CT420 REAL-TIME SYSTEMS

THE ESSENCE OF TIME: FROM MEASUREMENT TO NAVIGATION AND BEYOND

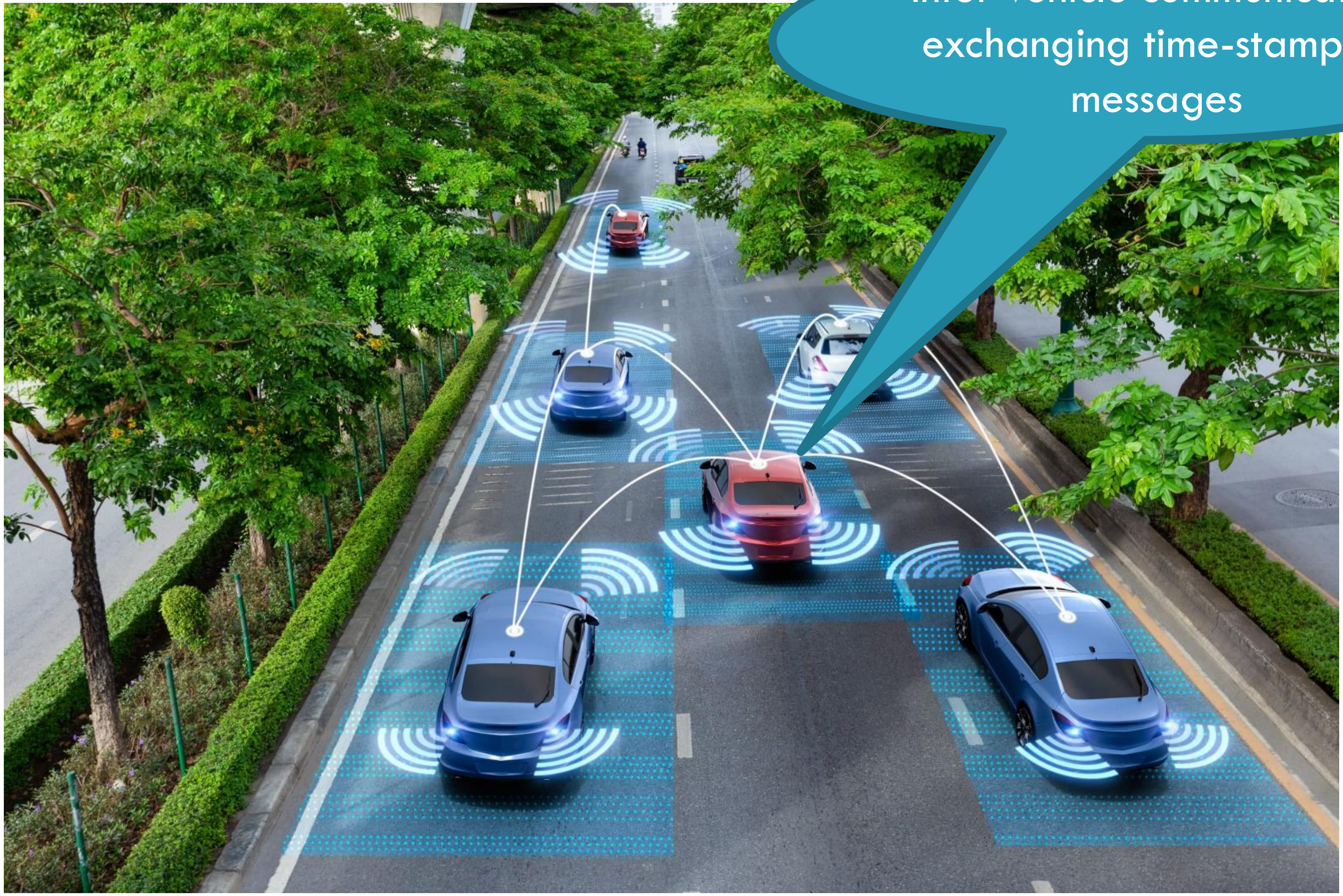
Dr. Michael Schukat

OLLSCOIL NA GAILLIMHE
UNIVERSITY OF GALWAY

Lecture Overview

- This slide deck covers some of the fundamental aspects of "Real-Time", including:
  - What is time?
  - How is time measured?
  - How do (global) navigation systems work?
  - How do computer clocks work?
  - What are quality attributes of clocks and oscillators?

