The Geophysics of Past and Future Variations in the Earth's Rate of Rotation

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Outline of Talk

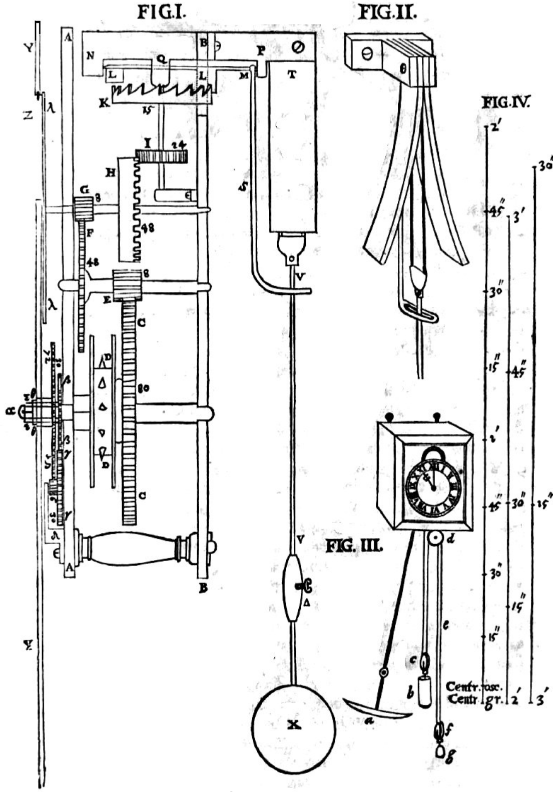
- What is the basic physics?
- What contributes to changes?
  - Fluid Motions
  - Shifts in Mass
  - External Torques
- What have these changes looked like in the past?
- What can be expected in the future for UT1 changes?

No one knows what time is....

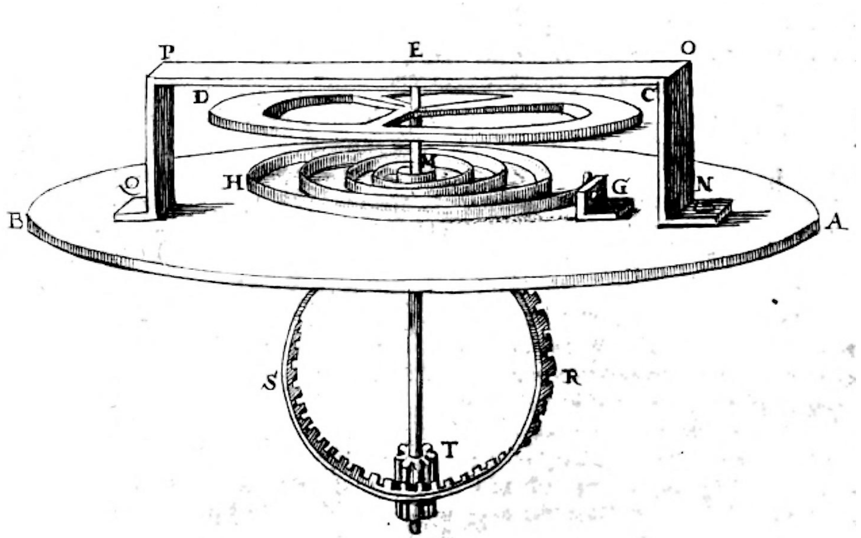
But we sure know how to measure it.

David Landes, *Revolution in Time: Clocks and the Making of the Modern World*

Physics of Time Measurement: Almost Always, **Angular Momentum**



Huyghens, 1657:
Pendulum clock
Orbital angular momentum



Huyghens, 1675:
Balance spring and wheel
Spin angular momentum

(also **Van der Waals forces**)

Time Measurement *Defined* by Angular Momentum

- Until 1960: [constant] spin angular momentum of the Earth
  - One day; 24 hours; 86400 seconds, all were one full rotation relative to the Sun.
  - UT1 is still defined by the spin (angular velocity integrated to give Earth Rotation Angle θ): $t_U = (\theta - \theta_0)/\omega_0$ where ω_0 is reference angular velocity.
- 1960-1967: [constant] orbital angular momentum of the Earth
  - And the rest of the solar system.
  - This definition implicitly still in use for times before 1955
- 1967-> change in spin angular momentum of cesium electrons

Earth Rotation Equation (for spin only)

$$L = C_A\omega_A + C_H\omega_H + \; C_S\boldsymbol{\omega_S} + C_C\omega_C$$

L is total angular momentum, C is polar moment of inertia, and ω is angular velocity: A, H, S, C are the Atmosphere, Hydrosphere (water/ice), Solid shell (crust and mantle), and Core (liquid Outer, solid Inner).

