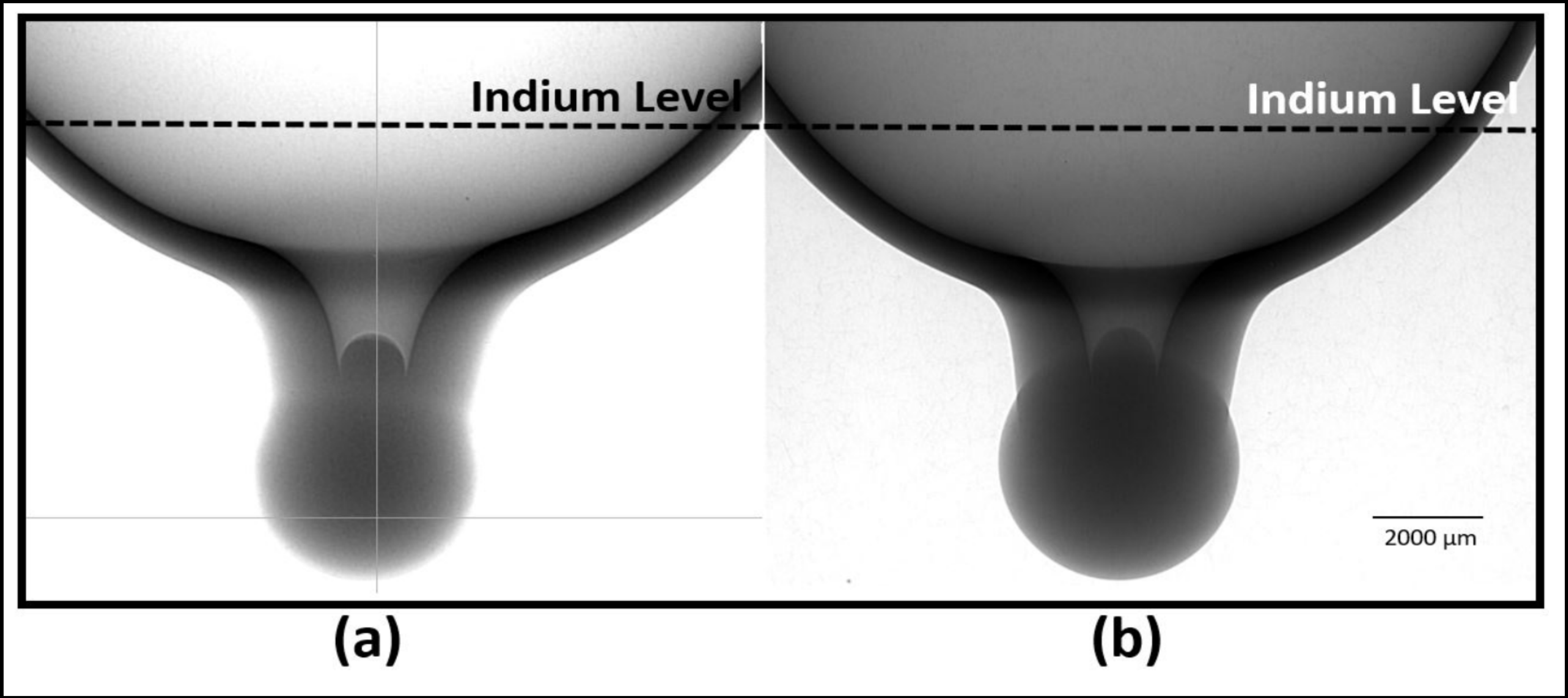
Bandi et al. TUFFC. 69 (4):1563, 2022.





Bandi et al. TUFFC. 69 (4):1563, 2022.

