University of BRISTOL

PROFESSOR ROBERTSON'S CLOCK

John Haine

University of BRISTOL

1876	University College Bristol founded
1885	“The Trade School” founded by the Society of Merchant Venturers*, later becomes MV School
1894	Trade school expands to include M. V. Technical College (MVTC)
1902	David Robertson appointed Professor of Electrical Engineering in MVTC
1909	MVTC merges with University College to become Bristol University; DR becomes first professor of Electrical Engineering in the University
1925	Wills Memorial Building opened – “Great George”, the bell, controlled by Robertson Clock
1941	Robertson dies
1960s?	Clock becomes redundant

* https://www.merchantventurers.com/

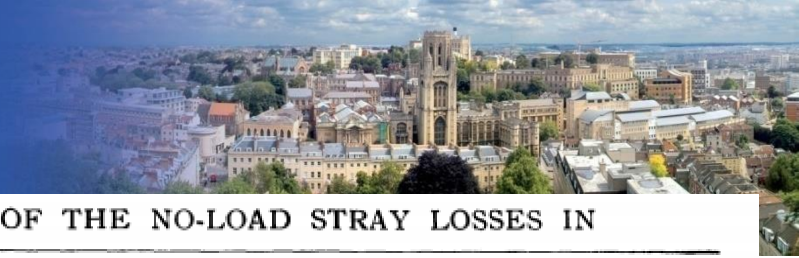
Wills Memorial Building

"Commissioned in 1912 by George Alfred Wills and Henry Herbert Wills, the magnates of the Bristol tobacco company W. D. & H. O. Wills, in honour of their father, Henry Overton Wills III, benefactor and first Chancellor of the University who donated £100,000."

(Wikipedia)

Professor David Robertson

- Born 1875, Cumbrae, died 1941
- B.Sc & D.Sc degrees from Glasgow University
- Appointed to MVTC 1902, Bristol University 1909 – its first professor of electrical engineering, until death in 1941
- Suffered from polio in 1911, confined to a wheelchair for the rest of his life
- Original work in electrical machines, popularised "vector analysis" for analysing AC circuits
- Intensely interested in horological science and engineering
- One student was Bristolian P.A.M. Dirac who abandoned EE for theoretical physics at Cambridge (and did quite well)
- Dirac later wrote that Robertson had a great influence on his approach to applying mathematics to physical problems



University of BRISTOL

SEPARATION OF THE NO-LOAD STRAY LOSSES IN A CONTINUOUS-CURRENT MACHINE BY STROBOSCOPIC RUNNING-DOWN METHODS.

By Professor DAVID ROBERTSON, D.Sc., Member.

Paper received 29 *June*, 1914.)

CONTENTS.

mined. Now, the deceleration at any instant is proportional to the torque acting at that instant, and so a comparison of the decelerations at different speeds shows how the stray-loss torque varies with the speed.

If the running-down test be repeated with the field circuit broken as well as the armature circuit, the frictional torques alone will act, and a comparison of the deceleration at any speed under this condition with that obtained before will enable the total resisting torque to be divided into two parts, due respectively to the friction and to the magnetic losses. A determination of the speed-time curve

University of BRISTOL

A MODE OF STUDYING DAMPED OSCILLATIONS BY THE AID OF SHRINKING VECTORS.

By Professor DAVID ROBERTSON, D.Sc., Member.

(*Paper received 30 August, 1915.*)

CONTENTS.

(1) INTRODUCTION.

The application of rotating vectors to sine waves has proved of very great service in connection with the theory of alternating currents. It has enabled us to form simple mental pictures of the phase relationships, and has facilitudes and for the R.M.S. values which are a fixed fraction of the latter.

The third property of the vector, which has not been emphasized so much as it deserves, is that it permits a simple geometrical representation of the rate of change and of the time-integral of a sine function. The rate of change of the function is given by that of the projection which represents it, and is thus the same as the vertical component of the velocity of the extremity of the rotating vector. In other words, the rate of change of the function is given by the projection on the vertical axis of that velocity. In the case of sine waves, the velocity is at right angles to, and equal to ω times, the vector, where ω is the rate of rotation or angular velocity of the latter ($= 2\pi f$). Consequently, the velocity is constant in amount and rotates uniformly with the original vector. The rate of change of the sine function is therefore itself a sine function, and the following well-known statement is thus obtained :—

"The rate of change of a sine function is another sine

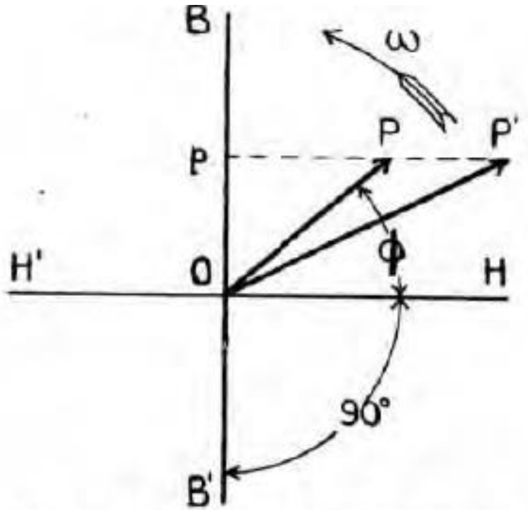


FIG. 1.—*Vectors and Projection.*

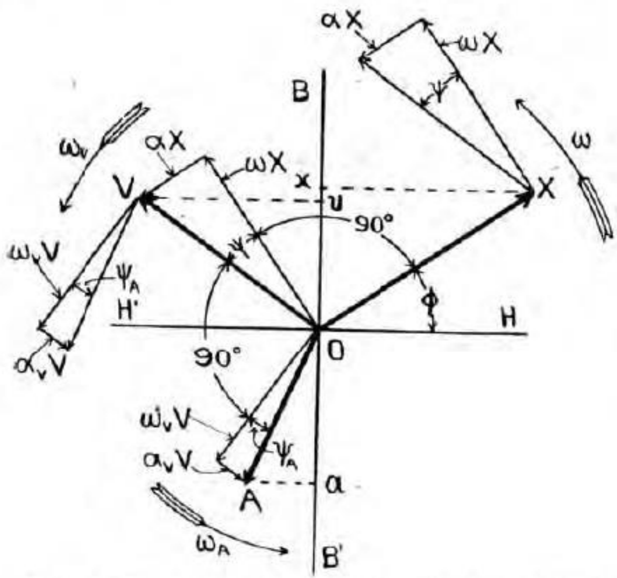


FIG. 4.—*Displacement, Velocity and Acceleration Vectors.*

THE THEORY OF PENDULUMS AND ESCAPEMENTS.

By Professor DAVID ROBERTSON, D.Sc., M.I.E.E.

(*Continued from page* 295, *vol. lxxi.*)

38. *Compensation of Circular Error* (*continued*).

duce errors of its own. But it seems not unreasonable to expect that the resultant

Greenwich time, state-of-the art in 1925

Synchronome Master Clock

Shortt "free pendulum"

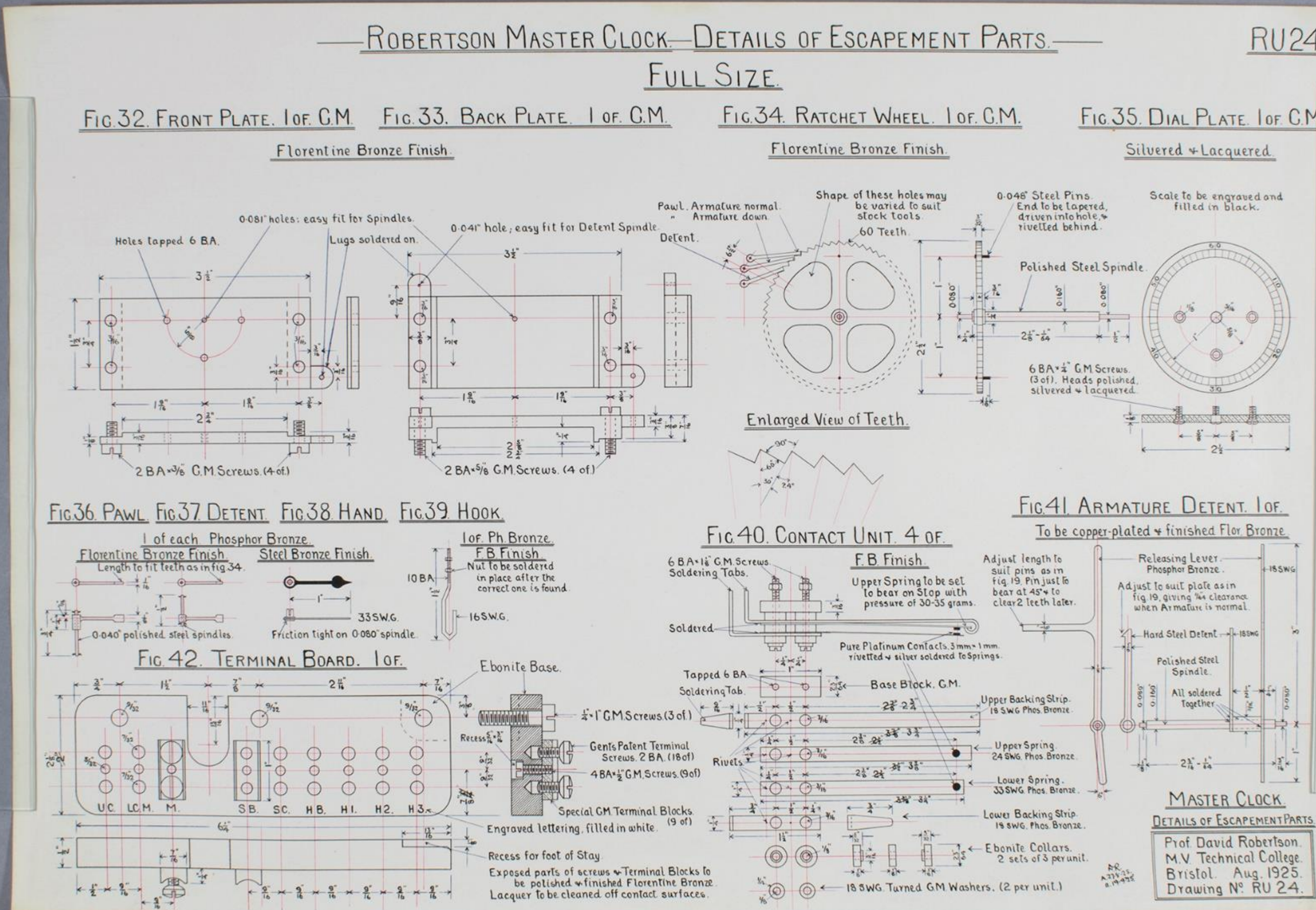
Source – Royal Museums Greenwich

Shortt – Synchronome "free pendulum" Clock

- Synchronome "master clock" as used in many public buildings, factories, schools etc… (why not Bristol University?)
  - Set to run 6s/day slow – tricky!
- Mechanically synchronised to very stable "free pendulum" housed in a vacuum tank for high Q and no pressure variation
  - Itself impulsed every 30s by a mechanism armed by slave pendulum
  - "Hit and Miss" synchroniser nudges slave phase to keep ***frequency lock***
- Widely used internationally as basic time standard until 1940s (superseded by quartz)
- Source of Greenwich time pulse distributed through UK by telegraph at 10.00 GMT every day
- NB: "solar" time in Bristol is 10 minutes later than London…

The Robertson Clock

- Designed by D.R. along his own principles
- Made by Bristol company Brecknell, Munro and Rogers, Ltd *“mechanical, electrical, and tramway engineers”*, for the then-new Wills Memorial Building
- Installed in WMB and started operation in 1925
- Kept University time, chimed Great George, operated slave clocks throughout WMB
- Synchronised to Greenwich telegraph time signals
- Operated until 1960s(?)
- Engineering drawings still in University archive


