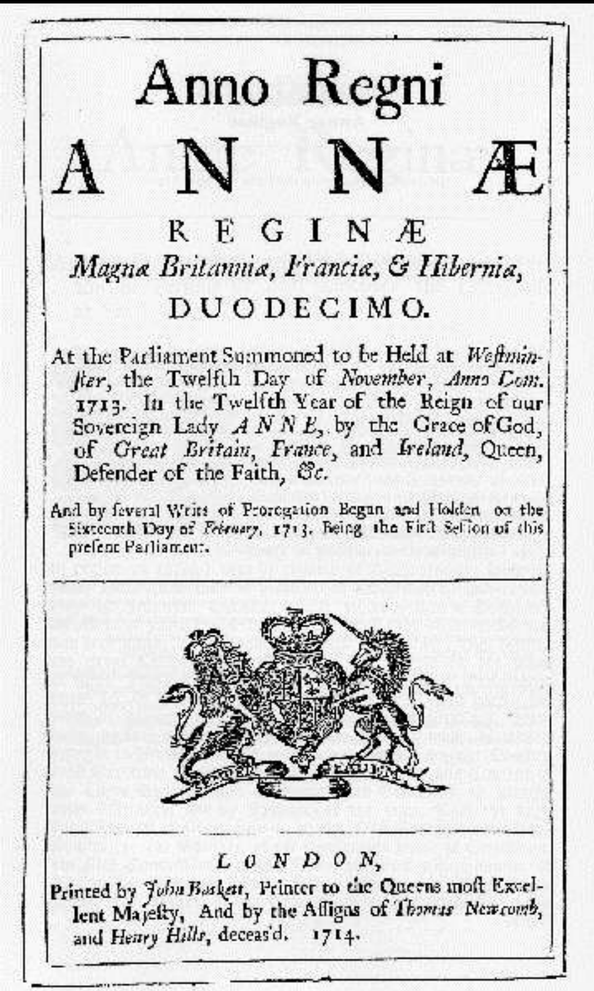
Evolution of the Marine Chronometer

The development of the Marine Chronometer from 1713 to 1942

Clocks in Navigation

- The Earth's poles are stationary and this allows the North-South position to be determined by the apparent height of a known star above the horizon. The North Star, Polaris, provides the most accurate reading.
- The East-West position is more difficult and eluded navigators for centuries.
- Early navigators found a North-South position and then sailed East or West until they made landfall. They estimated their position by dead reckoning of their speed on the sea.
- The use of local time with a precision clock showing the time at a known location allowed precise East-West position calculation.
  - The Earth rotates 360° in 24 hours
  - Each hour time difference equals 15° in longitude



Anno Regni

ANNÆ

REGINÆ

Magnæ Britanniæ, Franciæ, & Hiberniæ,

DUODECIMO.

At the Parliament Summoned to be Held at *Westminster*, the Twelfth Day of *November*, *Anno Dom.* 1713. In the Twelfth Year of the Reign of our Sovereign Lady *ANNE*, by the Grace of God, of *Great Britain*, *France*, and *Ireland*, Queen, Defender of the Faith, &c.

And by several Writs of Prorogation Began and Holden on the Sixteenth Day of *February*, 1713. Being the First Session of this present Parliament.

LONDON,

Printed by *John Baskett*, Printer to the Queens most Excellent Majesty, And by the Assigns of *Thomas Newcomb*, and *Henry Hills*, deceas'd. 1714.

Act of Queen Anne

- As sea commerce developed in the 17th century many tragedies occurred with loss of lives and ships.
- In 1707 Sir Cloudesly Shovel, returning from Gibraltar with his fleet, sailed in cloudy weather. After 12 days with no sight of land, they calculated they were west of the southern tip of England and decided to hold station. That night they ran aground on the Scilly Isles losing 4 ships and nearly 2,000 men including the Admiral.
- The one lone dissenter to the position calculation had been hanged the day before for mutiny.
- The Act of Queen Anne provided a prize for a method of "discovering" the Longitude at sea.
  - £10,000 for 1 degree (60 nautical miles)
  - £15,000 for 40 minutes (40 nautical miles)
  - £20,000 for ½ degree (30 nautical miles)

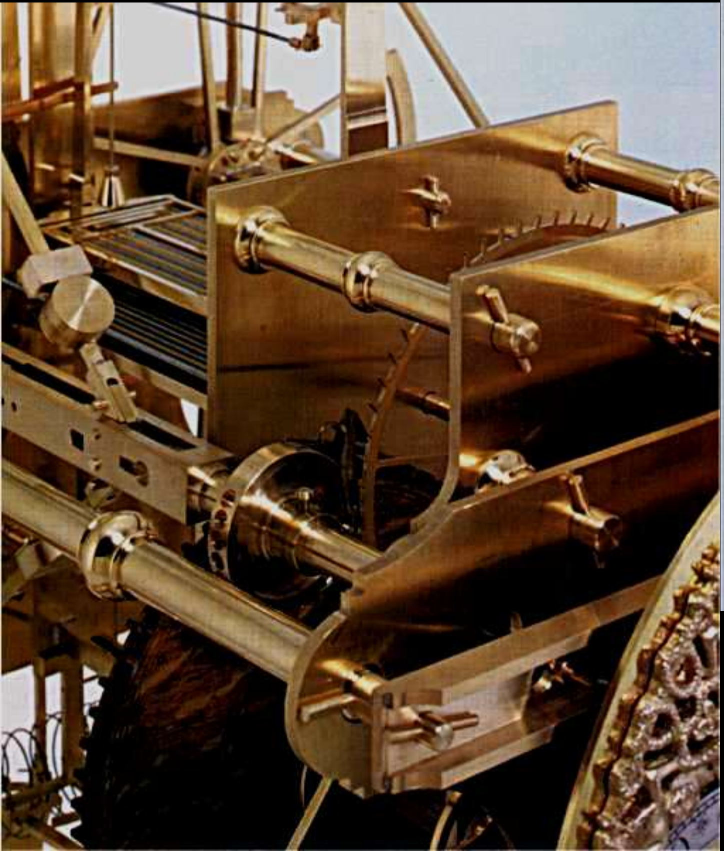
The International Competition

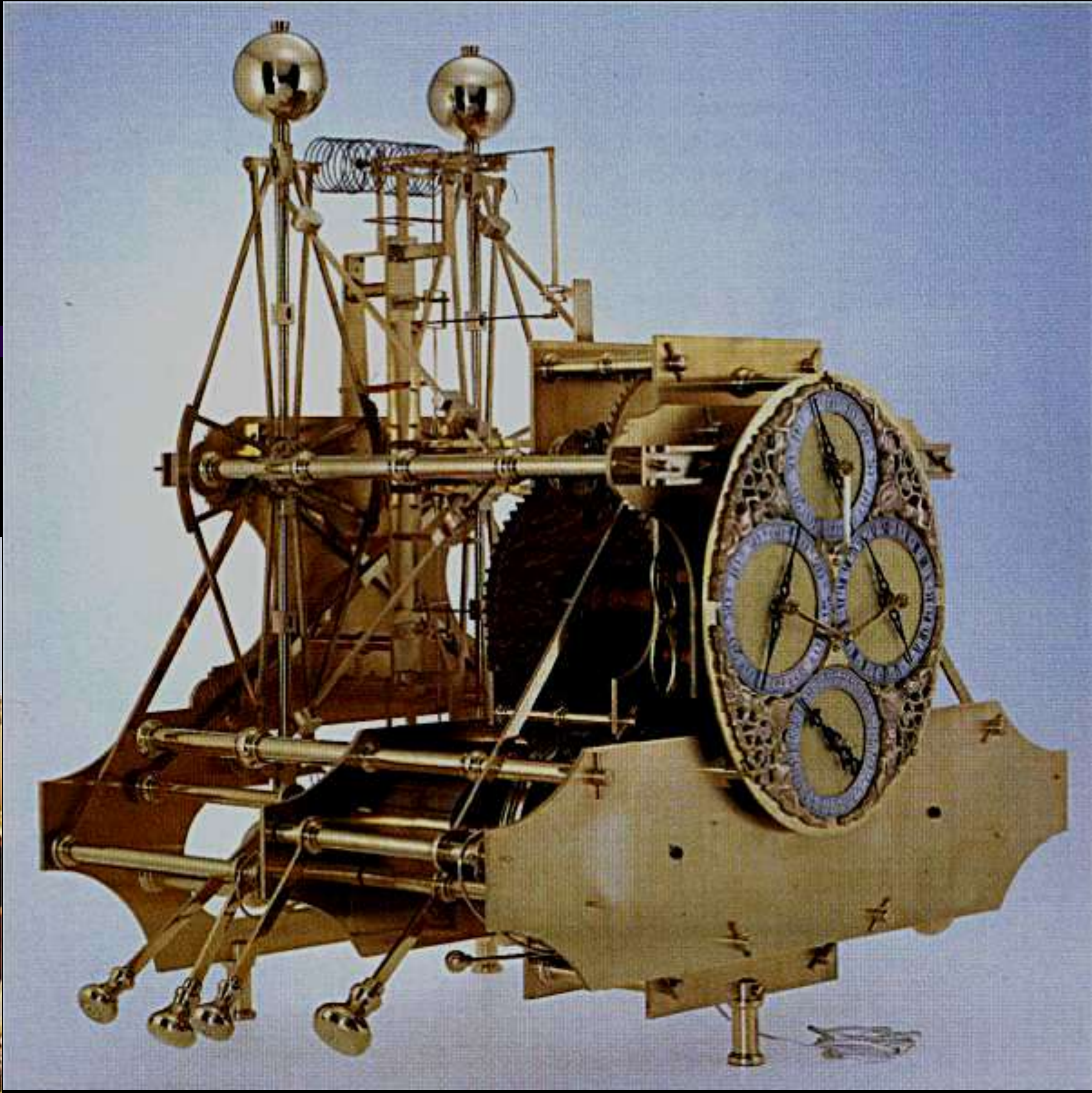
- The nation that could provide a commercial solution for the problem of the longitude would have a great advantage on the seas.
- The English had the Act of Queen Anne and the Longitude Board to spur interest.
- The French and Spanish governments offered similar prizes.
- Philip of Portugal had been a major influence in the earlier development of the use of the compass and North Star.
- The major competition in the 18th century was between the French and the English.