SPACE CLOCK BASICS: CHALLENGES

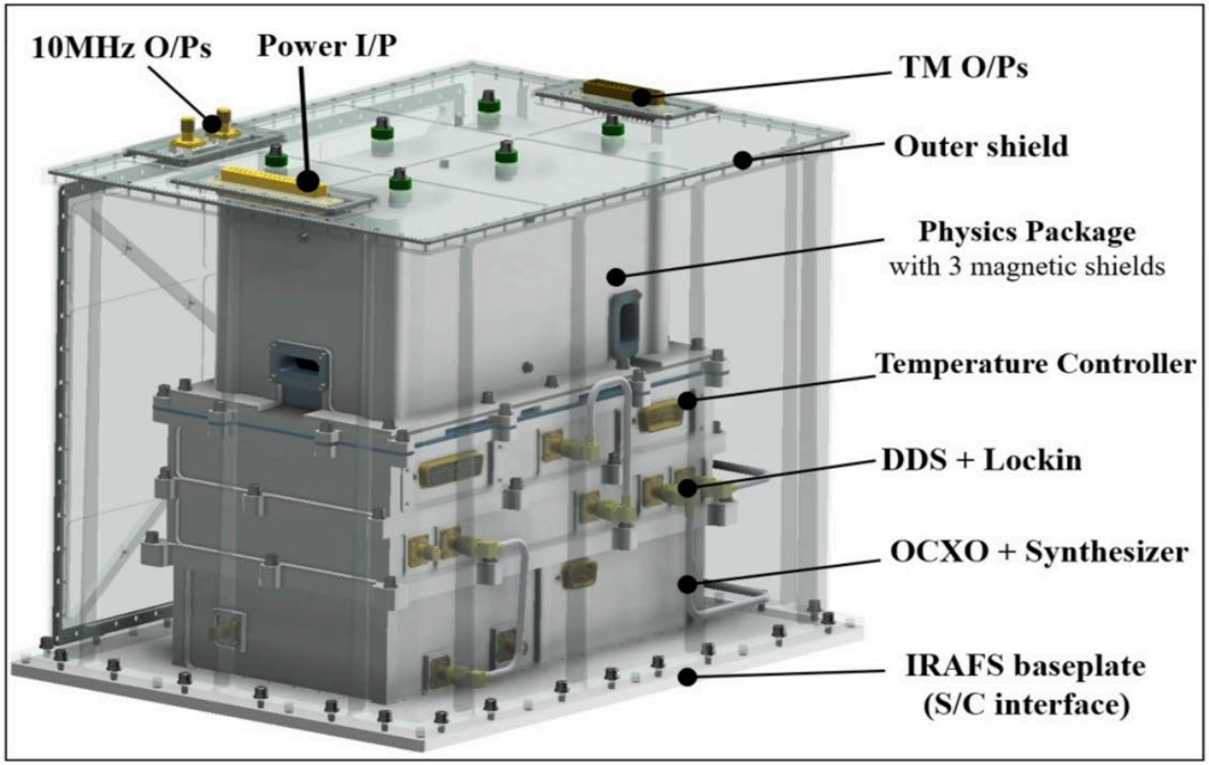


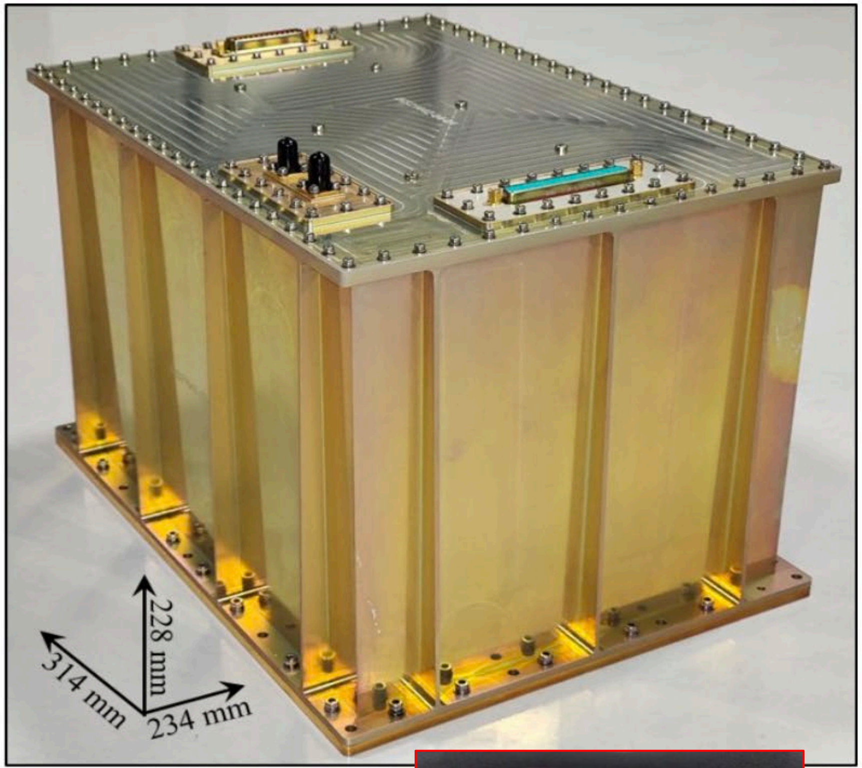
X-ray prior to bonding & Operation

X-ray post bonding & Operation 200 cycles

Bandi et al. TUFFC. 69 (4):1563, 2022.

