The Wonderful World of Clocks

Advanced Concepts Team
10 years Anniversary - Thinking the Future
ESA/ESTEC
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Pacôme DELVA
Outline

- What is a clock?
- Why measuring time?
- Going in space
- Relativistic Global Positioning Systems
- The far future
- Conclusion
What is a clock?

- **Clock** = Oscillator + Counter
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<table>
<thead>
<tr>
<th>Oscillator</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Earth Oscillator" /></td>
<td></td>
</tr>
<tr>
<td>( f )</td>
<td>( 10^{-5} \text{ Hz} )</td>
</tr>
<tr>
<td>Counter</td>
<td></td>
</tr>
<tr>
<td><img src="image2.png" alt="Counter" /></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>( 10^7 \text{ m} )</td>
</tr>
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What is a clock?

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<td><img src="image" alt="Earth Oscillator" /></td>
<td><img src="image" alt="Pendulum Oscillator" /></td>
</tr>
<tr>
<td>$f$</td>
<td>$10^{-5}$ Hz</td>
<td>1 Hz</td>
</tr>
<tr>
<td>Counter</td>
<td><img src="image" alt="Calendar" /></td>
<td><img src="image" alt="Mechanical Clock" /></td>
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<td><img src="image3.png" alt="Quartz Clock Oscillator" /></td>
</tr>
<tr>
<td><strong>f</strong></td>
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<td>1 Hz</td>
<td>$10^4 - 10^8$ Hz</td>
</tr>
<tr>
<td><strong>Counter</strong></td>
<td><img src="image4.png" alt="Calendar Counter" /></td>
<td><img src="image5.png" alt="Mechanical Counter" /></td>
<td><img src="image6.png" alt="Digital Counter" /></td>
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<td><img src="earth.png" alt="Image" /></td>
<td><img src="pendulum.png" alt="Image" /></td>
<td><img src="quartz_clock.png" alt="Image" /></td>
<td><img src="atomic_clock.png" alt="Image" /></td>
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What is a clock?

[Graph showing the fractional uncertainty over time for various types of atomic clocks, including Essen's Cs clock, iodine-stabilised HeNe, Cs redefinition of the second, Cs fountain clocks, and various other types of clocks.]
Time is Experimental Object

- **Special relativity**: space and time are relative to an observer
- **General relativity**: spacetime is a physical object, that depends on the energy/matter content of the universe

Fundamental Physics Tests

- Alternative theories (Quantum gravity, ...)
  - very small deviation from classical theories
  - fundamental constants variations, violation of equivalence principle ...

Scientific Applications

- Geophysics (Continental drifts, Heights, Gravitational Potential, ...)
- Reference systems (Terrestrial Frame, Universal Time Coordinate, ...)
- Navigation (Precise Point Positioning, Precise Orbit Determination, ...)
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**Why going in space?**

- Controlable environment: low noise, far from Earth, weightlessness → better accuracy and stability
- Large-scale experiment → global models, unification/comparison of local measurements

**The Future**

- ACES experiment: 2 atomic clocks on the ISS connected to ground clocks (GR tests, clock comparisons, relativistic geodesy...)
- STE-QUEST: a dedicated satellite for fundamental physics tests
- Relativistic Positioning Systems: an autonomous GNSS with inter-satellite links
- Solar System Clock Network: a network of interconnected clock in the solar system
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GOAL

- Define a spatio-temporal reference system with very high accuracy and stability based on satellite dynamics → ABC reference frame
- For high precision positioning and scientific applications

How

- Use Inter-Satellite Links (ISLs) to track the satellites
- Use satellite orbits as clocks with long-term stability to correct for satellite atomic clocks

Scientific Applications

- Relativistic geodesy, time & frequency transfer, gravimetry, fundamental physics tests
- Realize the primary reference frame (including the timescale) in space
- Geophysics (sub-millimeter accuracy, interior structure of the Earth, continental drifts, earthquake prediction, ...)

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Relativistic Global Navigation System (1/3)
Inter-Satellite Links (ISLs) → Emission coordinates → Satellites constants of motion → Realization of the ABC reference frame

User → Emission coordinates → Clock correction and data reduction → Coordinate transformation to the ABC Reference Frame
**ESA/ACT Ariadna Studies (2009-2010)**

- « Mapping the Spacetime metric with a Global Navigation Satellite System »
  - self consistent definition of reference frame using the GNSS clocks and inter-satellite links

**ESA/PECS Study (2011-2014)**

- Relativistic Global Navigation System (RGNSS)

**GSAC Recommendations (2012)**

- « Provide a net of inter-satellite links (optical or microwave) in the entire Galileo constellation, which will provide major improvements in the determination of the Galileo clocks and orbits. »

- « Deploy an « ACES-like » payload on a small number of Galileo satellites to provide a new type of links between Galileo satellites and ground stations, and a demonstrator for a general-purpose time and frequency transfer system (microwave). »
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Solar System Clock Network: a network of interconnected clock in the solar system
Clocks are wonderful tools for fundamental physics (let's not forget about inertial sensors...) and many other areas (geophysics, navigation, reference systems, ...)

2 complementary ways for future developments:

- Develop a **network of clocks in space** → Space Reference Frame (SRF)

- Develop the best clocks possible in space with **space-to-ground links** → attach the SRF to other frames (TRF, CRF...)

Many scientific applications (but also many other advantages...)

Conclusion
Time Activities

- Primary frequency standards (atomic clocks)
- Timescale realization (UTC-OP)
- Dissemination (time & frequency transfer)
- RNT activities (legal time, speaking clock...)

Space Activities

- Cold atom inertial sensors (gyrometers, gravimeters)
- Celestial reference systems
- Earth rotation

History of Astronomy