Harrison and the Act of Queen Anne

- John Harrison built the first successful Marine Chronometer, H1 in 1735, in response to the £20,000 prize offered under the November 12th, 1713 Act of Queen Anne.
- His final development, in H4, completed in 1759, was a very different mechanism but was the first true Marine Chronometer capable of supporting world wide navigation.
- We are indebted to the work of Rupert Gould for the restoration of these pieces and the the publication of his magnificent book *Marine Chronometer* in 1923 that spurred the revival of interest in the topic of early chronometers.

Working Model of H1

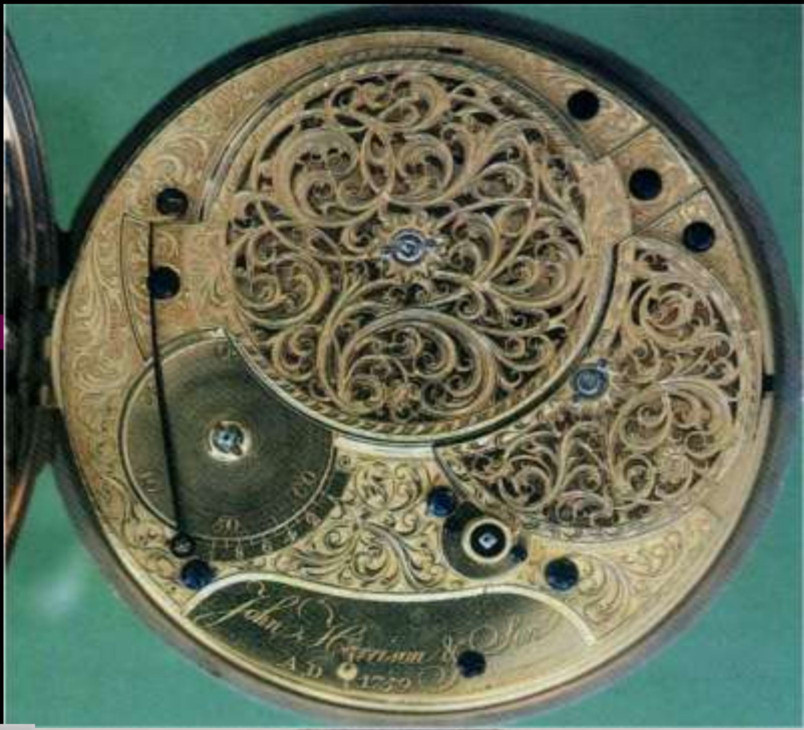




Harrison's H1 was the first working Sea Clock

This model is pictured in the Time Museum Catalog

Harrison's H4 The Chronometer that won the Longitude Prize



The Chronometer Problem

Harrison formulated the requirements for a marine chronometer. This work followed a great deal of discourse that preceded it for 50 years or so.

- First, the machine must be insensitive to the amount of power available to drive the regulator.
- Second, the machine must be insensitive to the temperature.
- Third, the machine must operate reliably for long periods of time in harsh conditions.

These requirements became known as Harrison's Principles and guided the further work of both the English and French makers.

Power and Isochronism

- Harrison’s first problem can be solved in two ways.
  - The power from the driving force to the governor can be kept constant over time.

    Fuzees, detached escapements and remontoires were the main approaches to this problem.

    The elegant constant force escapements were the ultimate development of the remontoire concept.
  - The governor can be insensitive to the power used to drive it.

    Isochronal hairsprings were the main expression of this solution to the problem

Temperature

- Harrison’s second problem was also approached from two directions. In a balance/spring oscillator the temperature problem is primarily due to changes in elasticity of the balance spring with temperature.
  - The **compensation curb** is a device that changes the effective length of the balance spring as a function of temperature

    This is the method Harrison used and was the dominant method for the first 30 years of development
  - The **compensation balance** is a device that changes the moment of inertia of the balance as a function of temperature.

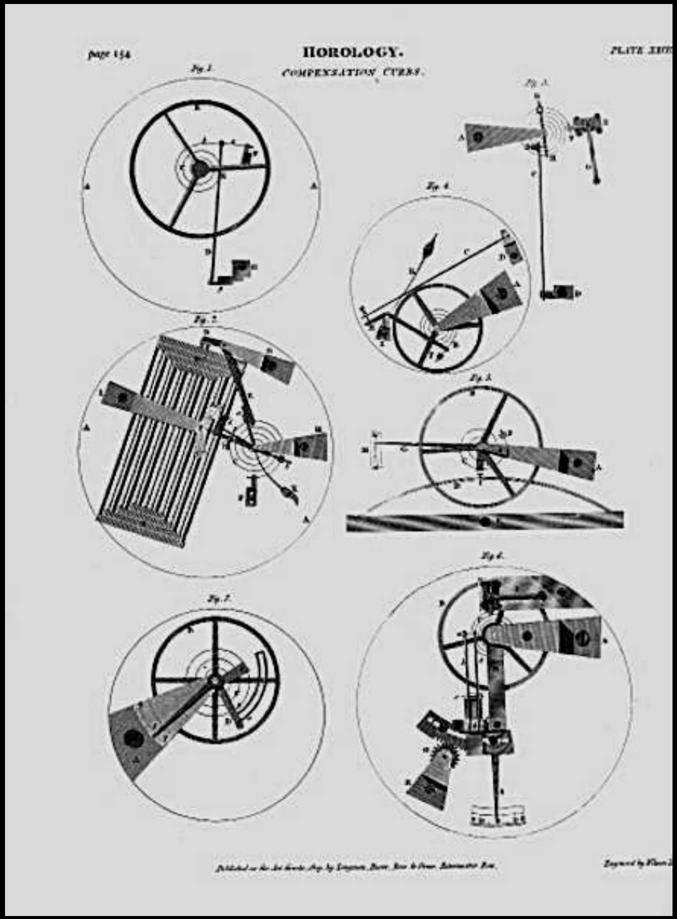
    The first temperature compensating balance was developed by Leroy in 1765 and the first practical form was patented by Arnold in 1775

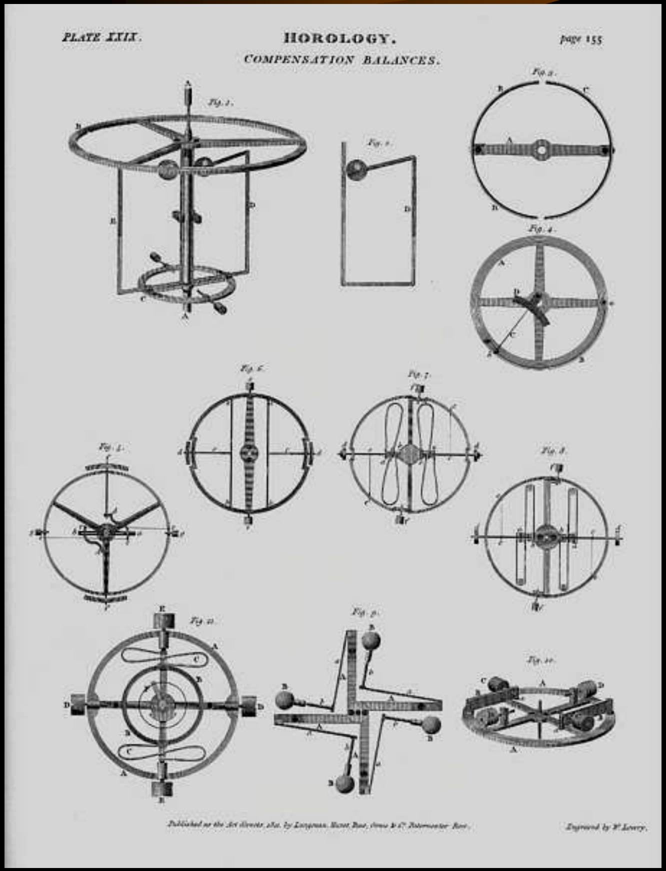
Both of these approaches were finally perfected with metallurgy in the early part of the 20th Century

Compensation

- Compensation Curbs
- Middle left was used by Harrison & Ferdinand Berthoud
- Lower left is commonly found on 19th Century French watches

- Early temperature compensation balances as pictured in Rees' Encyclopedia
- The examples in the middle are from Arnold's patents
- The example at the top left is the Le Roy balance of 1765