Recap: Autonomous Vehicle - Precise Time (and Location!) Aspects



Inter-vehicle communication exchanging time-stamped messages

Time – Some historic Aspects

- Time is the continued sequence of existence and events that occurs in an apparently irreversible succession from the past, through the present, into the future [Wikipedia]
- Methods of temporal measurement, or chronometry, take two distinct forms:
  - the **calendar**, a mathematical tool for organising intervals of time
  - the **clock**, a physical mechanism that counts the passage of time
- Historically, temporal measurements were based on astronomical observations, e.g.
  - the solar day, i.e. time between two consecutive transits of the sun
  - lunar movements / lunar cycle
  - star constellations, i.e. the 12 signs of the Zodiac

Time – Some historic Aspects

- Measuring time has been a concern in many early civilisations
  - Religious, e.g. Newgrange → Winter soliste
  - Social-economic, e.g. Flooding of the Nile → Agriculture
- Examples
  - From about 3000 BC Chinese used a calendar of 366 days, influenced by the movements of the Sun and the Moon
  - From about 500 BC the Babylonians broke down the year into 12 months of 30 days each, based on astronomical observations
  - Babylonians, Egyptians, and later Greeks and Romans divided the day into twelve hours from sunrise to sunset;
    - but since summer days and winter nights are longer than winter days and summer nights, the lengths of the hours varied throughout the year
    - Hipparchus of Nicaea (190 – c. 120 BC) proposed dividing the day equally into 24 hours, but this idea was not widely adopted until the 14th century when mechanical clocks were introduced

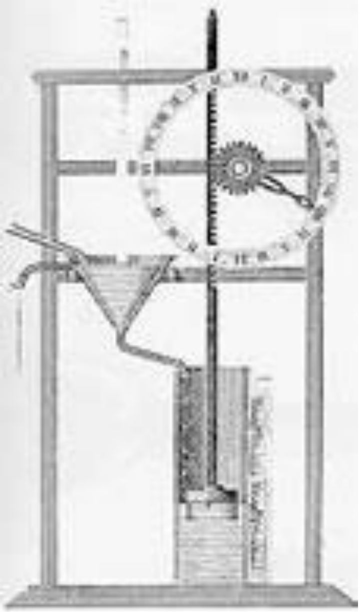
Early Inventions for measuring Time

- From around 3,000 BC oil lamps were used for lighting and religious purposes
  - The level in the oil reservoir was used to measure the passing of time, rather than tell the time of day
- Similarly, marked candles were used for telling the time in China from the sixth century
  - They were later used in England from the 10th century
- However, the rate of burning was subject to draughts and the variable quality of the oil / wax
- In contrast, more accurate sun dials were used by the Egyptians from 1,500 BC to measure the time of day
- Around the same time Egyptians introduced the water clock that allowed time of night measurements (for religious ceremonies), as happened also in Babylon

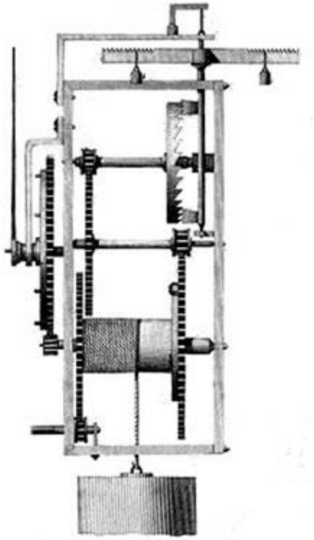
Egyptian Water Clock

Early Inventions for measuring Time

- Water clocks were further mechanised (e.g. by Ctesibius 285–222 BC), resulting in hydraulic clocks
- The hourglass was invented in the 9th century in France, but it did not become widely used until the 14th century, when the technology of glass-blowing developed
    - Subsequently marine sandglasses became very popular, as they were the most dependable measurement of time while at sea, because temperature, humidity and the motion of the ship did not affect them



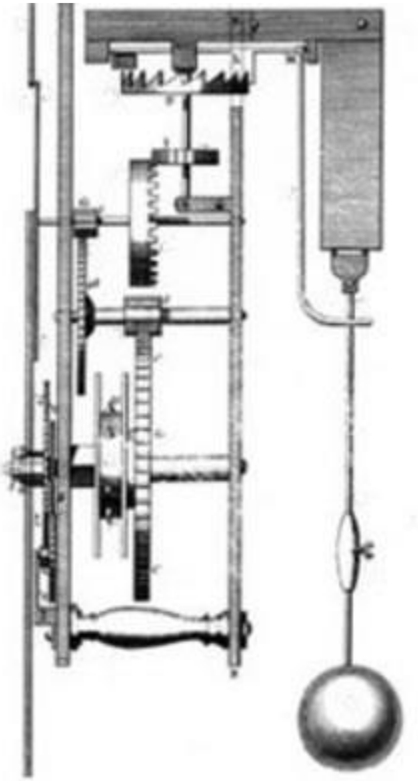
Mechanical Clocks



- Mechanical, gravity-driven clocks appeared in Europe from the 13th century
  - The weight rotates the drum which drives the toothed wheel; it gives impulses to the escapement, that periodically releases the gear train to move forward, advancing the clock's hands
  - See https://www.youtube.com/watch?v=Z6kjtd04by4
- The best clocks had an error of 6-8 minutes per day
- In later developments the heavy drive weights were replaced with a spring, permitted smaller and portable clocks and watches

