The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2025-12

Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

**Introduction to Clocks, GPS time, Precise Time Applications
(Part 2)**

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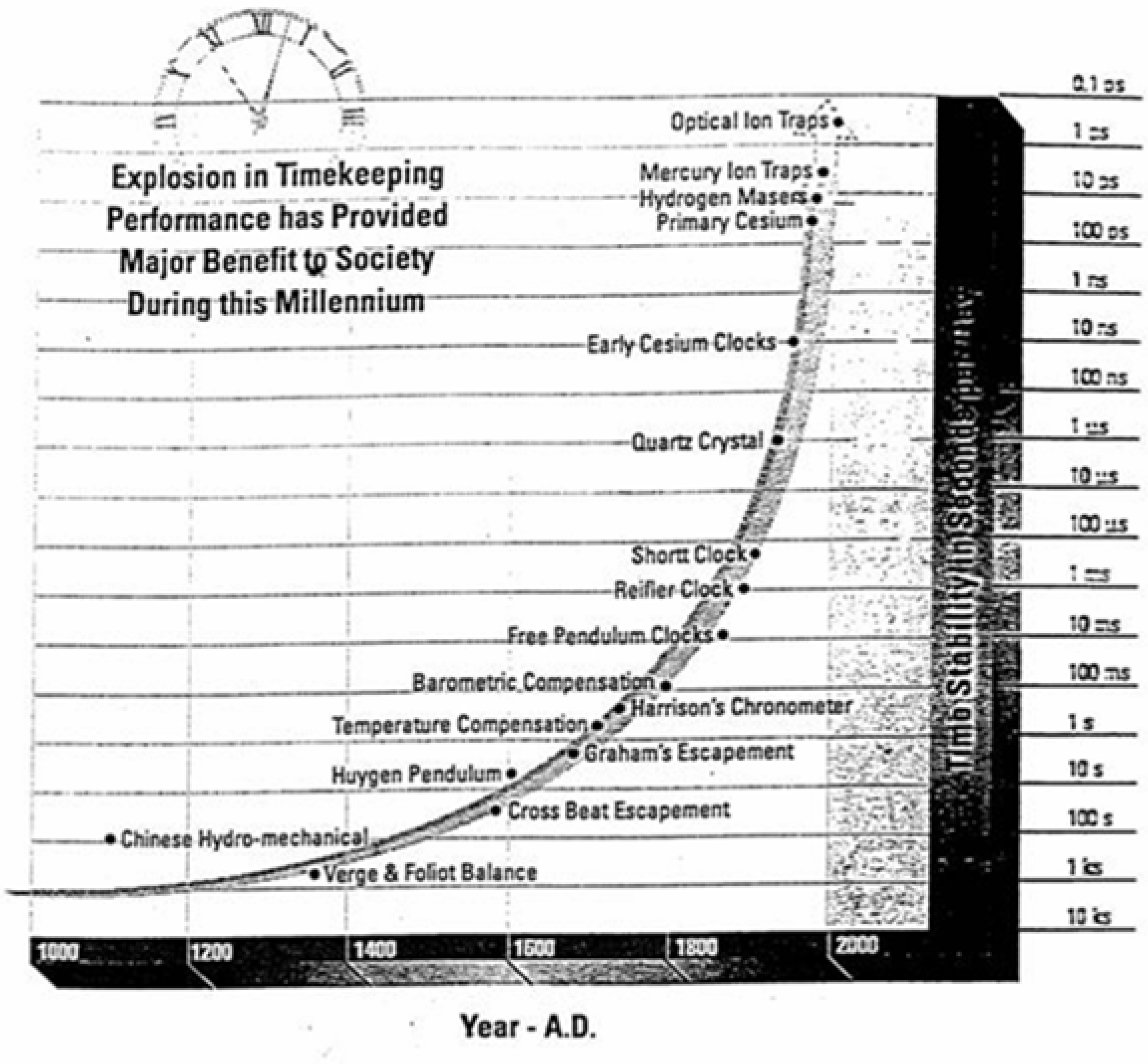
Washington
U.S.A.

Appendix I: Parade of Clocks



Source: Hewlett-Packard Appl. Note 1289

Each one has a High-Tech aspect

Rotating Earth: sundials => hour angle, seasonal corrections

Water clocks: Sung Dynasty's Time Service

Spring-loaded clocks: escapements serve to regulate

Pendulum clocks: master/slave (master/disciplined oscillator)
nitrogen/air conditioning

Quartz clocks: pure crystals to resonate, temperature-controlled

Rotating Earth: stars with photographic zenith tubes
->quasars with Very Long Baseline Interferometry

Atomic Clocks

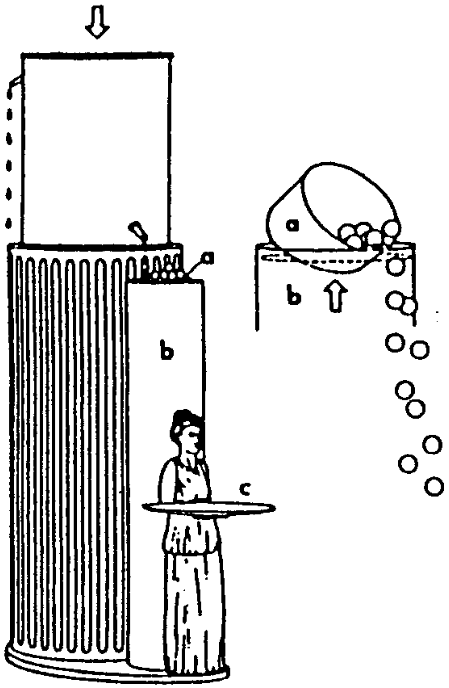
- Cesium Standards: beam tubes => fountains
- Hydrogen Masers: cavity-turned
- Trapped Ions: spherical => linear trap
  many ion => single ion => coherent few-ion
- Optical Frequency Standard
  Optical Comb

Rotating Neutron Stars (pulsars)

- pulsar => millisecond pulsar

Stonehenge: ~2975 BC

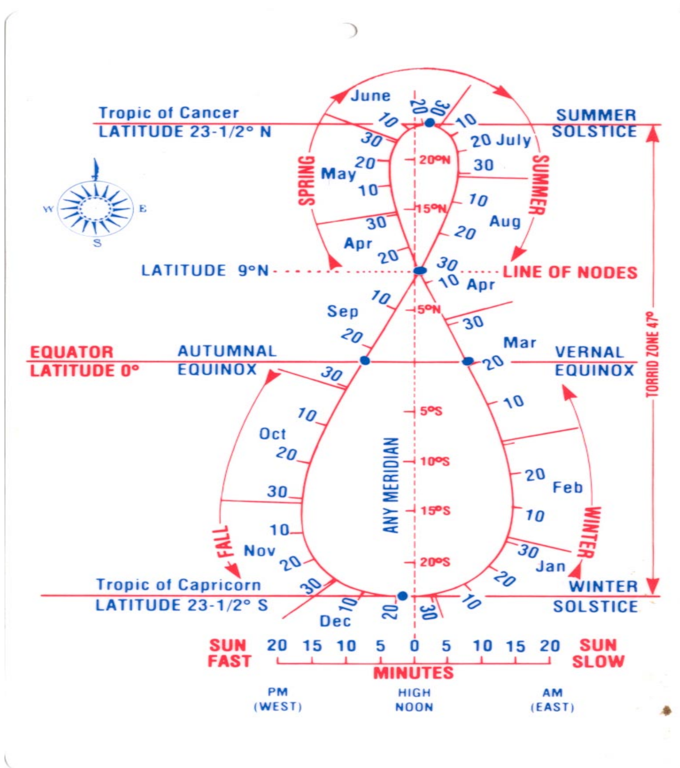
Plato’s Water-Powered Alarm Clock



5. Plato's inflow type water alarm clock. Water entered the (usually) graded vessel (b) at a constant rate. The vessel filled during the night. When the water reached the top, it tipped over a bowl containing lead balls (a), which was hinged to the top of the vessel. The balls then fell onto the copper platter (c) below, and woke up Plato's students.

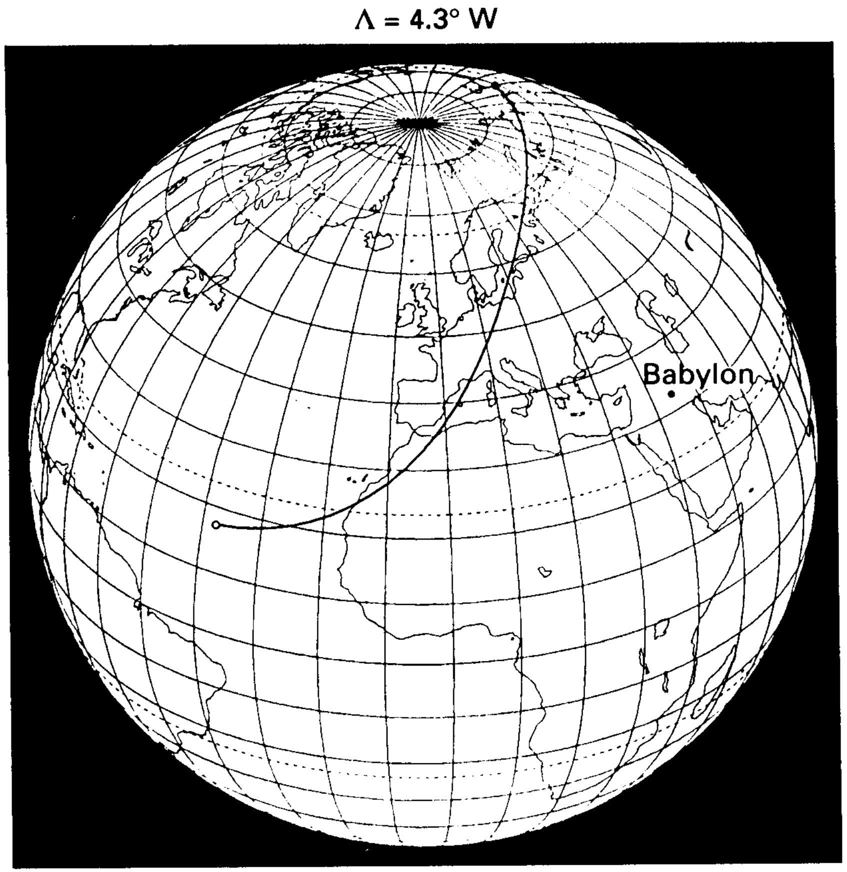
Source: J. Barnett, *Time’s Pendulum*, Plenum Press