ROBERTSON MASTER CLOCK — DETAILS OF ESCAPEMENT PARTS.
RU24.
FULL SIZE.
FIG. 32. FRONT PLATE. 1 OF. G.M.
FIG. 33. BACK PLATE. 1 OF. G.M.
Florentine Bronze Finish.
FIG. 34. RATCHET WHEEL. 1 OF. G.M.
Florentine Bronze Finish.
FIG. 35. DIAL PLATE. 1 OF. G.M.
Silvered & Lacquered.
Holes tapped 6 BA.
0·081" holes: easy fit for Spindles.
Lugs soldered on.
0·041" hole; easy fit for Detent Spindle.
2 BA × 3/16 G.M. Screws. (4 of.)
2 BA × 5/8 G.M. Screws. (4 of.)
Pawl. Armature normal.
" Armature down.
Detent.
Shape of these holes may be varied to suit stock tools.
60 Teeth.
0·046" Steel Pins. End to be tapered, driven into hole, & rivetted behind.
Polished Steel Spindle.
Scale to be engraved and filled in black.
6 BA × 1/4" G.M. Screws. (3 of). Heads polished, silvered & lacquered.
Enlarged View of Teeth.
FIG. 36. PAWL. FIG. 37. DETENT. FIG. 38. HAND. FIG. 39. HOOK.
1 of each. Phosphor Bronze.
Florentine Bronze Finish.
Steel Bronze Finish.
Length to fit teeth as in fig. 34.
0·040" polished steel spindles.
Friction tight on 0·080" spindle.
33 S.W.G.
1 of. Ph. Bronze.
F.B. Finish.
10 BA.
Nut to be soldered in place after the correct one is found.
16 S.W.G.
FIG. 40. CONTACT UNIT. 4 OF.
F.B. Finish.
6 BA × 1 1/8" G.M. Screws.
Soldering Tabs.
Upper Spring to be set to bear on Stop with pressure of 30-35 grams.
Soldered.
Pure Platinum Contacts. 3 mm × 1 mm. rivetted & silver soldered to Springs.
Tapped 6 BA.
Soldering Tab.
Base Block. G.M.
Upper Backing Strip. 18 SWG. Phos. Bronze.
Upper Spring. 24 SWG. Phos. Bronze.
Rivets.
Lower Spring. 33 SWG. Phos. Bronze.
Lower Backing Strip. 18 SWG. Phos. Bronze.
Ebonite Collars. 2 sets of 3 per unit.
18 SWG. Turned G.M. Washers. (2 per unit.)
FIG. 41. ARMATURE DETENT. 1 OF.
To be copper-plated & finished Flor. Bronze.
Adjust length to suit pins as in fig. 19. Pin just to bear at 45° & to clear 2 teeth later.
Releasing Lever. Phosphor Bronze.
Adjust to suit plate as in fig. 19, giving 1/64 clearance when Armature is normal.
Hard Steel Detent.
Polished Steel Spindle.
All soldered Together.
18 SWG.
FIG. 42. TERMINAL BOARD. 1 OF.
Ebonite Base.
1/4 × 1" G.M. Screws. (3 of.)
Gents Patent Terminal Screws. 2 BA. (18 of)
4 BA × 1/2" G.M. Screws. (9 of)
Special G.M. Terminal Blocks. (9 of)
Engraved lettering, filled in white.
Recess for foot of Stay.
Exposed parts of screws & Terminal Blocks to be polished & finished Florentine Bronze.
Lacquer to be cleaned off contact surfaces.
U.C. L.C.M. M. S.B. S.C. H.B. H.1. H.2. H.3.
MASTER CLOCK.
DETAILS OF ESCAPEMENT PARTS.
Prof. David Robertson.
M.V. Technical College.
Bristol. Aug. 1925.
Drawing No. RU 24.

Reprinted from Vol. LXX. of the Transactions of The Institution of Engineers and Shipbuilders in Scotland
1927

THE CLOCK AND STRIKING MECHANISMS FOR THE GREAT BELL OF THE UNIVERSITY OF BRISTOL.

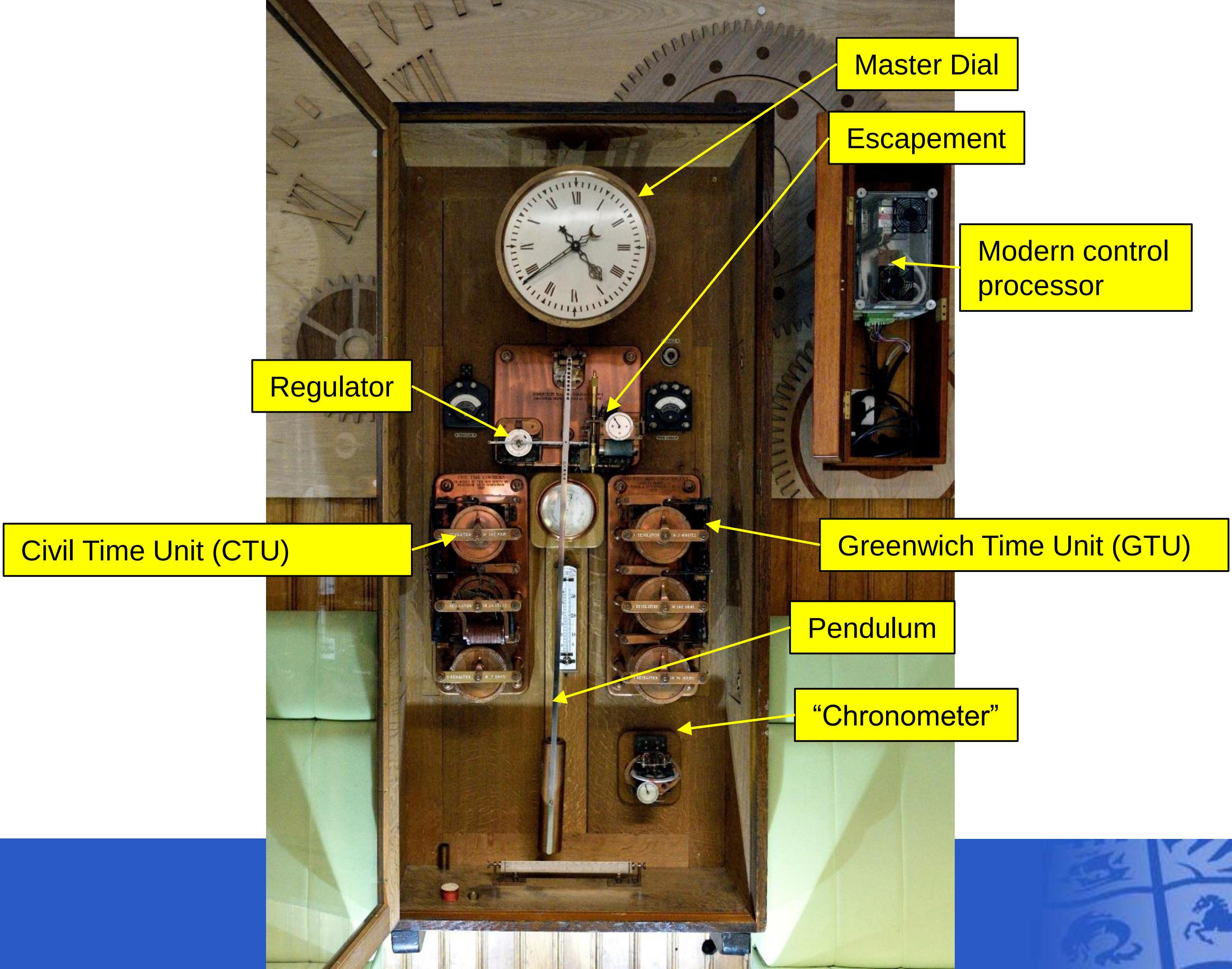
By Prof. David Robertson, D.Sc.,
Member of the Institution.

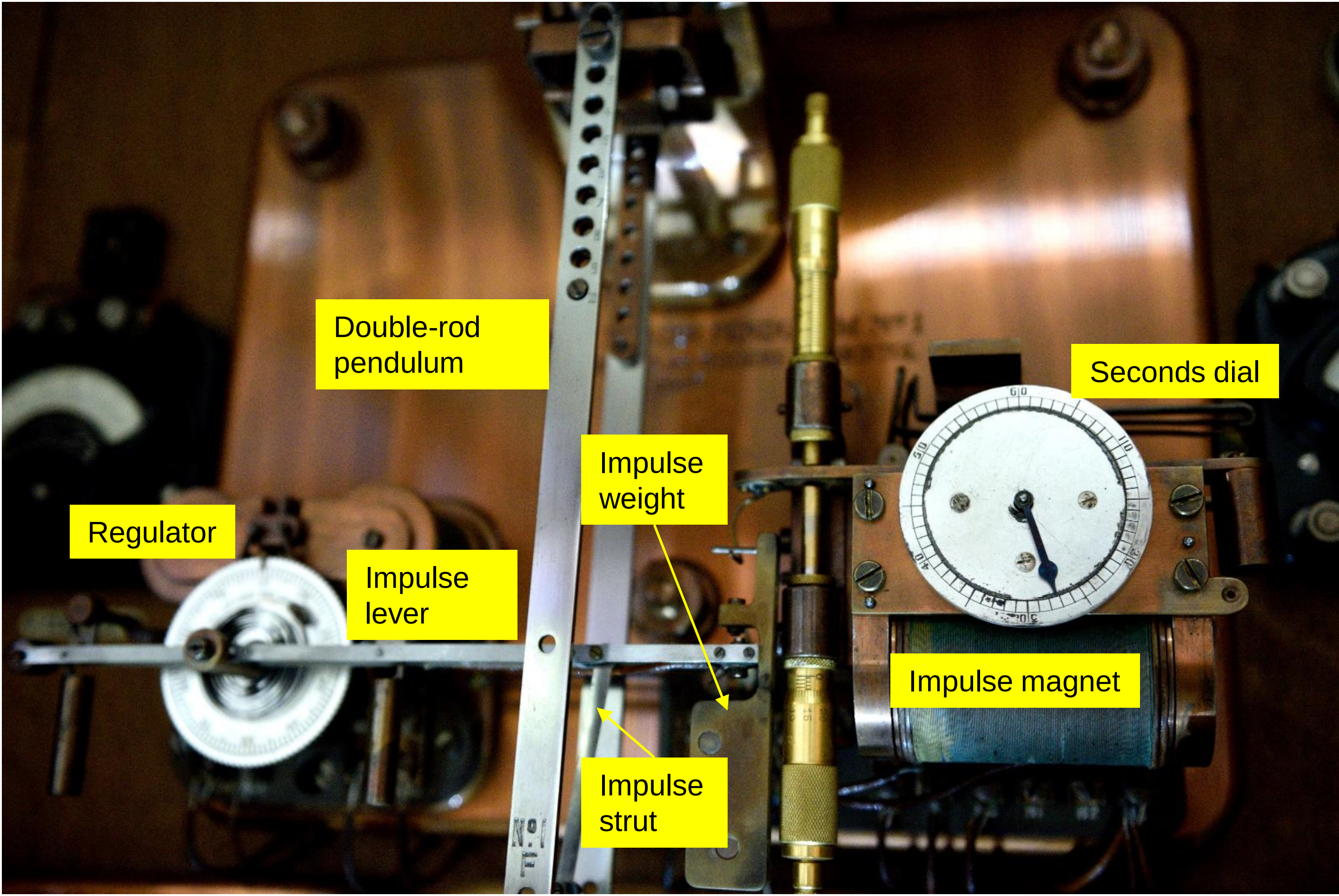
7th December, 1926.