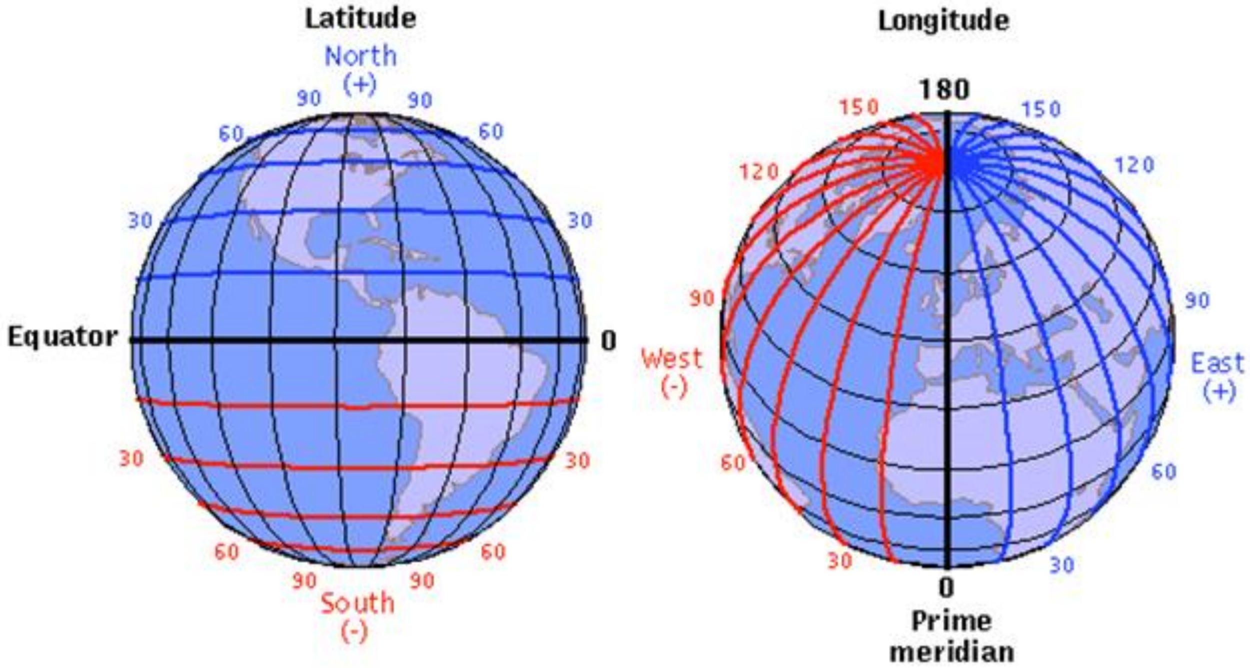
Pendulum Mechanical Clocks

- In 1656 Christiaan Huygens build the first gravity pendulum clock, regulated by a mechanism with a natural period of oscillation
- His design showed an error of less than 1 minute a day
- Later refinements reduced his clock's error to less than 10 seconds a day