$$\omega_s = \frac{L}{C_S} - \frac{\mathrm{C_A}\,\omega_A}{C_S} - \frac{C_H\omega_H}{C_S} - \frac{C_C\omega_C}{C_C}$$

Small Perturbations, Nondimensionalized

Express all small changes in fractional form; for example, small changes in spin rate, $\delta\omega_S$, become $\Delta_{\omega S} = \delta\omega_S/\omega_S$. Then the expression for changes in ω_S in terms of other changes is (given that all the ω's are nearly the same) is

$$\Delta_{\omega S} = \Delta_L - \Delta_{CS}[1 + \mathrm{r_A} + \mathrm{r_H} + \mathrm{r_C}] - \sum_{K=A,H,C}[\, r_K(\Delta_{CK} + \Delta_{\omega K})]$$

where $r_K = \frac{C_K}{C_S}$, the ratio of moments of inertia:

$r_A \approx 1.5 \times 10^{-6}$, $r_H \approx 5 \times 10^{-4}$ $r_C \approx 0.13$

$r_K \Delta_{CK}$ is the ***mass*** term for region K

$r_K \Delta_{\omega K}$ is the ***motion*** term for region K

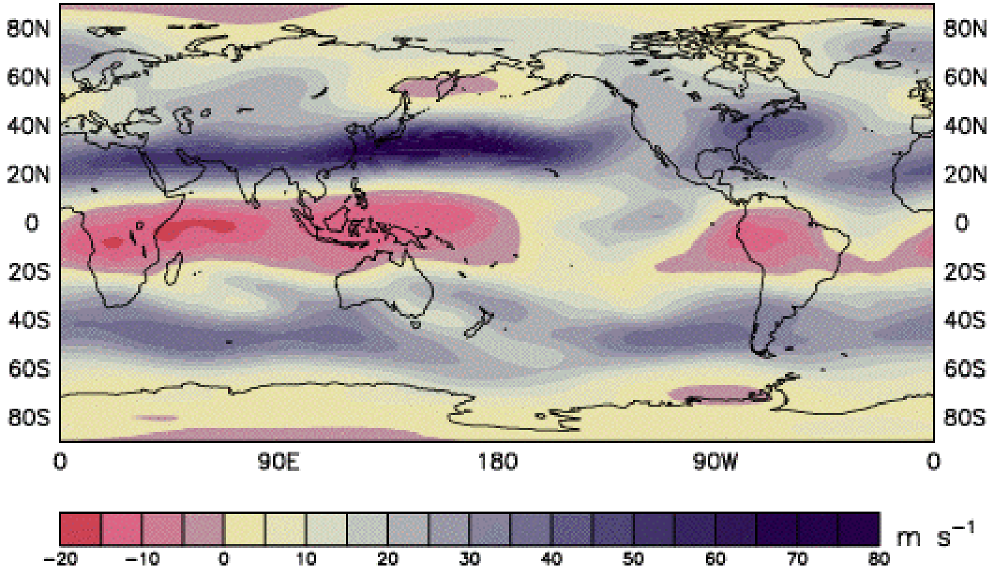
Units and Signs

- Because of the association of the Earth's spin with time, the usual term for changes in ω_S is changes in the Length of Day (LOD)
- Unit is milliseconds that the rotational day exceeds 86400 atomic seconds.
- 1 ms is a fractional change of $\frac{1}{8.64\times10^7} = 115.7 \times 10^{-10}$
- I will use fractional change, but follow the LOD convention for plotting: longer days (smaller ω_S) will be plotted ***upwards.***

1. Tidal Effects on Moment of Inertia

Largest tidal changes have periods of 14 days, 6 months, 18.6 years

2. Atmosphere/Ocean: Motion and Mass



Zonal wind field near jet stream levels (sampled here for January 1997), the primary contributor to atmospheric angular momentum and length of day changes.

Most of the change in AAM is from changes in the W-to-E flows of the jet stream (dark bands). Meteorologists have produced numerical models of the atmosphere for the past and present. If AAM computed from these is removed from the spin-rate data, what remains shows only slow changes.

The Complete Modern Dataset

View in the Frequency Domain

Subtracting the AAM/OAM contribution lowers the spectrum by almost a factor of 100 at period from 2 years to 1 month, showing that the models for AAM are quite good. But for periods longer than 2 years the AAM contribution is a smaller part, and at periods 5 years and longer some other process with a very red spectrum is what changes the spin rate.

At these long periods 4 different processes act to change the spin, and we review each one.