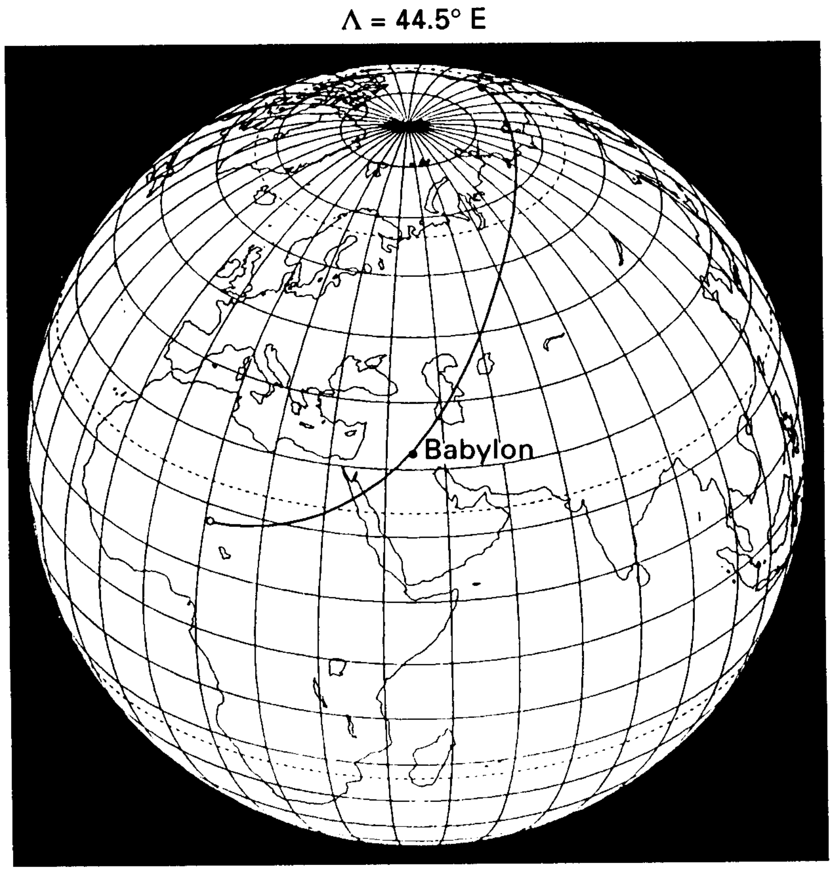
Sundials can be high-tech …



- Left Picture: Variable spacing of hour-dividers
- Right Picture: Analemma
  - Seasonal compensations for Earth's orbital eccentricity
  - Source: Marvin May

Eclipse of 136 BC observed from Babylon





$\Delta T = 0$

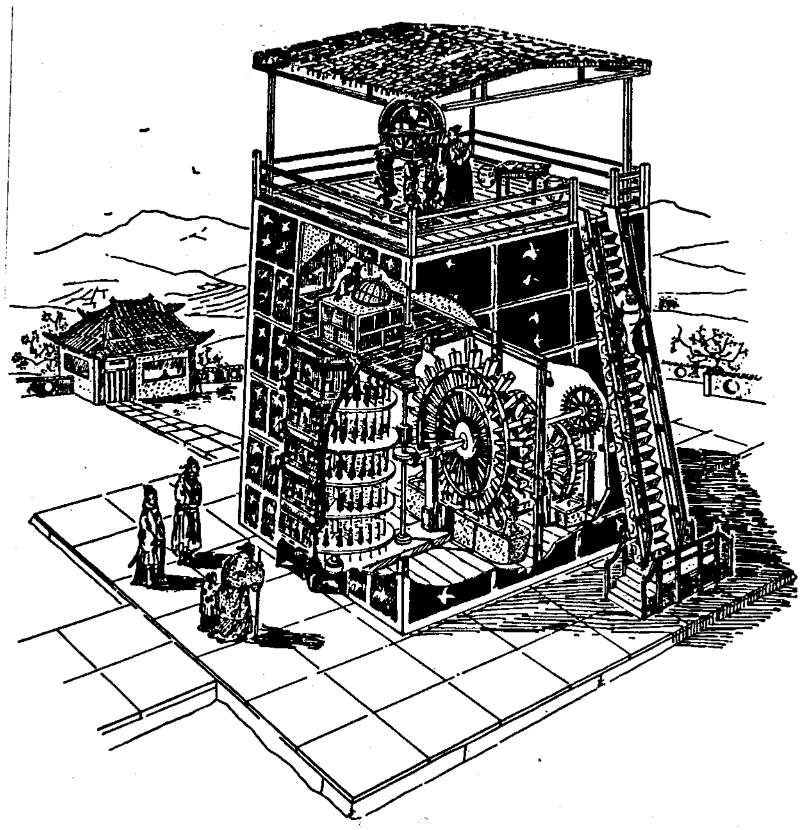
$\Delta T = 11\,700$ s = 3.25 h

Reference: F.R. Stephenson, *Historical Eclipses and Earth's Rotation* (Cambridge, 1997), p. 66

Chinese Constant-Level Water Clocks

Display at National Time Service Center, China

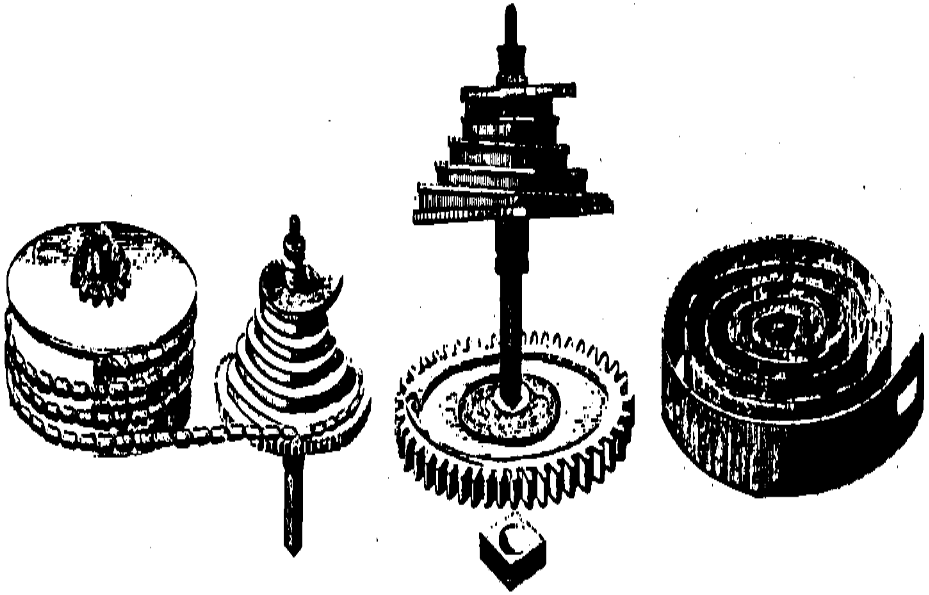
11th Century Chinese Water Clock



Source: Landes, *Revolution in Time*, Harvard Press

Crab Nebula
Remnant of Supernova of 1054 AD

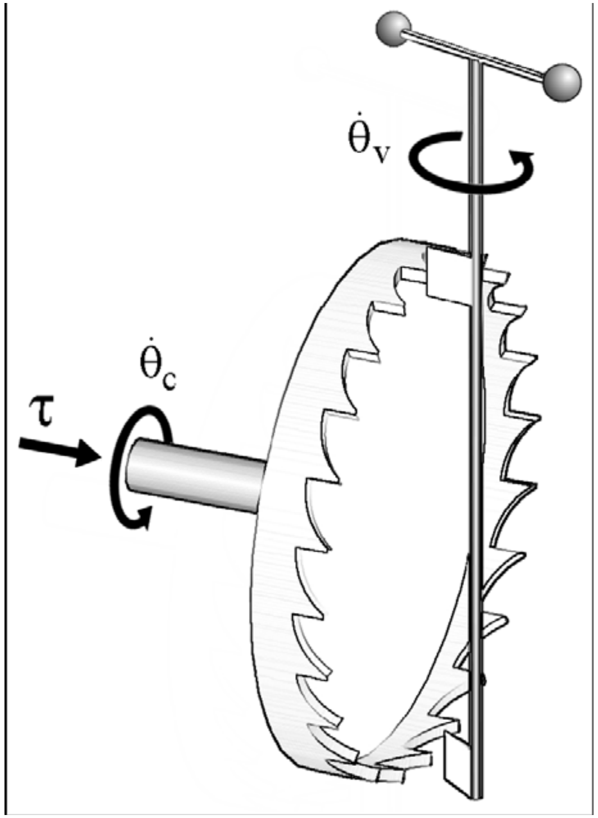
Spring-Loaded Clocks, 1430



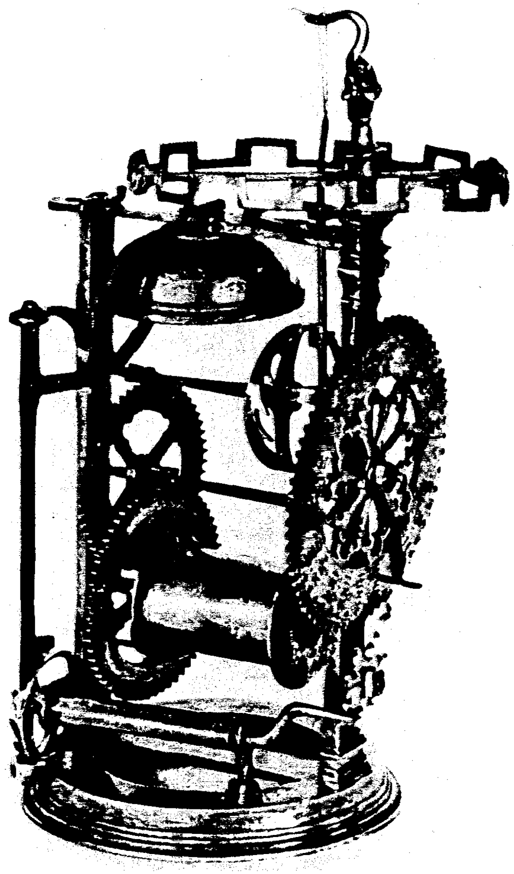
Note geometric compensation as spring loses tension

Source: Landes: *Revolution in Time*, Harvard Press

Verge and Foliot



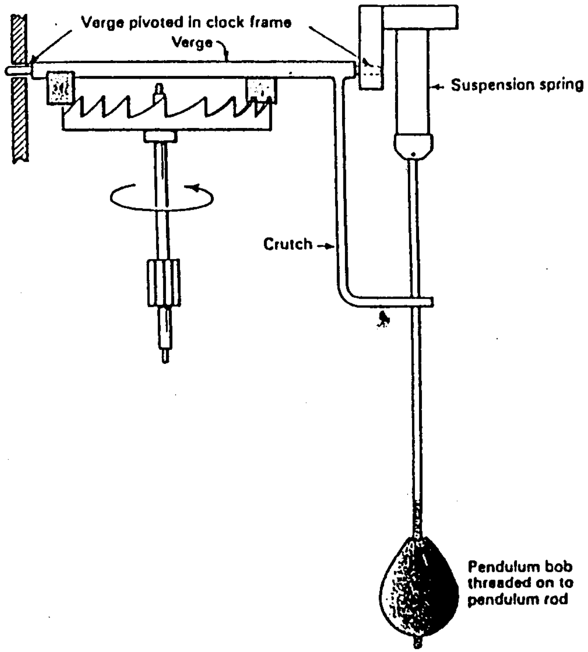
Verge and Balance-Wheel, 1450



- Roup *et al.* Int. J. Control 2003, 76, 1685-1608
- Landes: *Revolution in Time*, Harvard Press

Galileo Galilei (1554-1642)