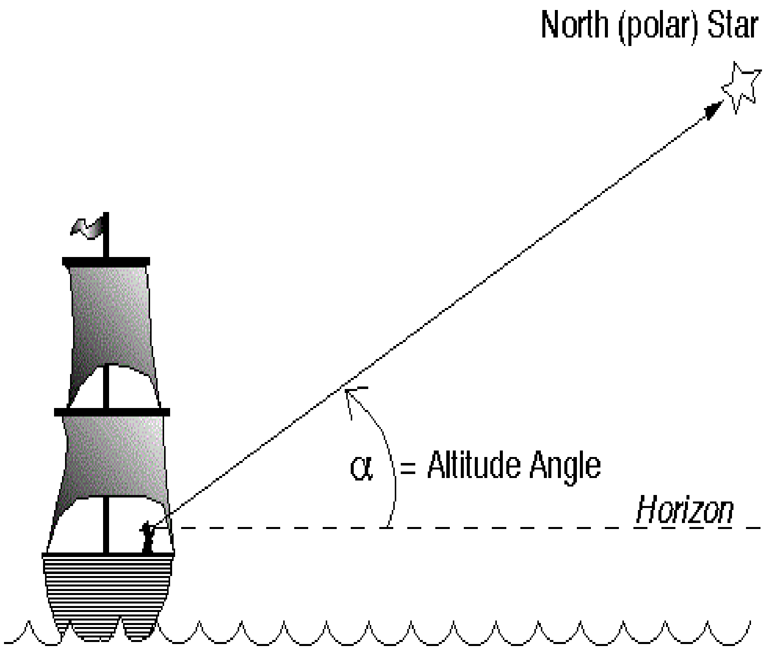
18th Century Global Navigation Problem

- Global (maritime) exploration requires exact maritime navigation, i.e. longitude and latitude calculation
  - Latitude (north-south orientation) is straight forward
  - Longitude (east-west orientation) requires a robust (maritime) clock



Determine Latitude using the North Star

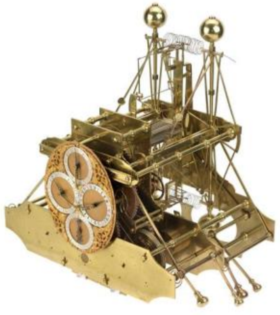
- If you are on Earth's North Pole, the North Star (Polaris) will be directly overhead, which is 90° above the horizon
- If you are on the equator, the North Star cannot be seen, as it is at 0°



- The altitude angle (e.g. measured with a sextant, an astrolabe or balesilha) correlates to the latitude
- The equivalent star in the southern hemisphere is called Sigma Octantis

17th Century versus modern Map of Europe

Time-based Longitude Calculation

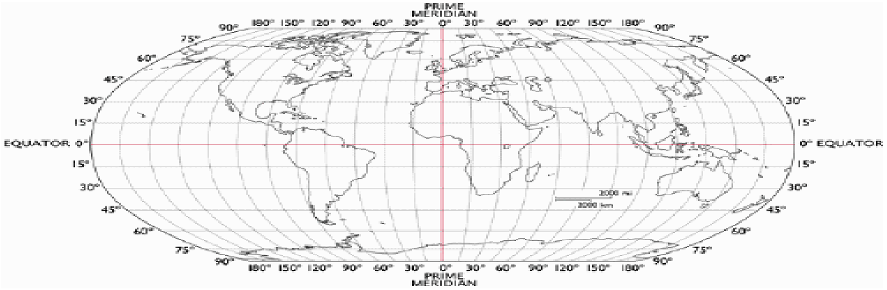


- Set ship clock to reference time before setting sail
  - E.g. Greenwich time ball (→ next slide)
- At sea, compare Greenwich clock time with 'local time’, e.g. mid-day (using a sextant), to give one's position east or west of the home port
  - 360° = 24 hr ➔ 15 ° = 1 hr and 1 ° = 4 minutes
  - E.g. local mid-day = 4pm GMT ➔ location is 60 ° West

- Problem: Getting a clock to work reliably on a ship
  - Clock operation is impacted by to ship’s movement, humidity, temperature changes, etc.
  - **4 minutes clock error ➔ 111.31 Km navigation error along the equator**

- Lincolnshire carpenter and clock maker, John Harrison, http://www.rmg.co.uk/Harrison, invented the marine chronometer
  - His clock H4 won him the great Longitude Prize by the British Government of £20,000. .. in 1759
  - His designs had reduced friction and build-in temperature compensation, achieving an accuracy of 1 second per month

History of Time: Greenwich

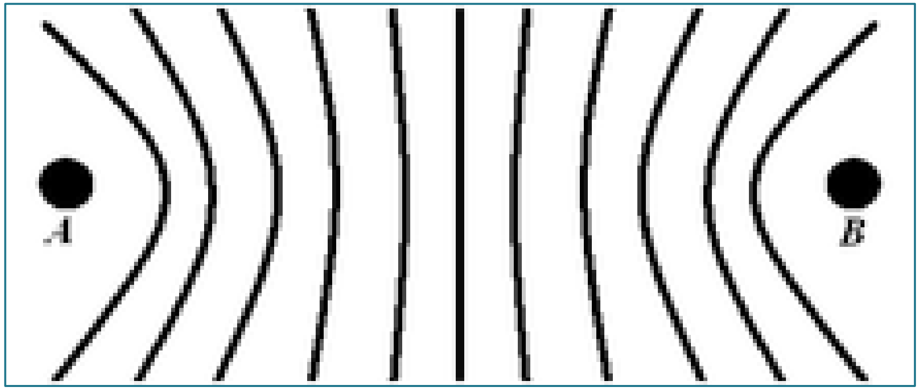


- Home of time & the prime meridian
- Longitude 0 & GMT (Greenwich Mean Time) agreed in 1884
  - GMT driven by expansion of railway system and need for national/international consistency
- "Timeball" rises and falls at 13:00 hrs
  - Then site of London docks
  - In service since 1833

