JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

APL Strategic Education Program

Fundamentals of Positioning, Navigation & Timing

Module 2A: Clocks and the Evolution of Timekeeping

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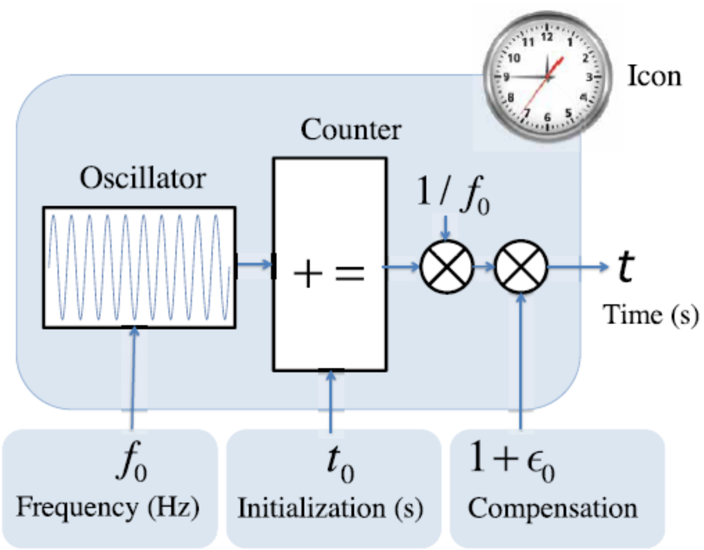
Module 2A Agenda

- The Evolution of Timekeeping and Social Benefit
- The Earth as a Clock
- The Pendulum and the Advent of Mechanical Clocks
- Harrison and the Solution to Longitude Navigation
- Quartz Oscillators and Radionavigation
- Atomic Clocks and Coordinated World Time
- Disciplined Clocks and GPS User Equipment
- Optical Clocks and the Redefinition of the Second

Timekeeping and Clocks

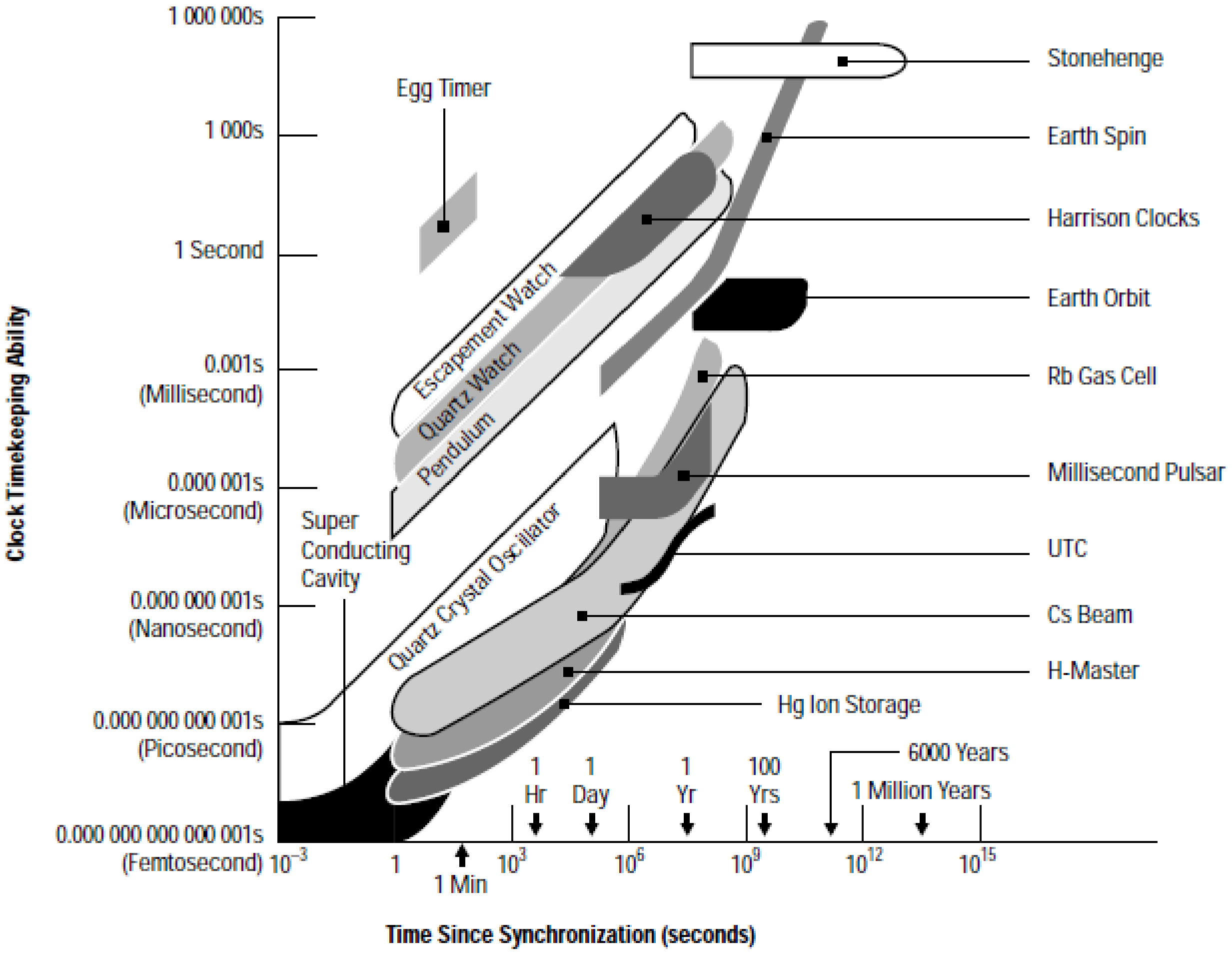


- A clock is composed of three fundamental components:
  - Frequency source (oscillator) derived from a physically stable phenomenon that maintains a cyclical relationship to a unit of timekeeping (Hz are cycle/s)
  - Counter or accumulator records the number of oscillation cycles, which by definition equals the timekeeping interval, s = 9,192,631,770 cycles for Cs atom
  - Timekeeper or phase recorder takes accumulator output to transfer and maintain a relevant timescale, e.g. 86400 s/day

Frequency stability is derived from the nature of the source

Synchronization is achieved by zeroing the clock phase to a comparative source, usually of much better frequency stability.

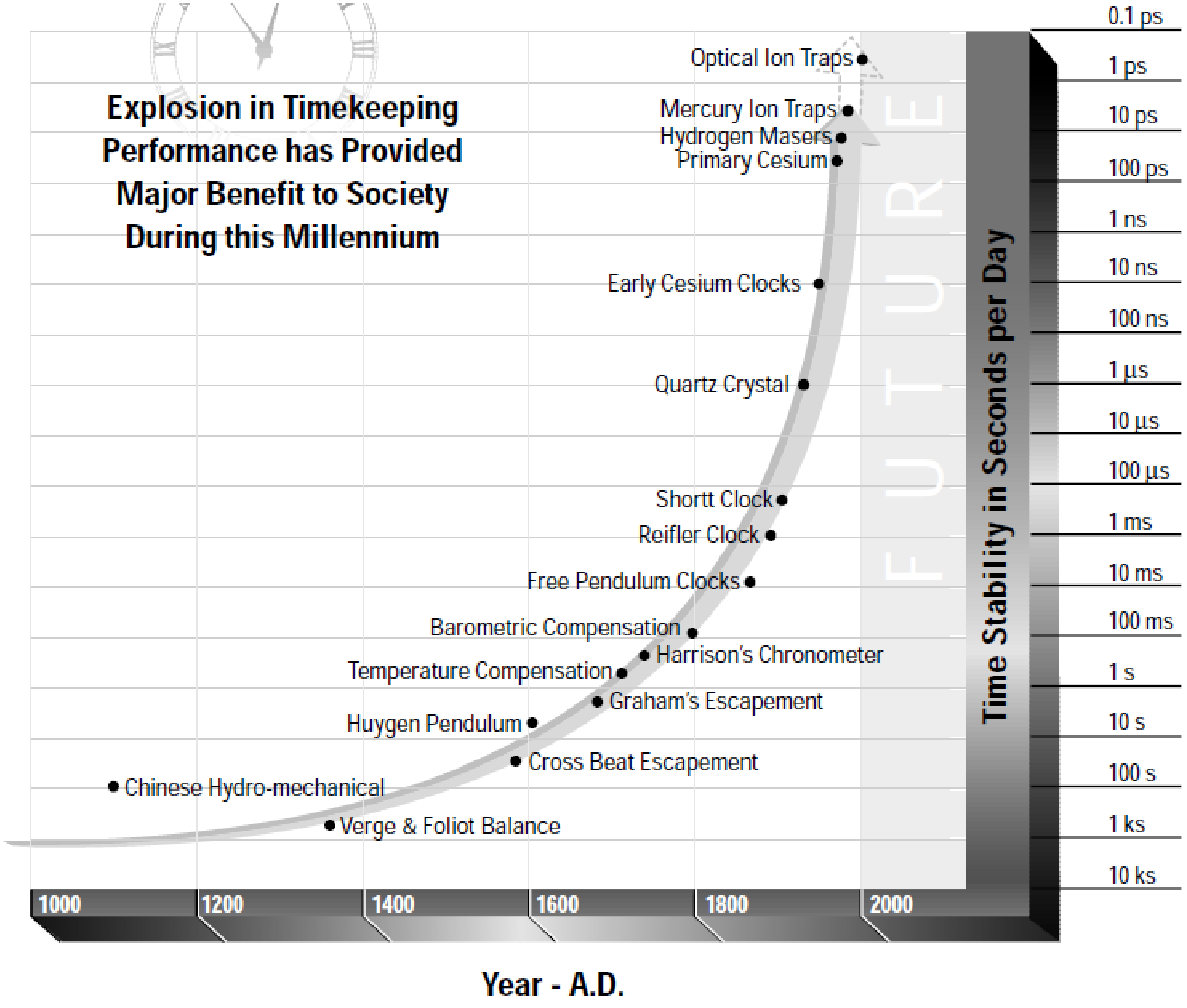
Timekeeping always involves clock comparisons.



The Evolution of Timekeeping and Social Benefit

- The historical interaction of human social development and timekeeping capability is routinely examined, and never understated.
- At its fundamental, the drive for improved commercial trade, national security, and human transportation is supported by the evolution of clock technology.
- In terms of navigation, the need for advancing clocks and timekeeping is correlated to the extent of geographic distance, and the velocity of the travel method.
- Rough progression of travel with timekeeping

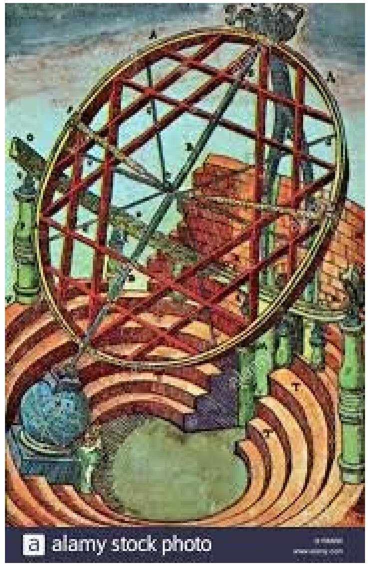
Mode	Velocity^{-1}	Timekeeping precision
Horse	2.8 s/m	100 ms/day
Train	0.4 s/m	10 ms/day
Aircraft	0.04 s/m	100 µs/day
Satellite	0.1 ms/m	100 ns/day
OC 192 data	0.1 ns/bit	10 ps/day

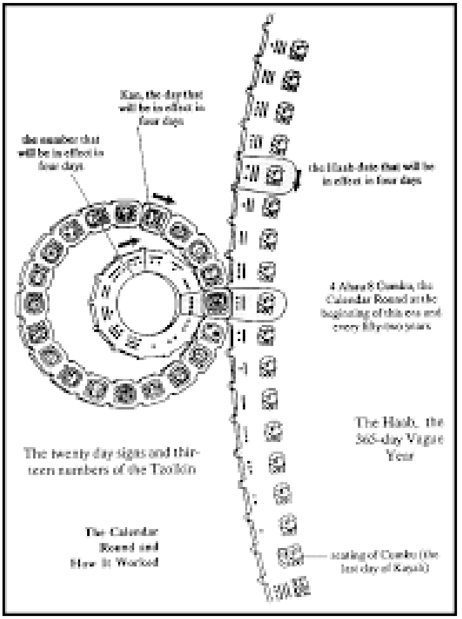


Explosion in Timekeeping Performance has Provided Major Benefit to Society During this Millennium

The Earth as a Clock – Astronomical Timekeeping

- The apparent motion of the Sun and stars with the independent cycles of the Moon and planets formed the human notion of timekeeping as the day.
- The calendar is the accumulator of the yearly timescale.
- The 16th century Copernican revolution, where the day was established as the rotation of the Earth, confirmed the Earth as the basis clock.
- With scientific advancement, the precision of astrometric observation remained concerned with measuring the transit of celestial objects to an artificial north-to-south zenith line, called the meridian.
- Stars were found fixed to the celestial sphere, while the apparent motion of the Sun drifted eastward by .066º/day leading to the apparent solar day, noon to noon, as the relevant time interval for navigation.
- Astronomer's define the sidereal day by the rotation period of the Earth, which is correlated to the orbital period as 365.256 rotations between vernal equinoxes.