No frequency jumps with the IRAFS

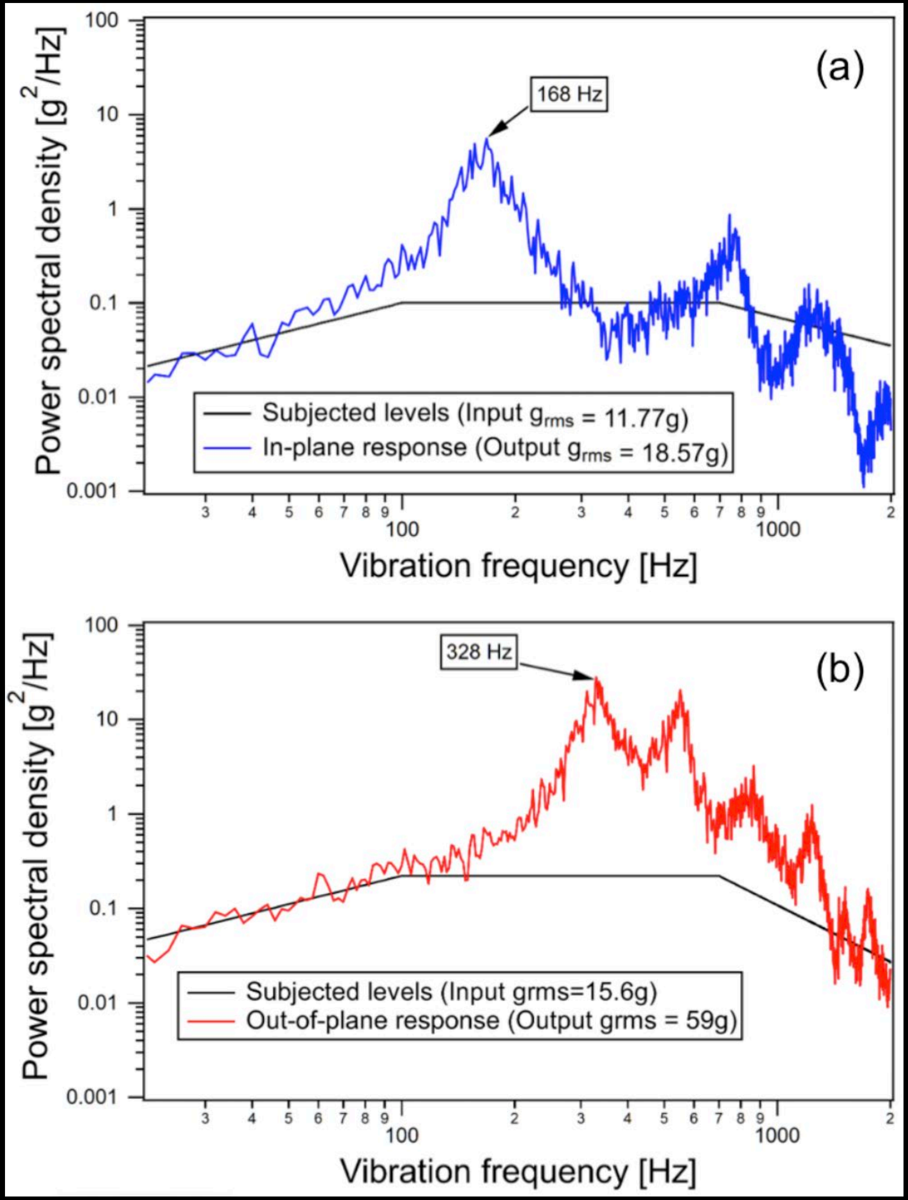




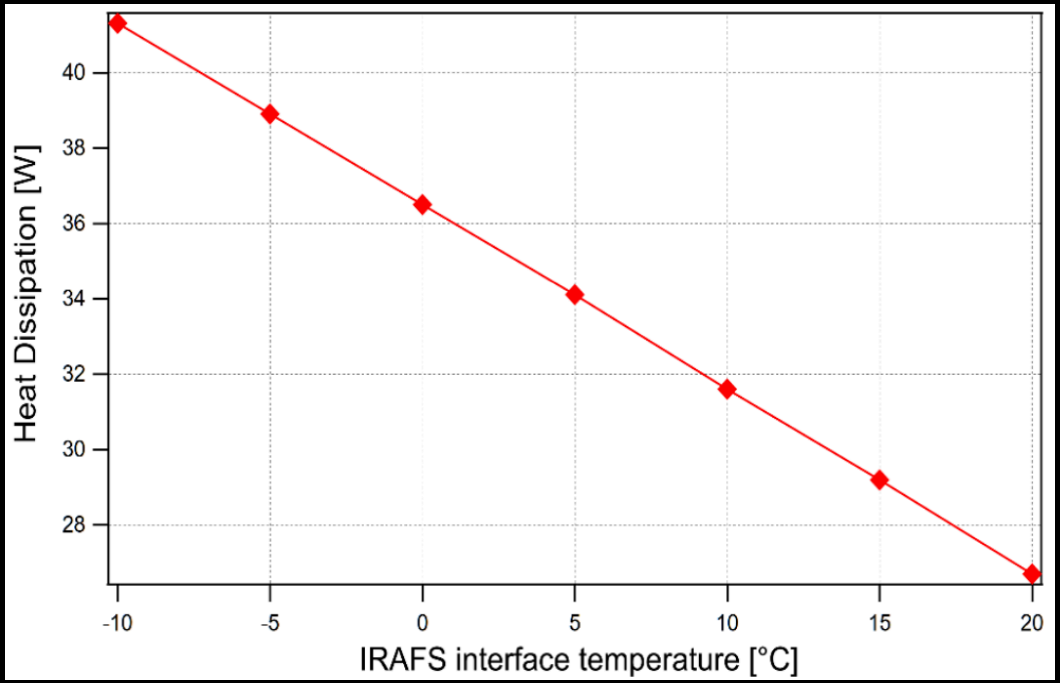
Power: <80 W (turn ON)
<40 W (steady state)
Weight: 7.52 kg (IRAFS)
<10 kg (IRAFS+EPC)

High-end OCXO designed & developed at Bengaluru, India. In support & directions from ACD, SAC-ISRO

Bandi et al. GPS Solutions. 26:54, 2022.