Ground- and Radio-based GNS

- With global transport, and long-range aviation there was obviously a need for accurate global navigation systems (GNS) that were available 24/7
- The outbreak of WW2 also required accurate navigation for military ships and aircraft
- Ground-based navigation systems like LORAN (Long Range Navigation), developed by the US in 1940, and in use until recently, required fixed terrestrial longwave radio transmitters, and receivers on board of ships and planes
- Principle:
  - A master with a known location broadcasts a radio pulse
  - Multiple slave stations with a known distance from the master send their own pulse, upon receiving the master pulse
  - A receiver receives master and slave pulses and measures the delay between them
  - This allows the receiver to deduce the distance to each of the stations, providing a fix
    - Also called hyperbolic navigation or multilateration

Example Hyperbolic Navigation (Source: Wikipedia)

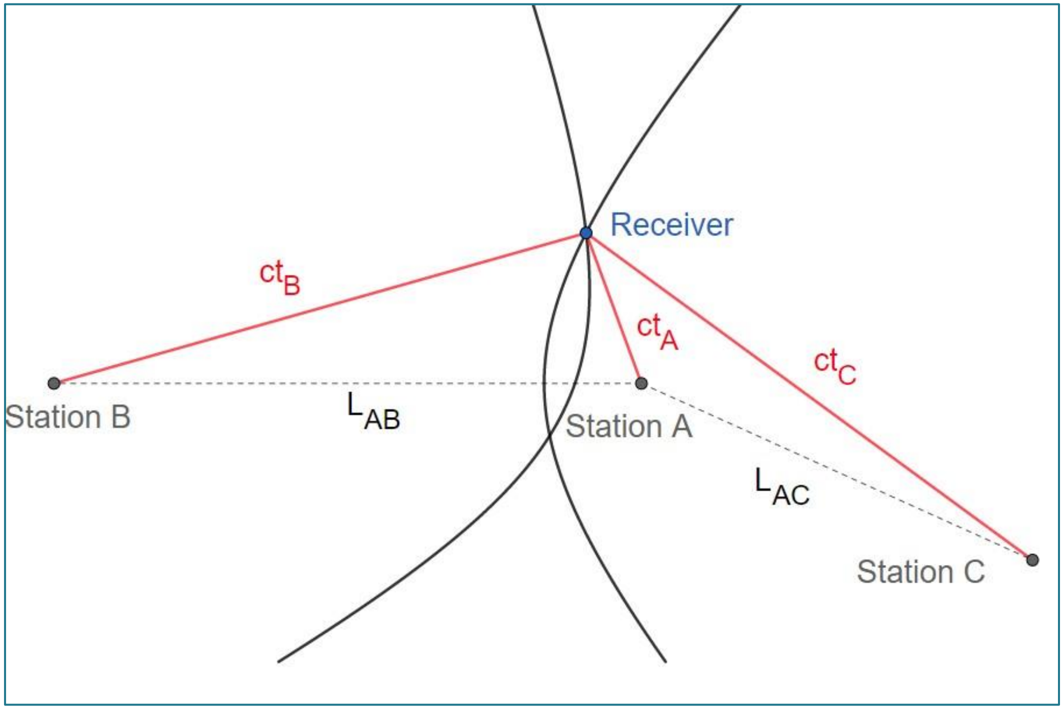


D = 0

- Consider two radio transmitters master A and slave B located at a distance of 300 km
  - The radio pulse from A will take ~1 ms to reach B (i.e., speed of light), at which point B will send another radio pulse
- A receiver receives these pulses and measures a delay D of 1.5 ms between their respective times of arrival (TOA)
- This implies that the difference in its distance to the two stations is 150 km
  - 1.5 ms – 1 ms = 0.5 ms equivalent to 150 km
- There are an infinite number of locations where that delay could be measured
  - E.g. 75 km from station A and 225 from station B, or 150 km / 300 km, etc.
- When plotted on a chart, the collection of possible locations for any given time difference D forms a hyperbolic curve (see hypothetical curves for different D in the diagram above)
- In order to take a fix, the receiver takes another measurements using another (second) slave
  - The intersections of two sets of curves result in two possible locations
  - Using a different third measurement or some other form of navigation, e.g. dead reckoning (extrapolation from last known position), one of these possible positions can be eliminated

Intersection of 2 hyperbolic Curves

- Master (Station A) and Slaves (Station B / C) with respective known distances L_{AB} and L_{AC}
- Receiver measures the difference of arrival times, i.e. t_C - t_A and t_B - t_A, resulting in two hyperbolic curves with 2 intersections
- One intersection is further eliminated, leaving the Receiver's position (i.e. longitude and latitude) only
- It's distance from A, B and C is ct_A, ct_B and ct_C respectively