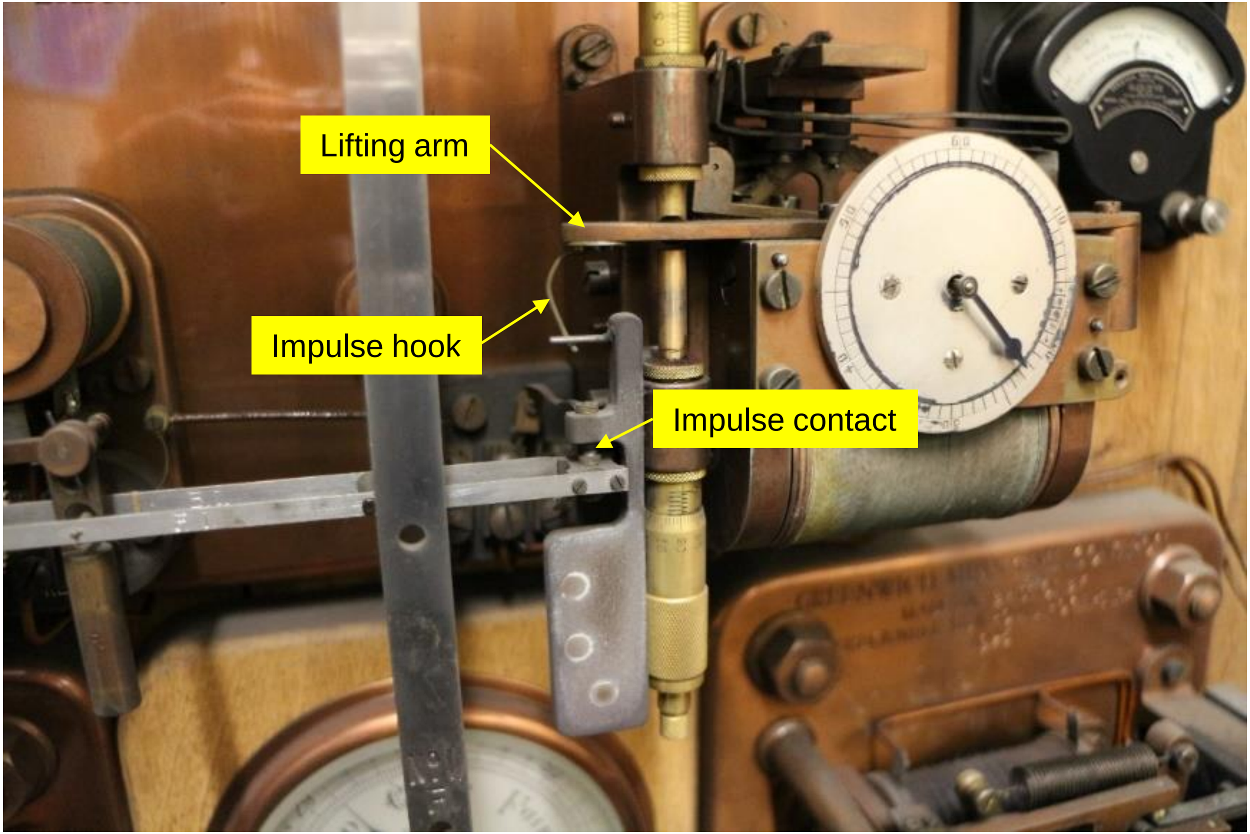
The Bell.

Among the many munificent gifts of the Wills family to the University of Bristol, not the least is the magnificent block of buildings erected by Sir George and the late Mr. H. H. Wills in memory of their father, Henry Overton Wills, the founder of the University. This fine pile was designed by Sir George Oatley, LL.D., R.W.A., F.R.I.B.A., and was opened by His Majesty the King in July, 1925.

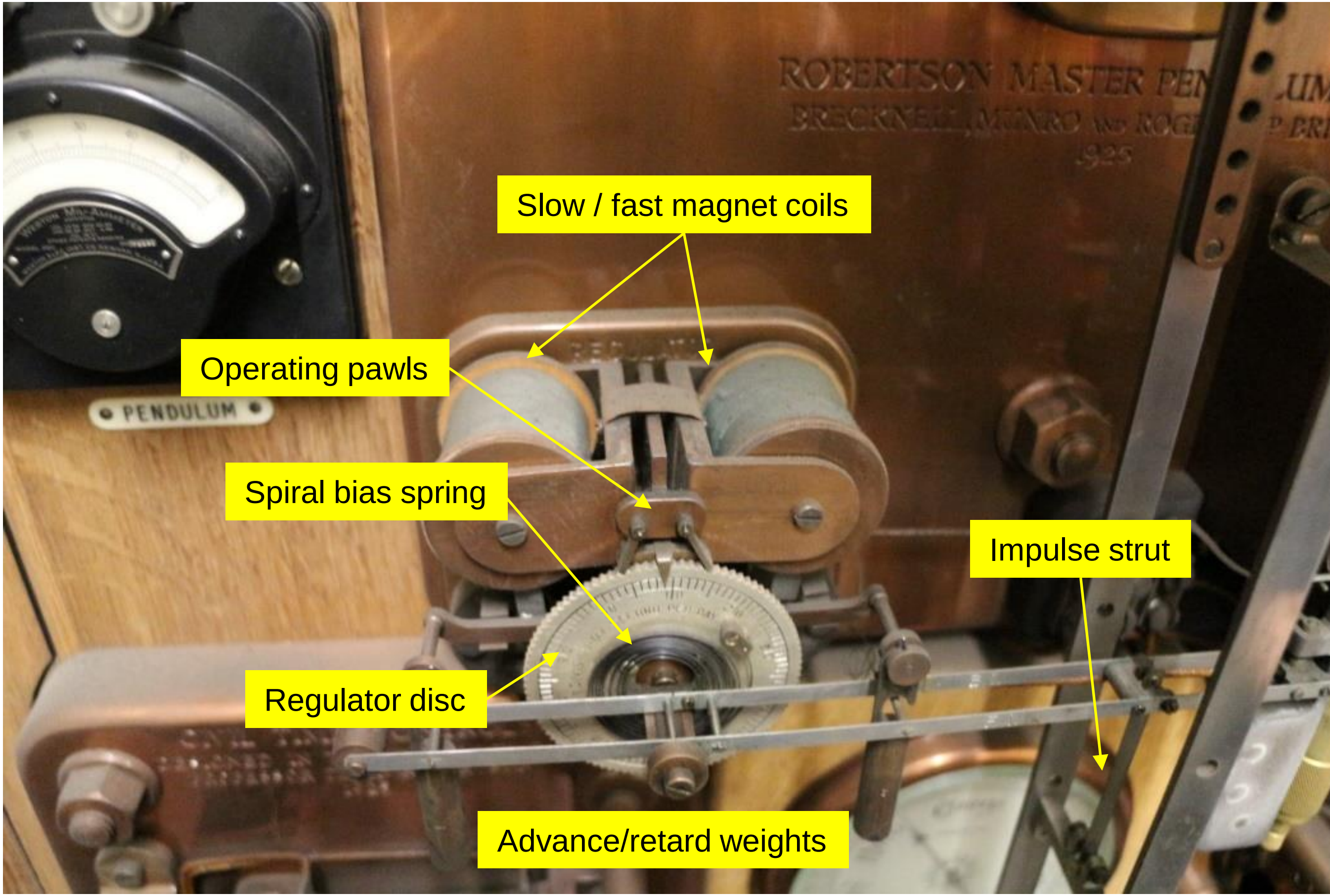
Its outstanding feature ...


Master Dial
Escapement
Modern control processor
Regulator
Civil Time Unit (CTU)
Greenwich Time Unit (GTU)
Pendulum
“Chronometer”

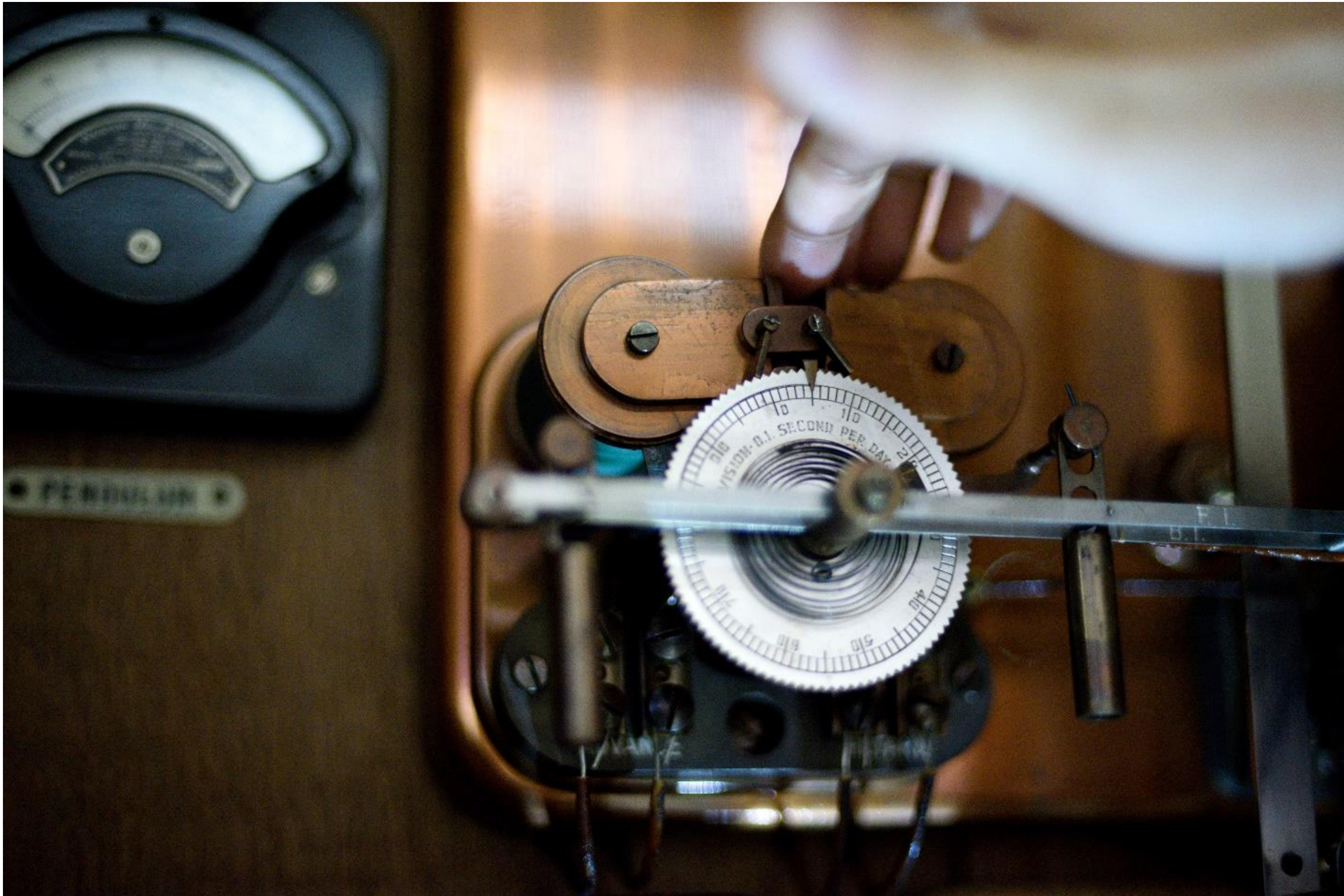

Double-rod pendulum
Seconds dial
Impulse weight
Regulator
Impulse lever
Impulse magnet
Impulse strut



Lifting arm
Impulse hook
Impulse contact



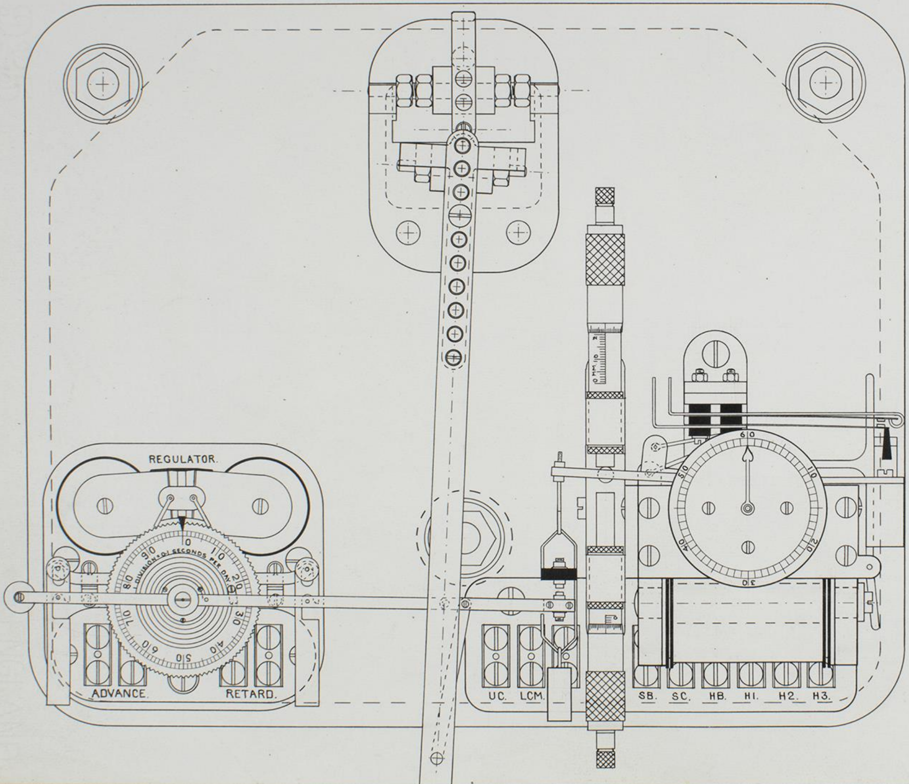
ROBERTSON MASTER
PENDULUM
Slow / fast magnet coils
Operating pawls
Spiral bias spring
Regulator disc
Impulse strut
Advance/retard weights