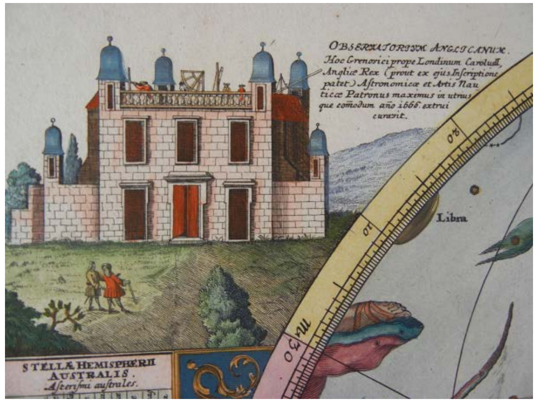


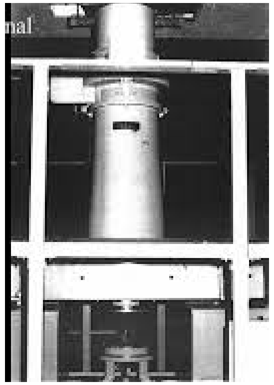


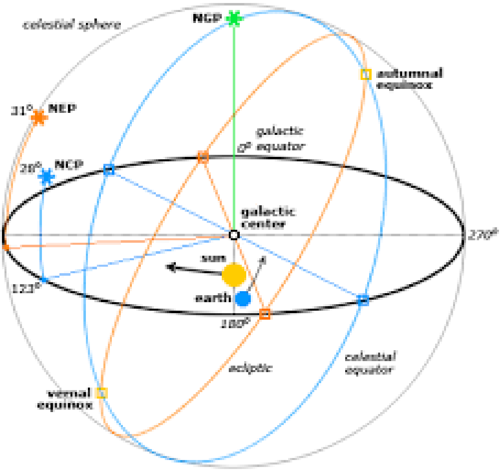
The Earth as a Clock – Astronomical Timekeeping

- The association of astrometric observation to timekeeping became inseparable by the 17th century due to both the pursuit of scientific achievement and maritime based trade through celestial navigation.
- European observatories were established by France (Paris Observatory) and England (Greenwich Observatory) almost contemporaneous,1671/1675.
- The most immediate product of the national observatories were almanacs, or catalogs of celestial observations coordinate with the local meridian. These meridians eventually became the lines of longitude used in geo-location.
- Almanacs revolutionized celestial navigation by allowing navigators to position themselves with motions not related to the sidereal day, notably the method of lunars.
- After the innovation of mechanical clocks into a seaworthy chronometer, observatories, such as the USNO in 1830, were established as calibration laboratories.
- Zenith transients by reference stars were used up to the 1950's to calibrate time transfer clocks and mark national time by photographic zenith tubes (PZT).
- The improvement of clocks through quartz and atomic sources in the 1950's disqualified the Earth's rotation as uniform and thereby stopped its use as a primary reference.

FIG. 4.

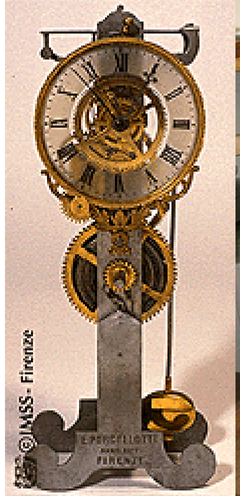


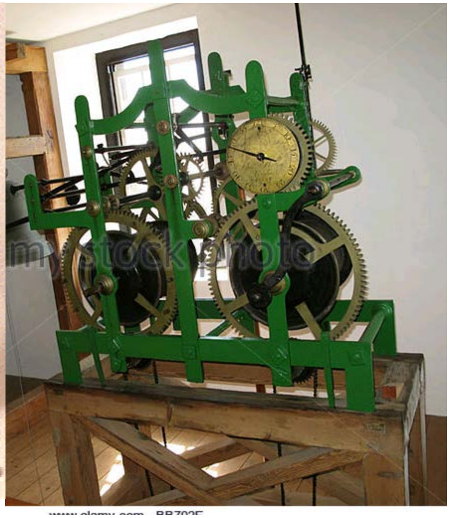


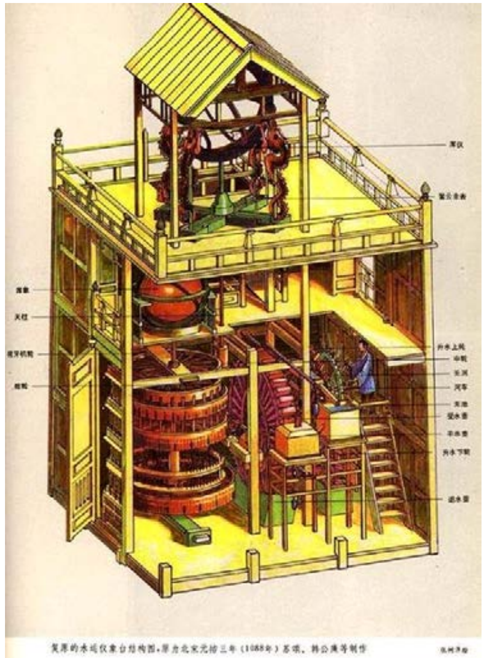


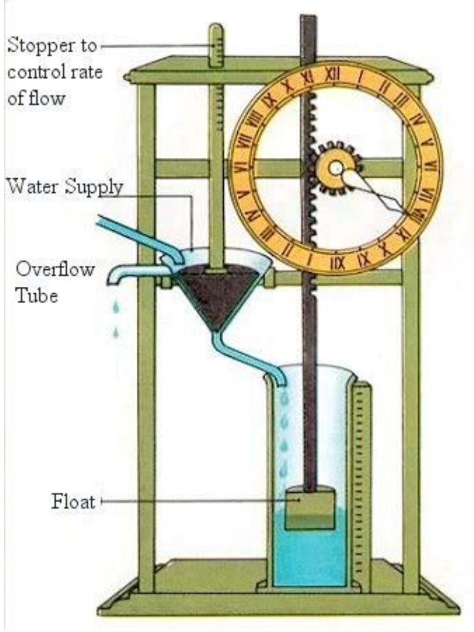
The Pendulum and the Advent of Mechanical Clocks

- The relationship of the apparent rotational motion of the celestial sphere, the concept of rate, and the invention of a gear work transmission inspired the development of mechanical clocks as timekeeping mechanisms for social benefit.
- Much as today, the transfer of astronomical observation and the mathematical operations to convert to practical timekeeping was confined to a unique set of specialists.
- Mechanical clocks were soon found to fill this gap by creating three highly useful utilities.
    - Transportability – carriage of a reference time for travel
    - Maintainability – the creation of a continuous local time
    - Dissemination – the broad transmission of reference time
- The progressive improvement of these utilities continues today at ever increasing levels of physical understanding and technology.
- Likewise, the discovery and innovation found in the development of mechanical clocks since the 15th century produced the major functional systems that can be traced into the most sophisticated timekeeping systems of today.
- The study of mechanical clocks is generally bifurcated by the frequency source (or resonator that creates harmonic motion): the pendulum, and the balance wheel.









The Pendulum, Escapements, and Pursuit of Precision

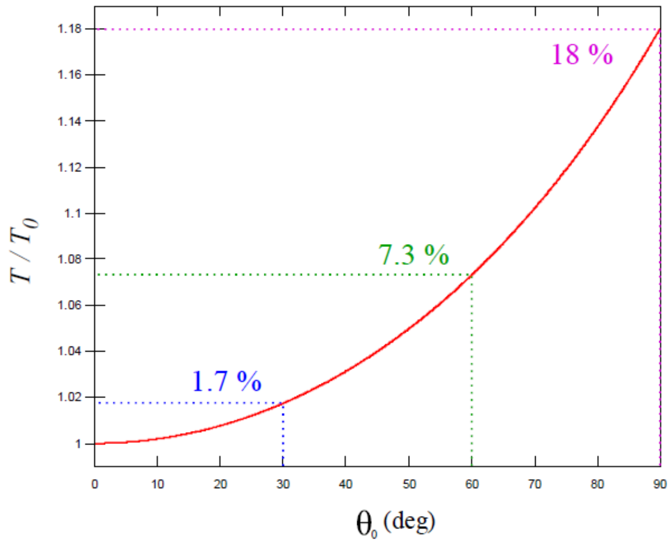
- The innovation of the pendulum as the frequency source or harmonic oscillator of a clock is attributed to Galileo in 1637, but invention is placed on C. Huygens from his studies in 1656.
- Pendulums were used in the most accurate clocks through the 1930’s given the “natural” reciprocating action based on the constant of local gravity.
- The equation of angular motion of the pendulum is derived from a second order equation:

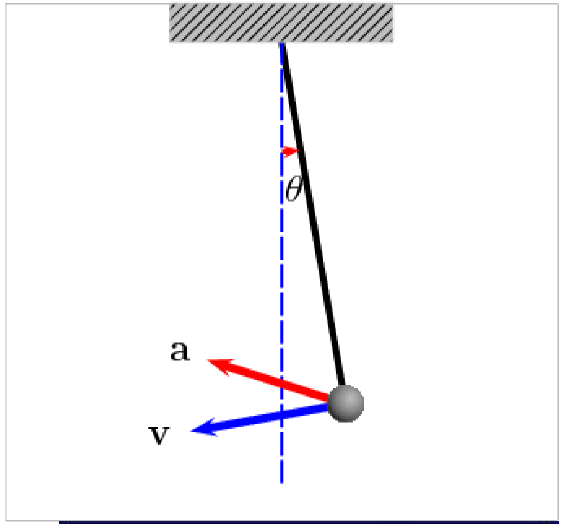
$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin\theta = 0$$

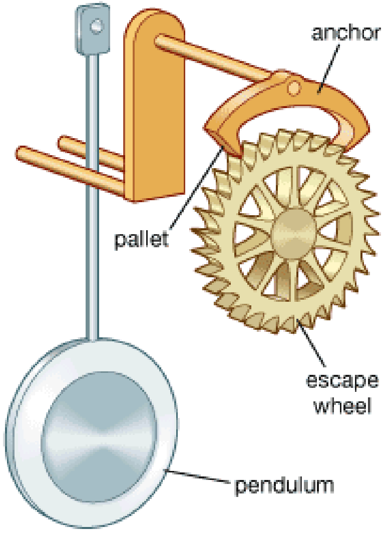
- The solution is non-linear over increasing angular displacement, which was mitigated by using the small angle approx. $\sin\theta = \theta$
- From this the period relation is derived:

$$T_0 = 2\pi\sqrt{\frac{l}{g}}$$

- For a one beat per second at $\theta = 0$, $l = 99.36\ cm$ at sea level
- These two design parameters were incorporated by W. Clement in 1680 into his tall casement regulators, forming the archetype of clocks for scientific timekeeping.