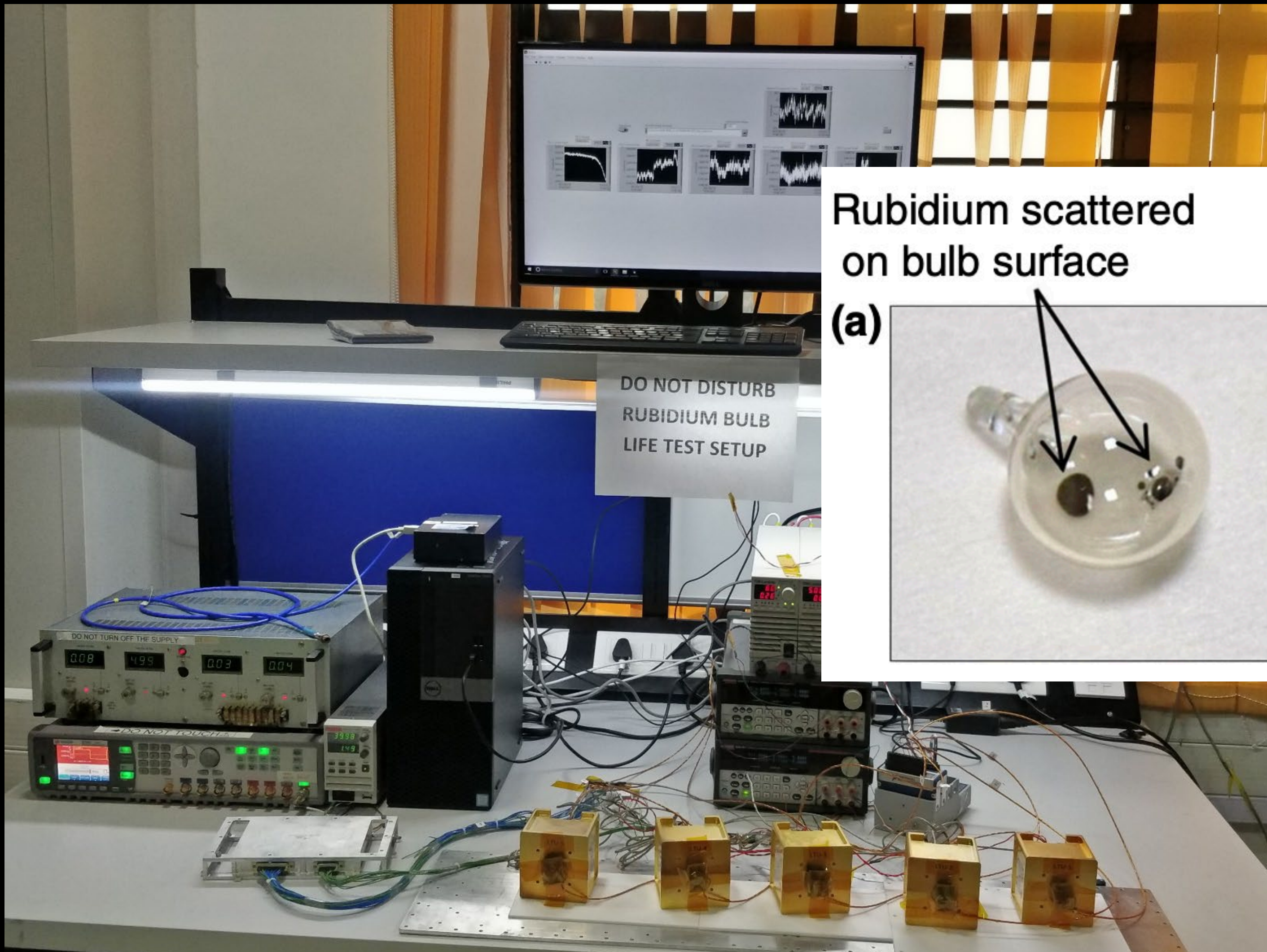
The IRAFS successfully passed the vibration tests and there was no difference in pre and post test results.

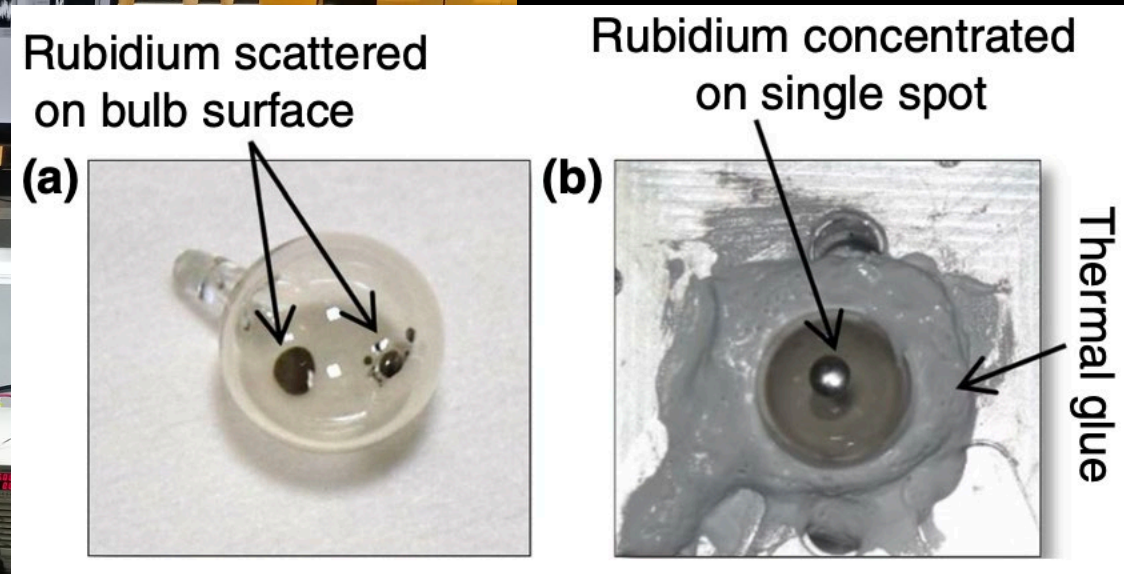


Thermal Dissipation to Spacecraft deck

Bandi et al. GPS Solutions. 26:54, 2022.