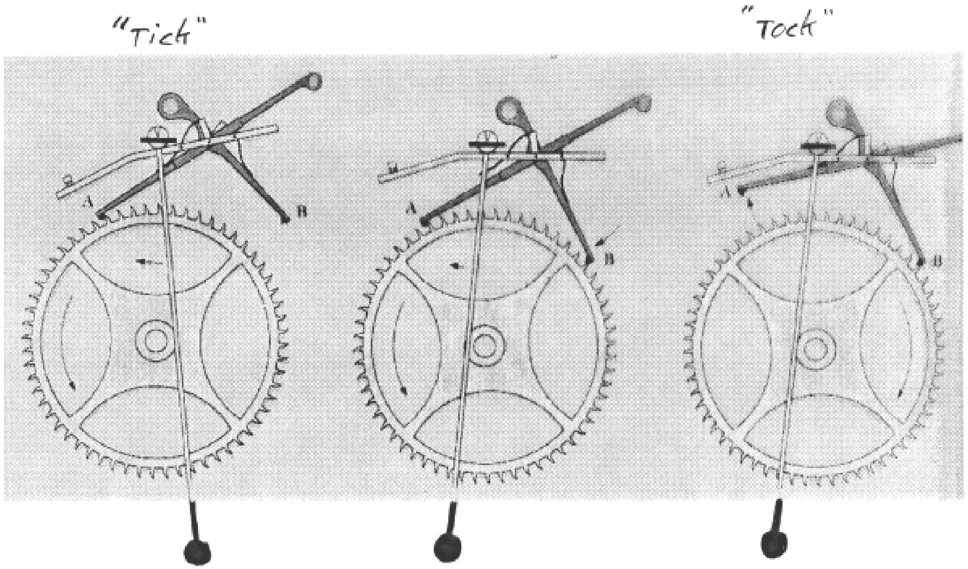
Pendulum Clock



12. Pendulum clock. The natural oscillation of the pendulum has replaced the mechanical oscillation of the old horizontal foliot with its weights. Otherwise, the instrument is essentially the same. Now it is the beat of the pendulum that controls the speed at which the verge with its pallets turns. As the pallets catch and release each saw tooth of the crown wheel, the pendulum's beats are counted, and the count is subsequently transmitted by the gear train (not shown) to the clock face.

Source: J. Barnett, *Time's Pendulum*, Plenum Press

Escapements in 1676



Source: J. Barnett, *Time's Pendulum*, Plenum Press

Big Ben

Frequency adjusted with pennies

The Great Contest

Fact: Must know the time to know longitude

Fact: Navigation error caused 2,000 British sailors to drown in 1707

Contest Prize: 20,000 pounds of solid gold

Goal: Measure time to 2 minutes accuracy after 5 months at sea.

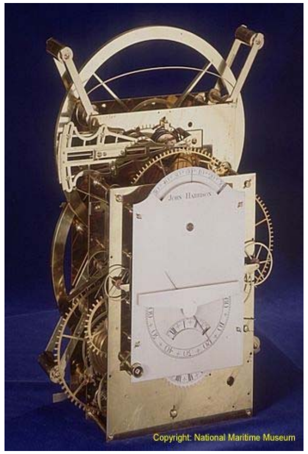
- Astronomers "upper class" tried Moon's motion
- Clockmakers "lower class" tried better clocks

The Winner: John Harrison

The Chronology

H1, 1730-35

H2, 1737-40



H3, 1740-55

H4, 1755-59

H5, 1772

H3: Bimetallic strip invented for thermal stability
H3: Caged roller-race (equivalent of caged ball-bearings)
1769 K1, a copy, was used by Captain Cook to explore Pacific
1772 H5, also passes test, after nearby magnets removed
1773 King George III intercedes and gives full payment

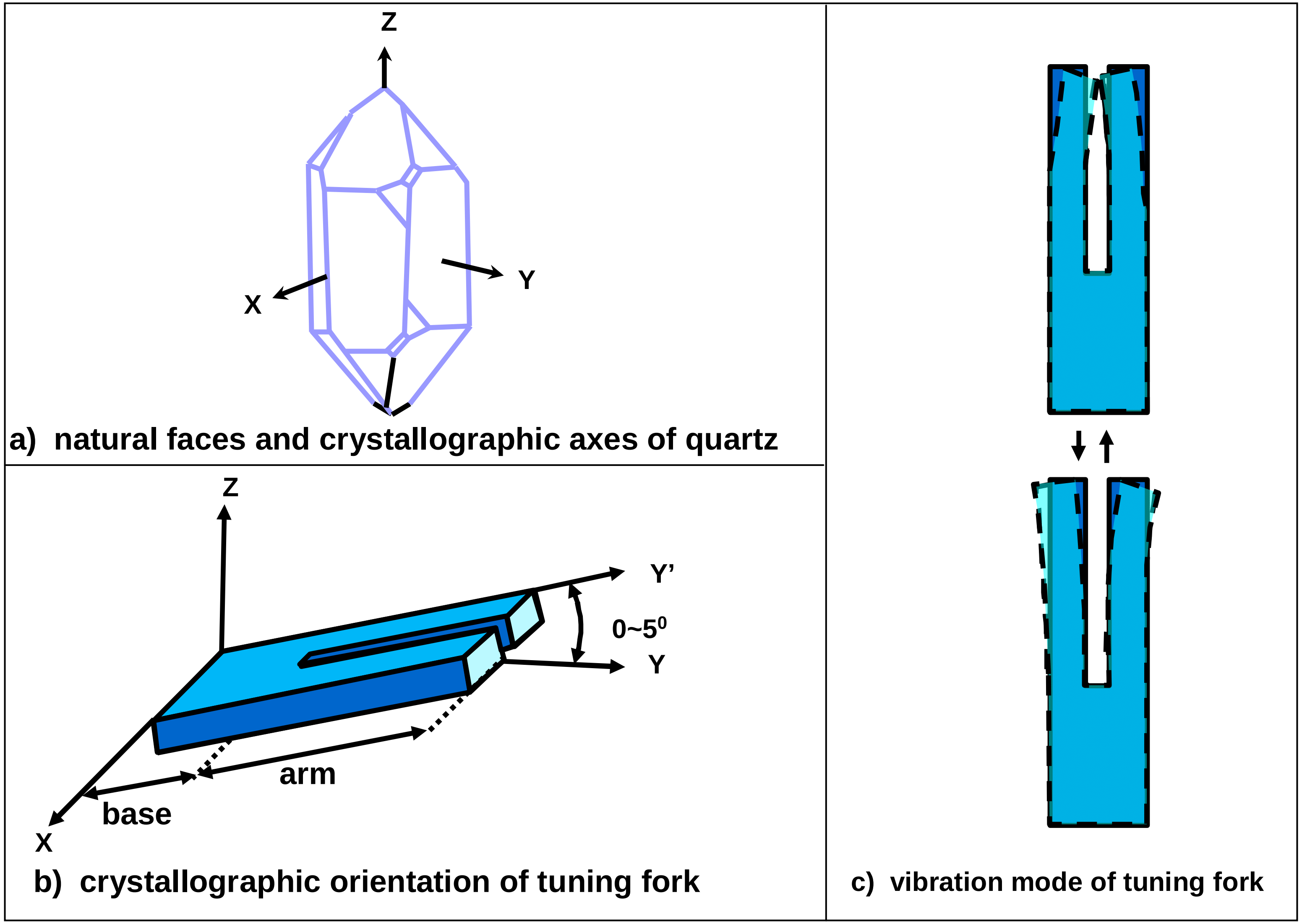
Pendulum and Spring Clocks Improved …

Ming Dynasty
Collection

Shortt Clocks
Master/Controlled

And by 1928 they had reached perfection!

Quartz Revolutionizes Timekeeping



Source: John Vig http://ieee_uffc.org/fc

Frequency Control Device Market

(as of ~1997)

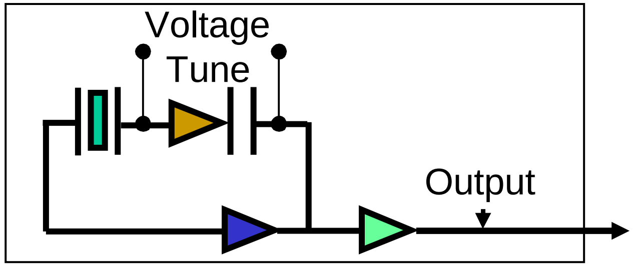
Technology	Units per year	Unit price, typical	Worldwide market, $/year
Crystal	~ 2 x 10^9	~$1 ($0.1 to 3,000)	~$1.2B
Hydrogen maser	~ 10	$200,000	$2M
Cesium beam frequency standard	~ 300	$50,000	$15M
Rubidium cell frequency standard	~ 20,000	$2,000	$40M

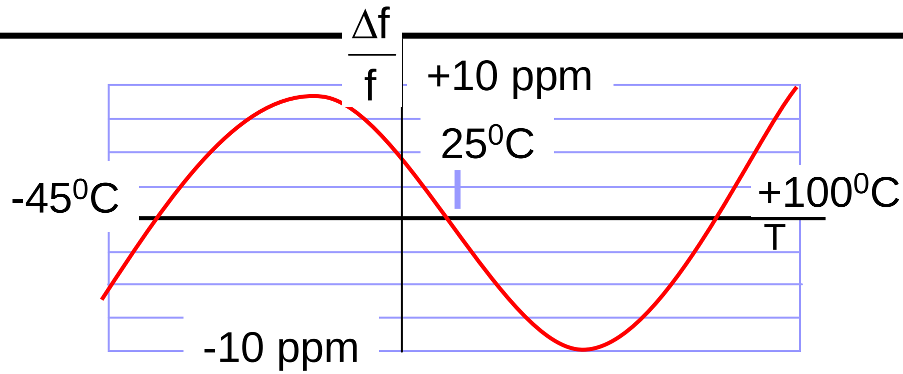
1-2

Oscillator Acronyms

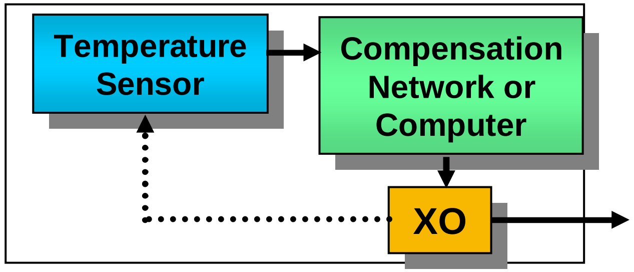
- **XO…………..**Crystal Oscillator
- **VCXO………**Voltage Controlled Crystal Oscillator
- **OCXO………**Oven Controlled Crystal Oscillator
- **TCXO………**Temperature Compensated Crystal Oscillator
- **TCVCXO..…**Temperature Compensated/Voltage Controlled Crystal Oscillator
- **OCVCXO.….**Oven Controlled/Voltage Controlled Crystal Oscillator
- **MCXO………**Microcomputer Compensated Crystal Oscillator
- **RbXO……….**Rubidium-Crystal Oscillator