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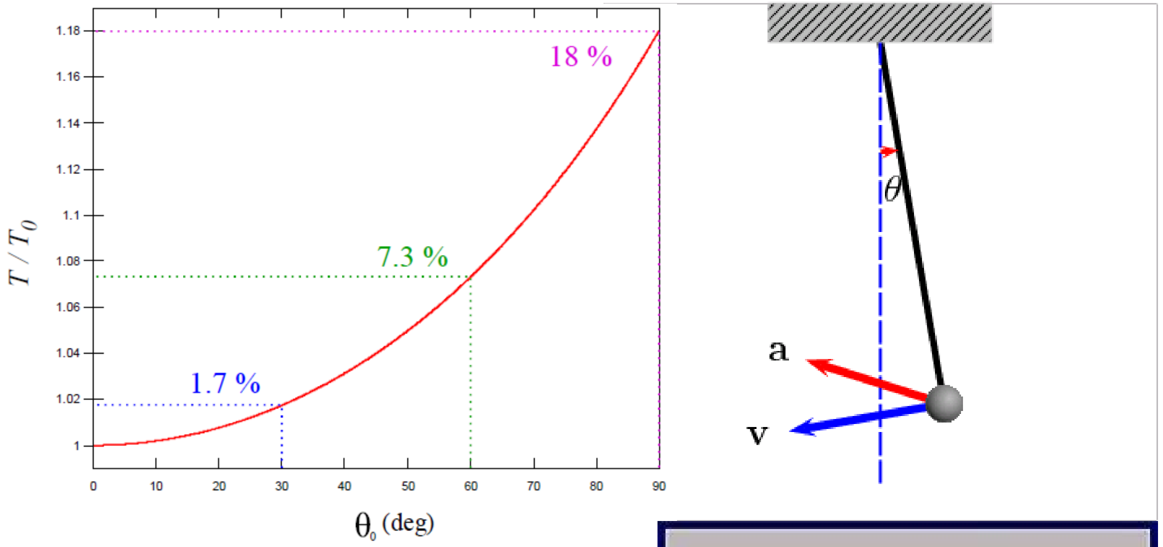
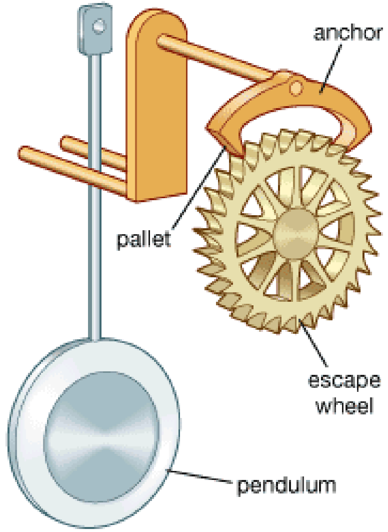
The Pendulum, Escapements, and Pursuit of Precision

- The mathematically derived equation of the pendulum gave clock designers a fundamental physical basis to estimate the performance of their timekeeping.
- This allowed clock characterization to be used to determine areas for improvements in precision, notably the escapement that changed variable energy into a regulated impulse or “tick to phase”.
  - Verge – most primitive, translated continuous rate to interval
  - Anchor – required for reciprocating pendulum, had drive recoil
  - Deadbeat – Latching mechanism that placed tick on zero
- Most importantly these escapements allowed the displacement angle of the pendulum’s reciprocal motion to be minimized.
- Culminating in 1921 with the Shortt synchronome, the evolution of the scientific regulator established these clock development concepts:
  - Temperature compensation – use of counteracting components, or thermally stable components to remove temperature variation.
  - Physical isolation – placing resonator in vacuum and using isolated mechanical mounting.
  - Q – decoupling the frequency source from the accumulator to minimize energy loss per cycle.
  - Disciplined synchronization – periodic phase correction of subordinate free running clocks to clock of higher accuracy .





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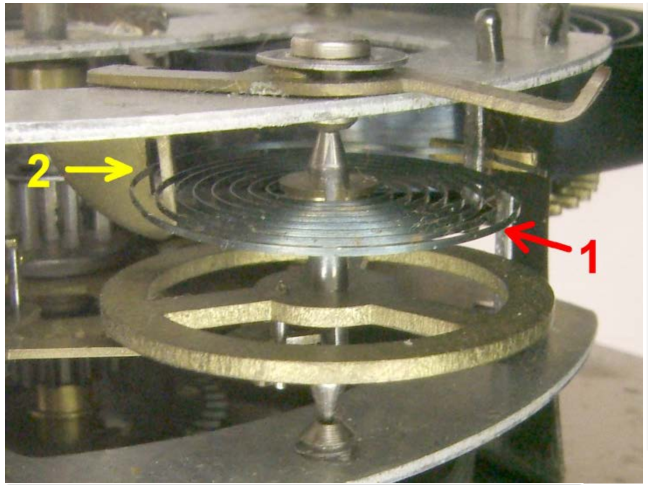
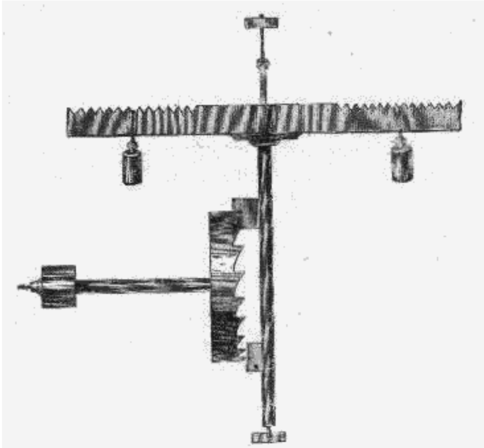
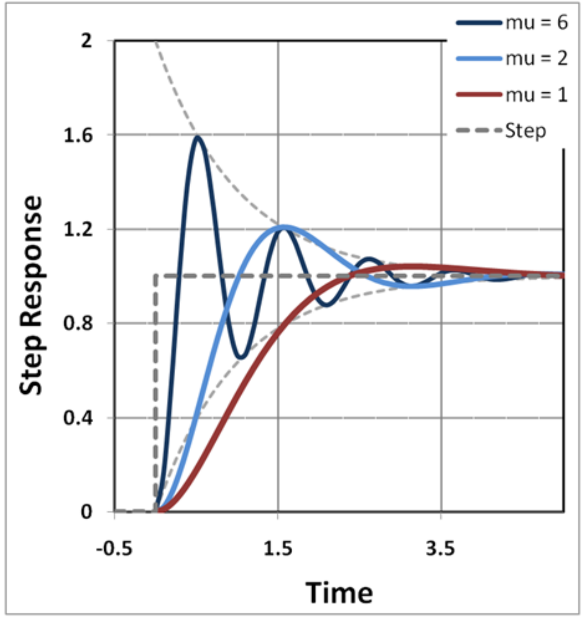
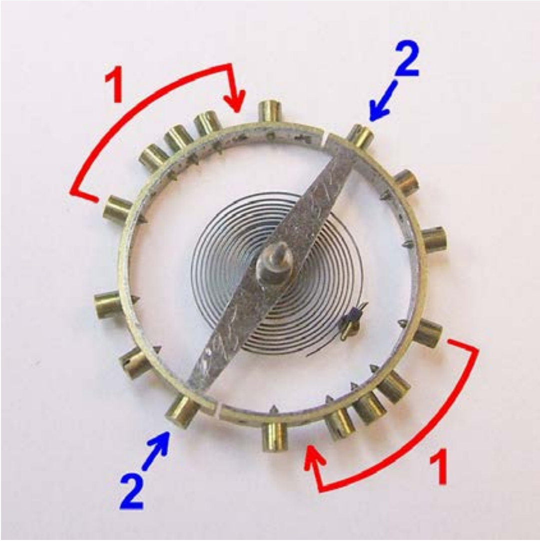
The Balance Wheel and Spring – Enabler of Transportability

- While the pendulum offered clock designers interaction with a physical constant to optimize laboratory devices, it offered no benefit to transportability.
- Transportable clocks where conceived early in the 14th century by the use of a balance wheel which transformed a continuous drive into reciprocal inertia stored in a wheel through the escapement.
    - The inertial storage made the device independent of orientation
    - The verge and foliot were early progenitors of a balance wheel clock
- However, precision was unachievable since no physical constant was involved, and mechanical translation was a function of the drive force.
- R. Hooke solved this problem in 1658 with the introduction of the balance spring, which added a counteracting force proportional to the rotational displacement of the balance wheel.
- The combination of the balance wheel and spring formed a mechanical harmonic oscillator which imparted the feature of a frequency source independent of the drive mechanism.
- The balance wheel spring innovation provided the commercial success of the portable pocket watch, and subsequently the marine chronometer, with the addition of temperature compensation, and rate adjustment.



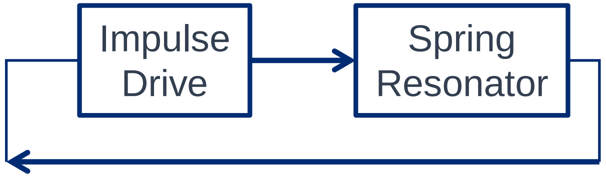






The Balance Wheel and Spring – A Harmonic Oscillator

- The pendulum was made to approximate a harmonic oscillator by constraining its motion to a small angular displacement.
- The balance wheel and spring form a true harmonic oscillator where the energy of the impulse of the driven wheel is stored in the spring.


Impulse Drive

Spring Resonator

Negative Feedback Loop

- The equation describing this torsional oscillator is:

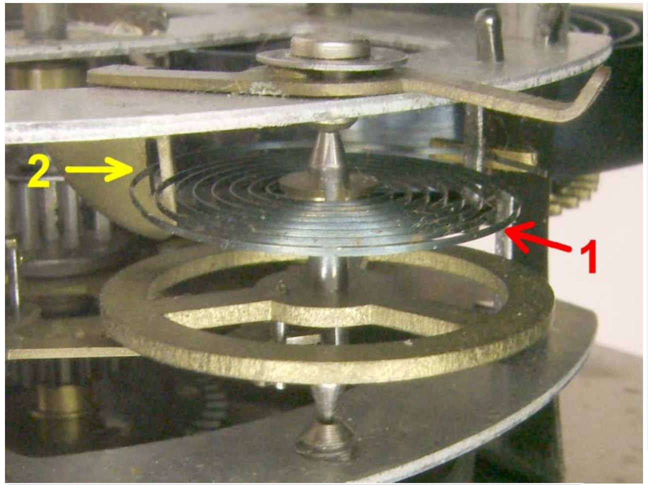
$$I\ddot{\theta} + \Gamma\dot{\theta} + \mu\theta = T(t)$$

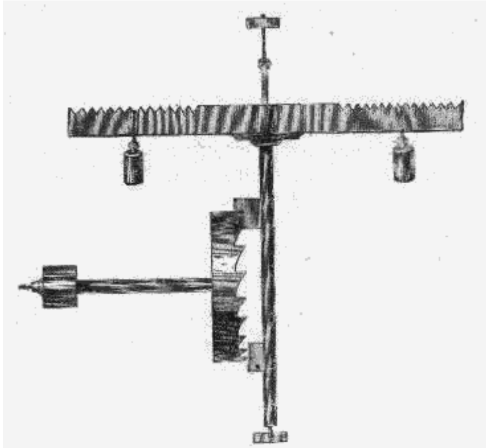
I is inertia
Γ is rotational friction
μ is torsional force
T(t) is dynamic torque

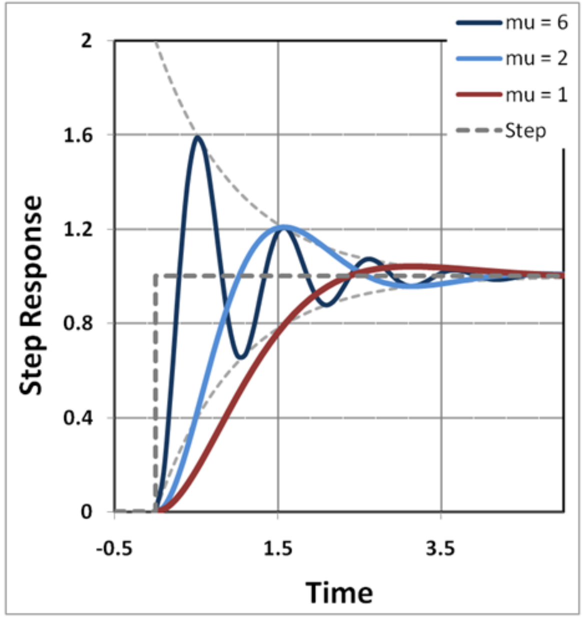
- With unndamped angular frequency f_n , that decreases with damping

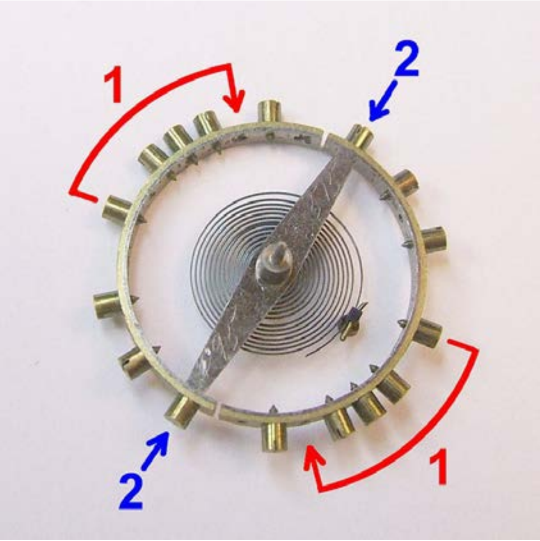
$$f_n = \frac{1}{2\pi}\sqrt{\frac{I}{\mu}} \qquad f_n\sqrt{1-2\Gamma^2} \qquad Q \propto \frac{\sqrt{\mu I}}{\sim\Gamma}\ \frac{energy\ stored}{energy\ lost}$$

- Note how I *and* μ can be used to affect the harmonic frequency.