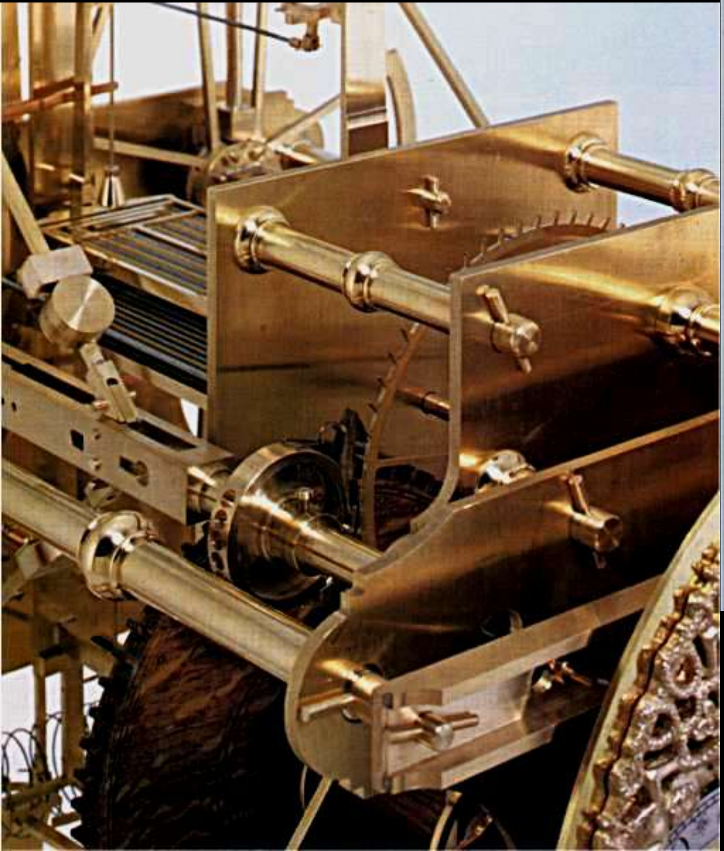


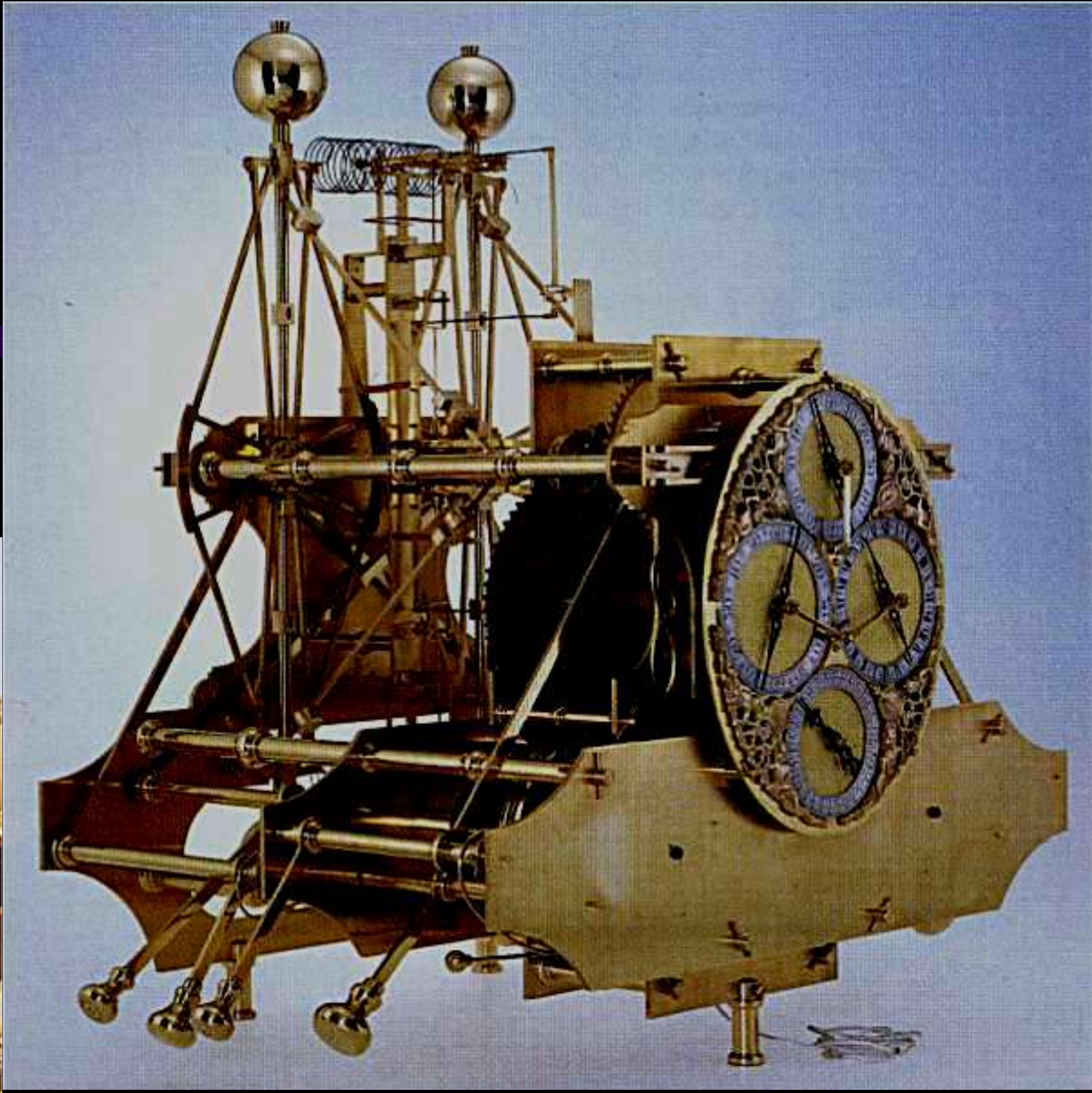
From Rees' Encyclopedia

Durability

- The major foes of durability were oil deterioration, rust and metal fatigue over time.
- Harrison addressed the problem with the use of lignum vitae laminated parts, anti-friction rollers and the frictionless Grasshopper escapement.
- Later Arnold used gold hairsprings to avoid rust
- Continuous improvements in steel during the 19th Century produced better and better hairsprings and mainsprings
- The production of Palladium Hairsprings by Paillard solved both the rust and magnetism problem introduced when iron replaced wood in the ships
- The final problem solved was the deterioration of oil. It finally fell to a group of Swiss chemists led by the Paul Ditisheim in the early 20th Century

Working Model of H1

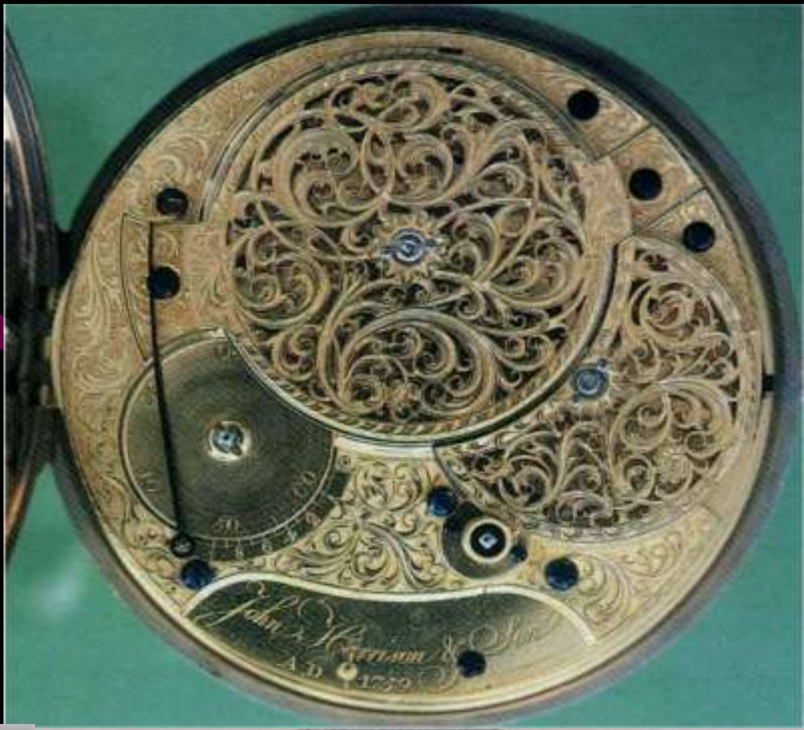




Harrison's H1 was the first working Sea Clock

This picture of Saltzer's model is from the Time Museum Catalog

Harrison's H4 The Chronometer that won the Longitude Prize



Larcum Kendall

Kendall's K1

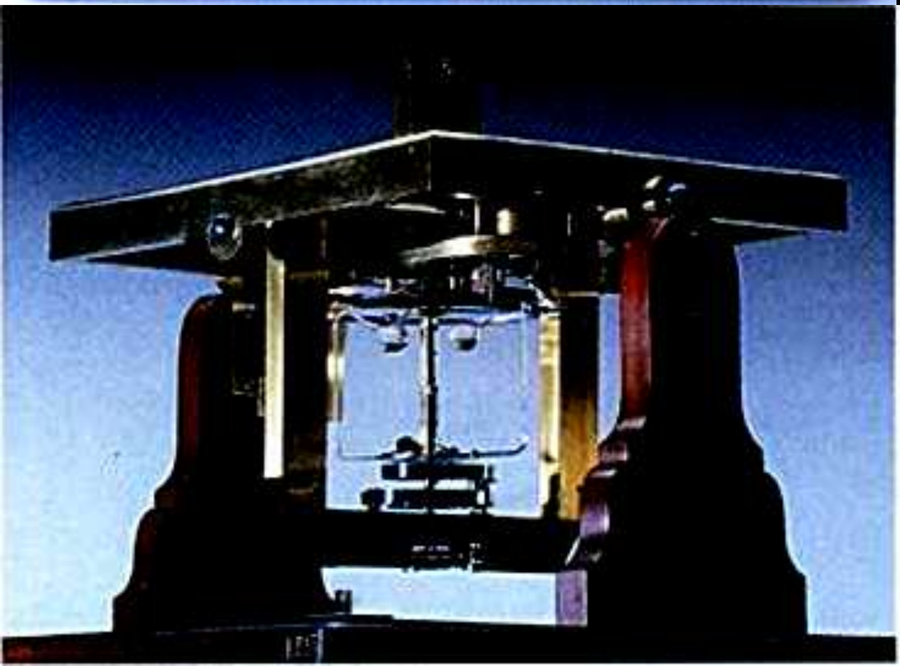
- Harrison had a difficult time convincing the Board of Longitude to pay his prize money. (Eventually the King ordered parliament to pay him.)
- The board insisted in knowing all the secrets of how to make the machines before they would award the prize. They also believed the chronometer was too expensive.
- Harrison was reluctant to part with what he had learned and developed.
- He agreed to train another chronometer maker, Larcum Kendall, to try to convince the Board that "one skilled in the art" could make the chronometers.
- Kendall produced 3 chronometers roughly to Harrison's design that had performance equal to that of H4.
- One of these chronometers (K2) was in use by Capt. Bligh on the Bounty at the time of the mutiny and it remained on Pitcairn Island for the next 50 years.