PENDULUM
VISION-0.1 SECOND PER DAY

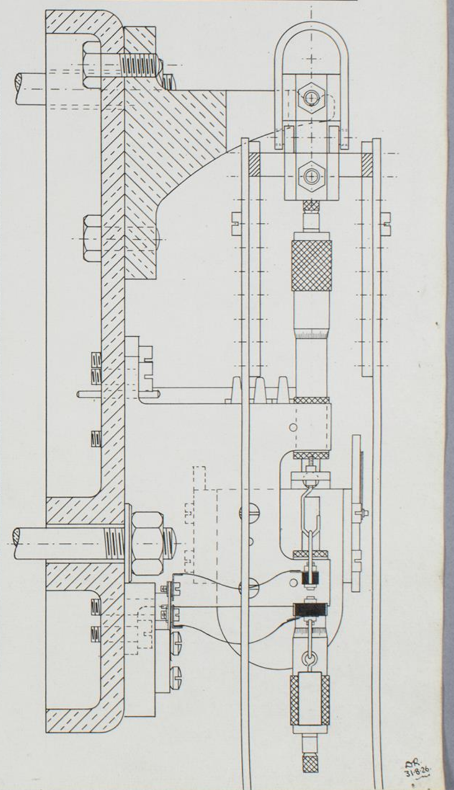
Robertson Master Pendulum with Automatic Regulator.

Plate VIII.

Front Elevation of Head, Regulator & Escapement.



Sectional Side Elevation.



D.R.
31.8.26.

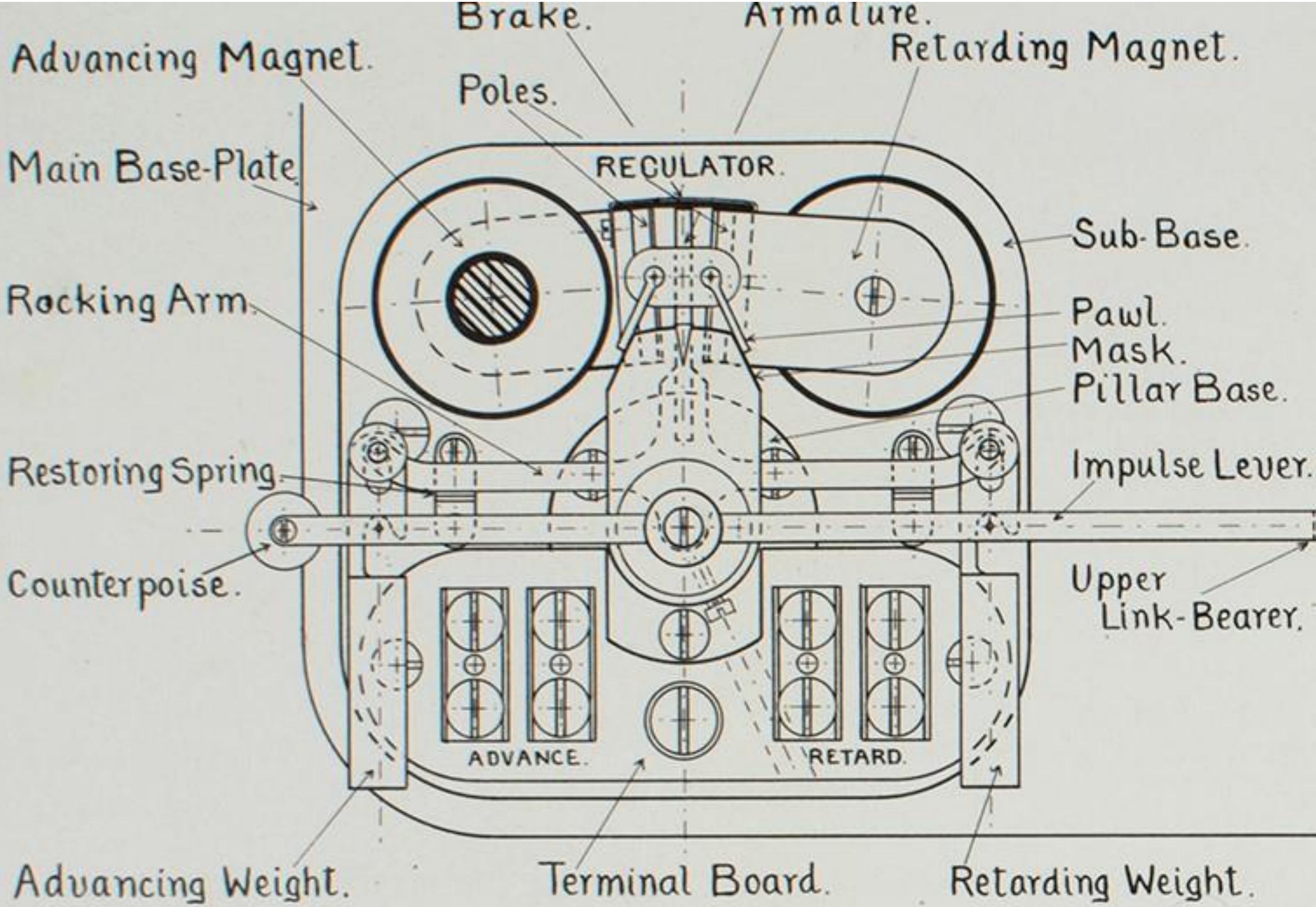
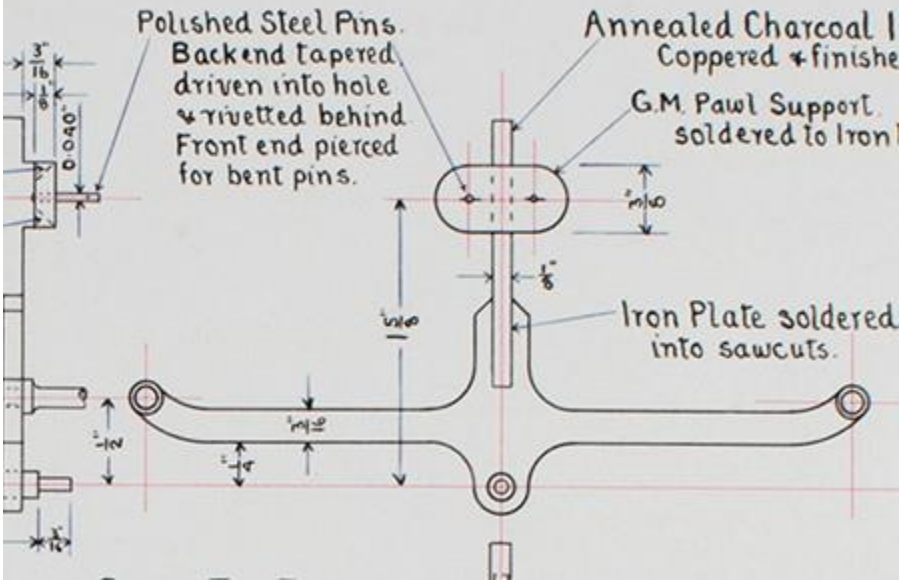
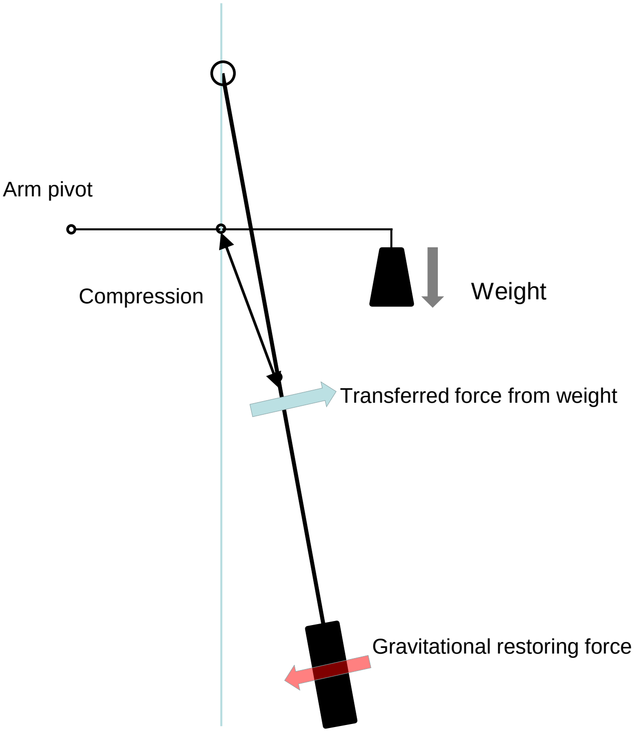
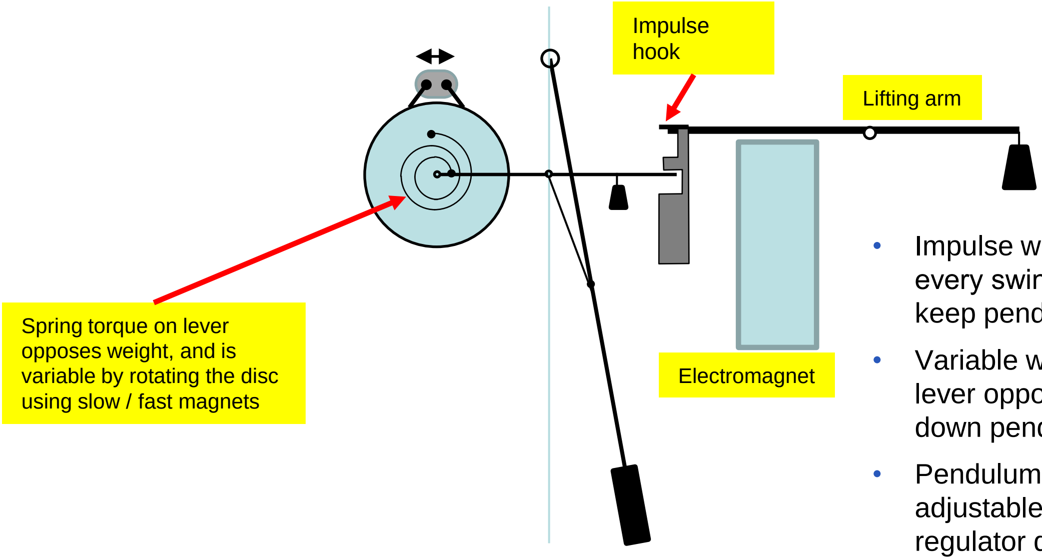

Brake.
Armature.
Advancing Magnet.
Retarding Magnet.
Poles.
Main Base-Plate.
REGULATOR.
Sub-Base.
Rocking Arm.
Pawl.
Mask.
Pillar Base.
Restoring Spring.
Impulse Lever.
Counterpoise.
Upper
Link-Bearer.
ADVANCE.
RETARD.
Advancing Weight.
Terminal Board.
Retarding Weight.

FIG. 65. ARMATURE. 1 OF.

Florentine Bronze Finish.