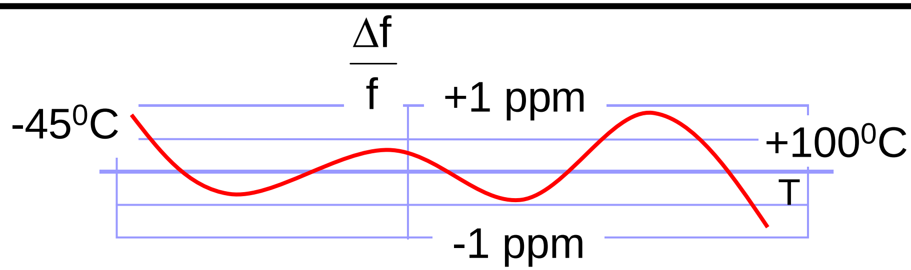
Crystal Oscillator Categories



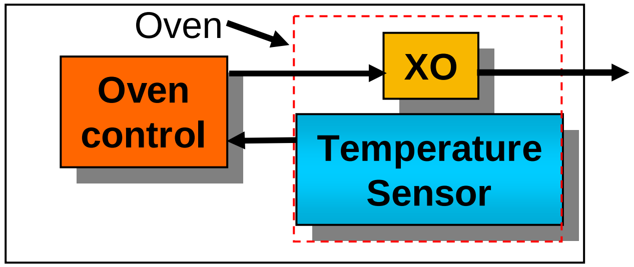


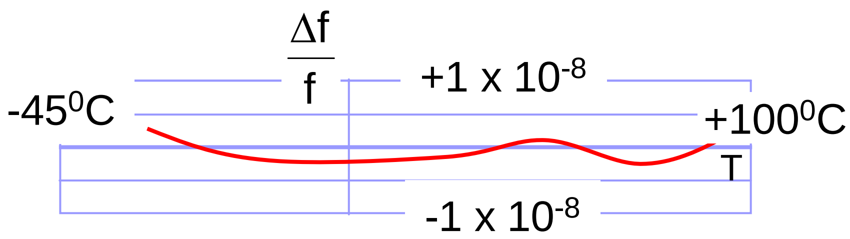
- Crystal Oscillator (XO)





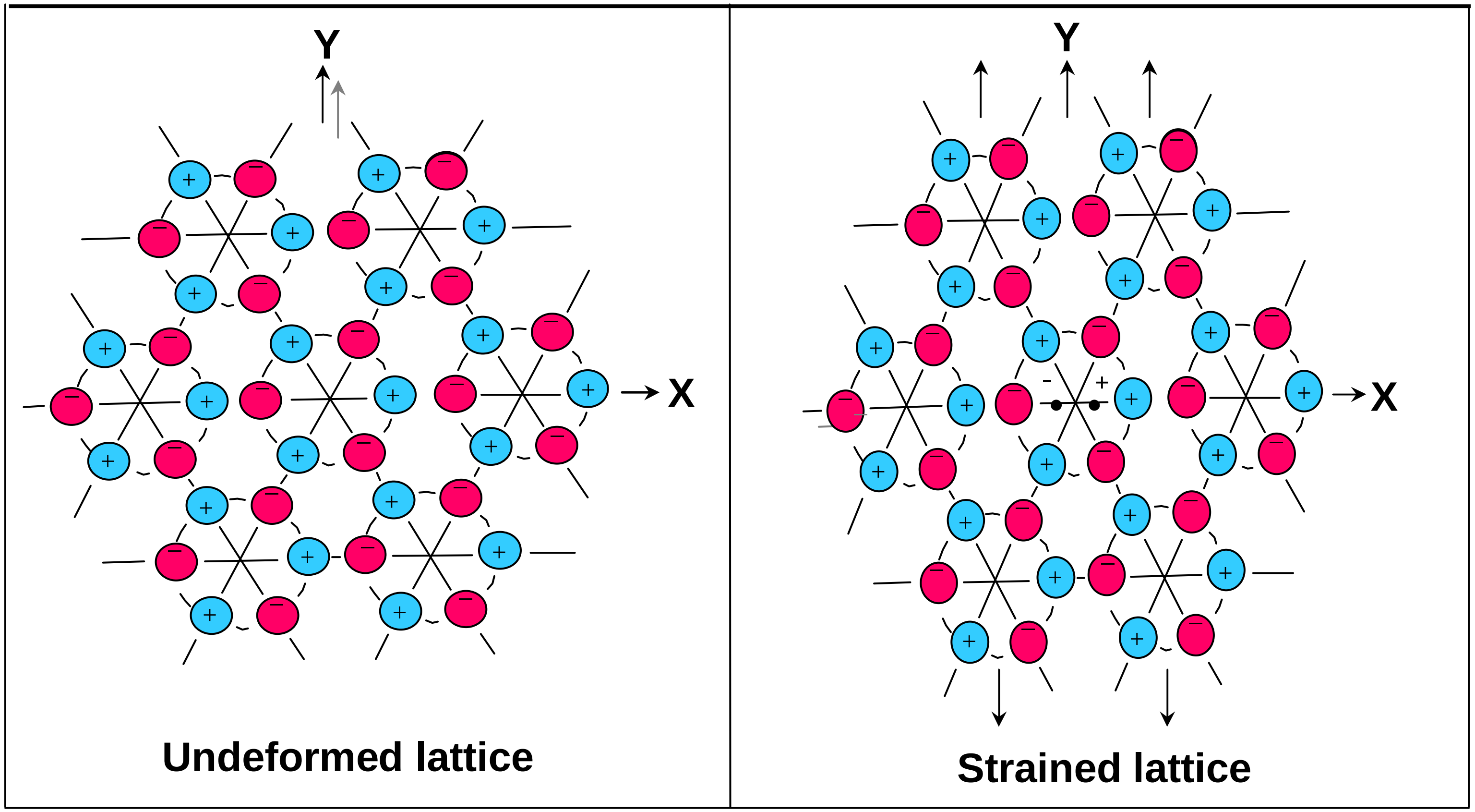
- Temperature Compensated (TCXO)





- Oven Controlled (OCXO)

The Piezoelectric Effect



The piezoelectric effect provides a coupling between the mechanical properties of a piezoelectric crystal and an electrical circuit.

Milestones in Quartz Technology

1880	Piezoelectric effect discovered by Jacques and Pierre Curie
1905	First hydrothermal growth of quartz in a laboratory - by G. Spezia
1917	First application of piezoelectric effect, in sonar
1918	First use of piezoelectric crystal in an oscillator
1926	First quartz crystal controlled broadcast station
1927	First temperature compensated quartz cut discovered
1927	First quartz crystal clock built
1934	First practical temp. compensated cut, the AT-cut, developed
1949	Contoured, high-Q, high stability AT-cuts developed
1956	First commercially grown cultured quartz available
1956	First TCXO described
1972	Miniature quartz tuning fork developed; quartz watches available
1974	The SC-cut (and TS/TTC-cut) predicted; verified in 1976
1982	First MCXO with dual c-mode self-temperature sensing

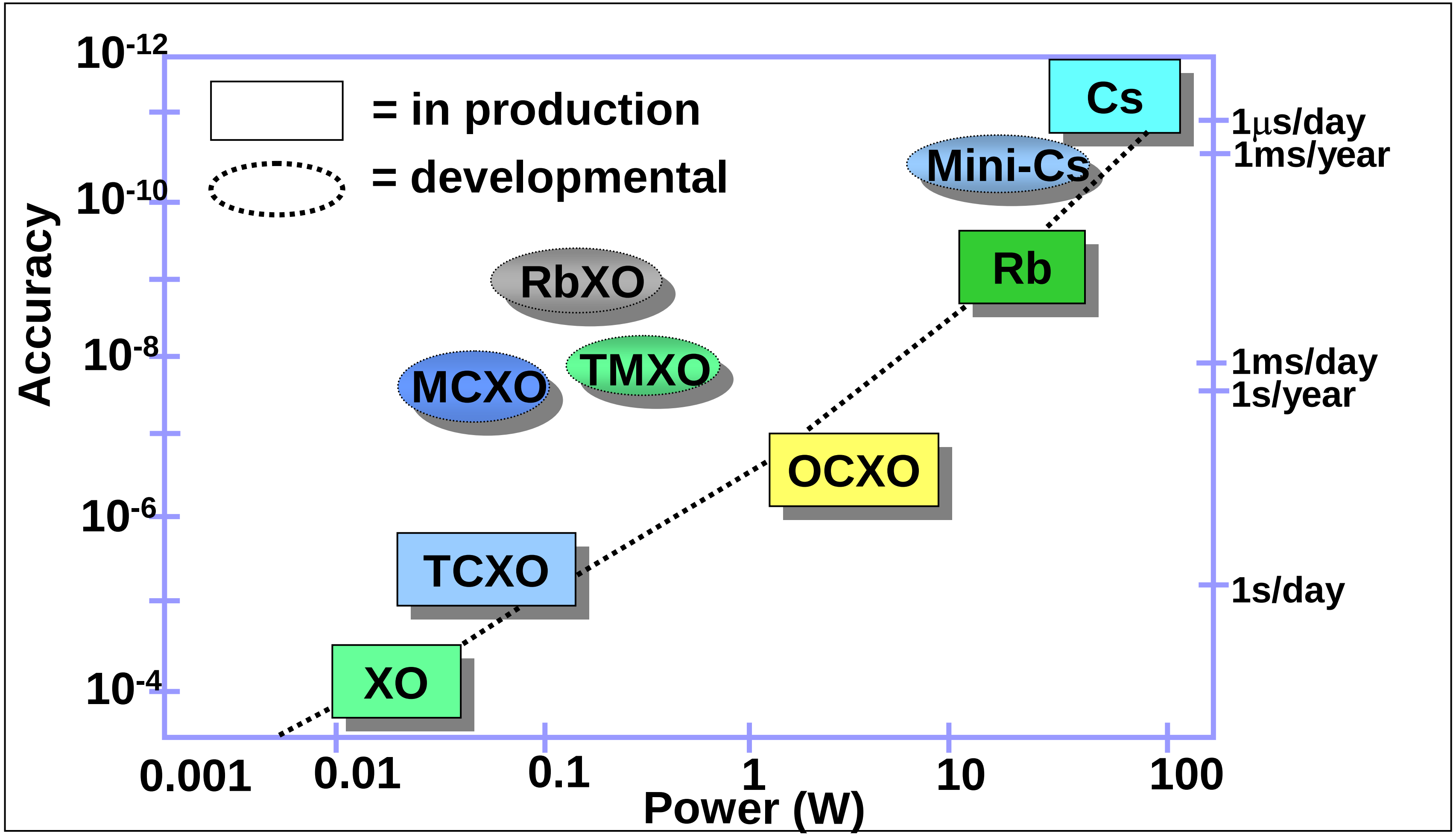
Oscillator Comparison

	Quartz Oscillators			Atomic Oscillators		
	TCXO	MCXO	OCXO	Rubidium	RbXO	Cesium
Accuracy * (per year)	2×10^{-6}	5×10^{-8}	1×10^{-8}	5×10^{-10}	7×10^{-10}	2×10^{-11}
Aging/Year	5×10^{-7}	2×10^{-8}	5×10^{-9}	2×10^{-10}	2×10^{-10}	0
Temp. Stab. (range, ^{0}C)	5×10^{-7} (-55 to +85)	3×10^{-8} (-55 to +85)	1×10^{-9} (-55 to +85)	3×10^{-10} (-55 to +68)	5×10^{-10} (-55 to +85)	2×10^{-11} (-28 to +65)
Stability, $\sigma_y(\tau)$ (τ = 1s)	1×10^{-9}	3×10^{-10}	1×10^{-12}	3×10^{-12}	5×10^{-12}	5×10^{-11}
Size (cm^3)	10	30	20-200	200-800	1,000	6,000
Warmup Time (min)	0.03 (to 1×10^{-6})	0.03 (to 2×10^{-8})	4 (to 1×10^{-8})	3 (to 5×10^{-10})	3 (to 5×10^{-10})	20 (to 2×10^{-11})
Power (W) (at lowest temp.)	0.04	0.04	0.6	20	0.65	30
Price (~$)	10 - 100	<1,000	200-2,000	2,000-8,000	<10,000	50,000

* Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

Clock Accuracy vs. Power Requirement*

(Goal of R&D is to move technologies toward the upper left)

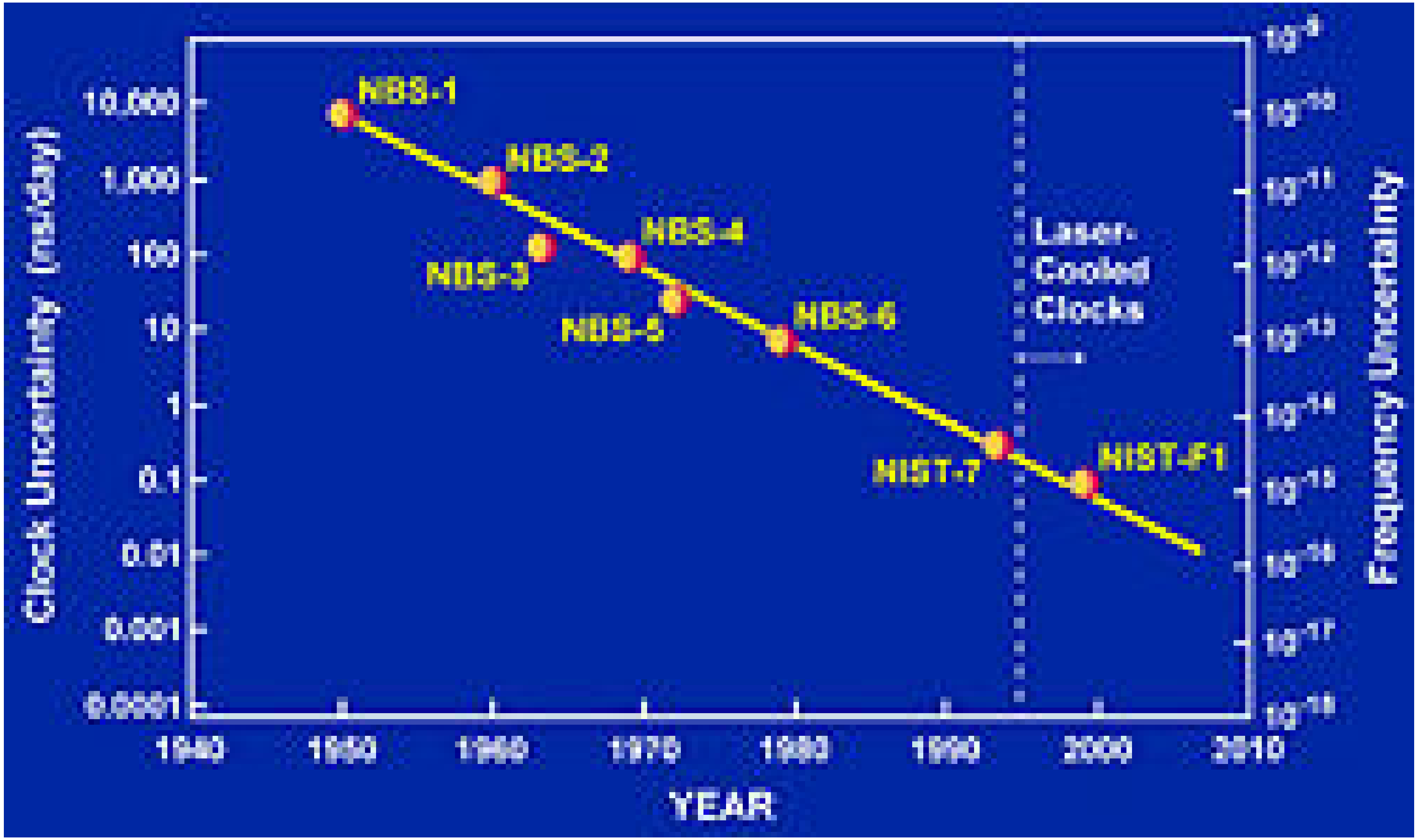


* Accuracy vs, size, and accuracy vs. cost have similar relationships

All of Mahatma Gandhi's Possessions, Jan 30,1948

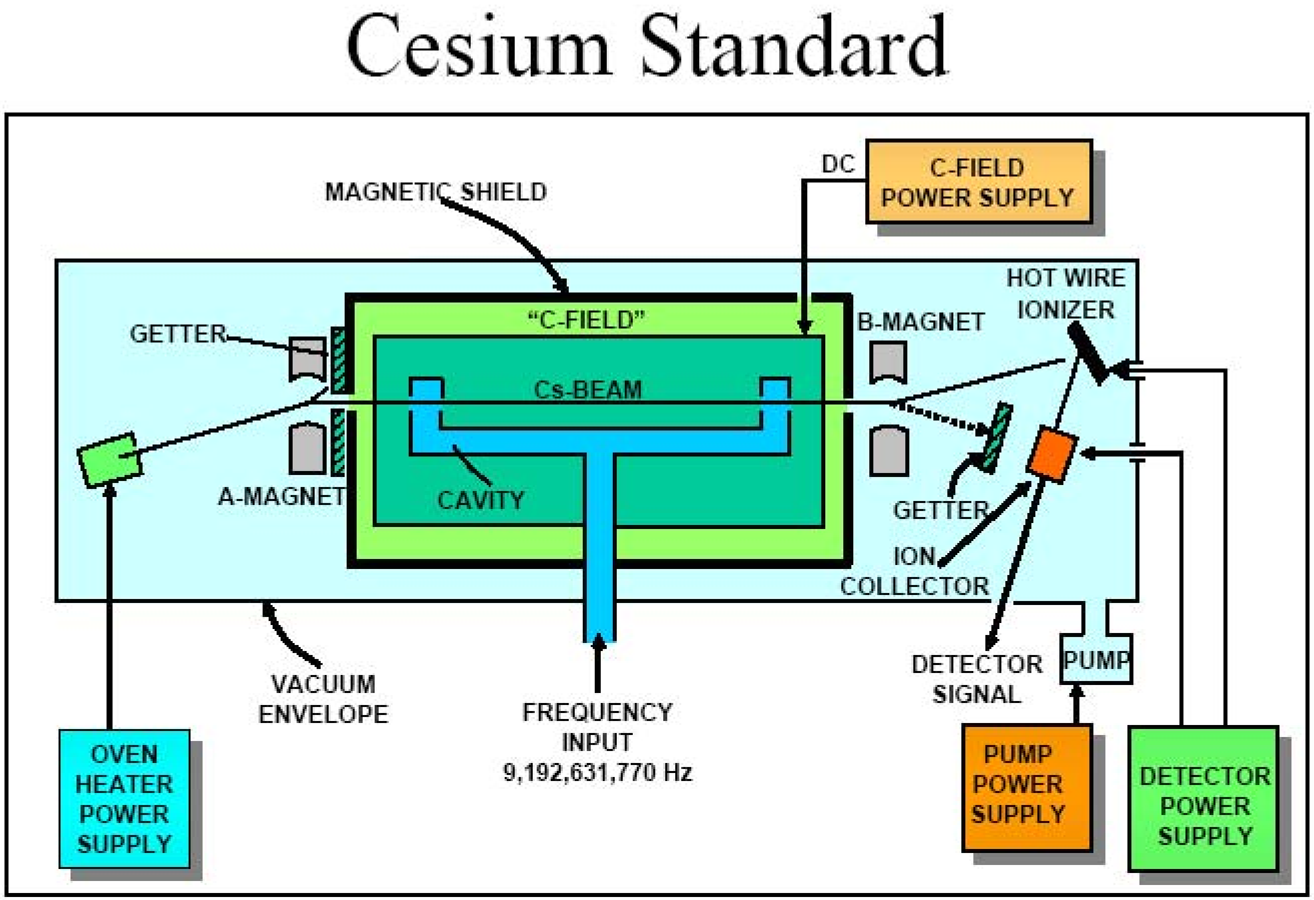
Photograph from the M.K. Gandhi Institute for Nonviolence

The Atomic Age



Source: NIST

Cesium is the PTTI Workhorse



Source: John Vig

First cesium clock was 1955

Masers and Lasers

MASER = Microwave Amplification by Stimulated Emission of Radiation

LASER = Light Amplification by Stimulated Emission of Radiation

How to make a maser or laser

1. Prepare atoms or molecules to radiate
2. Cause or allow radiation to stimulate them
   – All will radiate in unison (coherently)
   – Razor-sharp beam
   – Can be very intense

Hydrogen Maser Frequency Standard

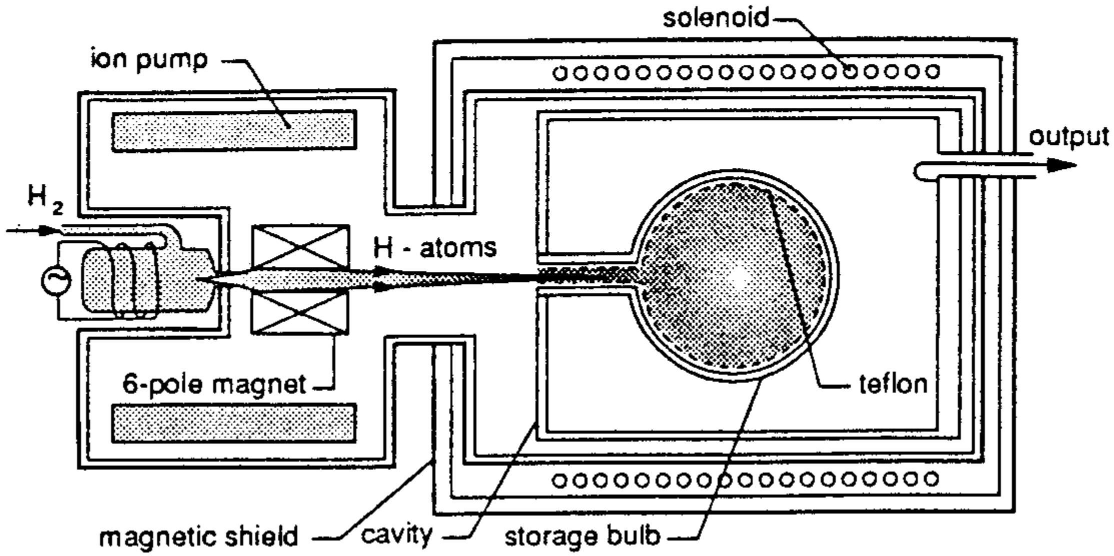


Figure 11.2 The basic elements of a hydrogen maser

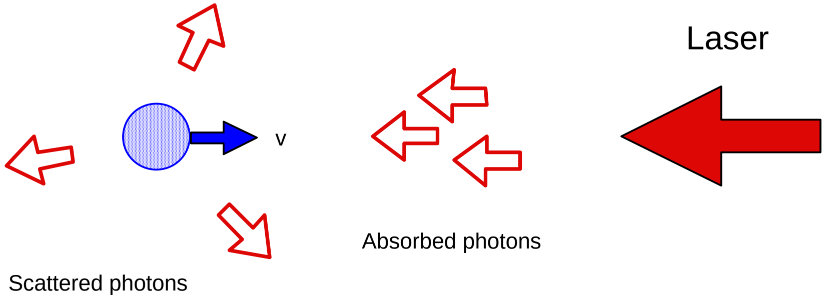
F.G. Major Springer, "The Quantum Beat", 1998

Doppler Shift

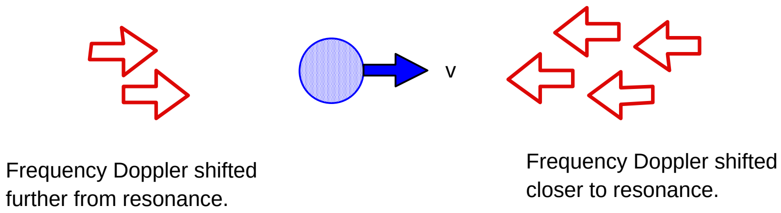
Christian Doppler
1803-1853

- Observer moving towards source of radiation sees frequency increased (blue-shifted)
- Observer moving away from source of radiation sees frequency decreased (red-shifted)
- Works for microwaves, light, sound, whatever.