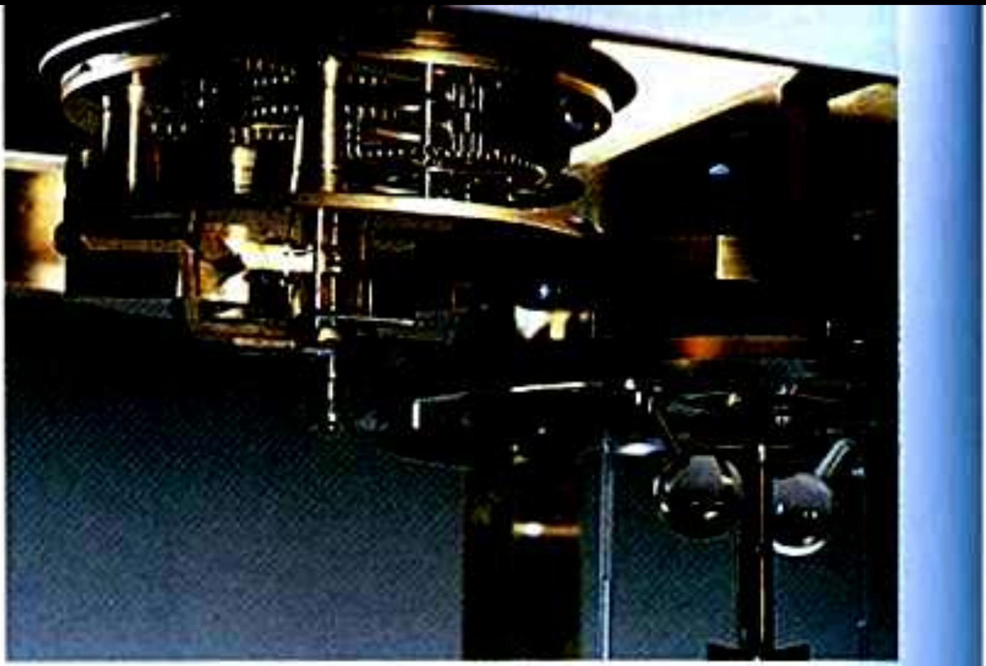
Pierre LeRoy and the French School

- Pierre LeRoy invented the detent escapement in 1765.
- LeRoy’s thermometric balance solved the temperature compensation problem 100 years before Loseby invented the same solution.
- Berthoud introduced gimbals to stabilize the motion of the chronometer.
- The works of Berthoud, Breguet and Motel continued a tradition of highly artistic but impractically expensive chronometers.

Pierre Le Roy's Marine Chronometer

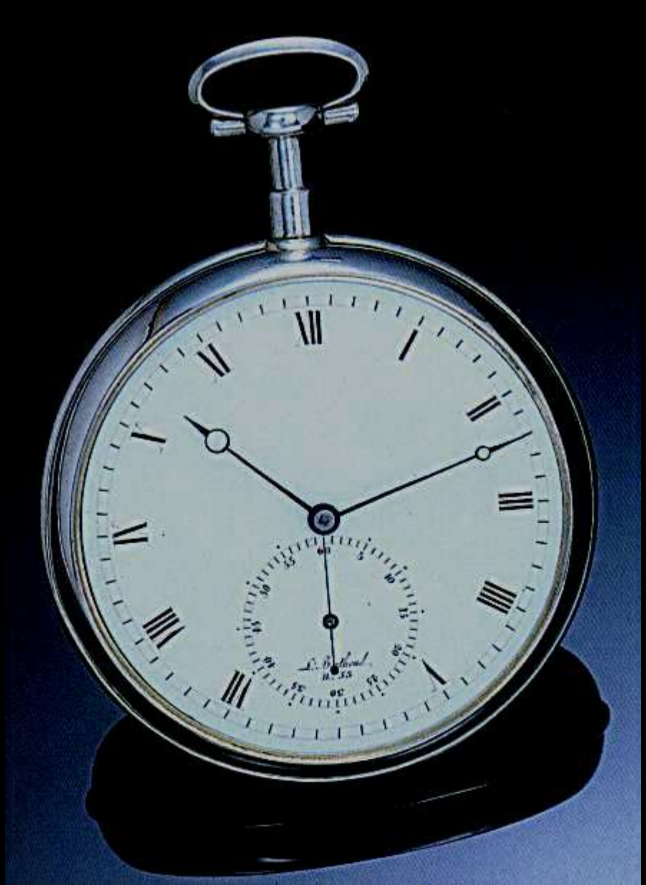
Although it's performance was below expectations, all the modern chronometer concepts were present in this piece by Pierre Le Roy





Ferdinand Berthoud's Montre Marine

Pocket Chronometer by Louis Berthoud



Three Chronometers by Breguet

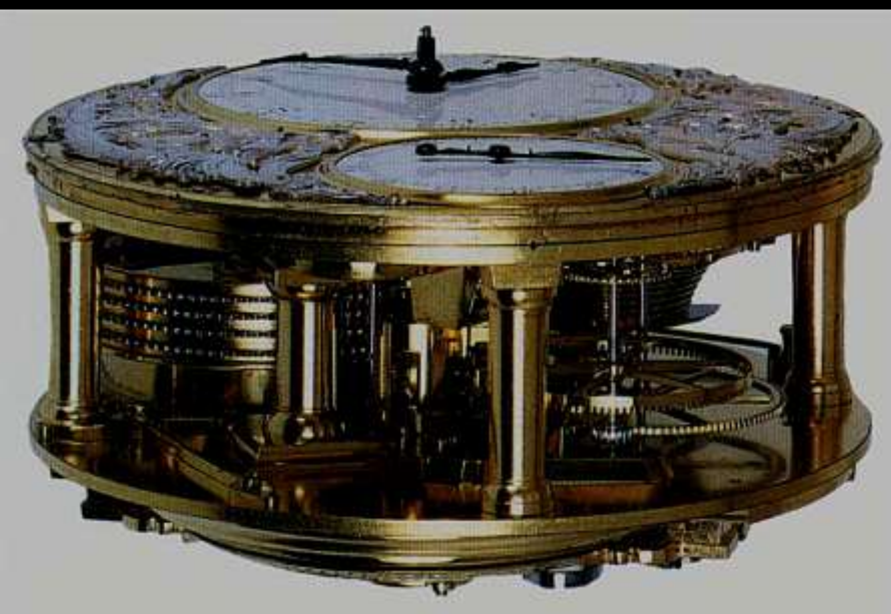
from Antiquorum "Art of Breguet"

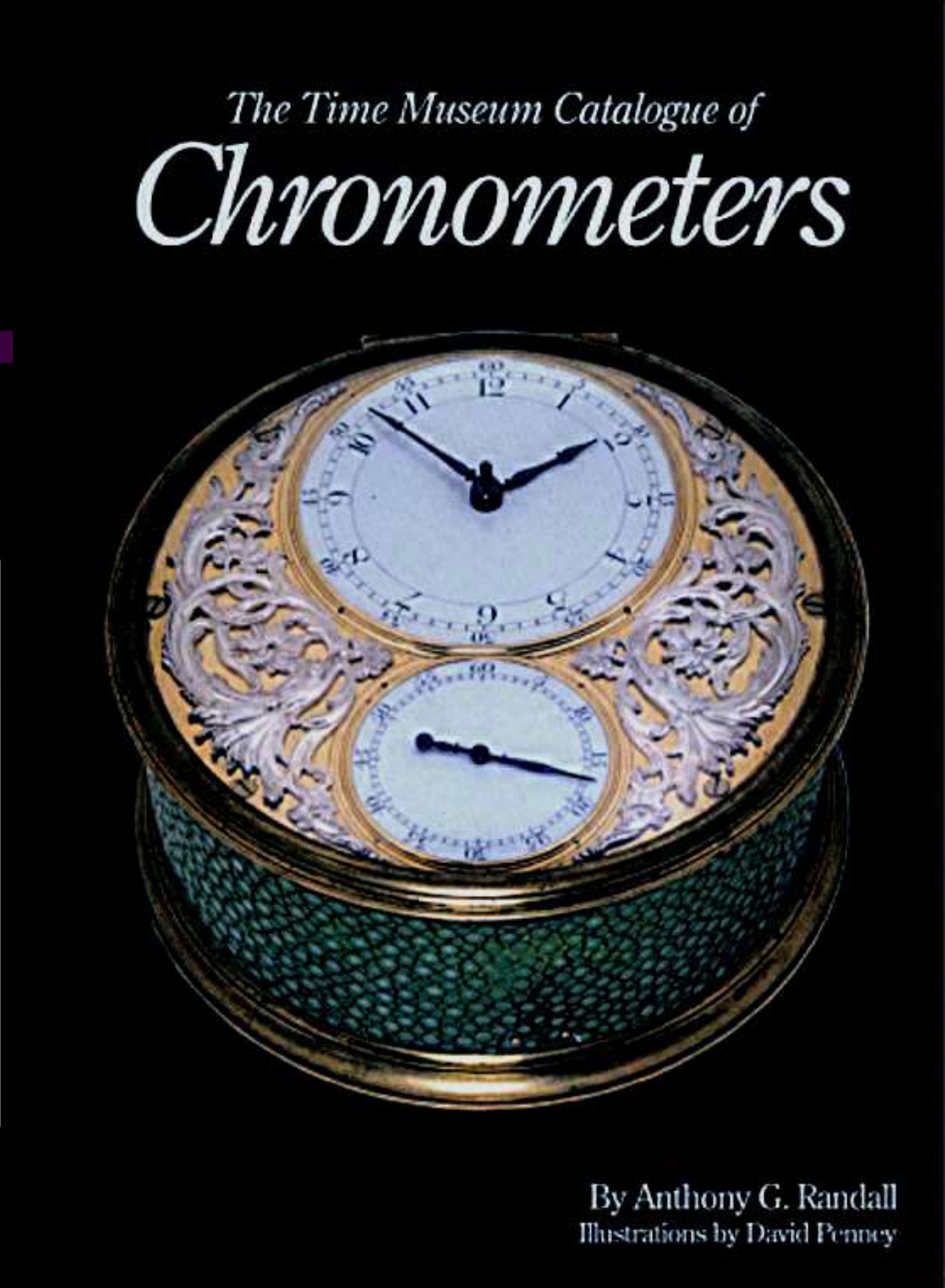
Mudge's Remontoire

- Thomas Mudge invented the lever escapement mechanism that was the dominant timekeeping mechanism in watches until the introduction of quartz electric watches.
- Mudge interrupted his career as a major maker of watches to pursue the prize for further improvements in Marine Chronometers.
- His Chronometer No. 1 and the copies "Green" and "Blue" represent the ultimate development of the remontoire concept.
- Mudge's son commissioned several additional chronometers on his father's design.