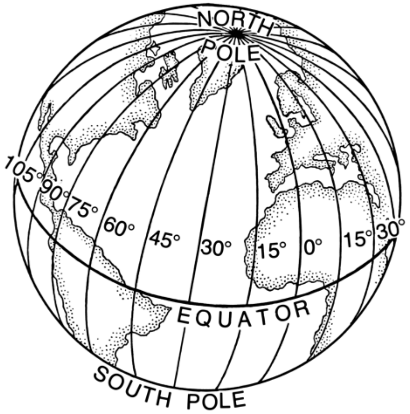


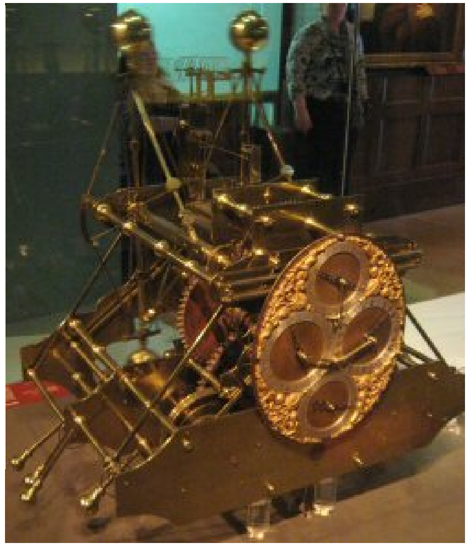


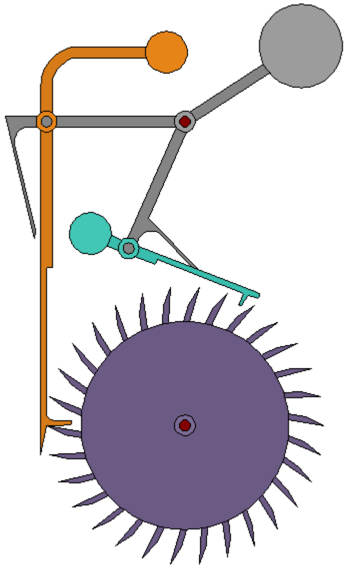


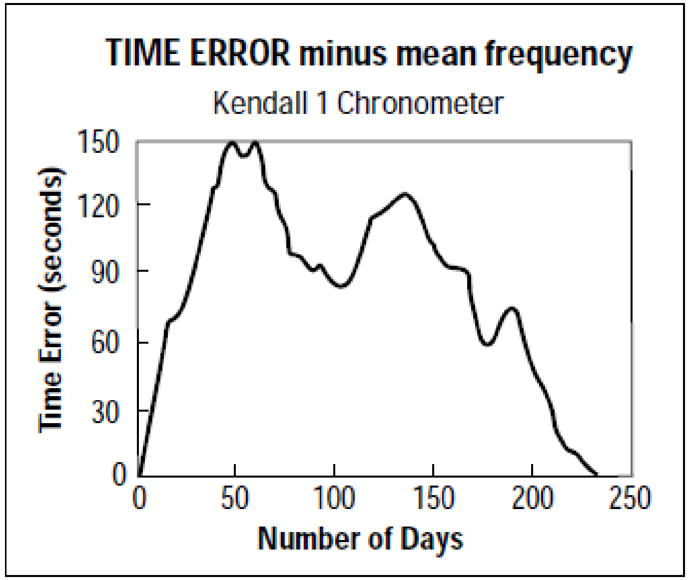
Harrison and the Solution of Longitude Navigation

- John Harrison (1693-1776) was a natural engineer, being a tradesman in carpentry and fine joinery with no scientific education.
- He built his first longcase clock in 1713 at age 20.
- Interestingly, his first clocks were made from wood, selecting material for complementary characteristics for self-lubrication.
- Harrison later used this principle for temperature compensation by using a bimetallic assembly for the grid-iron pendulum rod.
- Harrison’s pendulum clocks, including his first attempt at the maritime chronometer, featured the grass-hopper escapement, a near-frictionless mechanism, since petroleum based lubricant was not generally understood.
- Harrison invented the caged-roller bearing during the development of his first marine clocks , again overcoming the impact of friction as a mechanism for energy loss and frequency instability.



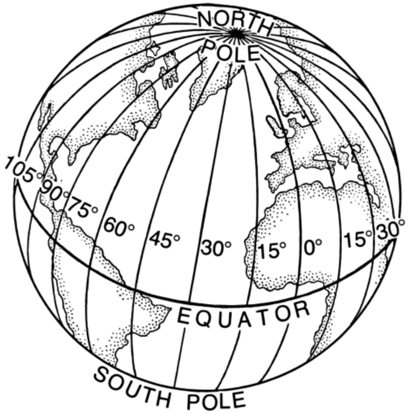


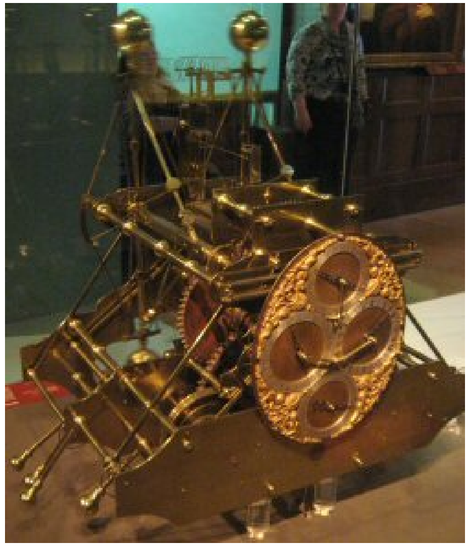


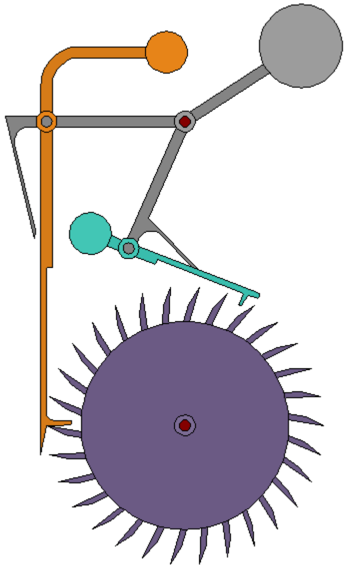


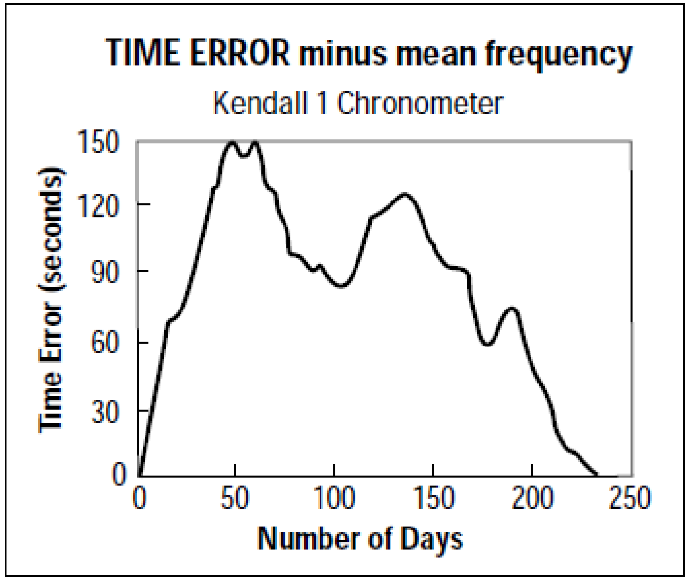
Harrison and the Solution of Longitude Navigation

- By the mid-18th century, the capability of marine vessels had expanded in both speed and provision for increasingly long trans-global voyages.
- Nonetheless, the limit to precise longitudinal navigation forced the encroachment of incremental waypoints and dead reckoning.
- The Scilly naval disaster of 1707 saw the loss of four British vessels and over 1500 sailors in England's home waters at the southwest mouth of the English channel.
- The cause of the disaster was attributed to the compromise of performing longitudinal navigation, although modern analysis points to a critical mistake in latitude and charts.
    - Positioning west of Ushant (48°27′29″N 5°05′44″W) when actually near the Isles of Scilly (49°56′10″N 6°19′22″W)
- The result of the investigation promoted the Royal government to issue the Longitude Act, which authorized a Board to award a staged prize for practical at-sea longitude navigation methods:
    - £ 10,000 for 1 degree of accuracy
    - £ 15,000 for 40 minutes of accuracy
    - £ 20,000 for 30 minutes of accuracy



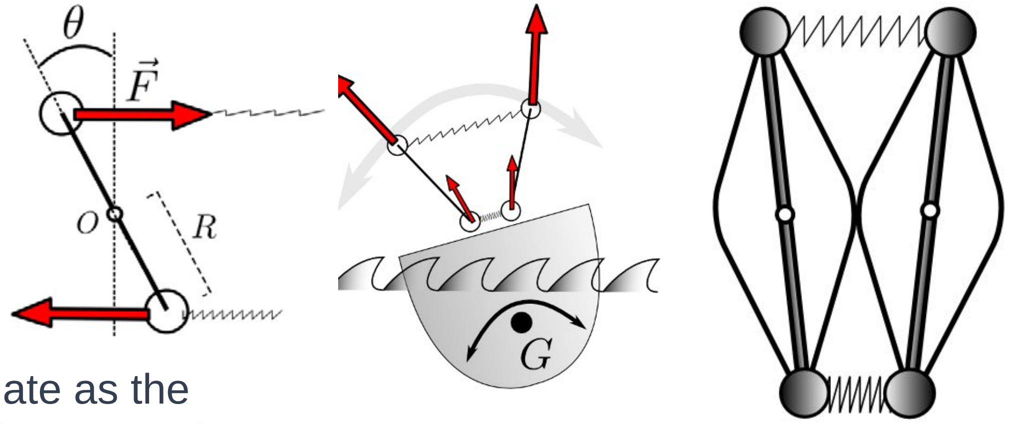


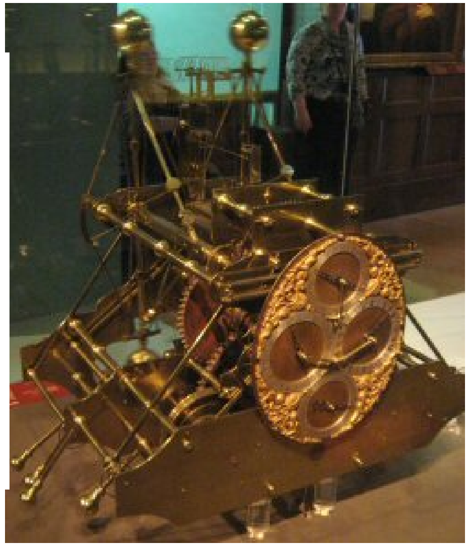


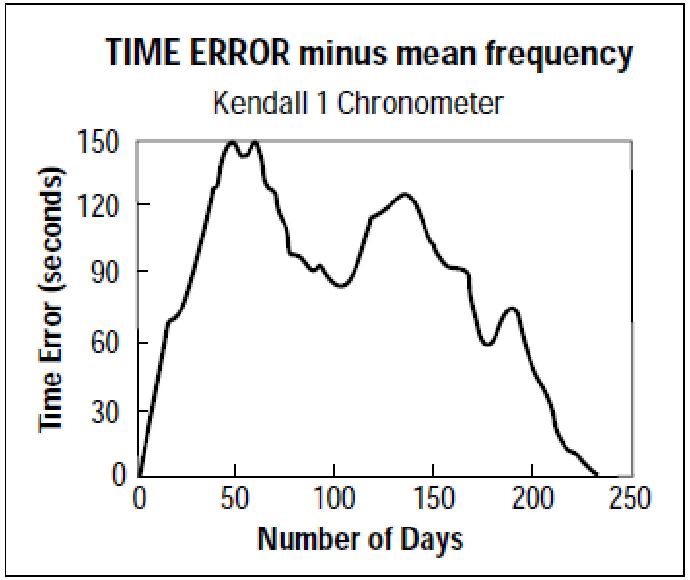


Harrison and the Marine Chronometer

- C. Huygens recognized that the practical mechanical harmonic oscillator enabled maintaining time at sea for longitude determination
- Harrison began his pursuit of the Longitude award by attempting to remove the action of gravity and the ship’s horizontal motion by creating a differential balance mechanism, through spring coupling.
- This mechanism, used in H1 and H2 proved inadequate as the rolling and yawing motion of the ship created a centrifugal mode actuated by the differential scheme.
- In H3, Harrison tried to form a differential balance wheel design, but never succeeded in having the independent oscillators work in phase.
- H4 is the historically famous “sea-watch” where in practice, Harrison added decades of innovative mechanical design to Huygens’ oscillator.
    - On the demonstration mission H4 was corrected for an estimated rate of -30 ppm at time of deployment.
    - After 81 days and 5 hours, H4 was found 5 seconds slow compared to the known longitude of Kingston, corresponding to an error in longitude of 1.25 minutes, or approximately one nautical mile.
    - This equates to an estimated drift of -0.06 s/day! [1s/day is 11 ppm]