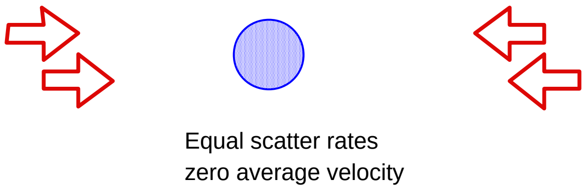
Manipulating Atoms With Lasers



Laser in one dimension exerts a scattering force on atoms in the direction of the laser



Lasers in two dimensions, red detuned, exert a velocity-sensitive force on the atoms



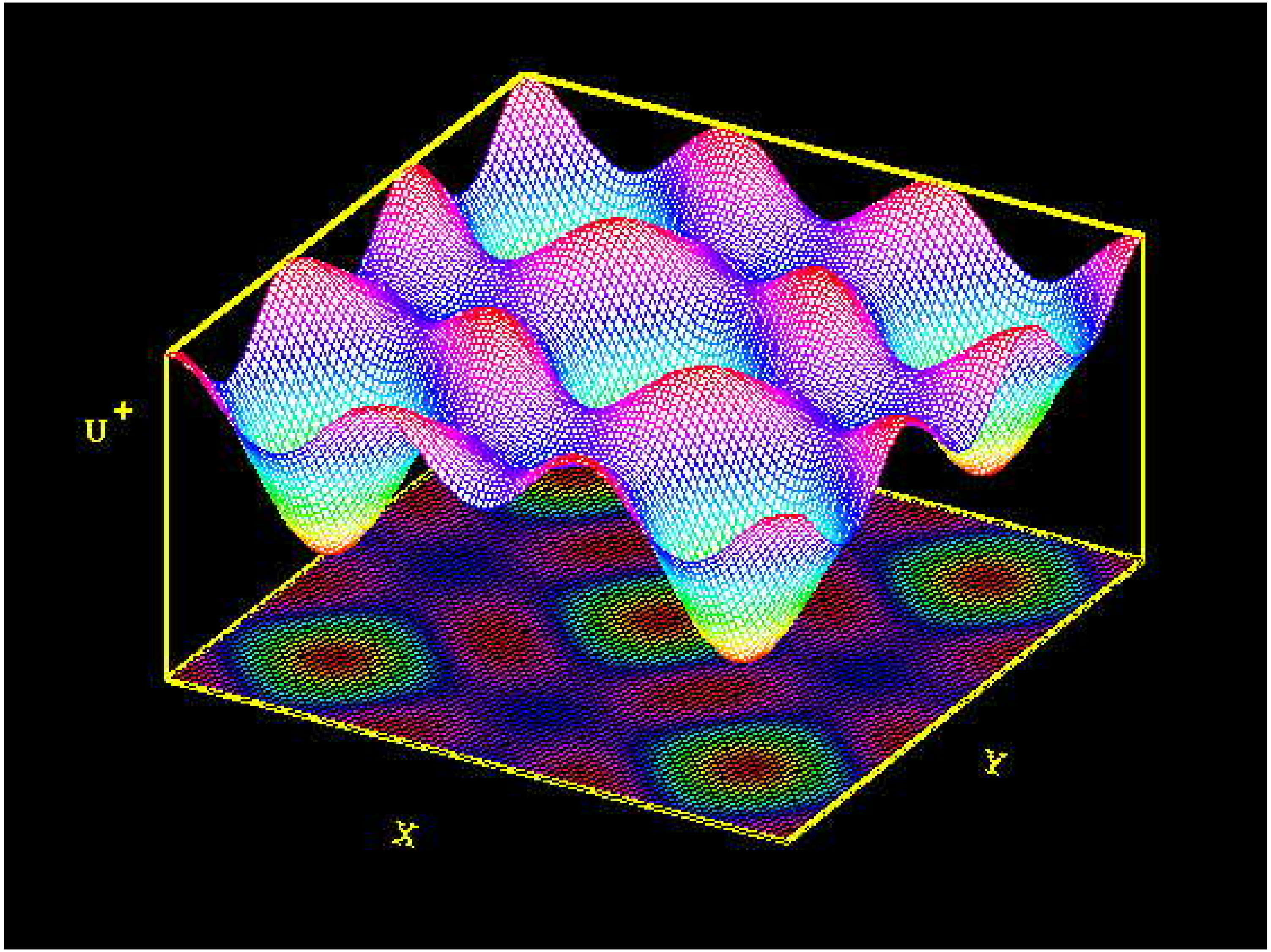
Atoms can be brought to zero average velocity, with very little residual motion (i.e. cold)

(Source: Tom Swanson, USNO)

Sisyphus Effect

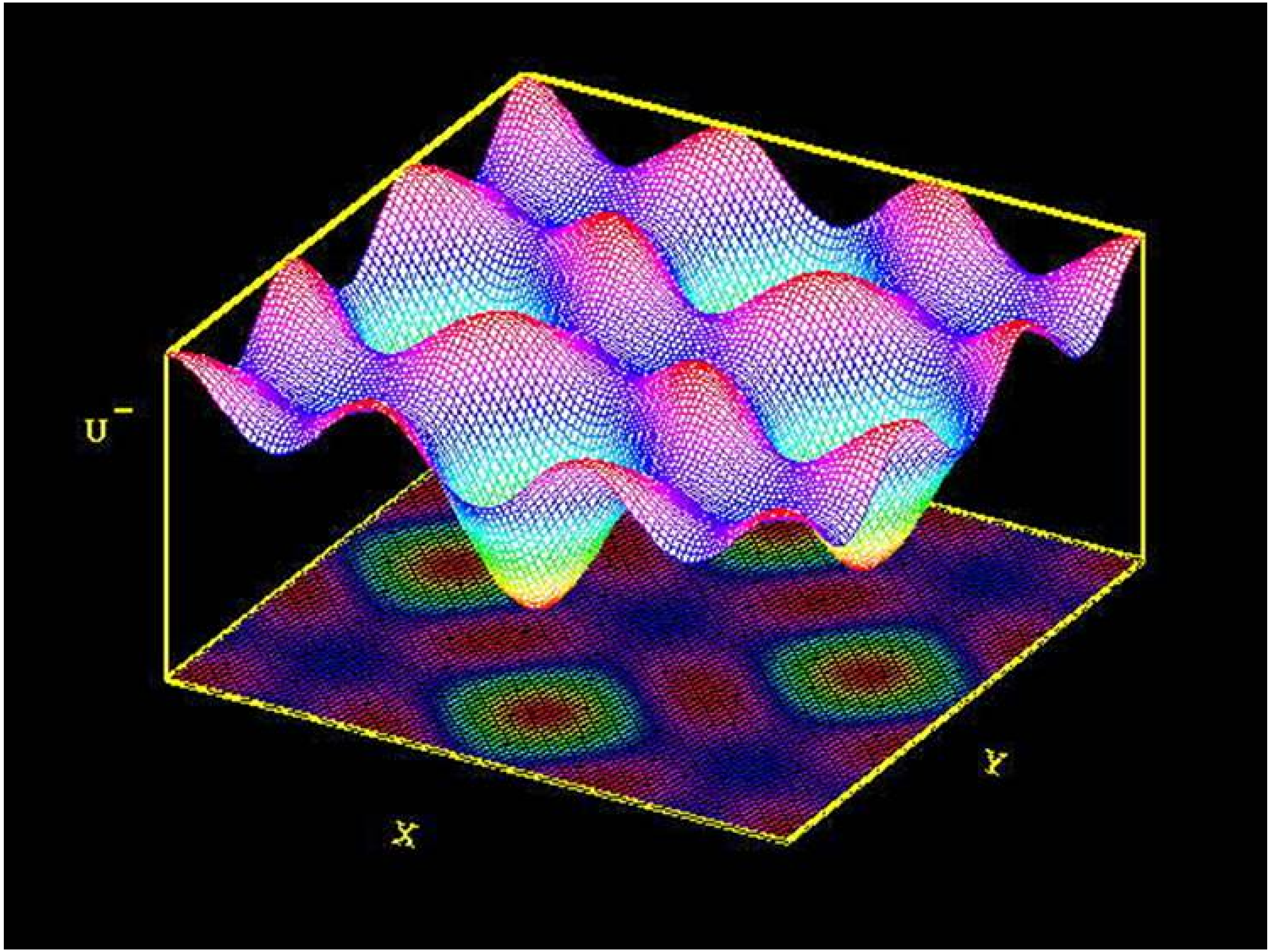
Ref: Encyclopedia of Greek Mythology http://www.mythweb.com/encyc/gallery/sisyphus_c.html

Potential Field of a Ground State Sublevel of an Atomic Ground State in an Optical Polarization Gradient



