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## EE C245 - ME C218 Introduction to MEMS Design Fall 2011

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Lecture Module 2: Benefits of Scaling

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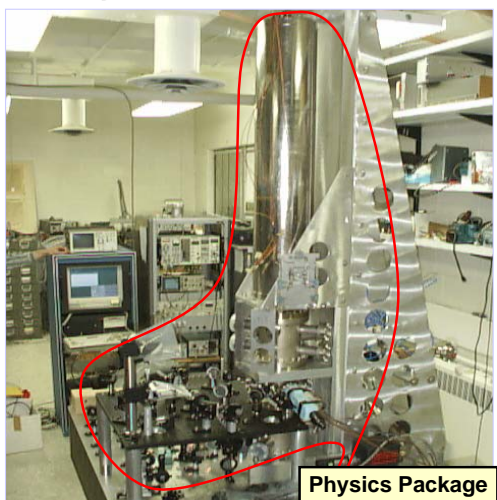
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## Chip-Scale Atomic Clocks (CSAC)

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## NIST F1 Fountain Atomic Clock



Vol: ~3.7 m<sup>3</sup>  
 Power: ~500 W  
 Acc:  $1 \times 10^{-15}$   
 Stab:  $3.3 \times 10^{-15}$ /hr

After 1 sec  $\Rightarrow$   
**Error:  $10^{-15}$  sec**

↓

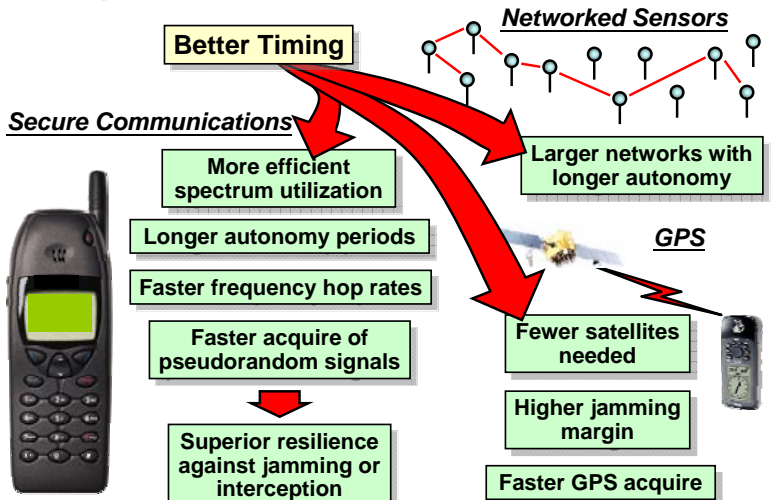
Loses 1 sec every  
 30 million years!

Physics Package

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## Benefits of Accurate Portable Timing



**Better Timing**

**Secure Communications**

- More efficient spectrum utilization
- Longer autonomy periods
- Faster frequency hop rates
- Faster acquire of pseudorandom signals
- Superior resilience against jamming or interception

**Networked Sensors**

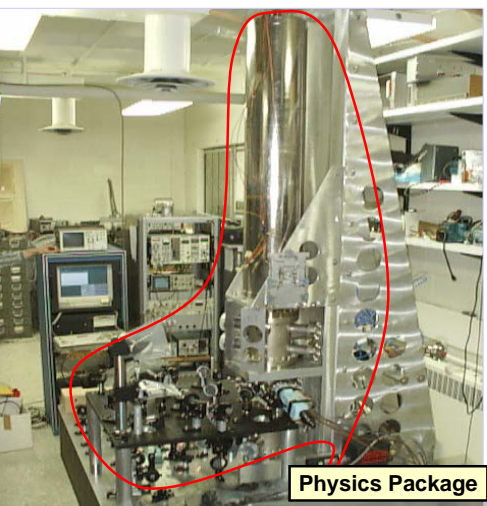
- Larger networks with longer autonomy

**GPS**

- Fewer satellites needed
- Higher jamming margin
- Faster GPS acquire

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### NIST F1 Fountain Atomic Clock