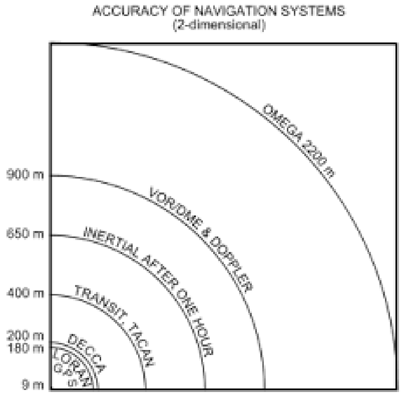


Quartz Oscillators and Radionavigation

- The early 20th Century brought the confluence of three technologies that would revolutionize transportation, timekeeping, and communications.
  - Aircraft and the use of radionavigation
  - Radio and the heterodyne receiver
  - Discovery of piezoelectricity and the quartz oscillator
- The use of radio for navigation is first associated with wireless telegraphy used by marine vessels starting around the late 1890’s.
- By WWI, the military was already highly leveraged in the use of radio to navigate and communicate.
- E. Armstrong in 1919 invented the super heterodyne receiver from his experience in the US Army Signal Corp.
- The “superhet” receiver allowed broad tunability by using a frequency mixer to convert the RF carrier to a lower Intermediate Frequency where demodulation was easier to process.
- The development of radar was soon to follow by 1934 at the Naval Research Laboratory.
- All of these were enabled by the quartz oscillator by W.G. Cady in 1921


German Radar


Great Britain Radar



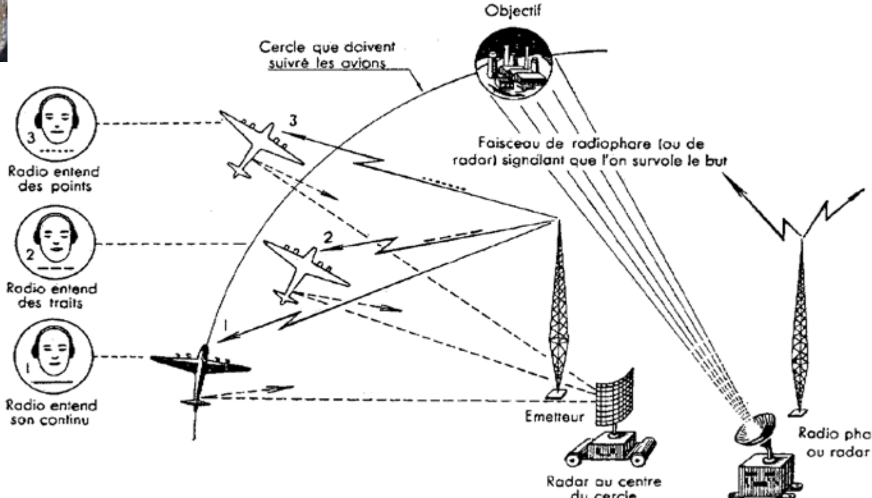
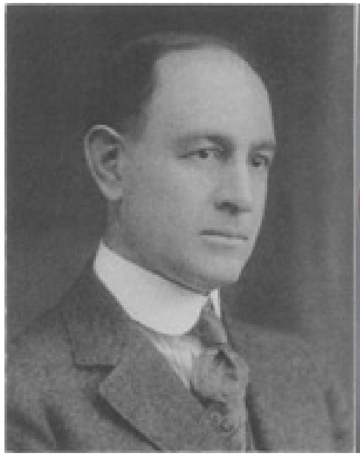
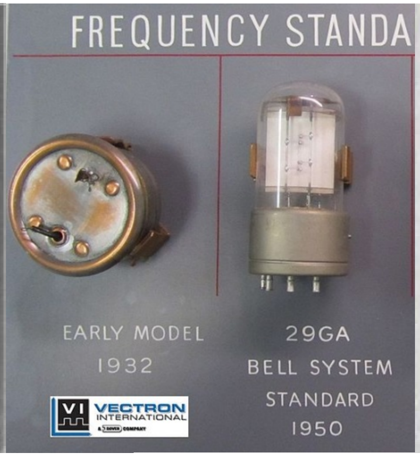


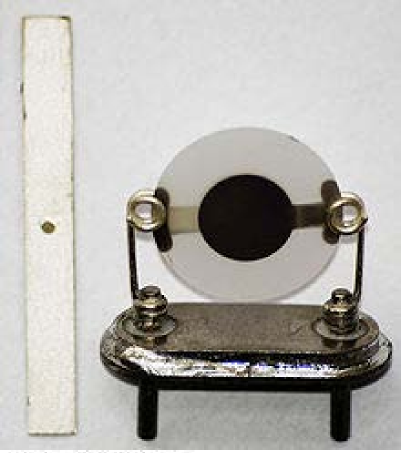
Fig. 31. — Radio-navigation (système Oboé).

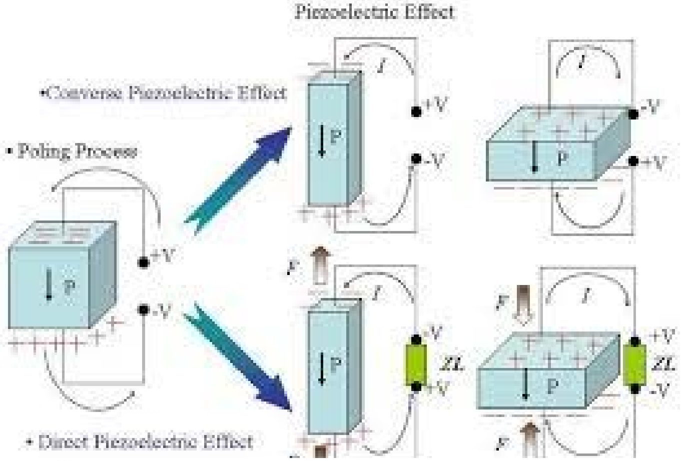
Quartz Oscillators – Enablers to Radio, Time, and Navigation

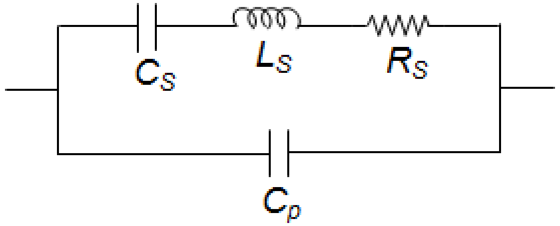
- Piezoelectricity was discovered by J and P Curie in 1880 but was not applied to practical purpose until WWI by P. Langevin for SONAR transducers.
- The early developers of crystal controlled oscillators understood that for radio communications and navigation to progress, the stability of the frequency source had to improve.
- W.G. Cady was the first to apply a quartz crystal to control an electronic oscillator, creating the world’s first electronic frequency standard in 1921
- G.W. Pierce soon simplified the circuit to a single cathode vacuum tube, more importantly deriving the motional impedance of the quartz crystal, recognizing the equivalence as a series resonant circuit with a parallel capacitance.
- The Pierce oscillator circuit is commonly applied, as it places the frequency determining network in a direct positive feedback arrangement.
- As a harmonic oscillator the quartz controlled system achieves equivalent electrical Q’s of >1000 times LCR circuits, leading to intrinsic frequency stabilities measured in the ppbs
- Additionally the process for making quartz oscillators was found to be highly economical, lending itself to large-scale commercial production.

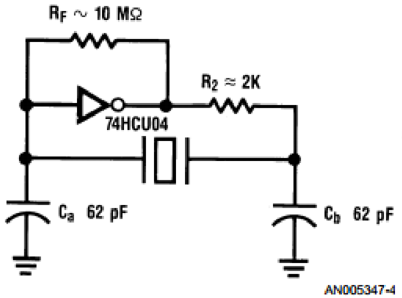


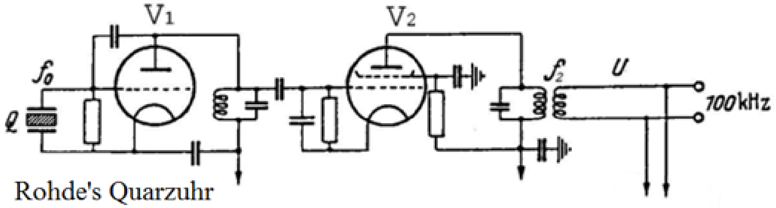








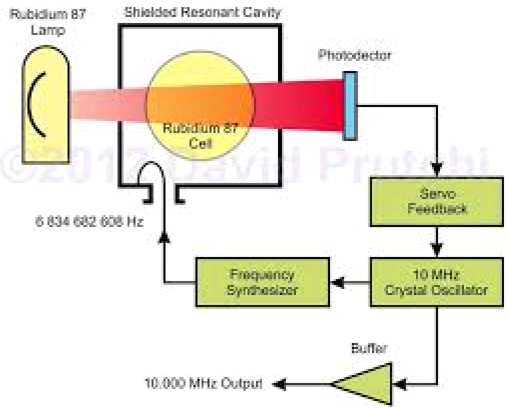


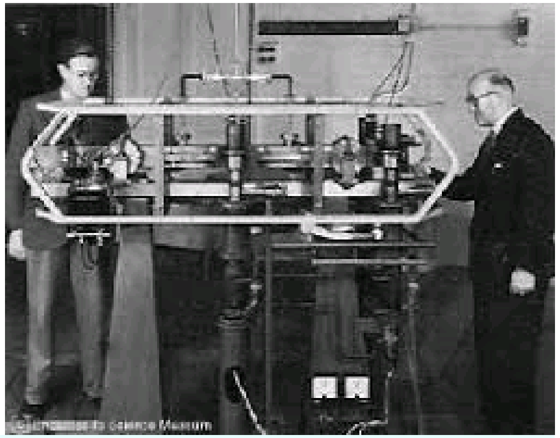


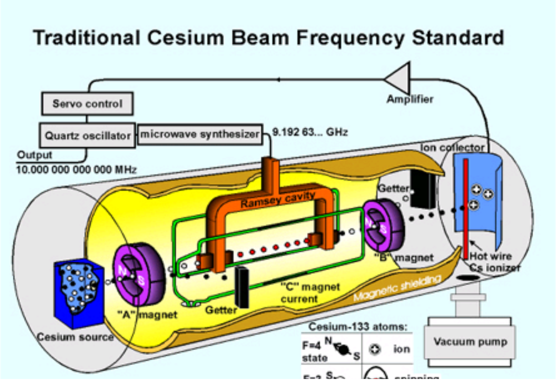
Rohde's Quarzuhr

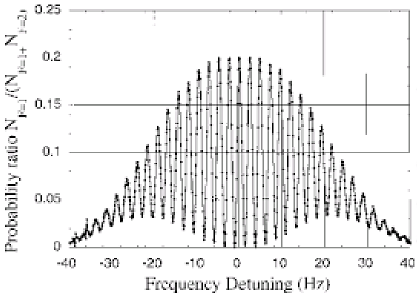
Atomic Clocks and Coordinated World Time

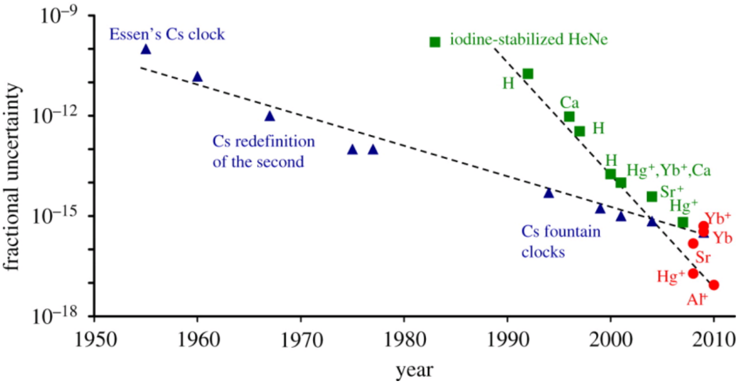
- The early adoption of the quartz frequency standard for reference clocks was short lived as the explosion of modern physics and the quantum mechanical description of the atom led to direct atomic interrogation.
- The deficiency of quartz is that its frequency stability is based on an solid state effect that is highly dependent on fabrication.
- Atomic clocks interact with immutable electron structures that are exactly determined by discrete energy states.
- Interaction is probabilistic in that the interrogation signal's energy $h\nu$ must match the selectivity of the atomic ensemble to achieve a detectable signal.
- Accuracy depends on two factors.
  - Temperature of the ensemble population, colder atoms allow longer interrogation times.
  - Frequency of the electronic transition, selectivity improves as frequency increases, unlike solid state acoustic systems.
- The first accurate atomic clock, was a cesium 133 standard built by L. Essen and J. Parry in 1955 at the UK National Physical Laboratory.
- The success of the cesium beam standard from its ability to be replicated and apparent drift free operation led to the adoption of the SI definition of the second to the absolute frequency, 9192631770 Hz.