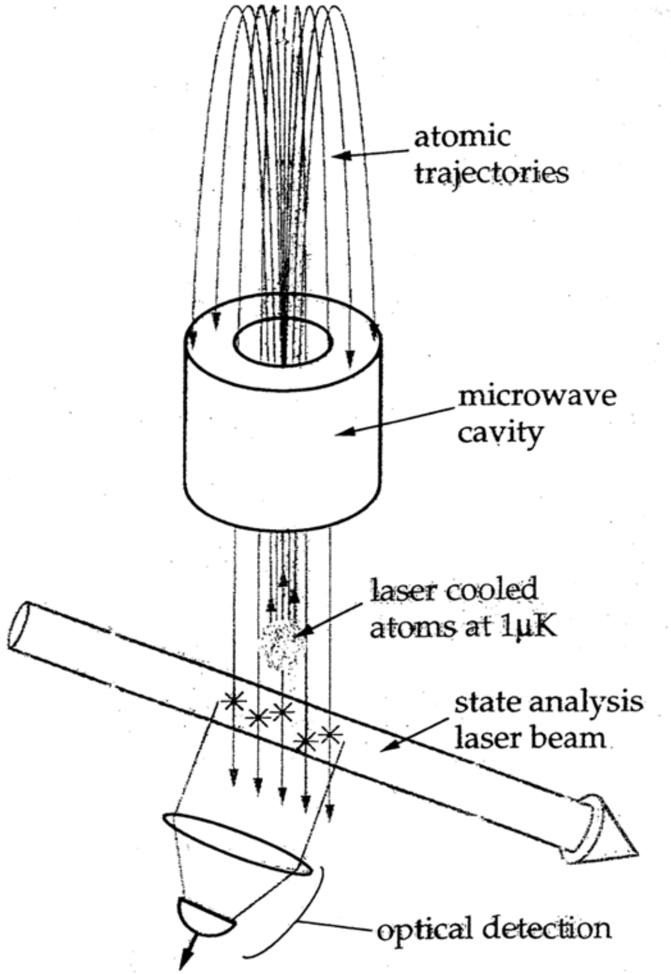
Ref: http://www.physics.helsinki.fi/~jpiilo/coolpr.html

Potential Field of a Different Sublevel



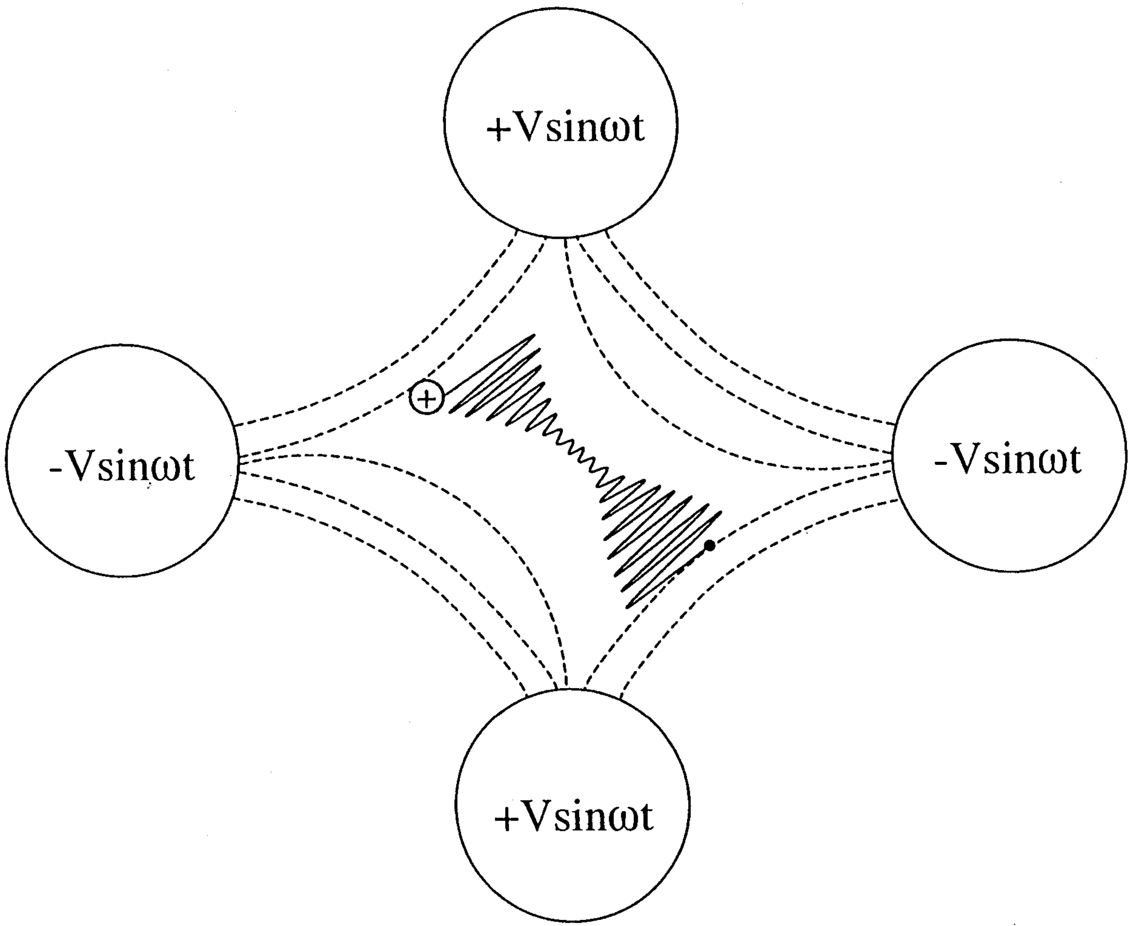
Ref: http://www.physics.helsinki.fi/~jpiilo/coolpr.html

The Cesium / Rubidium Fountain



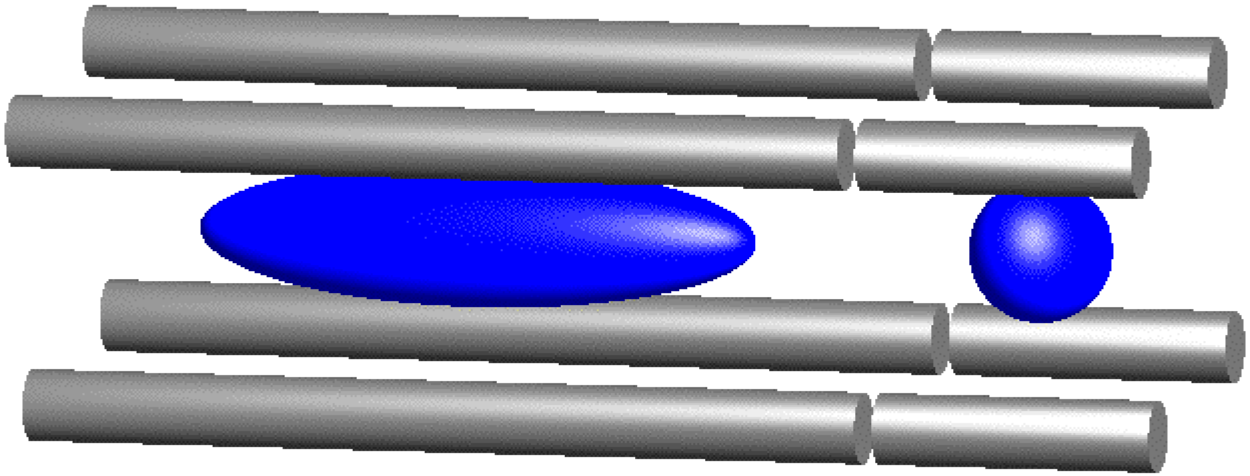
Source: Chris Ekstrom

Ion Trapped In Quadrupole Force Field



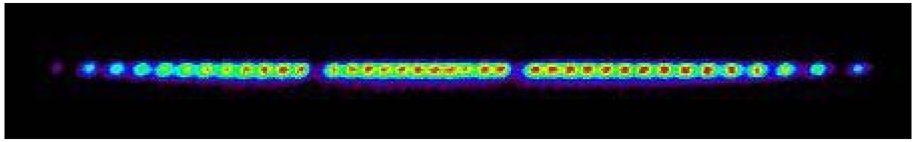
Source: Dr. Demetrios Matsakis

Linear Ion Trap Extended (LITE)



Source: John Prestage and Bob Tjoelker, JPL

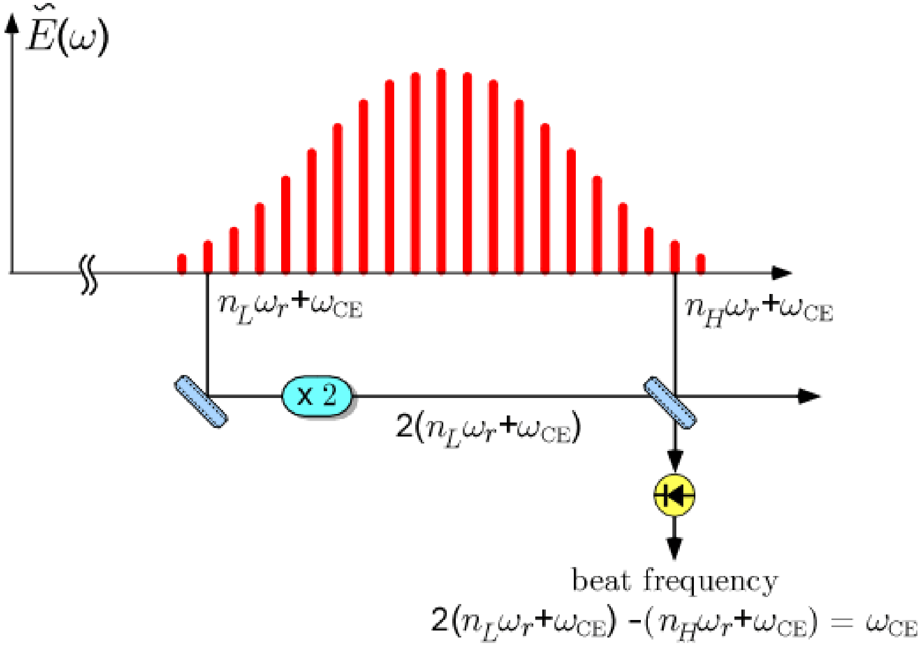
Individual Ions in NIST’s Ion Trap



(Gaps are position of different Hg isotope)