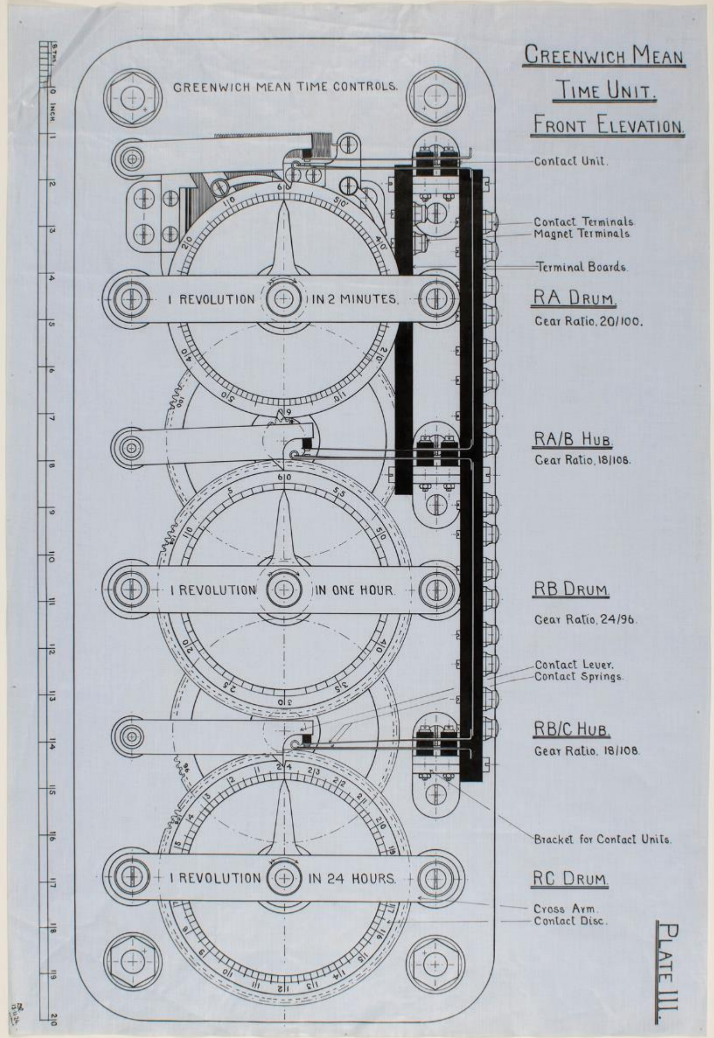

Arm pivot
Compression
Weight
Transferred force from weight
Gravitational restoring force



- Impulse weight applied briefly every swing just after “BDC” to keep pendulum swinging
- Variable weight from impulse lever opposes gravity, slows down pendulum
- Pendulum frequency adjustable by stepping regulator disc using coils

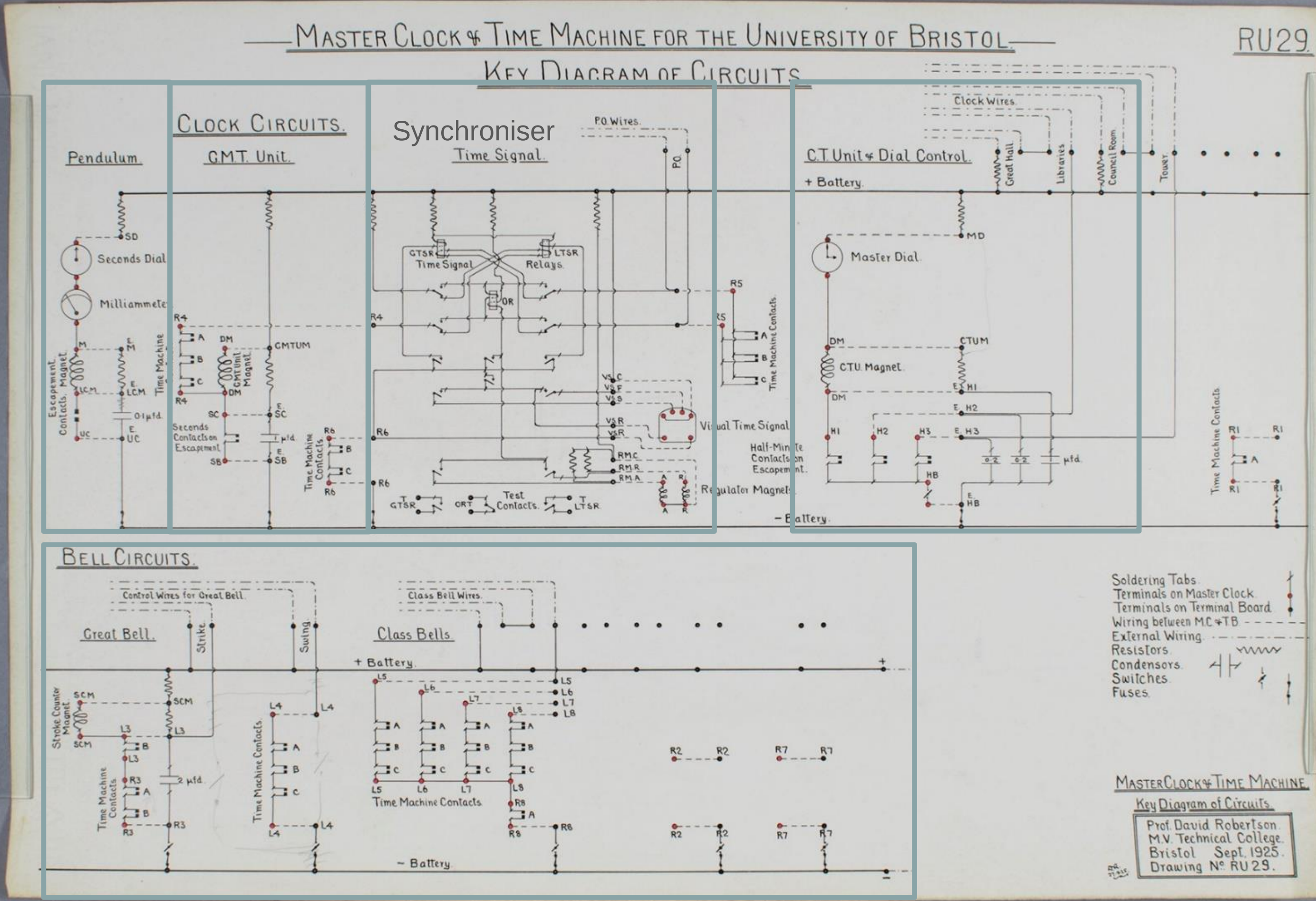
Greenwich Time Unit

- Essentially, a clock driven by 1s pulses from the pendulum
- Keeps track of GMT
- Generates control signals for the synchronising unit at 10.00 am GMT every morning
  - 09h55m55s: enables synchroniser
  - 10h05m: sequence ends



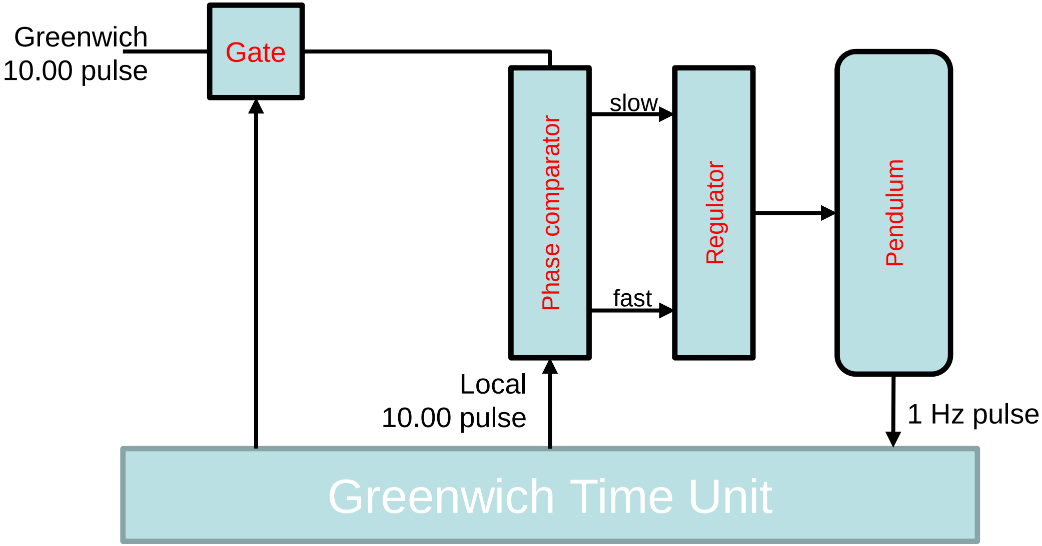
Civil Time Unit

- Similar structure to GMTU
- Keeps GMT/BST according to time of year
- Generates drive signals for the bell chiming mechanism:
  - Chimes the hours every 5 seconds starting on the hour
  - 0700 – 2100 daily…
  - …except Sunday

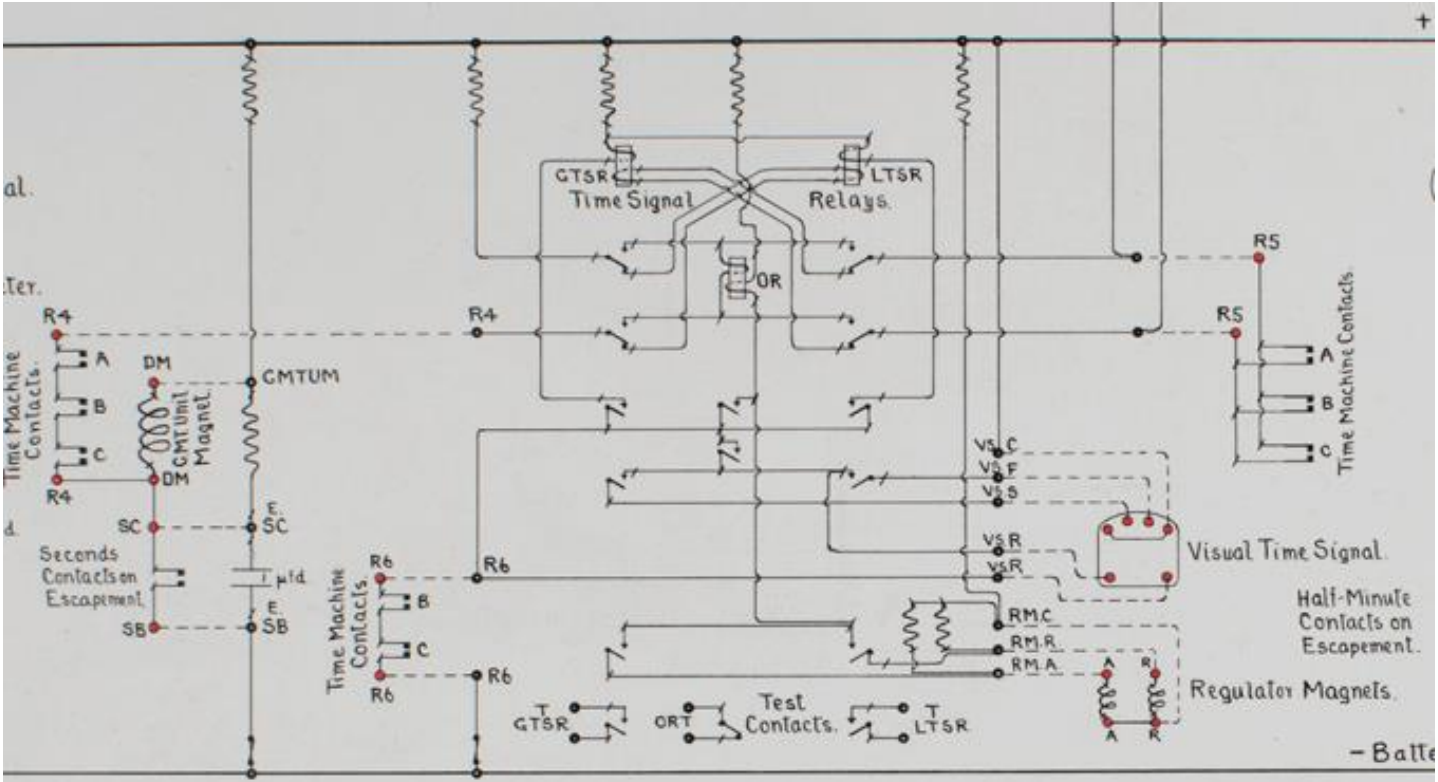

Master Clock & Time Machine for the University of Bristol
RU29
Key Diagram of Circuits
Clock Circuits.
Synchroniser
Pendulum
G.M.T. Unit.
Time Signal.
P.O. Wires.
C.T. Unit & Dial Control.
Clock Wires.
Great Hall
Libraries
Council Room
Tower
+ Battery
Seconds Dial
Milliammeter
Escapement Contacts. Magnet.
Time Machine Contacts
Seconds Contact on Escapement
GMT Unit Magnet
GTSR
LTSR
Time Signal
Relays
Test Contacts.
Visual Time Signal
Regulator Magnets
Master Dial
C.T.U. Magnet
Half-Minute Contacts on Escapement.
- Battery
Bell Circuits.
Control Wires for Great Bell.
Great Bell.
Strike
Swing
Class Bell Wires.
Class Bells.
Stroke Counter Magnet
Time Machine Contacts
Soldering Tabs.
Terminals on Master Clock.
Terminals on Terminal Board.
Wiring between M.C. & T.B.
External Wiring.
Resistors.
Condensors.
Switches.
Fuses.
Master Clock & Time Machine.
Key Diagram of Circuits.
Prof. David Robertson.
M.V. Technical College.
Bristol Sept. 1925.
Drawing No. RU 29.