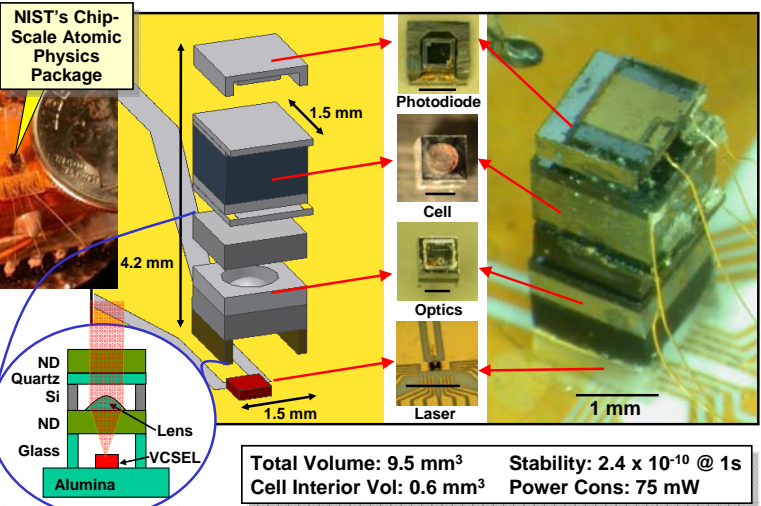
**Vol: ~3.7 m<sup>3</sup>**  
**Power: ~500 W**  
**Acc: 1 × 10<sup>-15</sup>**  
**Stab: 3.3 × 10<sup>-15</sup>/hr**

After 1 sec ⇨ **Error: 10<sup>-15</sup> sec**

**Loses 1 sec every 30 million years!**

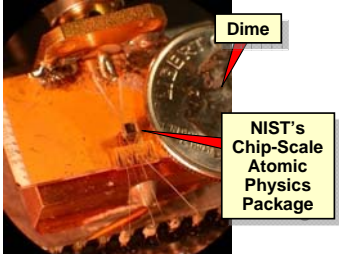
Physics Package

### 1<sup>st</sup> Chip-Scale Atomic Physics Package



**Total Volume: 9.5 mm<sup>3</sup>**      **Stability: 2.4 × 10<sup>-10</sup> @ 1s**  
**Cell Interior Vol: 0.6 mm<sup>3</sup>**      **Power Cons: 75 mW**

### Tiny Physics Package Performance

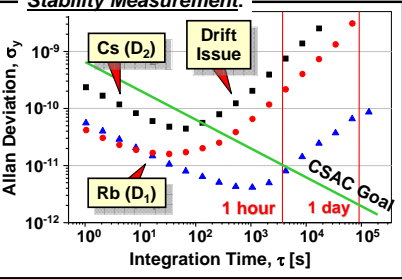


Dime

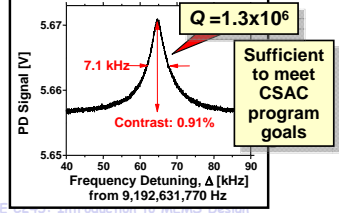
NIST's Chip-Scale Atomic Physics Package

- Experimental Conditions:**
  - Cs D2 Excitation
  - External (large) Magnetic Shielding
  - External Electronics & LO
  - Cell Temperature: ~80 °C
  - Cell Heater Power: 69 mW
  - Laser Current/Voltage: 2mA / 2V
  - RF Laser Mod Power: 70μW

**Stability Measurement:**



**Open Loop Resonance:**



Q = 1.3 × 10<sup>6</sup>

7.1 kHz

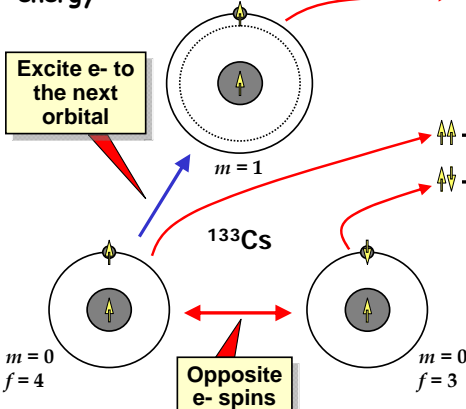
Contrast: 0.91%

Sufficient to meet CSAC program goals

### Atomic Clock Fundamentals

Frequency determined by an atomic transition energy

**Energy Band Diagram**



Excite e- to the next orbital

133Cs

Opposite e- spins

$\Delta E = 1.46 \text{ eV}$   
 $\nu = \Delta E/h = 352 \text{ THz}$   
 $\Rightarrow 852.11 \text{ nm}$

$\Delta E = 0.000038 \text{ eV}$   
 $\nu = \Delta E/h = 9\,192\,631\,770 \text{ Hz}$

### Miniature Atomic Clock Design

The diagram illustrates the energy levels of  $^{133}\text{Cs}$  atoms. The ground state is split into two hyperfine levels by a frequency of  $\nu = \Delta E/h = 9\,192\,631\,770\text{ Hz}$ . A carrier wave at 852 nm is shown with sidebands separated by 4.6 GHz and 9.2 GHz. A modulated laser at 852 nm is directed through a  $^{133}\text{Cs}$  vapor cell at  $10^{-7}$  torr. The atoms become transparent to light at 852 nm. A photo detector measures the signal, which is fed back to a VCXO (microwave oscillator) at 4.6 GHz to lock the system.