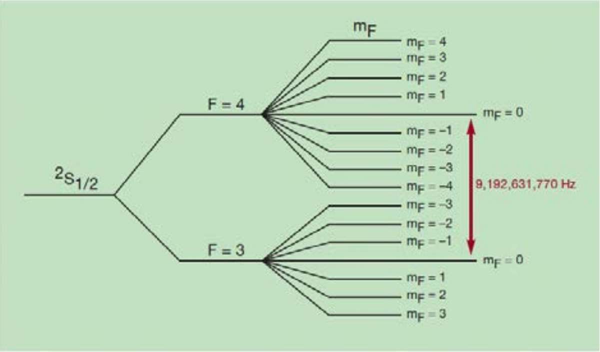


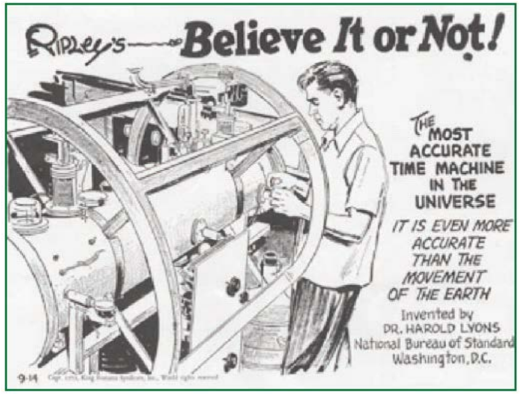




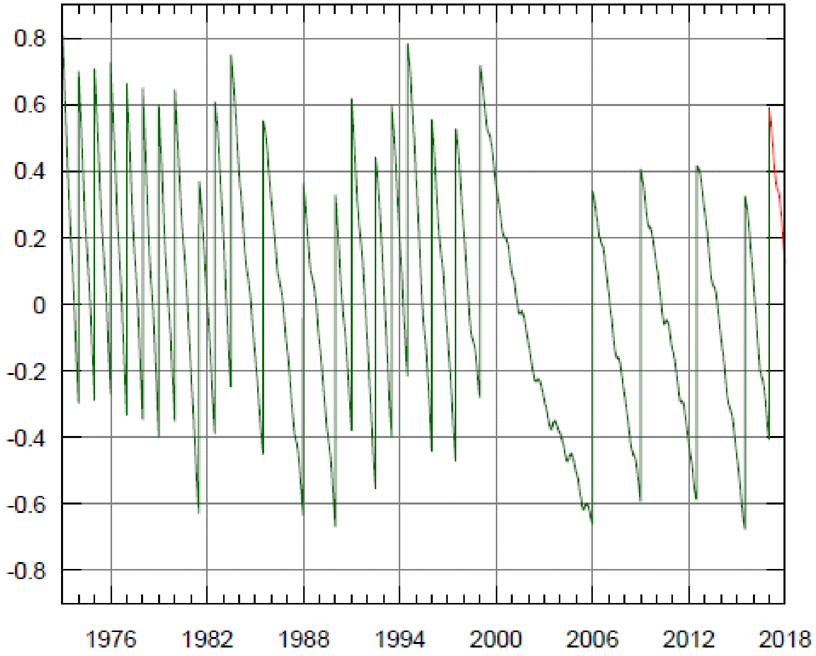
Atomic Clocks and Coordinated World Time

- The process of determining and maintaining a world convention of time became active in the early 20th century with the Bureau International de l'Heure (BIH), which began operations in 1919 at the Paris Observatory.
- From 1920 to the 1950's, coordination of the world's timekeeping laboratories was performed through calibration by astronomical methods.
- As stated earlier, quartz frequency standards had highly indicated that the rotation of the Earth was not stable enough as a primary standard.
- However, the orbital period of the Earth as compared to the orbit of the Moon against the background stars and radio sources appeared useful, this was known as Ephemeris Time (leading to UT1).
- Nonetheless, observations required to determine accurate Ephemeris Time were difficult and time consuming. The immediacy and replicable accuracy of cesium beam atomic clocks for timekeeping appeared as the modern solution.
- In 1970, Temps Atomique International (TAI) timescale was formulated by the clock contributions from the world's Cs standards.
- The algorithm ALGOS formed the TAI timescale as a synthetic clock, completely on a computational basis. ALGOS produced the Circular T report which gave contributing laboratories offset corrections for improving local accuracy.
- The calibration of the TAI second to Ephemeris Time produced a frequency offset that led to the creation of UTC, Coordinated Universal Time, or TAI-UTC, ultimately leading to the convention of leap seconds, $|UT1 - UTC| < 0.9\ s$





Leap seconds from UT1 – UTC began in 1972

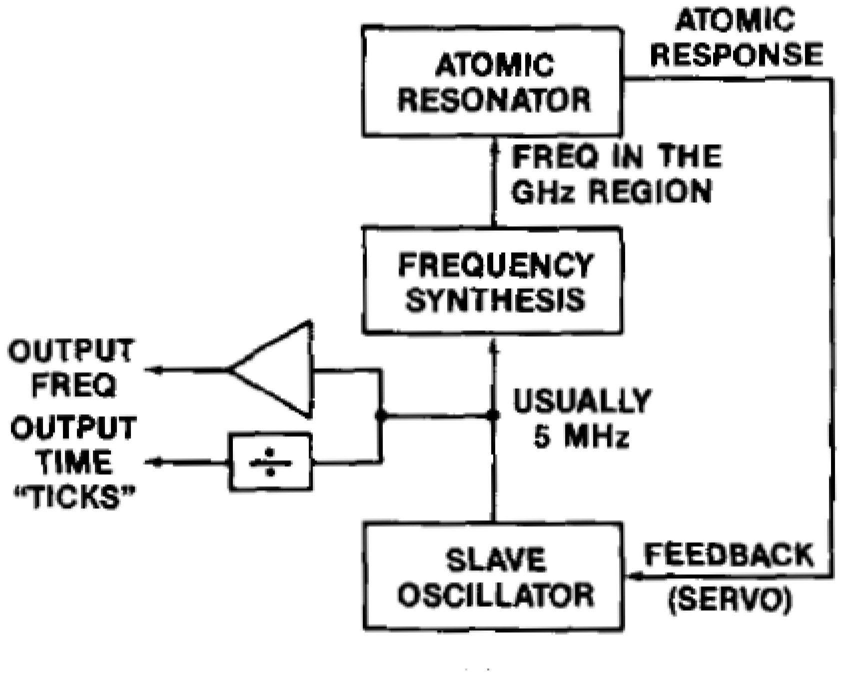


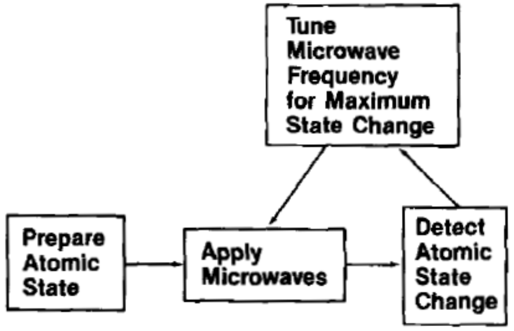
The Operating Principles of Atomic Frequency Standards

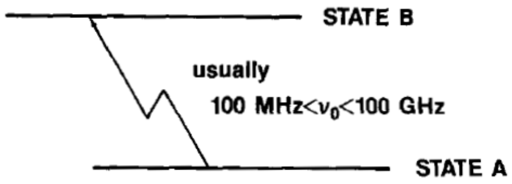
- Most atomic frequency sources (AFS) are passive in that they extract stability through the interrogation of an atomic resonance instead of stimulating oscillation.
- The most prevalent exception is the active hydrogen maser.
- The action of passive AFS is to prepare a population of atoms into one of two non-thermally distributed energy states, where one common state is the ground state of an alkali atom, e.g. cesium or rubidium.
- The state of higher energy is chosen to correspond to a convenient microwave or optical frequency for producing the interrogation signal.
- Maximum detection is produced when the interrogation signal frequency exactly matches the prepared energy states, transferring the highest number of atoms, usually from higher to lower energy.
- The operation of the atomic interrogation is sustained by the formation of a feedback servo control mechanism, which aligns the frequency synthesis chain to the atomic resonance.
- Noise performance is improved through the phase-lock control of a high performance quartz oscillator, which has a stability sufficient to “flywheel” through the interrogation period, better flywheel → longer interrogation → higher stability
- The stability of passive AFS is defined by the phase uncertainty divided by the number of frequency cycles over the time interval of observation, leading to

$$\sigma_y(\tau) = \frac{\kappa}{\sqrt{\tau}}\frac{1}{Q\sqrt{S/N_0}}$$

This is the basis of the Allan deviation for passive AFS improving as $\sqrt{\tau}^{-1}$, Q is state transition energy over resonance width.





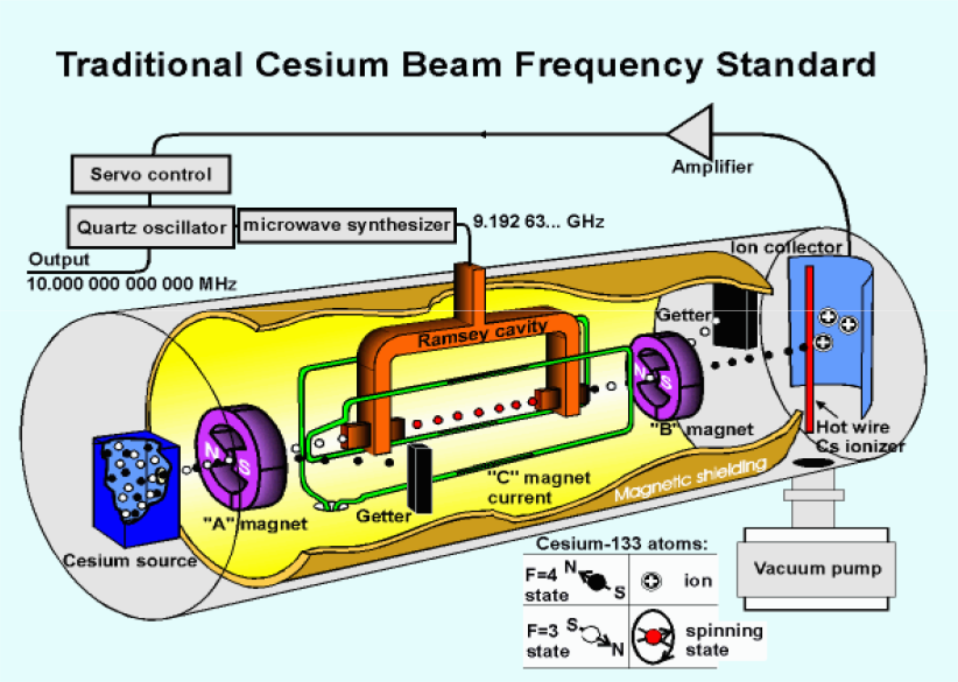


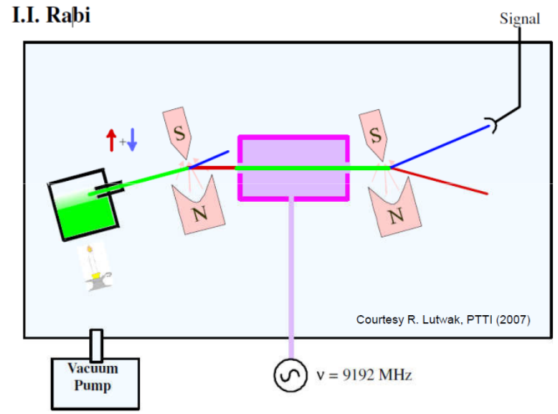
The Operating Principle of Cesium Beam Standards