Mudge's Green

One of the two copies of his marine chronometer developed by Mudge to compete for the prize. The other was "Blue."





Much of the material in this presentation is "borrowed" from the book shown here

Recent History of Green

Mudge's Green sold at Sotheby's New York October 2004.

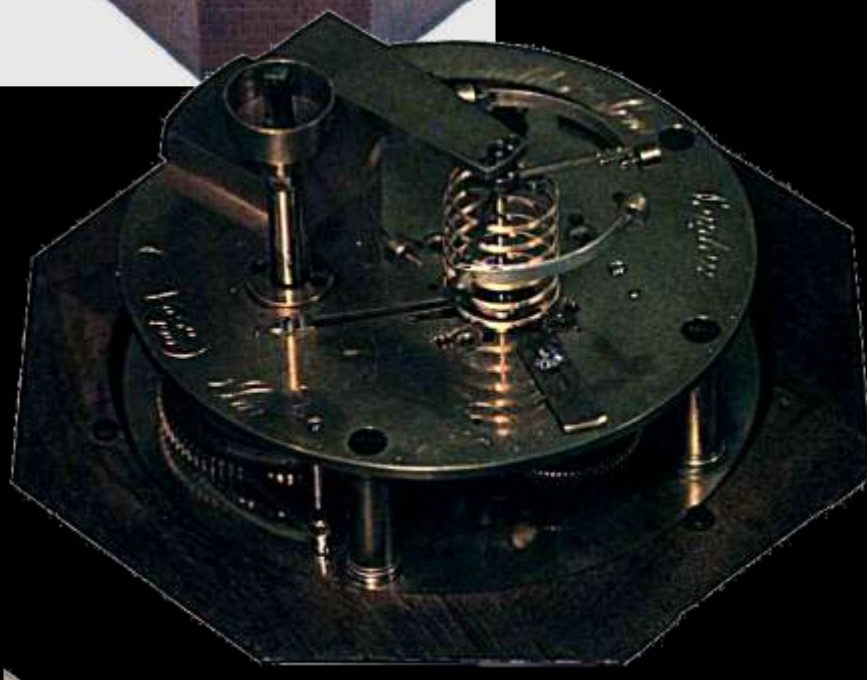
The current owner has lent it to the Greenwich Observatory to join the outstanding collection held there.

Several of us had the opportunity to examine Green during the preview at the time of its sale.

Arnold and Earnshaw

- Arnold invented a practical pivoted detent chronometer several years after Leroy.
- Arnold invented the bi-metallic temperature compensation balance.
- Arnold invented the helical hairspring and terminal coils.
- Earnshaw conceived of using a flat spring in place of the pivot on the Arnold detent.
- Earnshaw conceived of laminating the brass and steel components of the bi-metallic balance.
- Arnold invented a less practical form of spring detent escapement. There was considerable controversy over who had precedence

Arnold Marine Chronometer



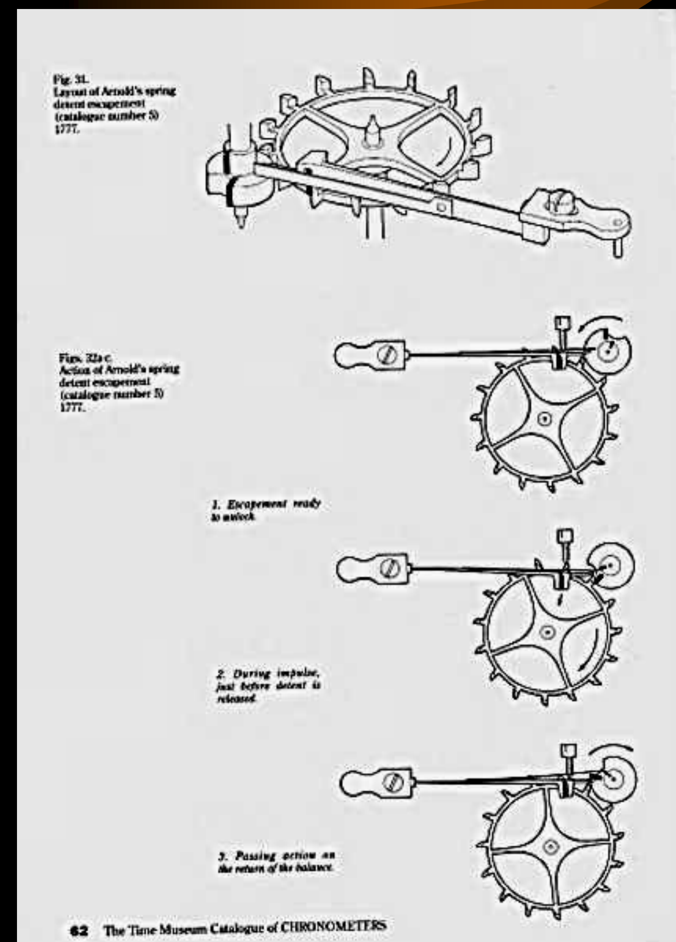


Fig. 31.
Layout of Arnold's spring detent escapement (catalogue number 5) 1777.

Figs. 32a-c.
Action of Arnold's spring detent escapement (catalogue number 5) 1777.

1. Escapement ready to unlock.

2. During impulse, just before detent is released.

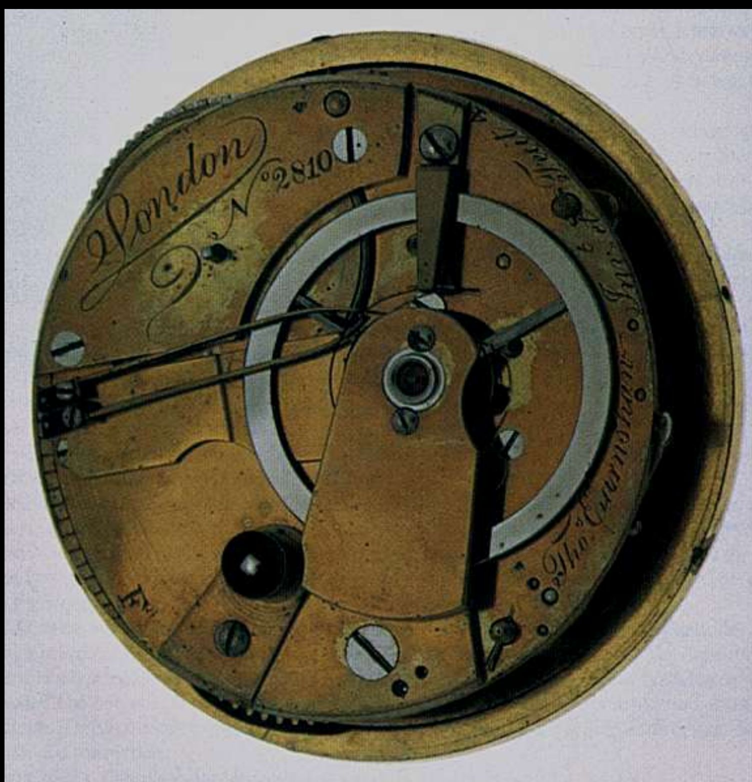
3. Passing action on the return of the balance.

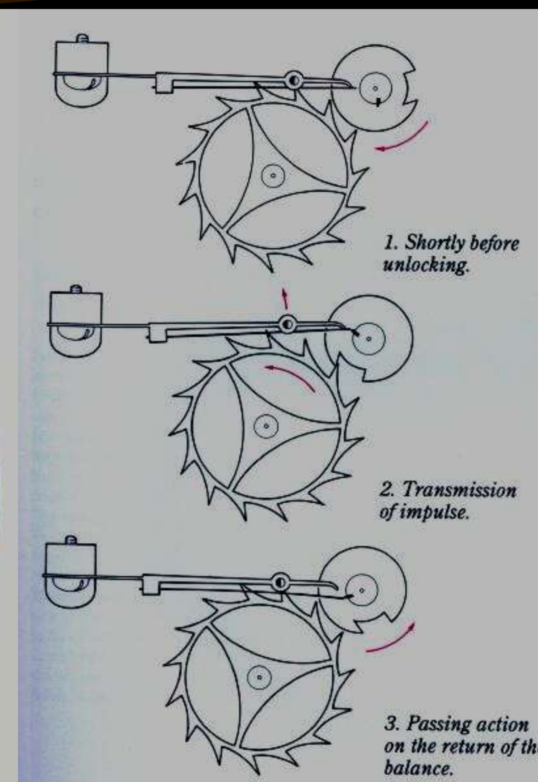
62 The Time Museum Catalogue of CHRONOMETERS

Large Arnold Pocket Chronometer

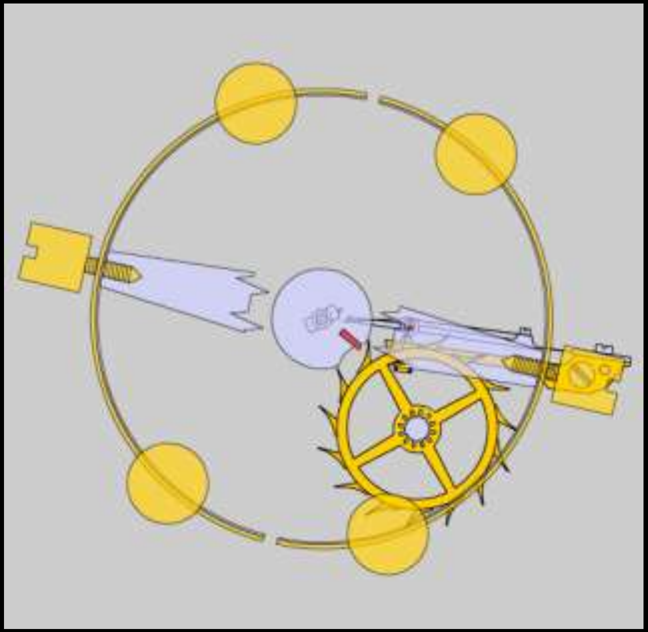
Arnold & Son Chronometer 1789

Earnshaw Pocket Chronometer
“In the Grey”