**Key components and labels:**  
 Carrier (852 nm), Sidebands, 4.6GHz, 9.2GHz, Atoms become transparent to light at 852 nm,  $\nu = \Delta E/h = 9\,192\,631\,770\text{ Hz}$ , Hyperfine Splitting Freq., Modulated Laser,  $^{133}\text{Cs}$  vapor at  $10^{-7}$  torr, Photo Detector, Mod  $f$ , VCXO,  $\mu\text{wave osc}$ , Close feedback loop to lock.

### Chip-Scale Atomic Clock

The diagram shows the atomic clock concept and its physical implementation. The concept includes a laser, a VCXO (microwave oscillator) at 4.6 GHz, a photo detector, and a GHz resonator in vacuum. The physical implementation is a chip-scale atomic clock with a VCSEL, Cs or Rb, glass, detector, and substrate.

**Key Challenges:**  
 thermal isolation for low power  
 cell design for maximum  $Q$   
 low power  $\mu\text{wave oscillator}$

**Chip-Scale Atomic Clock Specifications:**  
 Vol:  $1\text{ cm}^3$   
 Power: 30 mW  
 Stab:  $1 \times 10^{-11}$

### Challenge: Miniature Atomic Cell

The diagram compares a large vapor cell and a tiny vapor cell. The large cell has a volume that is 1,000X larger than the tiny cell. As the volume decreases, the surface area increases, leading to more wall collisions. This causes atoms to lose their coherent state, resulting in a lower  $Q$  factor and a broader atomic resonance peak. The resonance frequency is 9.2 GHz.

**Labels:**  
 Large Vapor Cell, Tiny Vapor Cell, 1,000X Volume Scaling, Surface Volume  $\uparrow$ , More wall collisions  $\Rightarrow$  stability gets worse, Atomic Resonance, Intensity, Mod  $f$ , 9.2 GHz, lowest  $Q$ , lower  $Q$ , Wall collision dephases atoms  $\Rightarrow$  lose coherent state.

### Challenge: Miniature Atomic Cell

The diagram compares a large vapor cell and a tiny vapor cell. The large cell has a volume that is 1,000X larger than the tiny cell. The tiny cell has a shorter mean free path of the atomic vapor. The solution is to add a buffer gas, which lowers the mean free path and returns the  $Q$  factor to a higher value. The resonance frequency is 9.2 GHz.

**Labels:**  
 Large Vapor Cell, Tiny Vapor Cell, 1,000X Volume Scaling, Buffer Gas, Sol'n: Add a buffer gas, Lower the mean free path of the atomic vapor, Atomic Resonance, Intensity, Mod  $f$ , 9.2 GHz, Return to higher  $Q$ .

### Chip-Scale Atomic Clock

**Atomic Clock Concept**

**MEMS and Photonic Technologies**

- **Key Challenges:**
  - thermal isolation for low power
  - cell design for maximum Q
  - low power  $\mu$ wave oscillator

**Chip-Scale Atomic Clock**

Vol:  $1 \text{ cm}^3$   
 Power:  $30 \text{ mW}$   
 Stab:  $1 \times 10^{-11}$

### Micro-Scale Oven-Control Advantages

**Macro-Scale**

Macro-Oven (containing heater and T sensor)  
 Atomic Cell @  $80^\circ\text{C}$   
 3 cm  
 Insulation  
 Laser  
 Thermally Isolating Feet

$R_{th} = 38 \text{ K/W}$   
 $C_{th} = 22 \text{ J/K}$   
 $P(@ 80^\circ\text{C}) = 1.5 \text{ W}$   
 Warm Up,  $\tau = 16 \text{ min.}$

**Micro-Scale**

$300 \times 300 \times 300 \mu\text{m}^3$  Atomic Cell @  $80^\circ\text{C}$   
 Heater  
 Laser  
 T Sensor (underneath)  
 Long, Thin Polysilicon Tethers

$R_{th} = 83,000 \text{ K/W}$   
 $C_{th} = 6.3 \times 10^{-6} \text{ J/K}$   
 $P(@ 80^\circ\text{C}) = 2.6 \text{ mW}$   
 Warm Up,  $\tau = 0.1 \text{ s}$

$T = P \times R_{th}$

$R_{th} \sim \frac{\text{support length}}{\text{X-section area}}$   
 $C_{th} \sim \text{volume}$

**550x lower power**  
**7,300x faster warm up**

### Physics Package Power Diss. < 10 mW

• Achieved via MEMS-based thermal isolation

Cesium cell  
 Heater/Sensor Suspension  
 VCSEL / Photodiode  
 Frame Spacer  
 VCSEL Suspension  
 Symmetricom / Draper Physics Package Assembly  
 20 pin LCC

Only ~5 mW heating power needed to achieve  $80^\circ\text{C}$  cell temperature

Power [mW]  
 Temperature [°C]

◆ Measured  
 — Model