Synchronising system

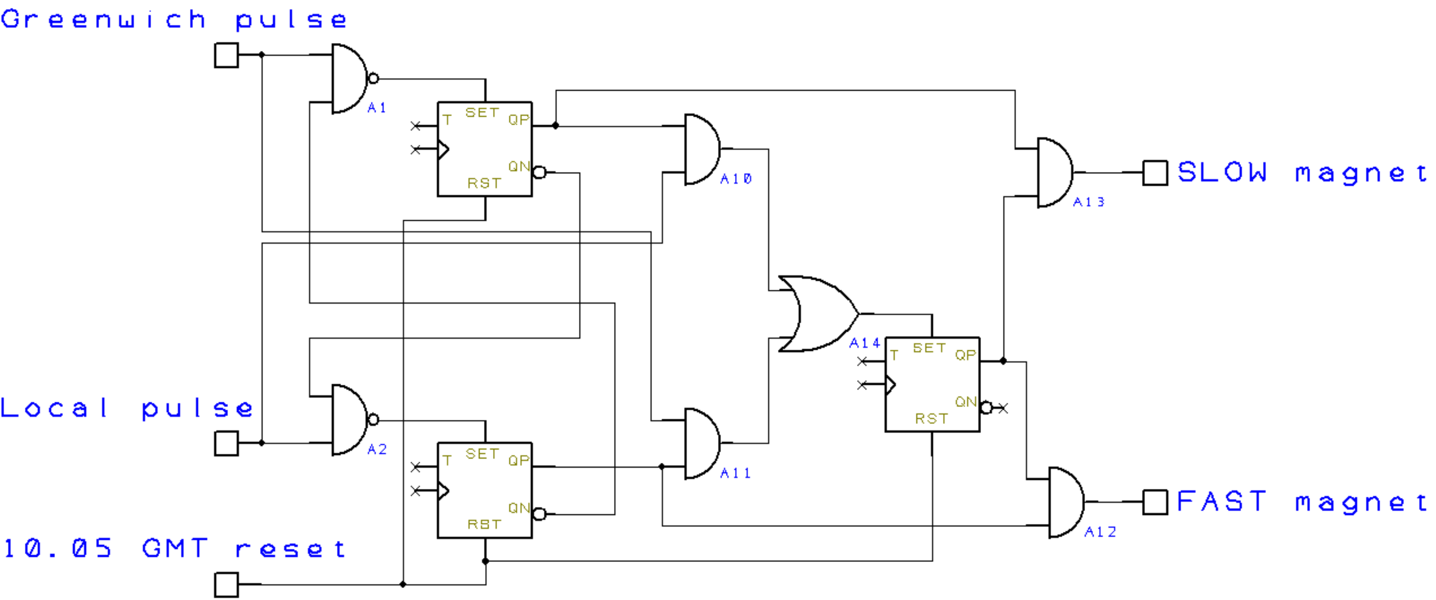
The world's first true phase-locked loop?



Phase detector using relay logic



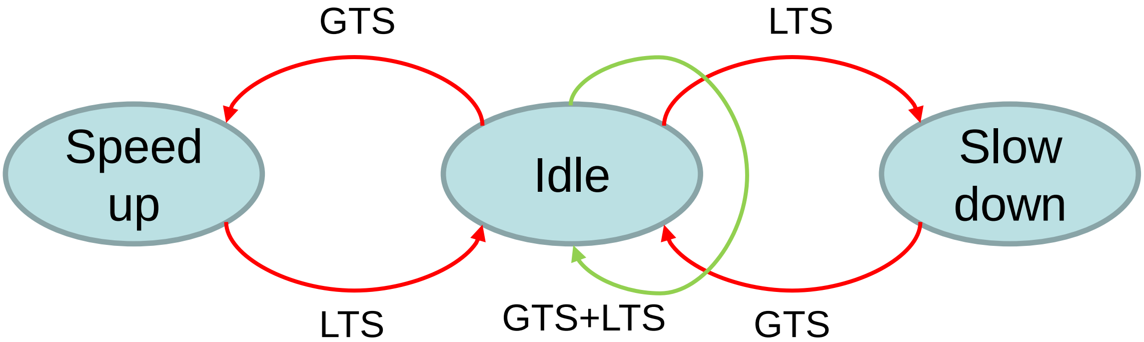
Robertson's phase detector in modern logic



Robertson's "synchronising algorithm" in words

- PD determines if clock is fast or slow relative to Greenwich
- If equal, do nothing
- If slow:
  - Speed up pendulum for 5 minutes by 60s/day = +0.2 s displayed time change
    - By adding fixed weight to *left* side of impulse lever
  - Increase rate by 0.2 s/day
- If fast:
  - Slow down pendulum for 5 minutes by 60s/day = -0.2 s displayed time change
    - By adding fixed weight to *right* side of impulse lever
  - Decrease rate by 0.2 s/day
- The +/- 0.2s increment is needed to get the time to converge rapidly but introduces hunting in the final displayed time relative to "real time"
- System easy to simulate in a spreadsheet

PD also acts as a *frequency detector*…



- GTS = Greenwich pulse; LTS = Local pulse
- If more GTSs than LTSs, “speed up” state dominates
- If more LTSs than GTSs, “slow down” state dominates
- Eventually pendulum frequency will stabilise to equal Greenwich, and lock in-phase

Phase-frequency detectors

- Essential part of modern PLLs
- Based on sequential logic
- Many different versions used
- Appeared in ICs and frequency synthesisers in early 1970s….(Brown, Proc IEEE April 1971)
- Robertson anticipated this by 45 years, using relay logic!

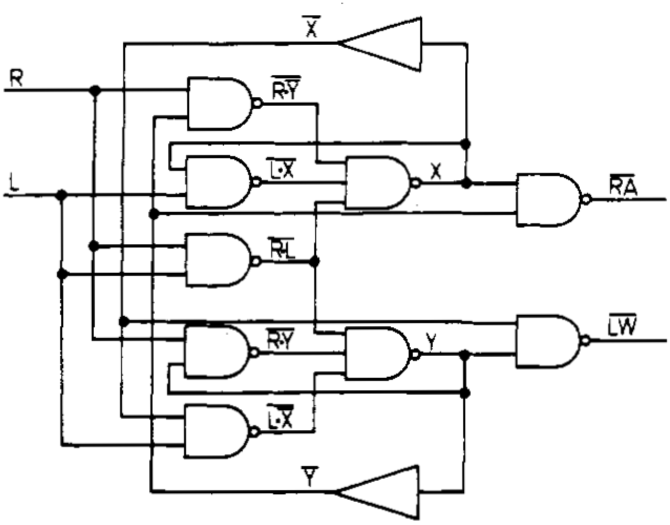


Fig. 3. The new PSD realized in TTL gates.

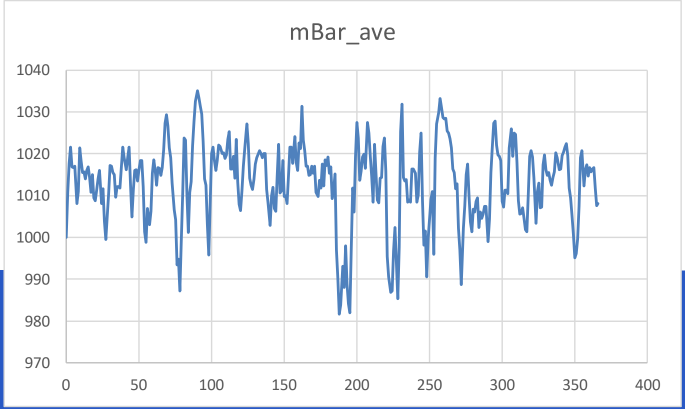
Comparison with a modern Phase-Locked Loop (PLL)

PLL	Robertson
Voltage Controlled Oscillator	Pendulum + regulator, giving incremental control of rate
Phase/frequency detector using semiconductor logic gates	Phase/frequency detector using relay logic
Loop filter driven by charge pump	Regulator accumulates early/late decisions; transient rate change is effectively a lead/lag filter
Error signal proportional to phase difference,	Fixed error signal: fast/slow, causes time & frequency increment

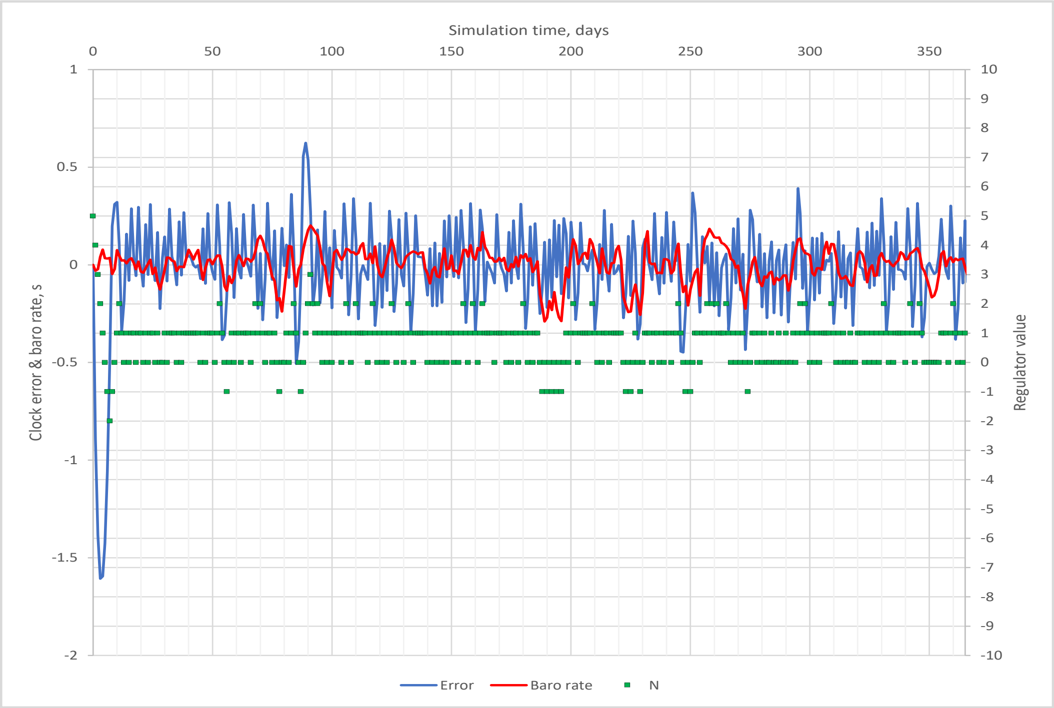
Timekeeping

- Robertson assumed that the regulator system would deal with major sources of error so absolute stability wasn't so important
- Pendulum "rods" use Invar with "tin whistle" style adjusters for tempco
- No barometric pressure compensation was provided
- Barometric pressure variation was a major problem - that Robertson didn't have the data on *rate of variation* to design the control system properly