Barystatic Changes (Water mass transfer)

If ice near the poles melts, the water spreads out over the Earth, increases I_H and so reduces ω_S .
Shavandi et al (2024) computed this effect from 1900 on starting with changes in land ice (and water stored on land). It is not large but has recently accelerated

Barystatic Time Series Shows Another Change

Changes in the total moment of inertia cause a change in the degree-2 component of the gravity field, often designated J_2 which is monitored by tracking satellites.

When the barystatic effect on I_H is subtracted from the observed change in J_2, the residual is a change in moment of inertia that is very linear in time.

In terms of spin-rate changes it is the rate of change of J_2 times 1.696, which is a change of -0.79×10^{-10} per year

The negative sign means that this is increasing ω_S

Glacial Isostatic Adjustment (GIA)

During the last Glacial Maximum, icecaps covered Northern Canada and Fennoscandia; the weight of the ice compressed the rock underneath and formed a depression.

When the icecaps melted, the solid Earth beneath them rebounded. This includes a gradual readjustment because rocks, over a long time, deform under steady stress. This is still going on; the rate is decaying only very slowly.

Net, this is the same as mass moving from South to North, *decreasing* I_s and *increasing* ω_s: this is what is steadily changing J_2

Tidal Friction: Constant Slowing

The ocean tides have a complicated pattern, but the lowest-order spherical harmonic of this has its bulge (highest tide) *delayed* after the Moon is overhead.

If we replace this bulge by two spheres and look at the accelerations of each body on the other:

1. There is a couple (a torque) applied to the Earth that decreases the spin rate.
2. The Moon is accelerated in its orbit.

Measurements of (2) with Lunar Laser Ranging give a change of spin rate of 2.78×10^{-10}/yr

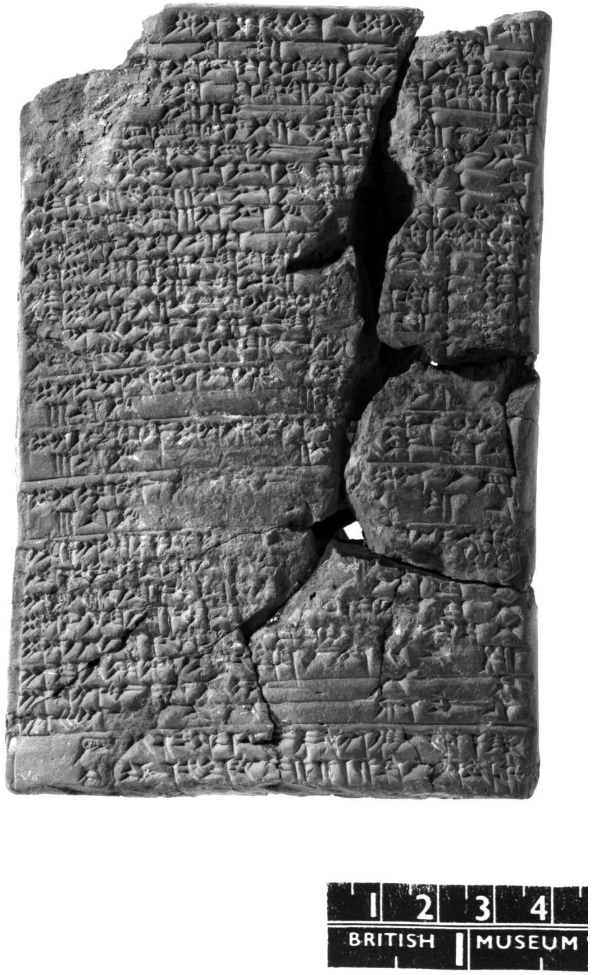
Two Estimates of Long-term Changes

So we have

1. Tidal friction changes ω_s by 2.78×10^{-10}/yr
2. GIA changes ω_s by -0.79×10^{-10}/yr

giving an overall long-term rate of 1.99×10^{-10}/yr

3. The latest estimate of long-term change using Babylonian and Chinese eclipse data back to 720 BCE is, independently, 1.99×10^{-10}/yr



Two Hundred Years of Spin Changes (1)

Two Hundred Years of Spin Changes (2)

Putting All the (Recent) Pieces Together

This plot shows all the different contributions over the last 62 years:

On the left, to spin rate

On the right, to angle (spin integrated): that is, UT1.

Note the different scale on the right for the top 3 series: the tides and the atmosphere do not have a large effect (though it is enough to interest some.

UT1 and its long-term future depend on TF and GIA (very predictable), Bary (somewhat) and the Core (not at all).