Current Revolution: Optical Comb

Translates Optical Frequencies to Microwave



Ref: http://www.mpq.mpg.de/~haensch/comb/research/combs.html

Chip-Scale Atomic Clocks

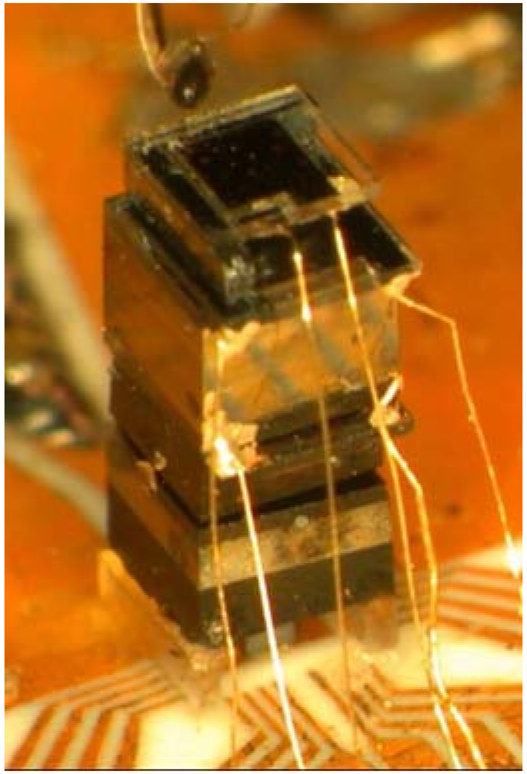
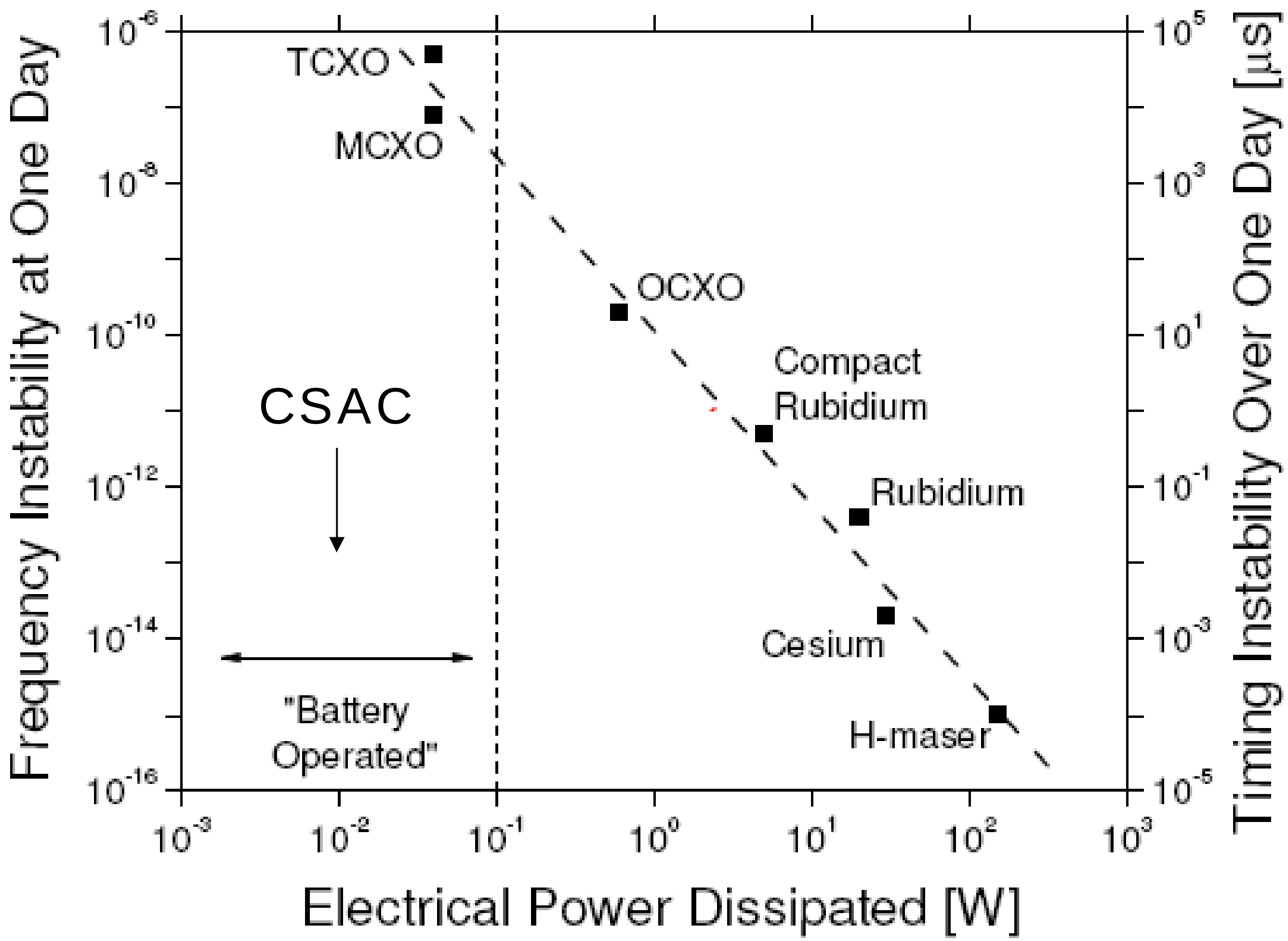


Photo from NIST
web pages

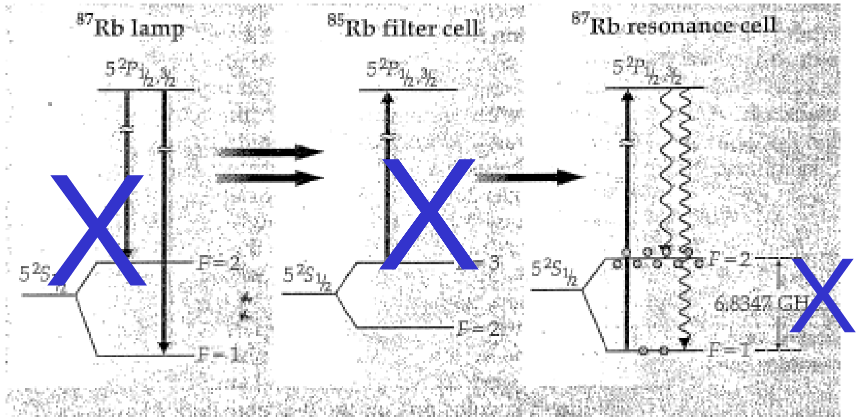
- Specifications
  - Size in mm
  - Power in mW
  - Precision in 10^{-11}@1sec
- Applications
  - GNSS receivers
  - Hand-held wireless
  - Replace quartz?

Electrical Power and Chip-Scale Stability



Source: Mike Garvey, Symmetricom

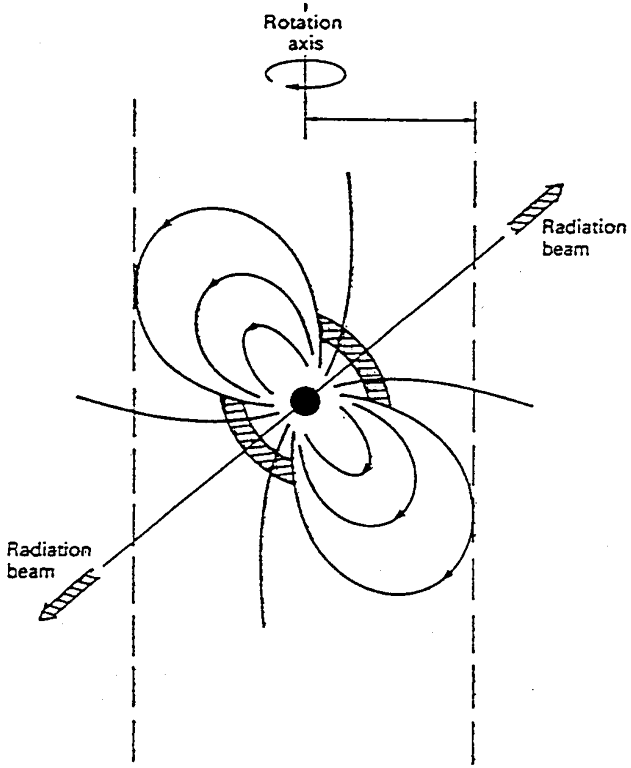
Biggest Change From Normal Rb



- Eliminate lamp/filter/resonantor
- Install all-optical system
  - laser modulated @ 6.8 GHz
- Less power, fewer parts

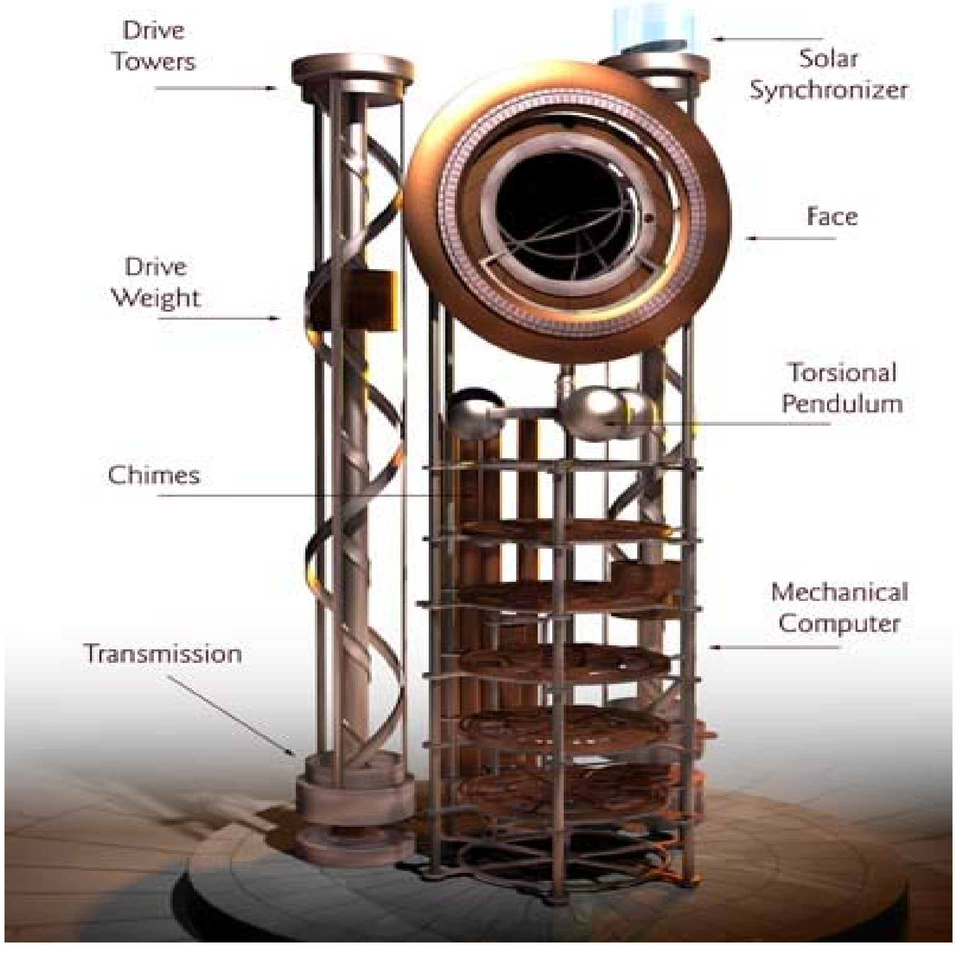
Millisecond Pulsars

Fig. 2.2. The essential features of a pulsar magnetosphere. Within a radial distance $r_c = c/\omega$ of the rotation axis there is a charge-separated, co-rotating magnetosphere. The magnetic field lines which touch the velocity-of-light cylinder at radius r_c define the edge of the polar caps. Radio emitting regions in the polar caps are shown cross-hatched.



Source: Lynne and Graham-Smith, *Pulsar Astronomy*, 2nd Ed., Cambridge University Press

Clock of the Long Now



http://www.longnow.org

Prediction: State-of-the-Clock-Art, 2015

UTC will be computed hourly using:

- Masers for hours to weeks
- Atomic Fountains for weeks to years

Exciting clocks, just becoming operational, will include

- Optical Frequency Standards
  - Some may be trapped-ion
- Space-based trapped-ion and beam clocks
  - [space clocks delayed by launch problems]

Predictions For Time Transfer, 2015

Direct GNSS: 1 ns (as seen by calibrated receiver)

Post-processed carrier-phase GNSS: 10 ps accuracy

Real-time carrier phase GNSS almost as good, using predicted orbit and reference clock data

Carrier-phase based Two Way Satellite Time Transfer will be at 10 ps level for experimental satellites

Optical time-transfer technology will be slowly advancing to operational levels

Predictions For End-User, 2015

Trend towards cheaper clocks, with greater reliance on time transfer to GNSS, etc.

Rubidium clocks steered to GNSS may be replaced by crystals steered to GNSS.

Improvements to middle-end clocks may languish, though they will never, ever stop.