- An oven heats a Cs reservoir to ~100°C which forms a Cs vapor that is accelerated to a beam of speed approaching 100 m/s.
- The beam proceeds into an evacuated cavity of 10 to 20 cm in length giving an interaction time of 1 to 2 ms; the Q of the instrument is dependent on length, with the standard grade instrument Q = 10 million, custom national metrology references of 4 m approach 100 million.
- The beam of Cs atoms is sensitive to diverging magnetic fields, so that the atoms are deflected proportional to their quantized hyperfine magnetic moments,

$$F_i = \dot{-}\mu_i . \nabla B$$

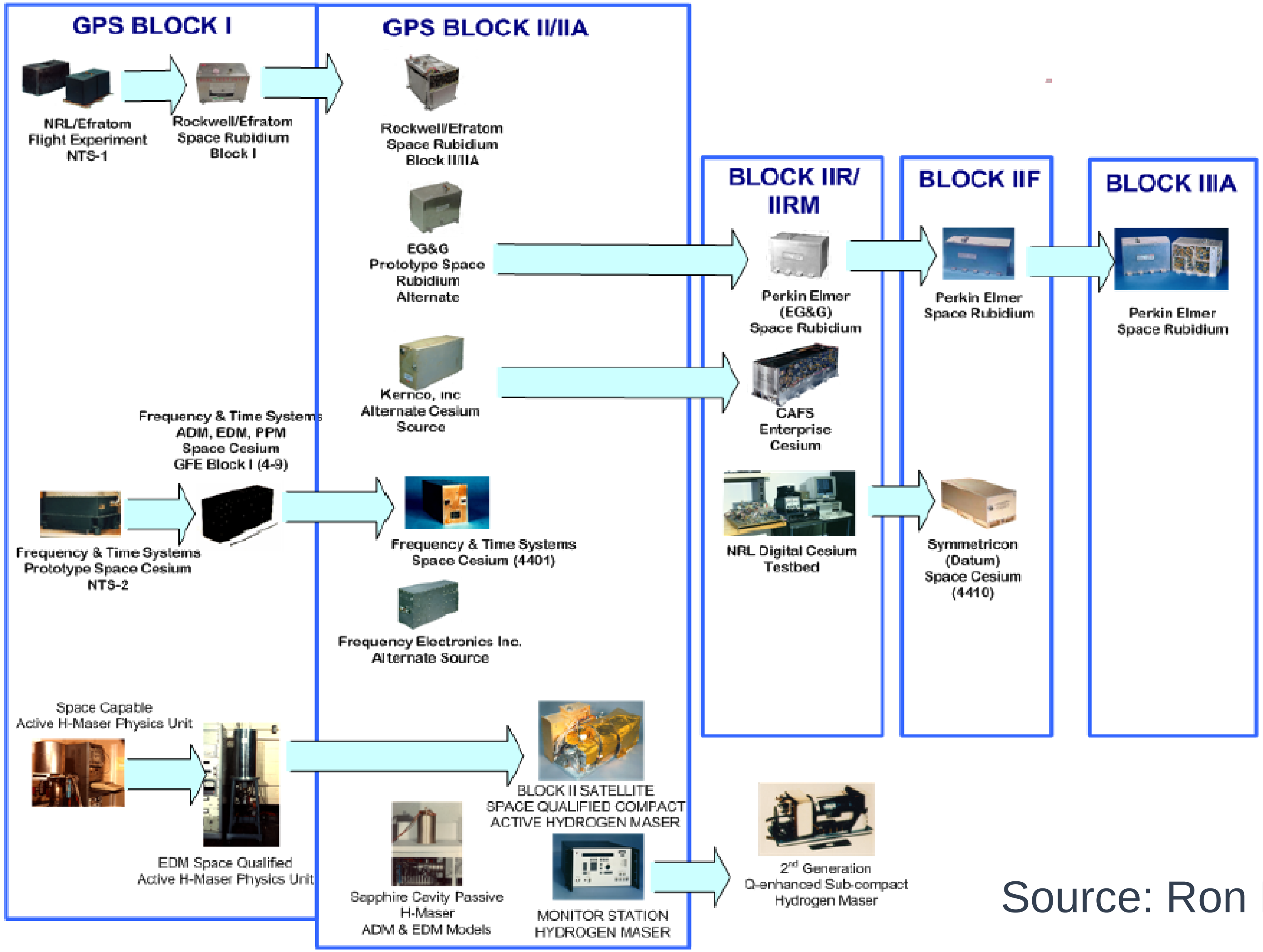
- The 3rd and 4th magnetic hyperfine magnetic moments are separated by a C-field of 0.06 gauss, or about 40 kHz in separation.
- The 3rd and 4th moments have a small quadratic dependence on magnetic field; so the C-field must be stable and uniform; a high degree of shielding is required.
- The first state selecting magnet selects one of the two atomic levels; interaction with the applied microwave causes a state change; the second magnet deflects the atoms which have undergone the state change A to B to the detector.
- Detector is a ribbon or wire at ~900°C; Cs atoms are ionized and collected similar to an electron tube cathode, the current is amplified into the servo feedback network.
- The servo steers the microwave frequency to the frequency of maximum ion current, so the atomic transition frequency controls the microwave frequency.





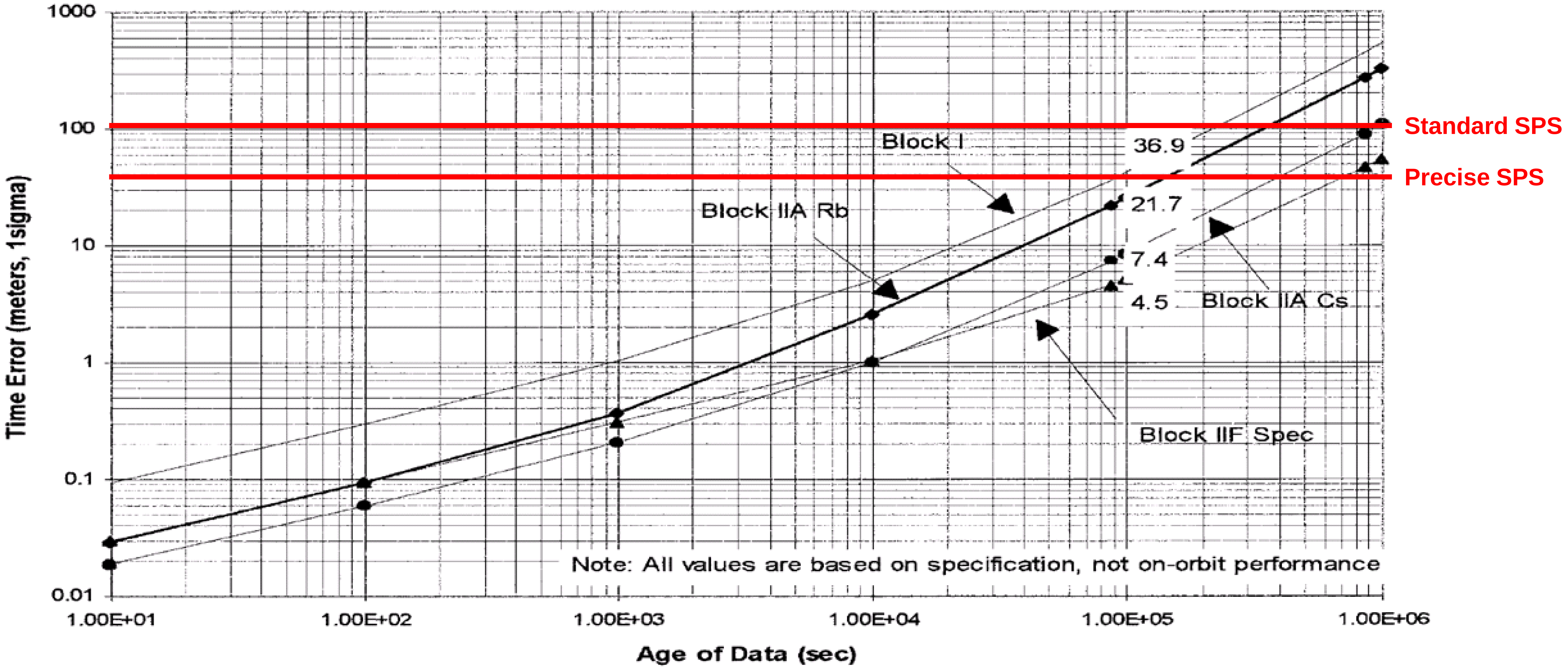
Courtesy R. Lutwak, PTTI (2007)

GPS Space Atomic Clocks



Source: Ron Beard, NRL

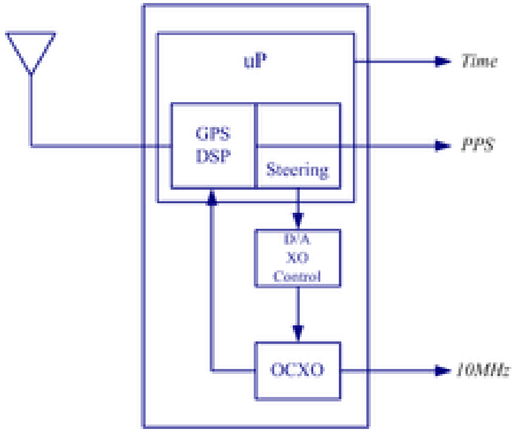
GPS On-board Clock Performance Specification



Note: All values are based on specification, not on-orbit performance

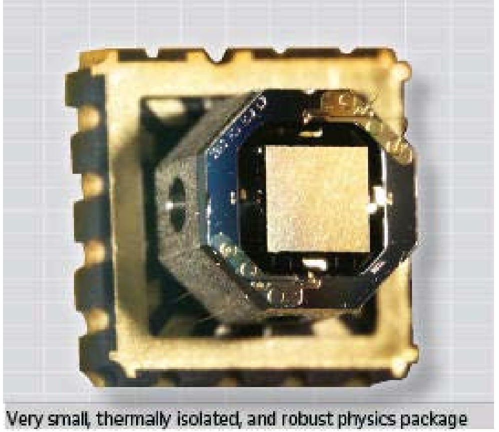
Disciplined Oscillators and GPS User Equipment

- The ubiquitous use of GPS for navigation would not have occurred without the application of GPS receivers to transfer highly precise time and frequency to the local oscillators of the user equipment.
- The local oscillators of GPS equipment are disciplined, meaning that their free run characteristic is periodically corrected by the GPS code and carrier phase.
- Disciplining is different from phase or frequency locking to a reference because the system expects to not have the GPS signal available at all times.
- When a GPS-DO is not using GPS information, it is in holdover mode, which can be simply returning to a free running condition or following the control of an on-board microprocessor system that steers the character of the clock against external effects such as temperature, or corrects intrinsic aging.
- As microprocessors advanced, the steering systems of the flywheel local oscillator progressed from look-up tables to recursive filters.
- In general, the stability of the local oscillators drives the cost of GPS-DO, which range from inexpensive quartz TCXOs to Rb AFS.
- The stability of the LO in holdover, and more importantly, during cold start GPS acquisition determines the parameter known as “time to first fix”.
- The chip scale atomic clock (CSAC) was first applied to enable rapid GPS acquisition of direct P(Y) code.
- The CSAC has evolved GPS-DO systems into composite clocks, where the CSAC, OCXO and GPS are concerted for their best stability intervals.

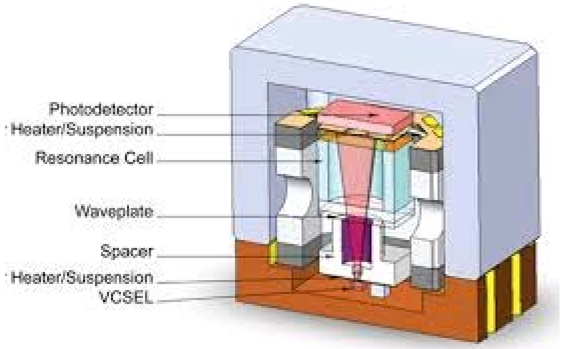


CSAC for GPS Resilience and Integrity Monitoring

- In 2004, the DARPA Microsystems Technology Office (MTO), launched an ambitious technology thrust to develop a chip-scale atomic clock to pursue the practically elimination for time dissemination to most DoD equipment.
- The first generation performance goals of the CSAC set by the MTO were:
    - ±1µs/day accuracy < 1 cm^3 volume < 30 mW power consumption
- In 2005, the NIST team led by J. Kitching and S. Knappe announced the realization of the first micro-fabricated CSAC physics package.
- The approach taken by NIST used the following innovations:
    - Application of Coherent Population Trapping (CPT) for atomic state preparation
    - MEMS fabrication and low power techniques allowing miniaturization
    - Vertical-cavity surface-emitting laser (VCSEL) diode laser sources
- By 2015, three of the original DARPA performers, Microsemi, Teledyne and Honeywell had delivered products of sufficient capability to supply both military and commercial demand, although no performer had reached the MTO goals.
- The most prominent CSAC device, the SA.45a, supplied by Microsemi is used by the US Army in the Manpack radio systems to allow both GPS independent digital communications and direct P(Y) acquisition.
- To achieve power consumption goals, the SA.45a CSACcompromises its performance as a frequency source (noise) to act as a clock system.