- Generally, if d is the number of receiver coordinates sought, we need at least m = d + 1 TOA (e.g. m = 3 for longitude and lattitude)
- Larger m allow to compensate for measurement errors

LORAN Coverage in WW2

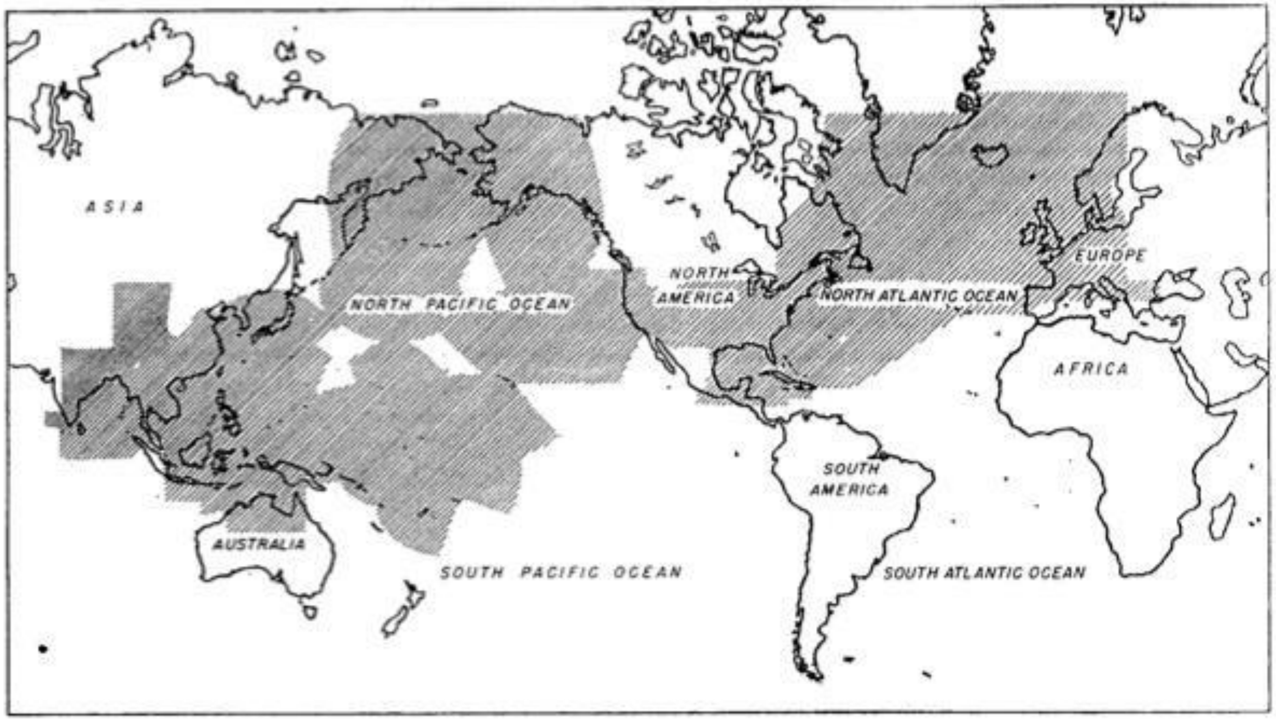
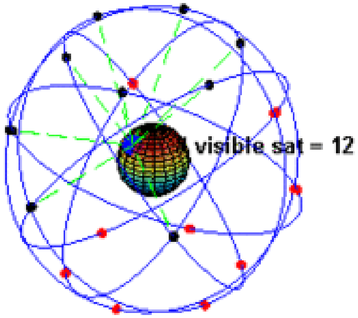


Fig. 1. The shaded area shows where loran can be used for navigation at night (as of August 15, 1945). By day the service area is about one fourth as great.