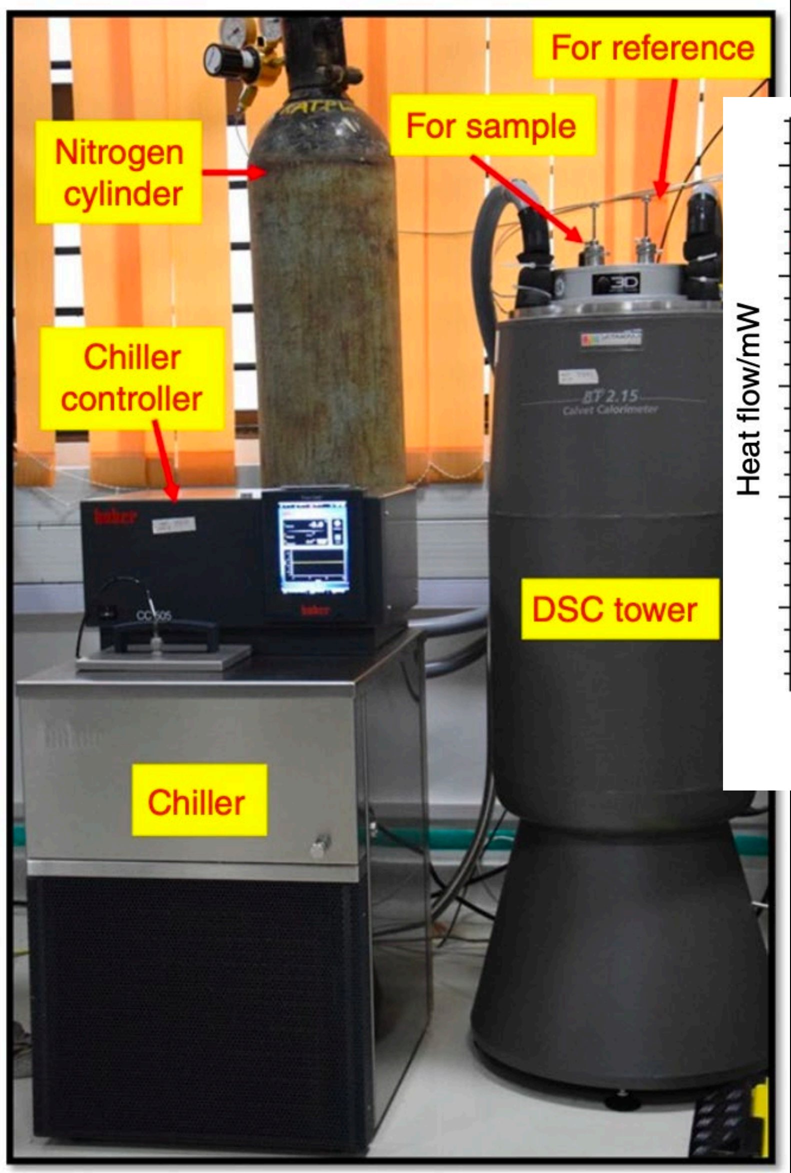
SPACE CLOCK: LAMPS LONG-TERM TESTING

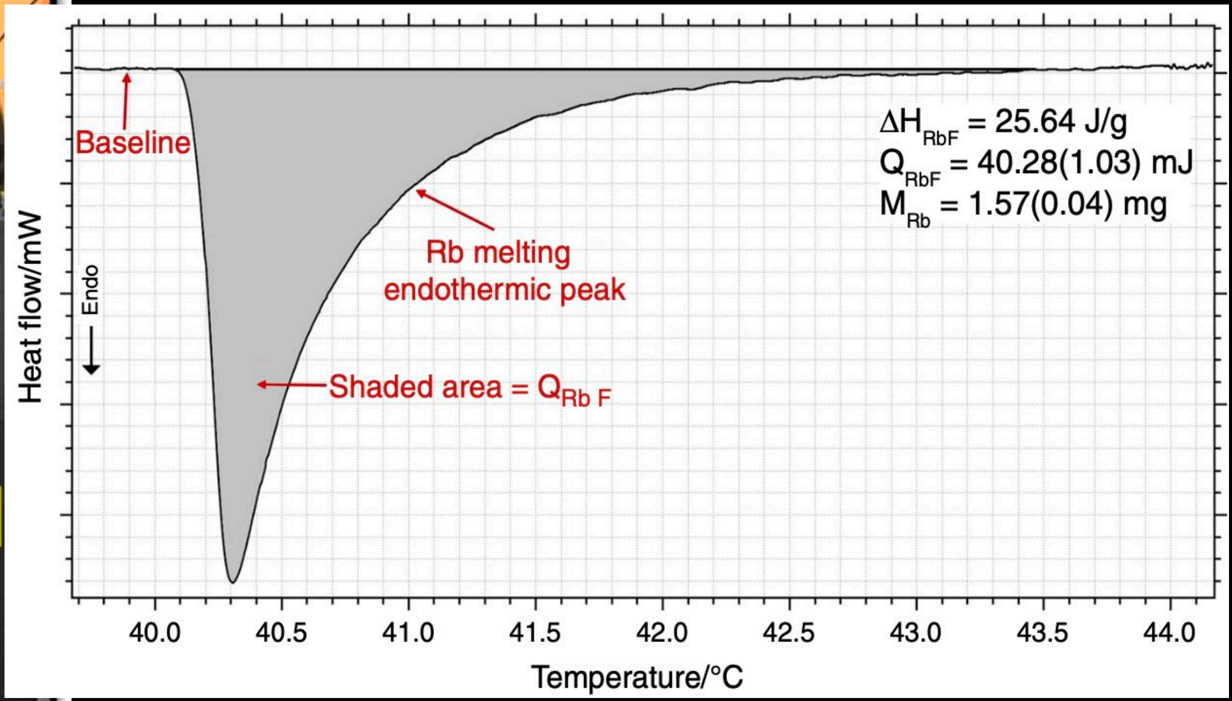




Rigorous long-term testing (1 year) at various operating conditions

Kesarkar et al. J. of Thermal Analysis and Calorimetry. 147:10049-10056, 2022.