Chronometer Escapement

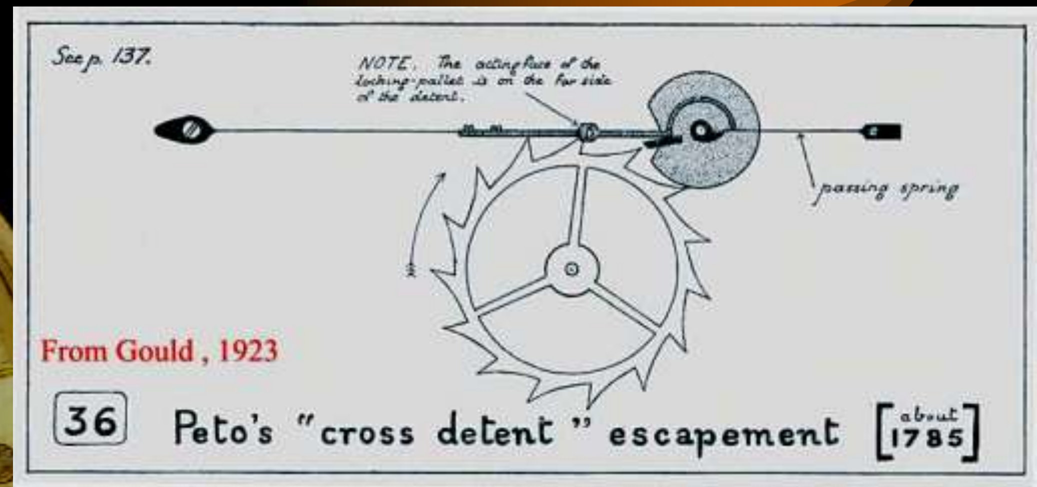


Animation courtesy of

Volker Vyskocil
Klostergasse 1
D-41334 Nettetal
Germany

www.clockwatch.de

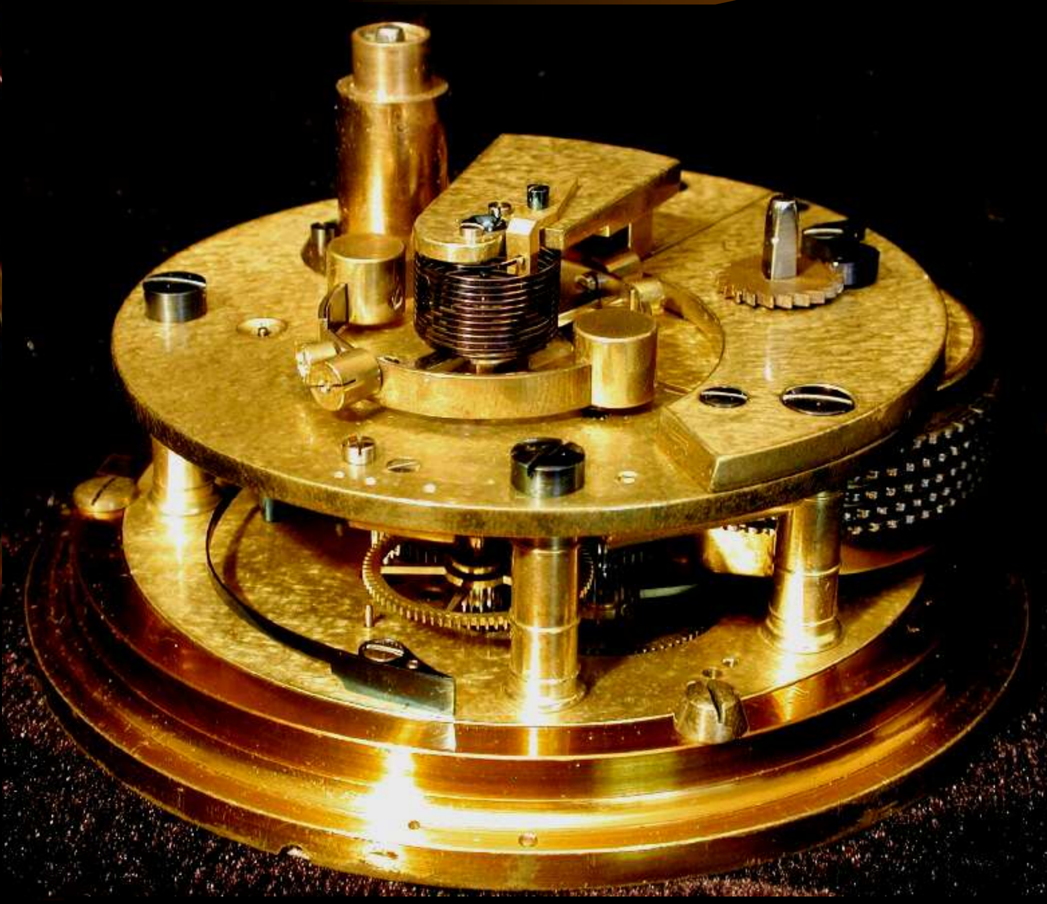
Brockbanks Peto Cross Detent ca 1800



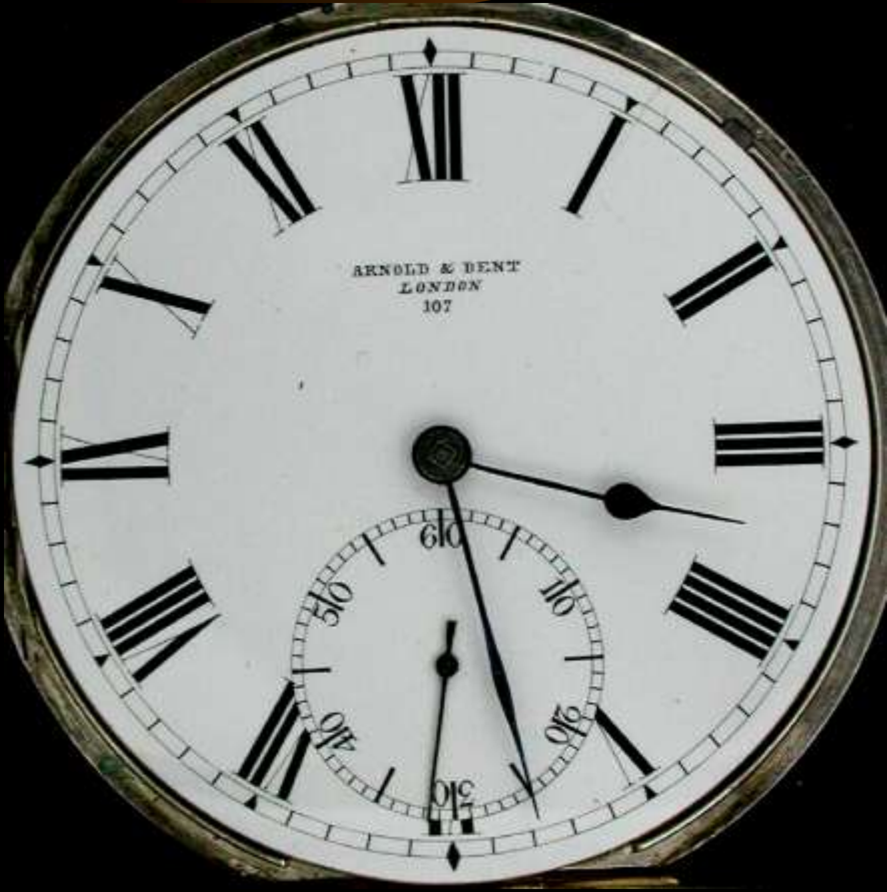
Practical Chronometers

- Dozens of English makers entered the competition in the early 19th Century for the annual prize chronometer to furnish to the Admiralty.
- The Kew trials spurred an intense competition that soon solved essentially all the problems of adjusting for isochronism and temperature.