Daily mean barometric pressure at NPL Teddington, 2015

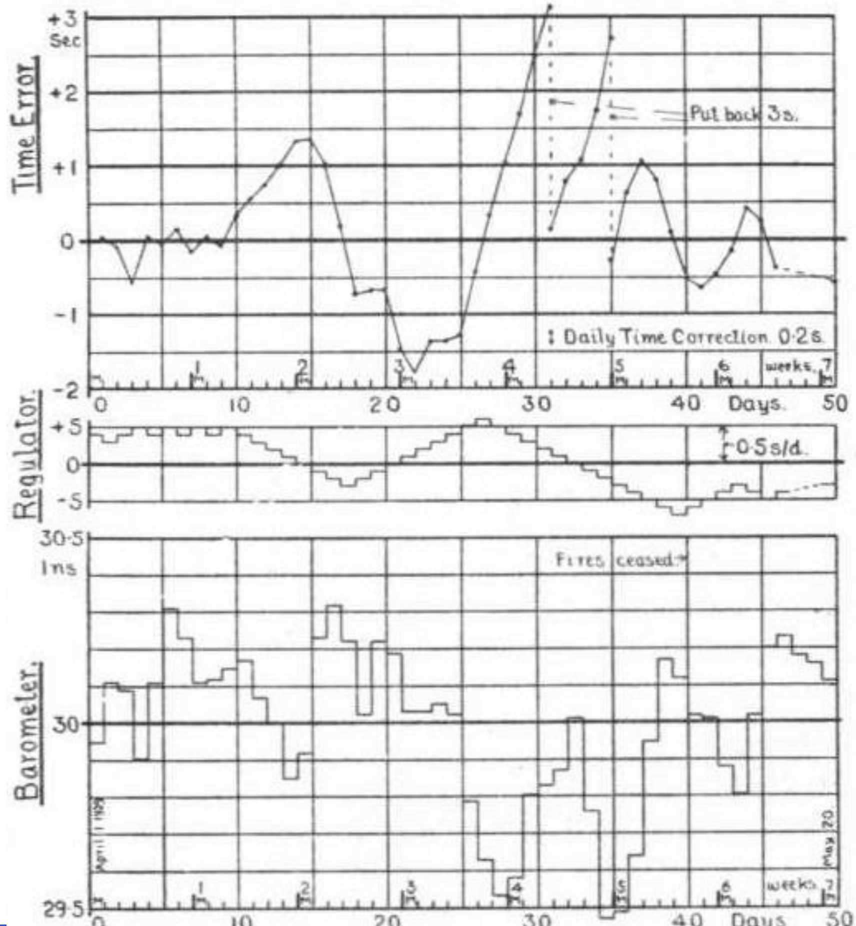


Simulated performance with NPL baro data



Assuming “standard” barometric error due to buoyancy & “access to inertia”

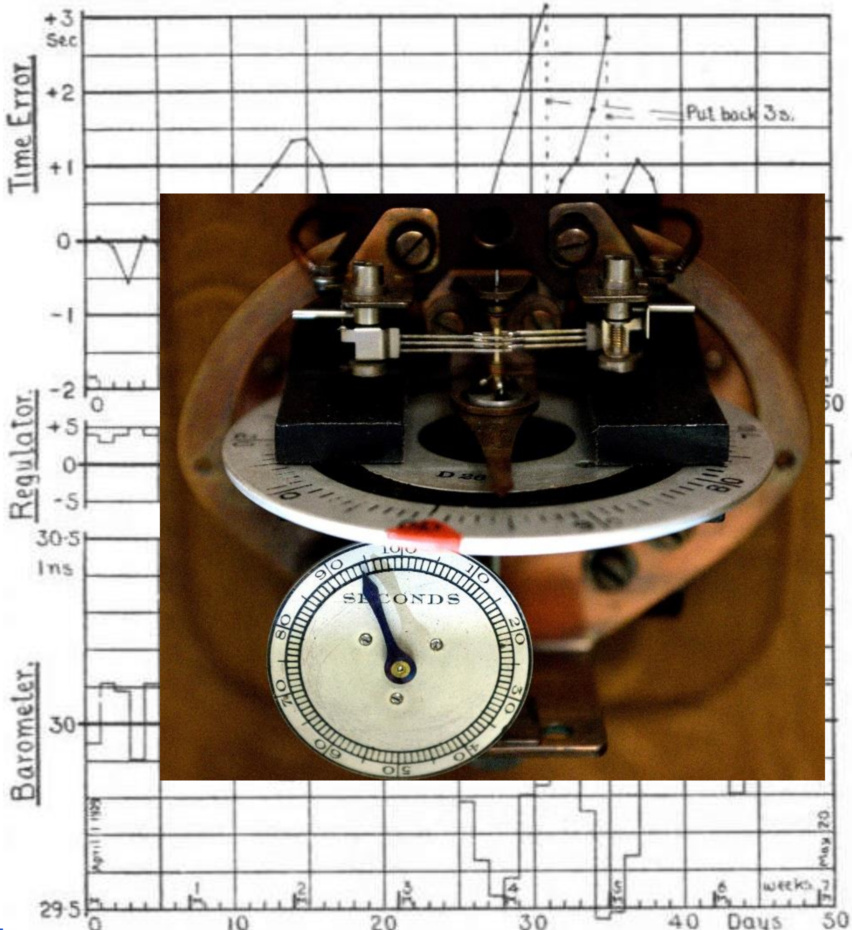
- Time errors seemed to be dominated by barometric pressure variations
- Results show that these were sometimes too fast/large for the regulator to accommodate
- Modification made to vary length of frequency transient depending on phase error – but results not published
- Manual adjustment was needed using adjusting weights on pendulum bob (“graduate student method”)



Source: Alfred Ball, HJ Dec 1929, pp 64 - 66

Measured results (spring 1929)

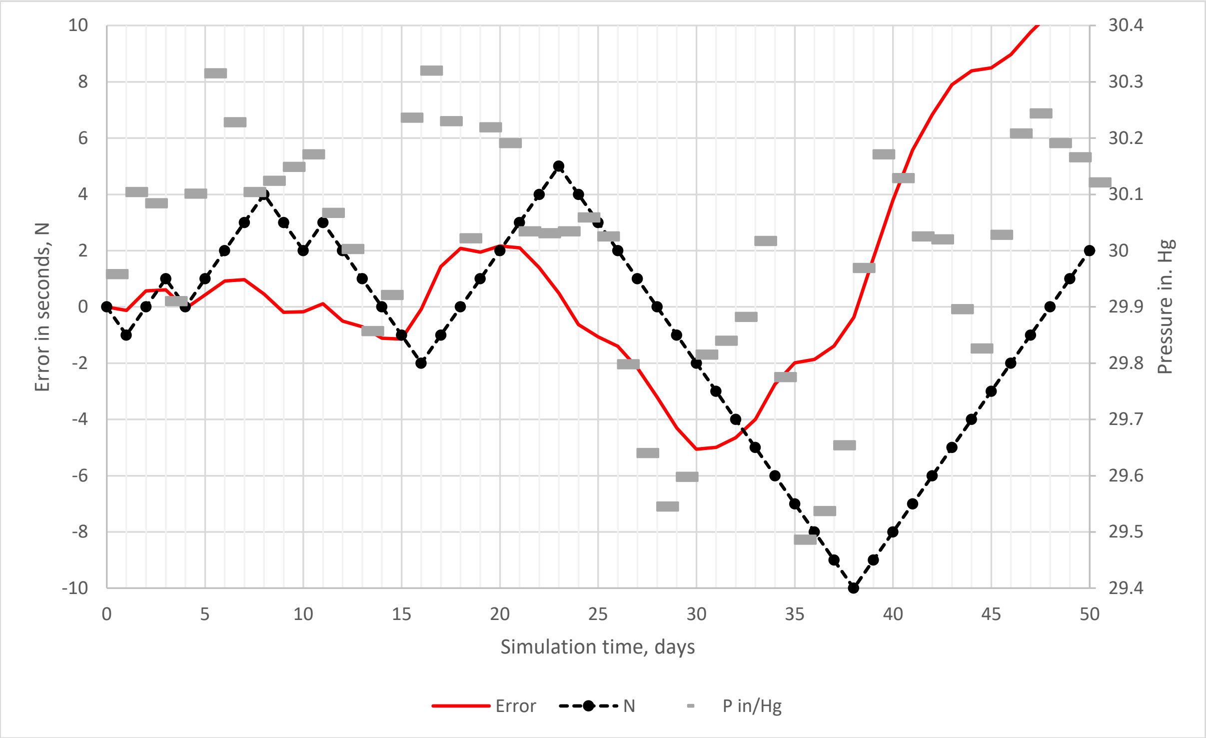
- Robertson adapted a “dc electricity meter” to try to measure the actual time error – “chronometer”
- Runs in one direction of the other while a time error is seen; runs in opposite direction at different speed to increase the time increment
- Results not recorded but the unit is still mounted in the case



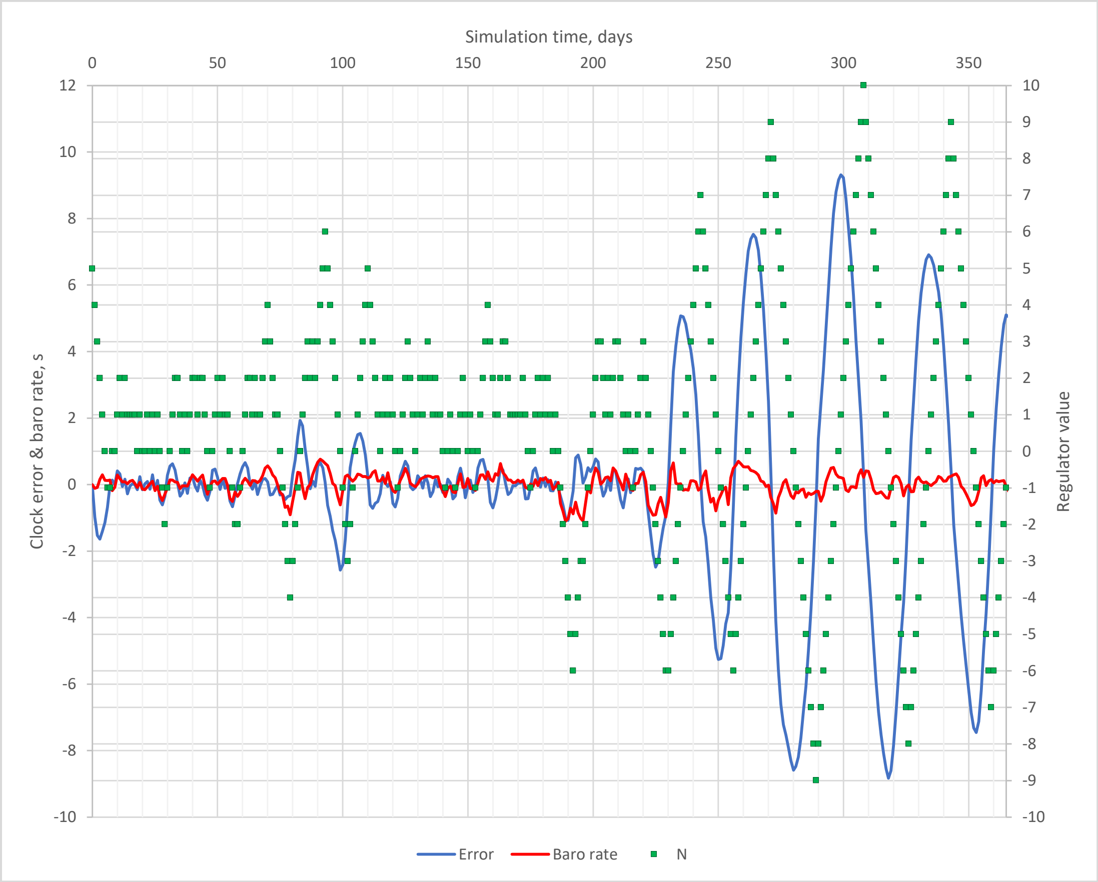
Source: Alfred Ball, HJ Dec 1929, pp 64 - 66

Measured results (spring 1929)