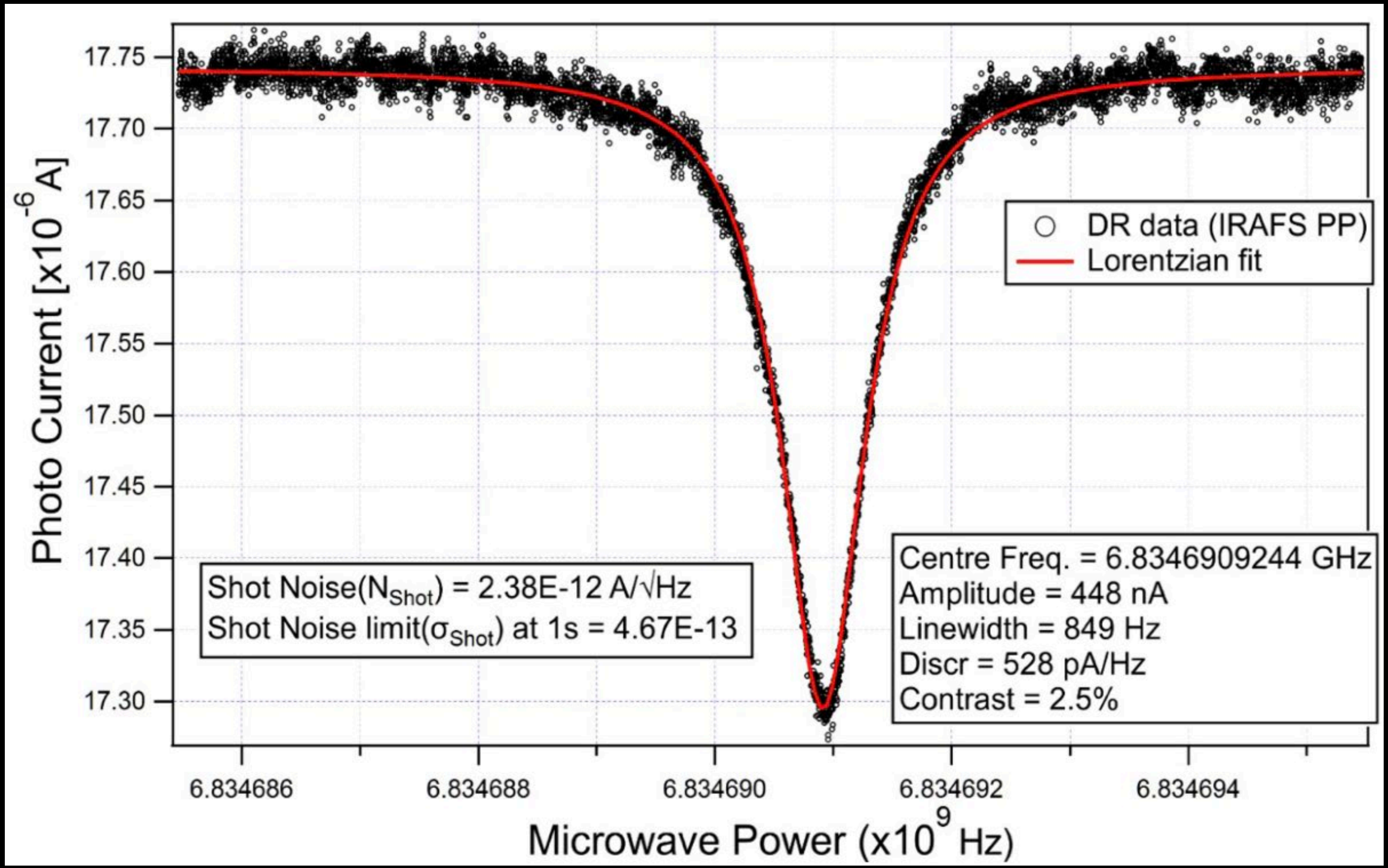




Rb consumption rate: $0.64 \mu g/\sqrt{hr}$

Kesarkar et al. J. of Thermal Analysis and Calorimetry. 147:10049-10056, 2022.

CLOCK ATOMIC SIGNAL



- Short term stability:

$$\sigma_y(\tau) = \frac{N_{PSD}}{\sqrt{2}.D.\nu_{Rb}} \tau^{-1/2}$$

- Shot-noise limit: <5x10^{-13} $\tau^{-1/2}$

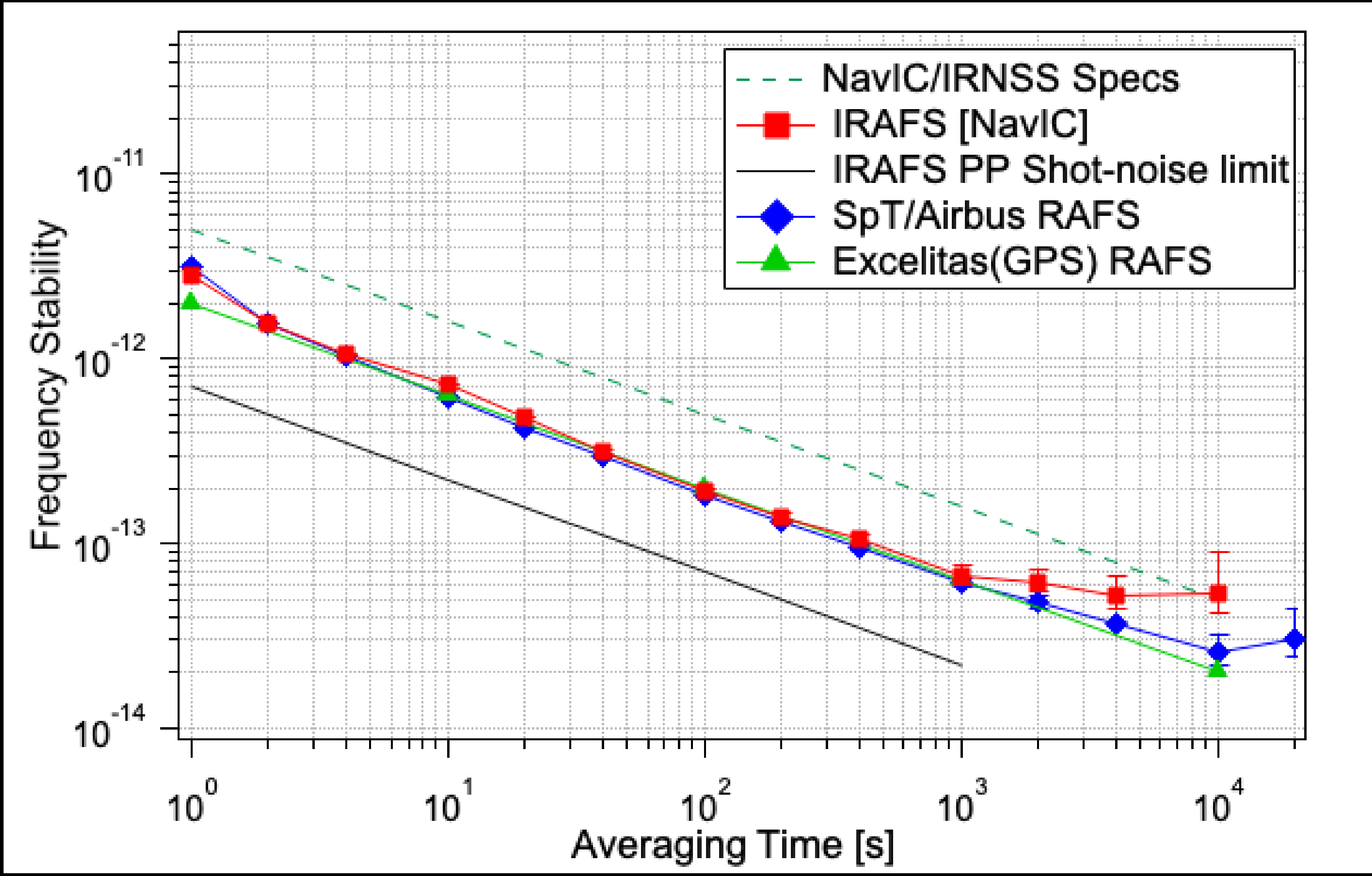
CLOCK FREQUENCY PERTURBATIONS

$$\sigma_{overall} = \sqrt{\sigma_{LTC}^2 + \sigma_{CTC}^2 + \sigma_{MPS}^2 + \sigma_{CFC}^2 + \sigma_{LSC}^2}$$

Perturbing parameter	Coefficient of perturbation	Measured variation at 10^4 s	Estimated stability limit at 10^4 s
Lamp Temp. Coefficient (LTC)	9×10^{-11} /°C	1×10^{-4} °C	9×10^{-15}
Cell Temp. Coefficient (CTC)	5×10^{-11} /°C	5×10^{-5} °C	2.5×10^{-15}
Microwave power shift Coefficient (MPS)	3.5×10^{-11}/mW	3.5×10^{-4} mW	1.22×10^{-14}
C-Field current Coefficient (CFC)	2×10^{-9} /mA	6.2×10^{-7} mA	1.24×10^{-15}
Light Shift Coefficient (LSC)	1×10^{-11} /%	3.5×10^{-3} %	3.5×10^{-14}
Overall Instability Limit (@10,000s)			4×10^{-14}

Bandi et al. GPS Solutions. 26:54, 2022.

STABILITY PERFORMANCE



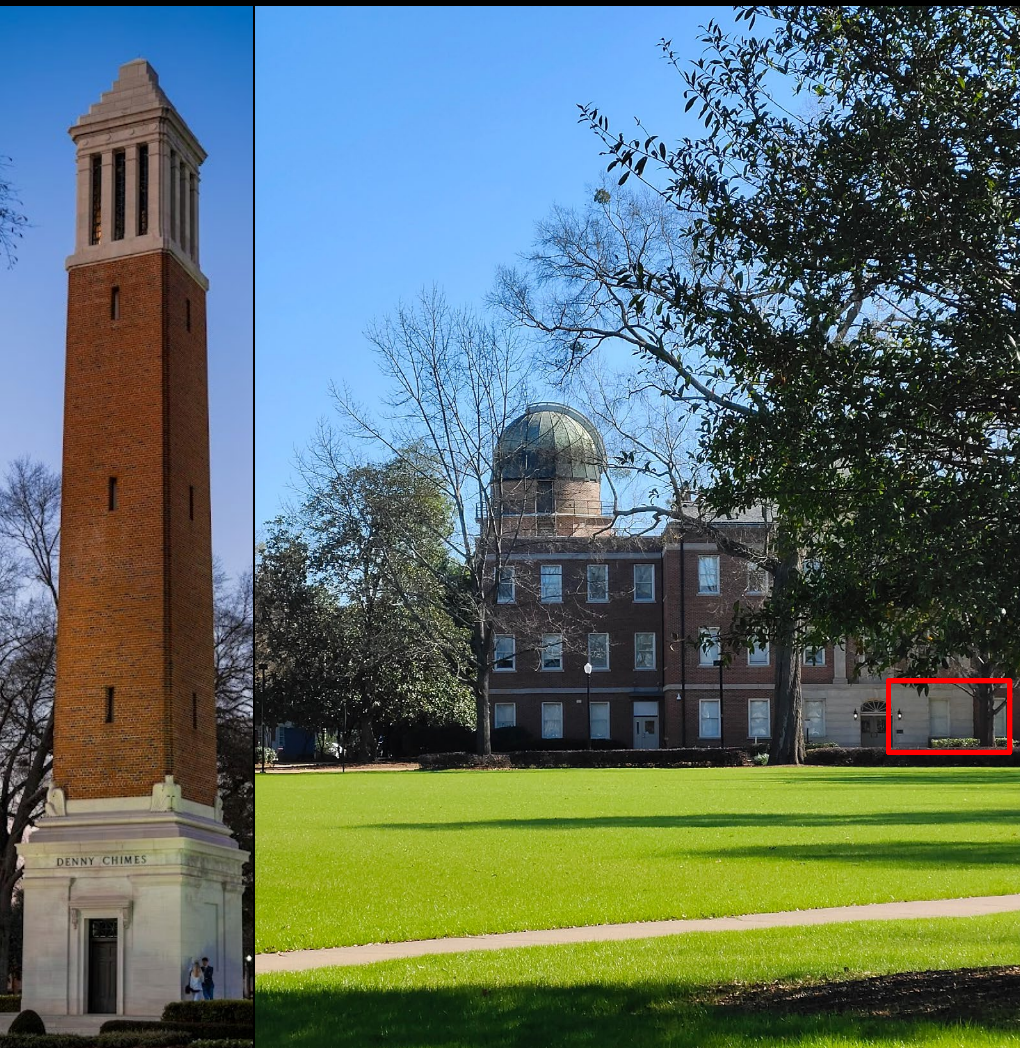
Bandi et al. GPS Solutions. 26:54, 2022.