Source: https://ethw.org/Milestones:Loran,_1940_-_1946

Global Navigation Satellite Systems (GNSS) Overview



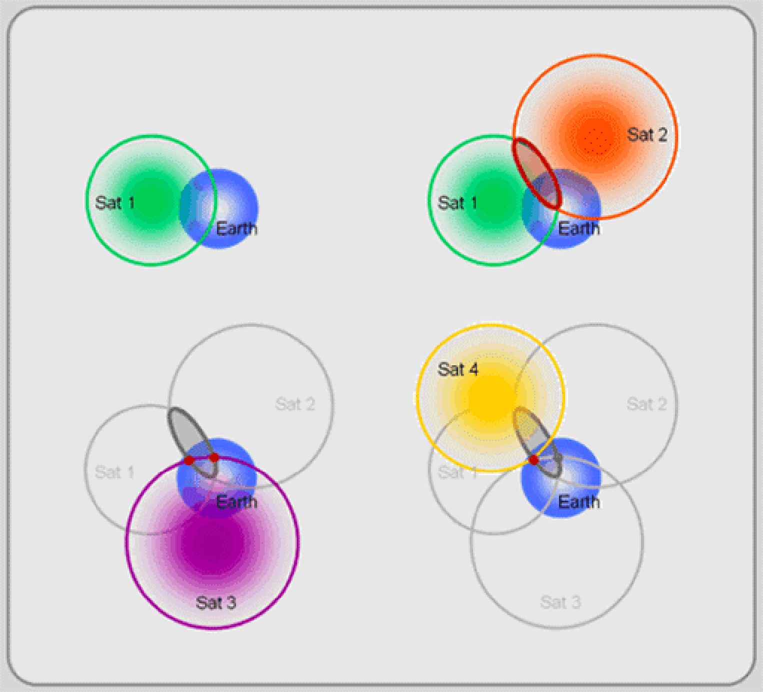
- Various different systems, e.g. GPS (NAVSTAR), Glonass and Galileo
- Based on fleets of dedicated satellites on well-known orbits, , i.e.
  - IRNSS (India) and Bei-Dou-2 (China) satellites sit on geostationary orbits above their countries and are not world-wide systems
  - GPS (US), Glonass (Russia) and Galileo (EU) satellites sit on non-geostationary orbits and allow global navigation (see animation)
- No master / slave approach, instead a receiver calculates the time-of-flight of radio signals coming from multiple visible satellites
  - At any given time 4+ satellites must be visible to a GNSS user
- These periodical broadcasts contain a satellite's orbital data (from which the position of the satellite can be calculated) and the precise time when the signal was transmitted
  - Satellites have atomic clock on board
  - A GNSS receiver consists of a radio receiver, a quartz clock and a computer to process the satellite data

➔ **High quality & cheap source of accurate time (±0.1 - ±1ms best case) and location**

➔ **Not working indoors though…**

GNSS (i.e. GPS) Details

- Assume a GPS receiver R with its's clock being synchronised to the satellites' (Sat 1, … Sat 4) atomic clocks (that's a simplification for now)
- It determines Sat 1's signal time-of-flight upon arrival, and (by multiplying it with the speed of light c) its distance d_1 from Sat 1
- Sat 1's orbital position in space is known, so R's location must be somewhere on the surface of a sphere with radius d_1 and with Sat 1 in its centre
- Repeating the process with Sat 2's signal results in a second sphere that intersects with the first one, the overlapping ring indicating the possible location of R



- Repeating the process with Sat 3's signal will narrow down R's possible location to 2 points
- Repeating the process with Sat 4's signal will narrow down R's possible location to a single point

The Real Thing

- There are four unknown variables that need to be established:
  - R's coordinates in space: *x*, *y* and *z*
  - The offset of R's local clock t_c (difference in time in relation to the satellites' atomic clocks)
- Hence, we need 4 signals resulting 4 equations as follows:

$$d_1 = c\left(t_{t,1} - t_{r,1} + t_c\right) = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + \sqrt{(z_1 - z)^2}}$$

$$d_2 = c\left(t_{t,2} - t_{r,2} + t_c\right) = \sqrt{(x_2 - x)^2 + (y_2 - y)^2 + \sqrt{(z_2 - z)^2}}$$

$$d_3 = c\left(t_{t,3} - t_{r,3} + t_c\right) = \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + \sqrt{(z_3 - z)^2}}$$

$$d_4 = c\left(t_{t,4} - t_{r,4} + t_c\right) = \sqrt{(x_4 - x)^2 + (y_4 - y)^2 + \sqrt{(z_4 - z)^2}}$$

- d_n is R's distance from satellite n
- $t_{t,n}$ and $t_{r,n}$ are the signal transmit and receive timestamps respectively for satellite n, with the latter having an offset error of t_c (i.e. we don't need a synchronised receiver clock)
- x_n, y_n, and z_n are satellite n's coordinates in space
- Solving these equations does not only provide the receiver's location, but also allows to synchronise the receiver's local clock by incorporating t_c