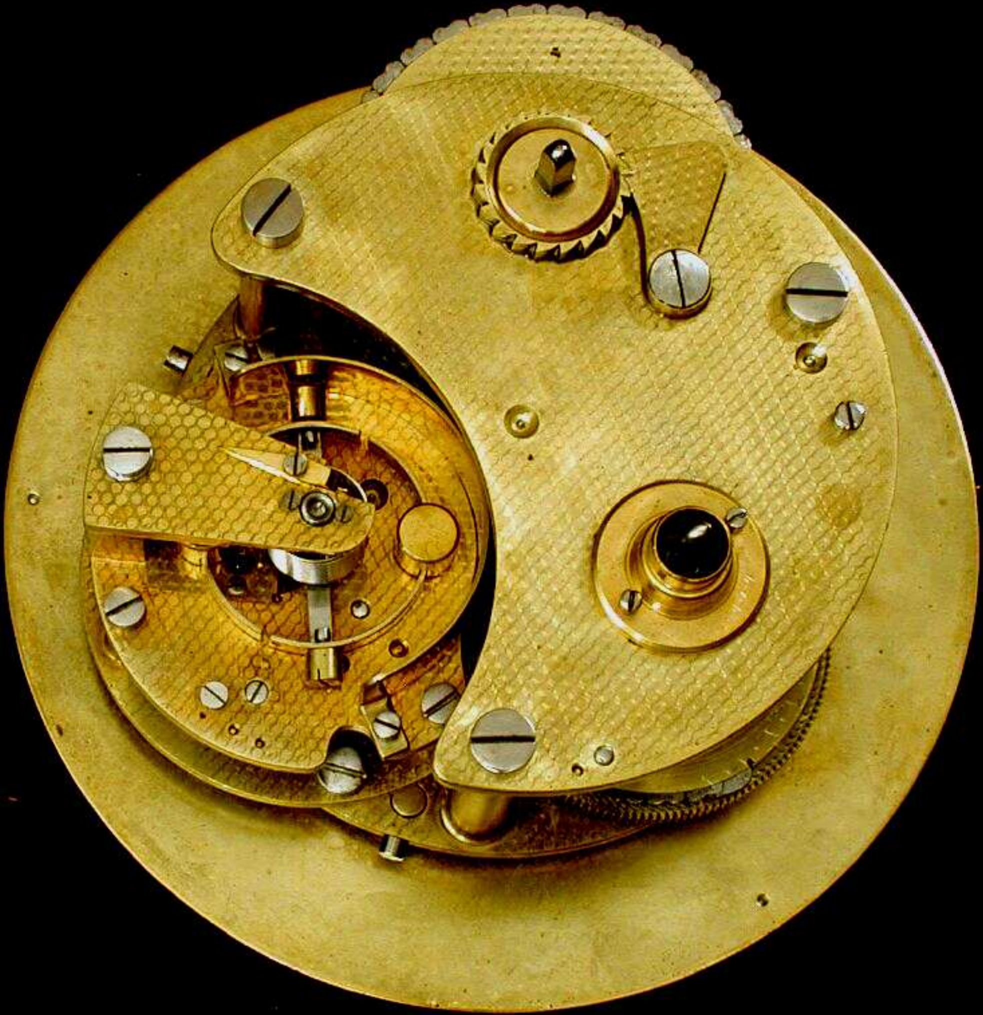
Wm. Bond & Son Survey Chronometer



John Roger Arnold Chronometer w/ Prest's Keyless Works



Kelvin & White 8 Day

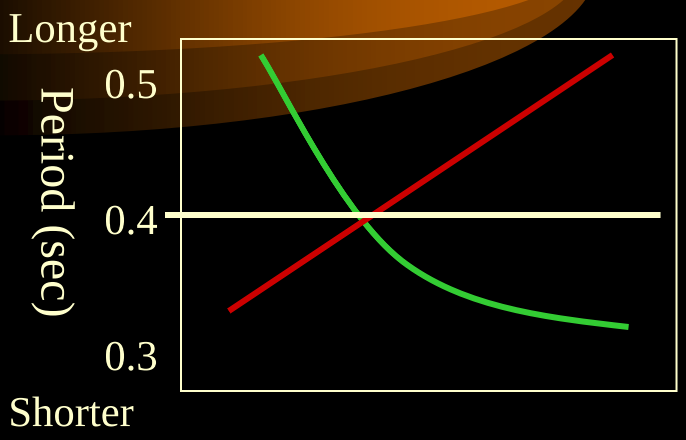


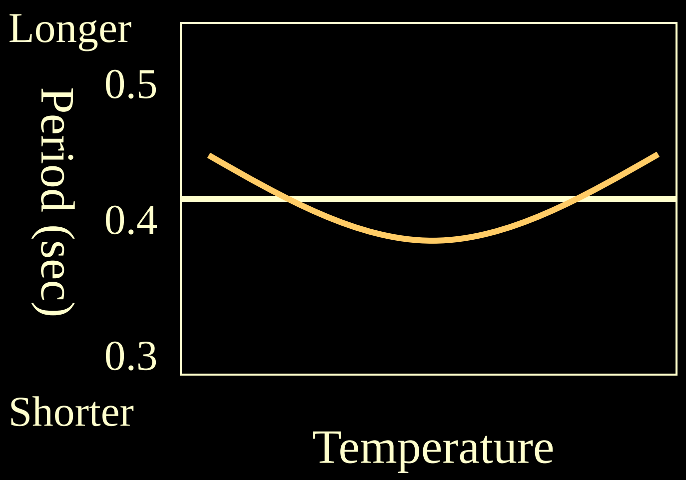
The Last Frontier

- The remaining problem that plagued makers in the middle of the 19th Century was the error in the middle temperature region.

The Middle Temperature Problem

- The hairspring loses elasticity as the temperature rises (it also elongates slightly)
  - **This causes the oscillation of the balance to slow down.**
  - **A plain balance expands as the temperature rises which also causes the oscillation of the balance to slow down.**
- A bi-metallic balance decreases its radius as the temperature rises
  - **This causes the oscillation of the balance to speed up.**
- Unfortunately, these two phenomena do not have the same shape because the inertia of the balance goes by the square of the radius.
  - **Therefore the period as a function of temperature will only be correct at two temperatures**

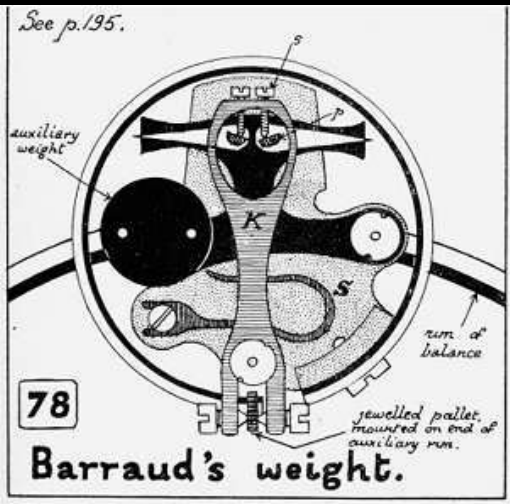


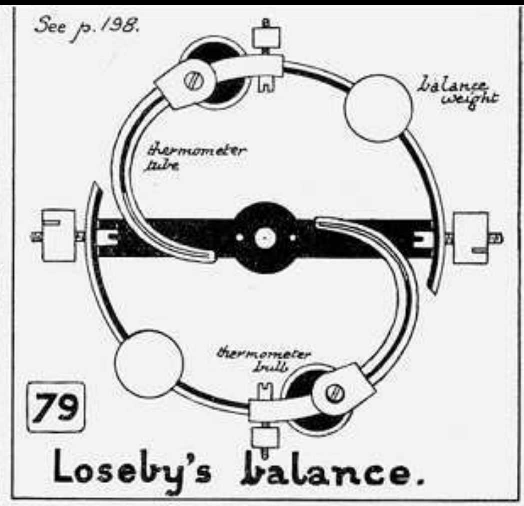


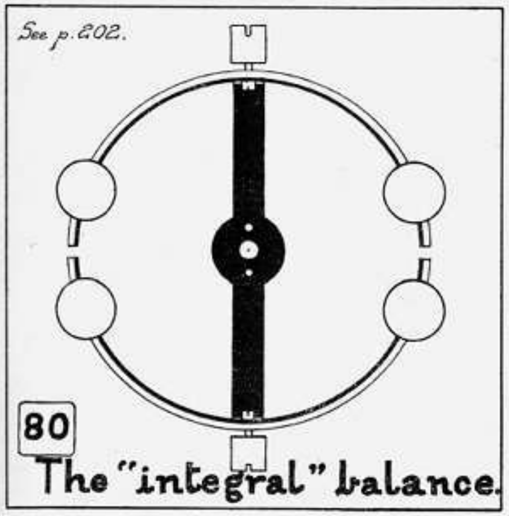
Middle Temperature Solutions

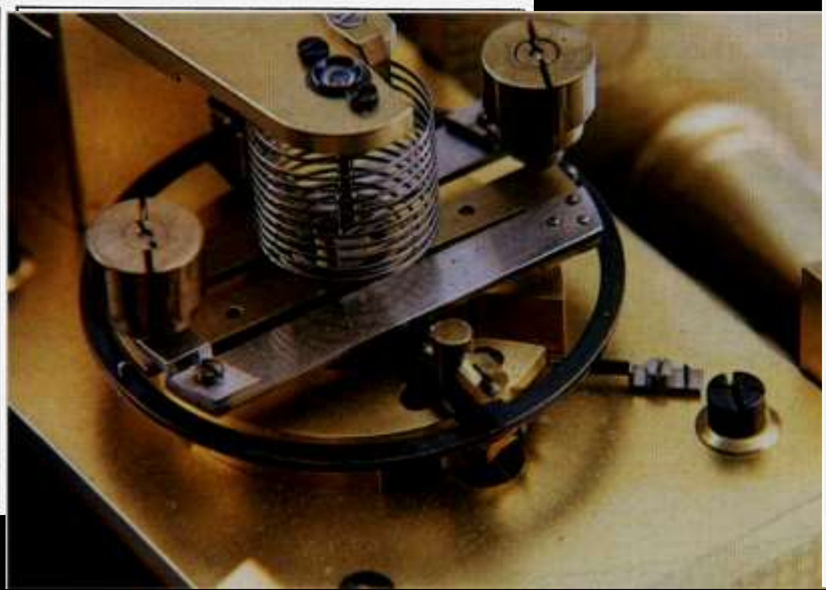
- Discontinuous Compensation
  - **A mechanical stop inhibits the movement of the balance either in heat or cold (Poole)**
- Non-linear Compensation
  - **A secondary bi-metallic system partially corrects the bi-metal function of the balance (Lund, Frodsham, Kullberg, Dent and many others)**
- Thermometric Compensation
  - **Glass thermometers either replace or supplement the the bi-metal function of the balance (LeRoy, Loseby)**
- Inherent Material Compensation (Metallurgy)
  - **The hairspring material is insensitive to temperature (Elinvar)**
  - **The balance material has an expansion curve that matches the hairspring (Guillaume)**