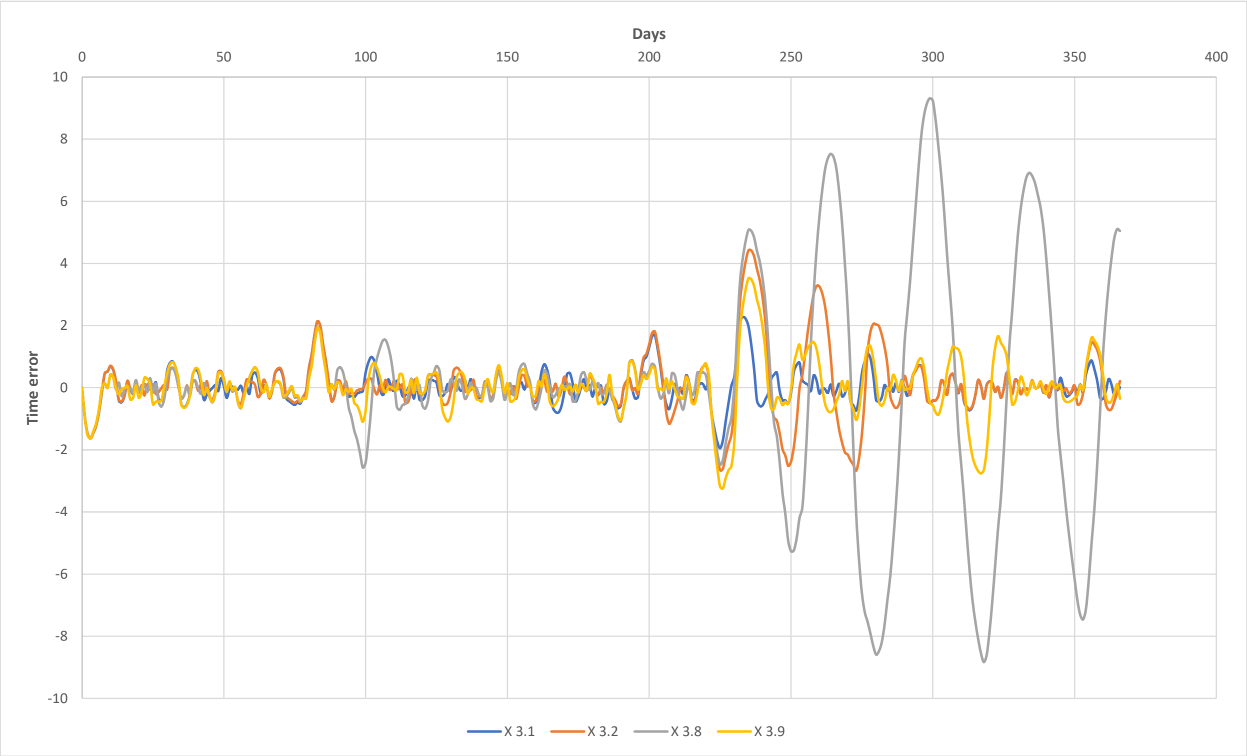
Simulation with Ball pressure data & enhanced baro coefficient – x9.5



Simulation with NPL pressure data & enhanced baro coefficient – x3.8



Simulation with various baro multipliers



Performance

- The system can clearly synchronise itself initially given reasonable starting error in rate and phase; and track slow variations in barometric pressure
- When pressure changes are fast/large (i.e. rate of change is large) the system allows quite large errors to build up
- Essentially the system can't make corrections quickly enough
  - "Sampling rate" of error is too low at 1 sample/day
  - Incremental corrections are too infrequent to track baro variations
- System is very sensitive to parameters in certain regimes, it is maybe "quasi chaotic"

Why is baro sensitivity much higher than expected?

- The escapement has a distinct lagging impulse so that its rate is sensitive to amplitude
- Amplitude will vary with air density, giving another mechanism whereby rate can change with pressure
- Though Robertson was aware of the “Harrison hill” he didn’t try to exploit it for barometric compensation
- The pendulum Q is quite large (10,000) so amplitude changes lag pressure changes – what affect does this have?
- Nevertheless though barometric changes affect timekeeping at the “seconds level” the clock doesn’t completely lose synch.
- Dial time would apparently be accurate but Great George chiming could be 5 seconds or so out – as e.g. radio time signals became available this would be increasingly apparent

Historical notes

- Robertson’s clock seems to have been the first to make continuous fine corrections of rate to phase-lock to an external reference, using a separate relay-logic phase/frequency detector – a “phase-locked loop” (PLL)
- First description of the electronic PLL in the modern sense was by de Bellescize, 1932; French and US patents 1931
  - Robertson’s publications in 1926 were prior art
- The clock contains a clear precursor of the **sequential PFD**, made using relay logic, first described in electronics in ***1971***
- Some evidence that Robertson did not fully understand the scope of his innovations!

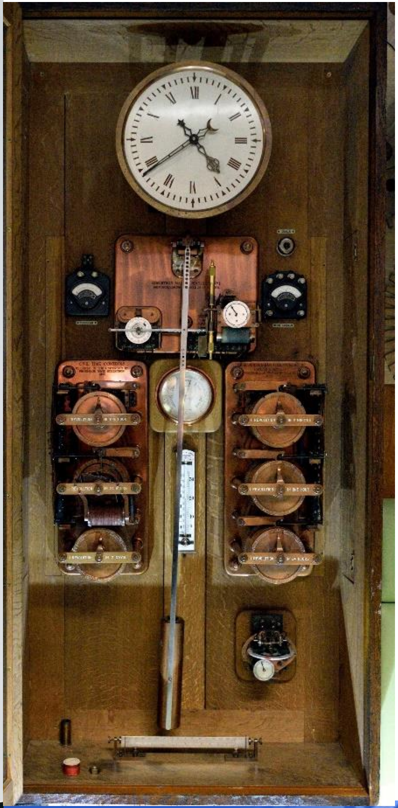
What might have been…

- Phase-lock techniques only fully developed in 1960s/70s
- Robertson’s clock had all the elements for accurate phase locking, but:
  - Reference signals were only available from Greenwich once a day – sampling rate too slow to follow barometric variations
    - Nyquist (1928), Shannon (1948)
  - His “VCO” was “slew-rate limited”, which would also have made a higher sampling rate necessary
  - First systematic treatment of automatic feedback control systems was by Bode in 1930s – needed to understand stability considerations
  - Non-linear sampled-data systems not properly understood until 1960s

- The clock is an engineering prototype, appearing too late to influence development of time standards
- Horological establishment (and Robertson himself?) failed to appreciate the key details of the system

What might have been…

- Robertson's clock combined with Shortt "reference oscillator"
- Reference pulses every 30s
- True phase-locking rather than the "hit and miss" frequency lock of the Shortt-Synchronome
- The "Shortt – Robertson" could be self-regulating and much easier to set up



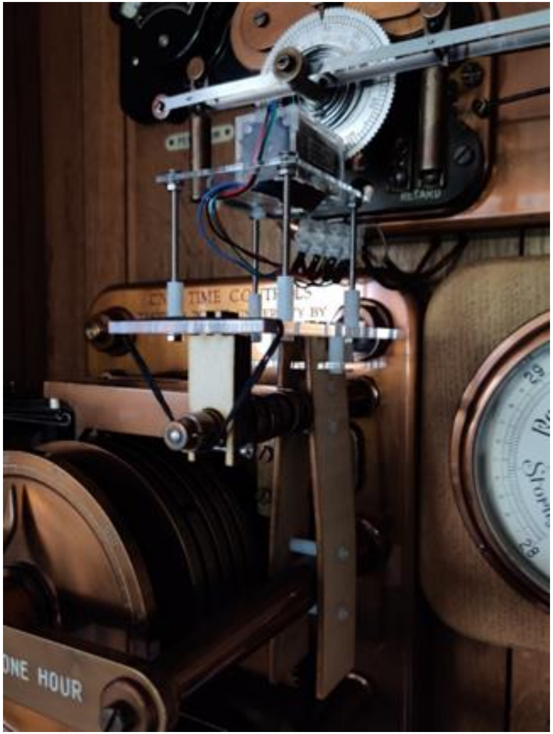
Conservation

- Works removed from case in July 2017
- Mechanism conserved at "The Clockworks" by Johan ten Hoeve & James Harris
- Case removed from Wills Building and refurbished & reinstallation in new location
- Memorial to a pioneering engineering educator
- Platform for student projects
  - *E.g. evaluating possible synchronising performance*

Installed in Queen’s Building, home of the Engineering Faculty, inaugurated 10 October 2019, 16:24 by Prof. Judith Squires (deputy VC) & Prof. Ian Bond (Dean of Engineering)

- Needs some supporting electronics to replace worn mechanism, to drive the clock face
- The GTU and CTU are cleaned but not working – they do not add to the functionality and would be very noisy in operation
- One of the regulator magnets is open-circuit, and we know that Robertson had problems anyway with the regulator, so it is now non-operational

First student project - get the regulator working?



The future – making the clock self-reliant

- Replace platinum escape contacts with solid-state sensor for long-term reliability

- Implement automatic regulation
  - A GPS-derived time source has been installed on the building, wired to the controller cabinet
  - Two approaches to regulation:
    - Low risk: correct dial time by manipulating the half-minute counter that increments the dial, to make BST/GMT change, correct for accumulated rate errors, initial time set
    - Higher risk: remake regulator assembly, possibly using modern stepper motor hidden inside

- Provide battery backup so clock doesn't stop on power outage

- Connect to the Internet for remote monitoring

Further reading

David Robertson; *The theory of pendulums and escapements*; Horological Journal, December 1928 – April 1931.

David Robertson; *The Clock and Striking Mechanism for the Great Bell of the University of Bristol*; Proceedings of the Institute of Engineers and Shipbuilders in Scotland; available for download via https://www.bristol.ac.uk/engineering/news/2019/robertson-clock.html

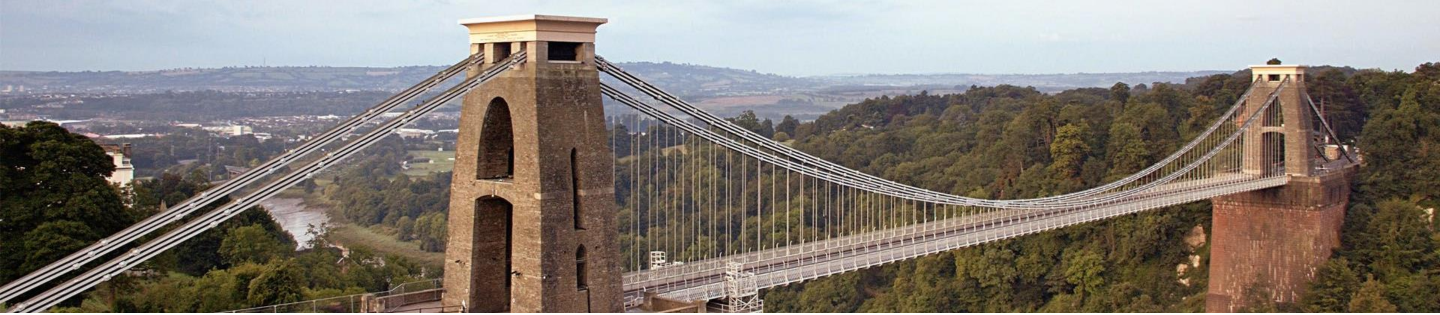
Paul Dirac's memories of Robertson as a teacher: https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-1

The Strangest Man by Graham Farmelo, a biography of Dirac

A.E. Ball; *The automatic synchronisation of clocks by wireless waves*; Horological Journal, December 1929, pp64-66.

J.L. Haine; *The Robertson Regulator;* Horological Science News (HSN) 2021-5

J.L. Haine & A. Millington; *More on the Robertson Regulator;* HSN 2022-2



Thank you!

(Academic trivia)

- Dirac was a pupil at Merchant Venturer's school before enrolling at the University (the school shared premises with MVTC)
- His first physics teacher was a Mr. Willis
- Dirac went on to win a Nobel Prize in 1933 for key contributions to Quantum Mechanics with Werner Heisenberg
- The school moved and became Cotham School, and 30 years later Mr Willis taught a certain Peter Higgs who in 1964 predicted a new "boson"
- In 2012 CERN announced the discovery of the Higgs Boson in the LHC
- Peter Higgs & François Englert awarded Nobel Prize in 2013