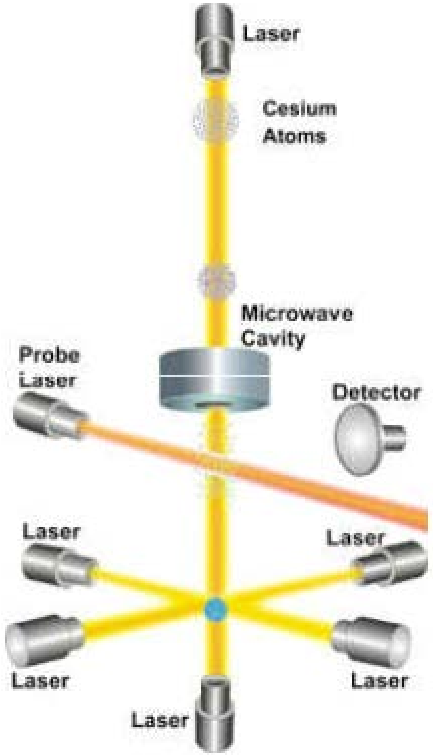


Very small, thermally isolated, and robust physics package

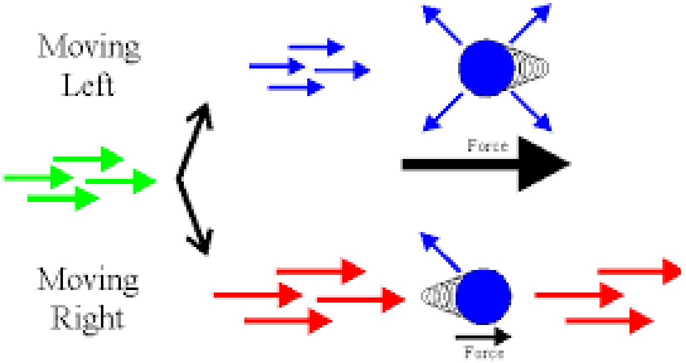


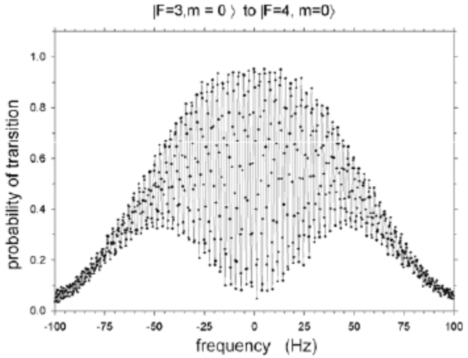
The Fountain Clock and the Limit to Microwave AFS Stability

- The microwave fountain clock concept was attempted in the 1950s by J. Zacharias using a thermal beam of atoms, under the assumption that sufficiently cooled atoms could be used to execute a practical parabolic trajectory to enhance atomic interrogation time.
- The idea was dismissed since the temperature to keep an assembly of atoms comingled for seconds of operation (below 1 mK absolute) was considered beyond practical science.
- In the early 1990’s, W. D. Phillips of NIST introduced the application of optical cooling to form an optical molasses or trap, demonstrating cooling of a cloud of atoms to < 1μK absolute.
- In 1997 W. D. Phillips, with C. Cohen-Tannoudji and S. Chu shared the Nobel Prize in Physics for the technique, which has since revolutionized the study of atomic condensates.
- The optical trap unlocked the creation of the microwave fountain clock with rapid advancement throughout the last 20 years.
- Returning to the principles of the Cs beam standard, the fountain clock achieves the highest degree of determination of the F =4 to F = 3 transition by:
  - Constraining the uncertainty of the ground state energy
  - Maximizes the time in the Ramsey state preparation region
  - Eliminates the hot ion detector, for direct microwave frequency detection
- With typical frequency stabilities approaching 10^{-16}, the fountain clock is becoming the primary clock for national metrology labs.



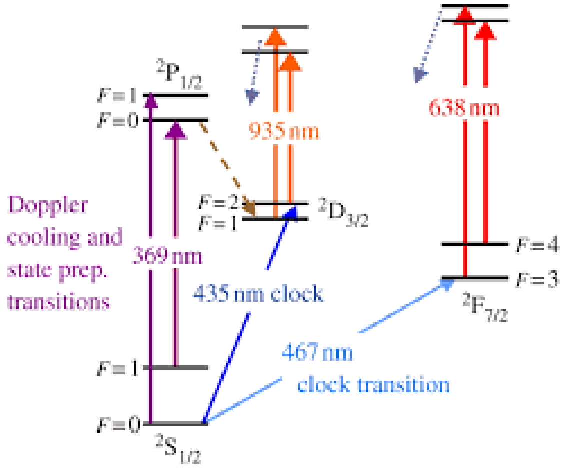
OPTICAL MOLASSES

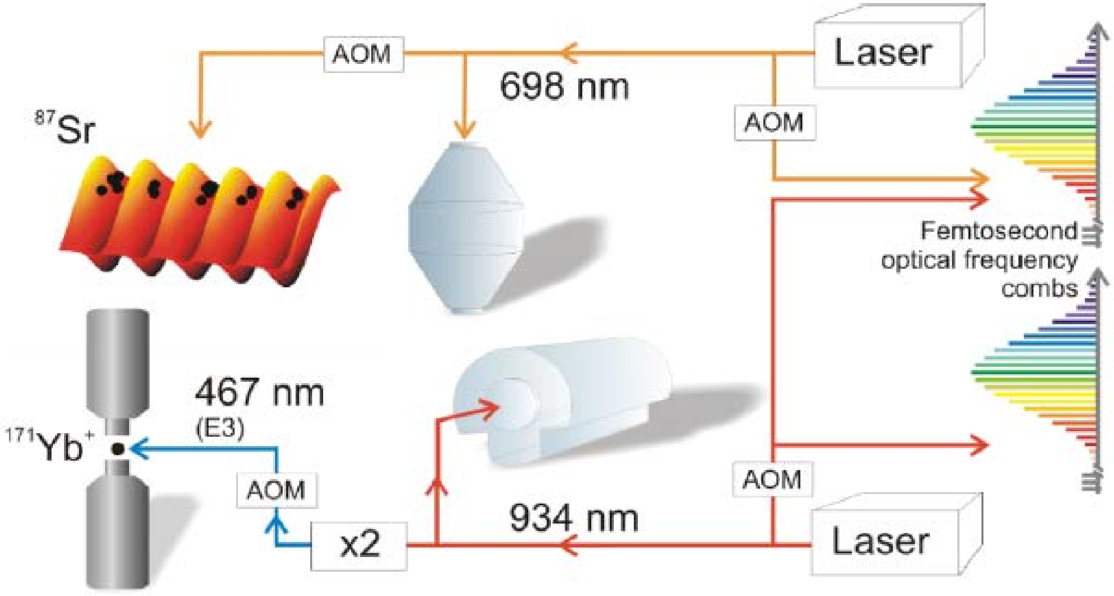




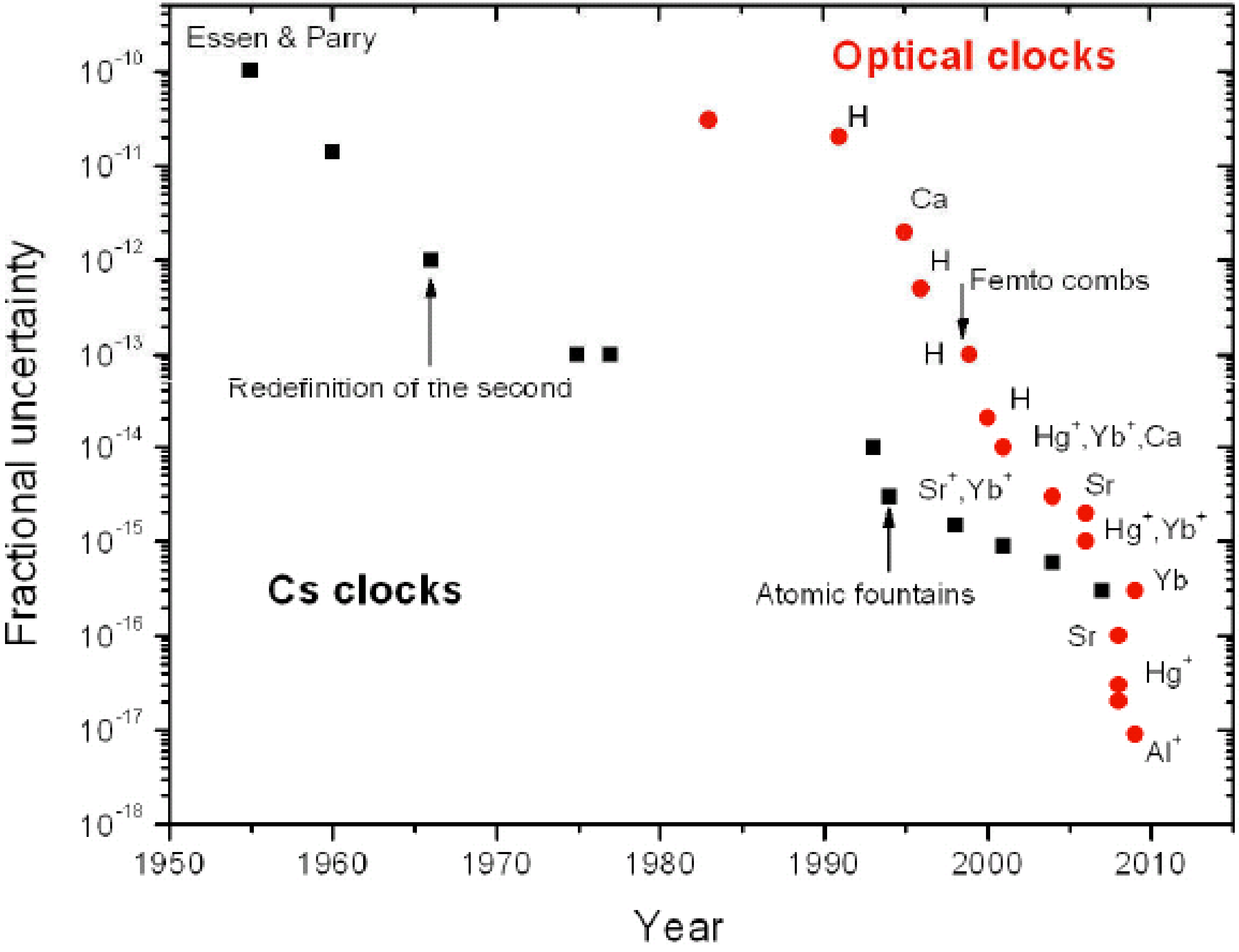
Optical Clocks and the Redefinition of the SI Second

- The move from microwaves as the atomic "escapement" to the optical range was pioneered by J. L. Hall and T. W. Hänsch, winning the Nobel Prize in Physics in 2005.
- D. J. Wineland is recognized as the pioneer in exploiting the properties of a single ion held in a trap to develop optical clocks approaching 10^{-18}.
- The basic advantage of the optical clock is the translation of the atomic state by 10,000 times in frequency with a proportional increase in the Q of the atomic discriminator.
- The limitation of the use of optical transitions is the current lack of direct frequency measurement of the energy at wavelengths of 300 to 700 nm.
- Rather, optical clocks use a complicated chain of interstitial photon transitions to down convert the atomic state stability to mode-lock a laser as the LO.
- Recently, the use of optical combs for the direct conversion from the optical domain to the microwave domain has enabled optical metrology techniques, including the use of ratio measurements of two optical clock systems as exploited by P. Gill and his group at the UK NPL.
- Proliferation of optical clock realization is forming a rejuvenation, as past novel physics has, toward the redefinition of the second, now limited by
  - Dissemination techniques
  - Local gravity variation
  - Species determination (best performing/replicable optical system)





The Progression from Microwave to Optical Definition of the Second



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