LASERS

We investigate basic precision quantum physics principles & develop niche timing, frequency, and navigation tools.

MASERS

PULSARS



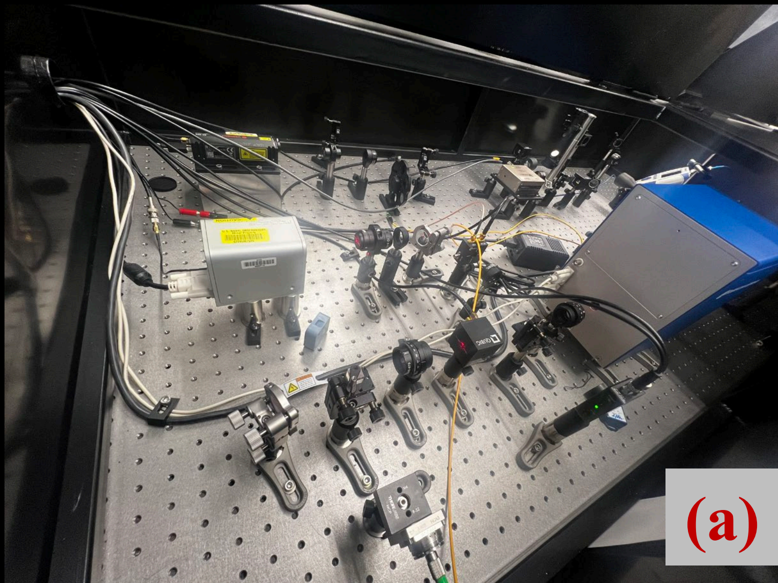
What we do?

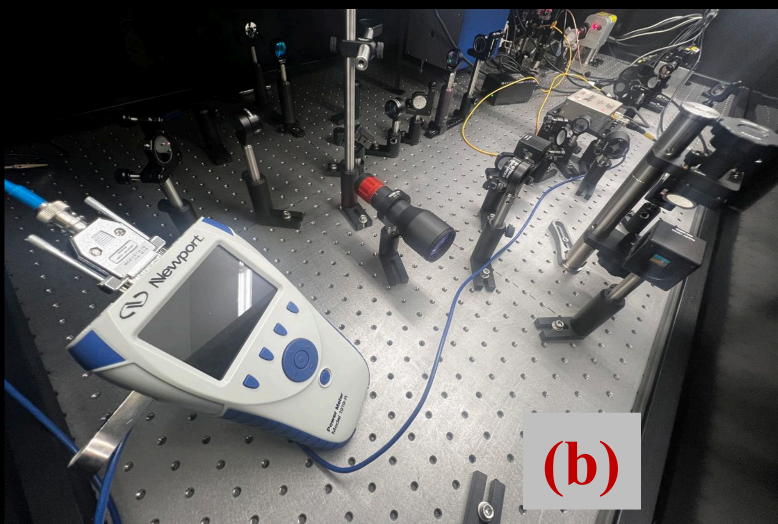
- ❖ Precision Timescale
- ❖ Filters & Algorithms
- ❖ Optical atomic clocks
- ❖ Quantum metrology
- ❖ Safe GNSS methods
- ❖ Synchronization schemes

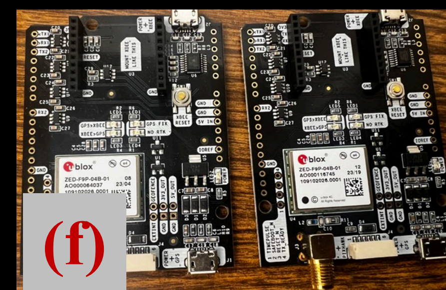
How we do?

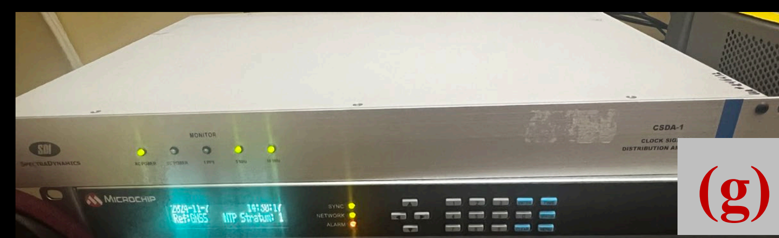
- ✓ Well trained students in PNTF research
- ✓ Collaborations with diverse expertise within UA
- ✓ Industrial collaborations
- ✓ Collaborations and links with Government labs

QUANTIME LAB RESEARCH









CONCLUSION AND PROSPECTS

- Space clocks are ubiquitous for everyday applications
  - – dependence is only increasing…. 5G, 6G and beyond…

- Rb clocks continue to be reliable space clocks, ion clocks and optical clocks are making their way….

- Quantime Lab PNTF research and training… next-gen workforce.

THANK YOU FOR YOUR ATTENTION

https://Quantime.ua.edu

Contact: tbandi@ua.edu

https://accept.ua.edu

ACCEPT
Alabama Collaborative for Contemporary Education in Precision Timing

ACKNOWLEDGEMENTS

NIST National Institute of Standards and Technology U.S. Department of Commerce

United States Naval Observatory

NASA JPL

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MICROCHIP

SAFRAN