Middle Temperature Balances



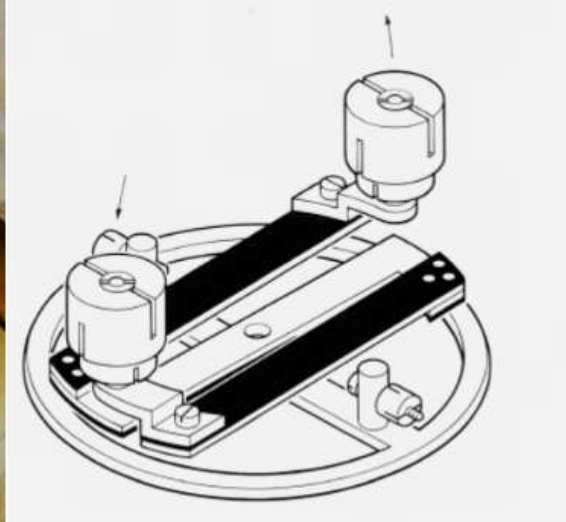




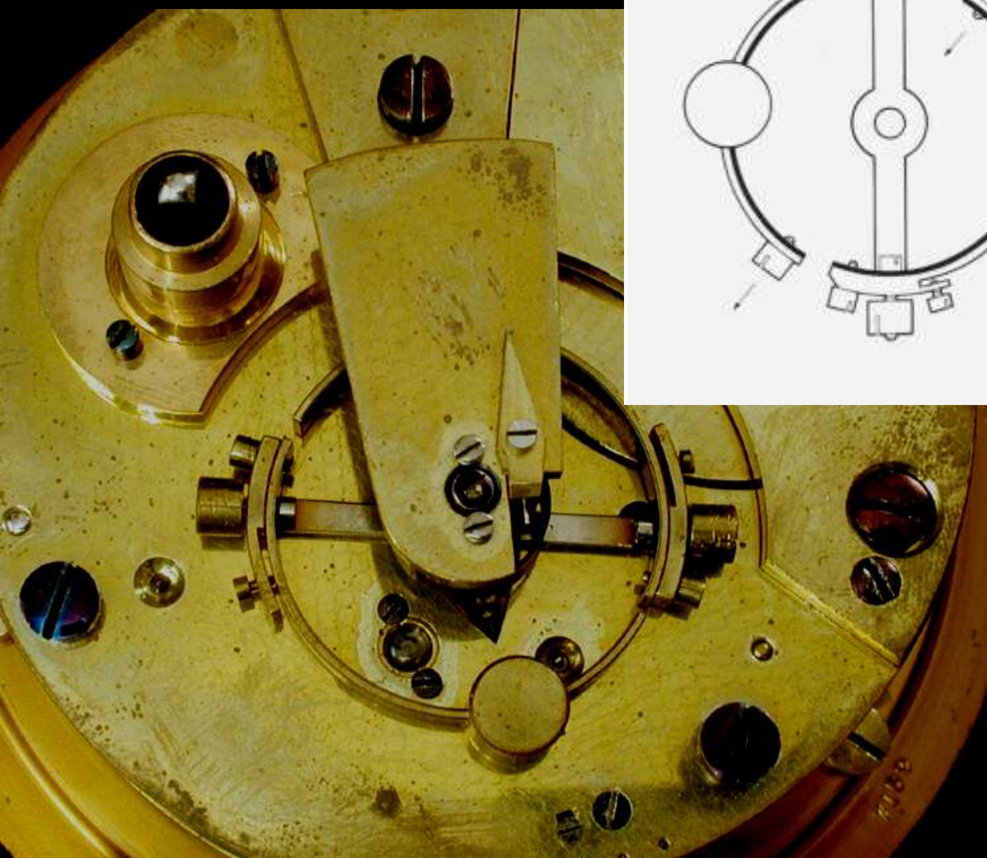


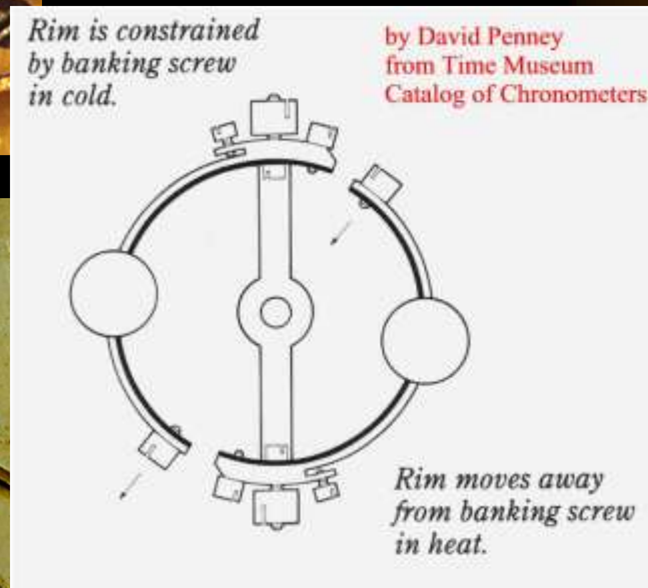
Figs. 107a & 107b.
Photograph and illustration of Frodsham's micrometric balance.
Charles Frodsham, No.1845
(catalogue number 68)
1888.

The weights move in an arc in a vertical plane.



Kelvin & White w/ Poole's Auxiliary





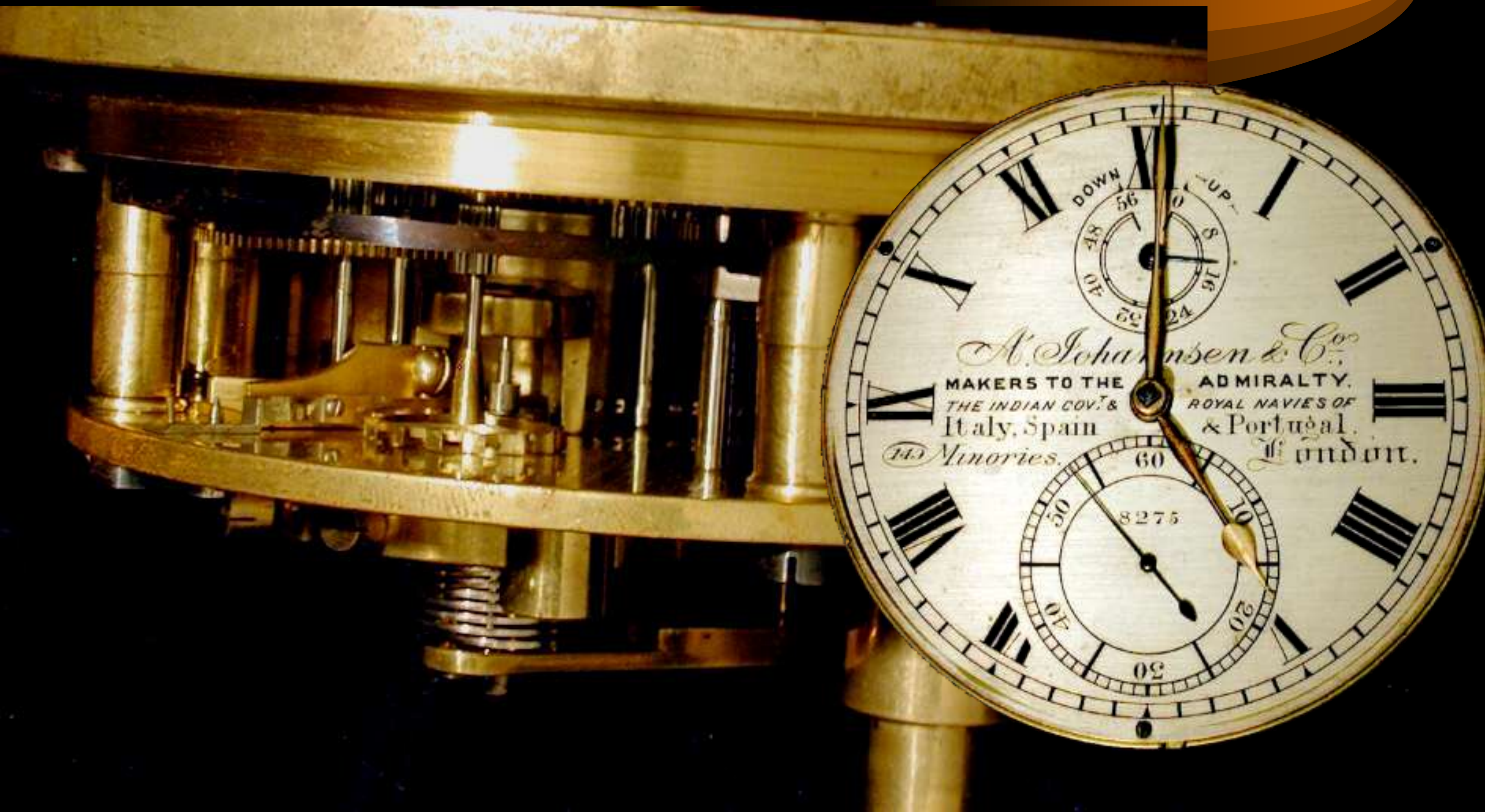
Dent Staple Balance

The Golden Age 1880 to 1910

- Springers and Adjusters became the stars of the industry by the 1880s
- Kullberg, Johannsen, Walsh, and the Frodsham family took leadership of the British chronometer industry.
- Ditisheim, Paillard, and Nardin led the development of the Swiss chronometer industry.
- Lange began the development of a German chronometer industry in Glasshutte.

Fletcher Marine Chronometer w/ Airy's Bar

Johannsen Marine Chronometer



Johannsen Deck Watch

The Decline of the Chronometer Industry

- By the 1920's lever wristwatches could compete and win the Kew trials
- The long peace from 1918 to 1939 and a large inventory of chronometers led to economic hard times
- The shortage of makers and the Atlantic blockade created a crisis during the Second World War

Jurgensen Conversion to Deck Watch

Hamilton WW I Torpedo Boat Watch

WW II Revival

- The US Navy issued a request for mass produced Marine Chronometers at the beginning of WW II.
- Hamilton developed a new design loosely based on the Swiss Nardin ebauche using a newly designed balance, hairspring and detent.
- Elgin developed a new design with special features for maintainability using the proven Guillaume Balance
- The Elgin entry failed the purchase trials and was not used by the Navy. It was sold in small numbers for civilian use after the war.
- Large numbers of lever pocket watches were finished and adjusted for navigation use

Hamilton Marine Chronometer M21

Elgin Marine Chronometer Grade 600

Satellites and the Final Solution to the Longitude Problem

- Global Positioning Satellite System is the ultimate solution to the navigation problem. The satellites allow the position of an observer to be determined by "triangulation" from a set of known objects in the sky.
- GPSS is oddly similar to one of the "insane proposals" brought to the Longitude Commission in the early 18th Century. The idea was to station ships across the ocean that would place flares in the sky for ships to observe and determine their position.