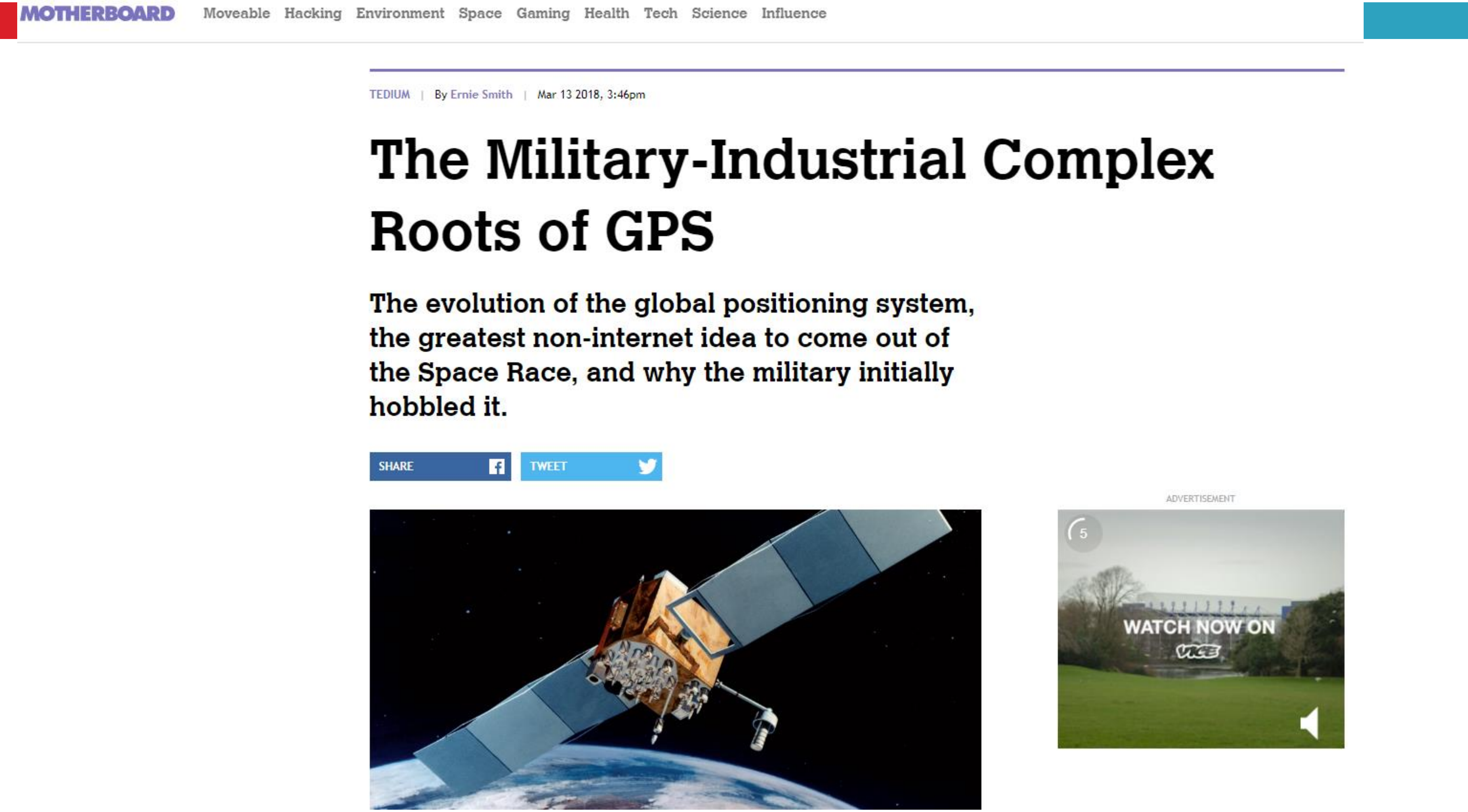
GNSS Features and Challenges

- GPS allows localisation with a maximum error of about 15 meters, which is also a consequence of Ionospheric interferences with the signals (→ ionospheric delays)
  - Ionosphere is a layer 60-2000 km above the earth's surface
  - Signals passing through that layer are delayed with those from satellites right above a receiver being less affected than those from satellites at the horizon (signals travel a shorter distance through the ionosphere)
  - 1 nanosecond delay == 1 foot miscalculation
- Handled by ionospheric correction mechanisms
- Other systems have similar error margins

GPS: Relativistic Effects

- Einstein's theory of Relativity explains some unwanted phenomena:
  - Moving clocks go slower than stationary clocks
    - Satellites' atomic clocks go about 7 microseconds per day slower than on earth
  - On the other hand, a clock goes slower the closer it gets to a massive object (i.e. earth)
    - making the satellites' clocks go 45.9 microseconds per day faster
- Both result in a total error of about 37 microseconds per day, which is compensated for

The History of GPS



TEDIUM | By Ernie Smith | Mar 13 2018, 3:46pm

The Military-Industrial Complex Roots of GPS

The evolution of the global positioning system, the greatest non-internet idea to come out of the Space Race, and why the military initially hobbled it.

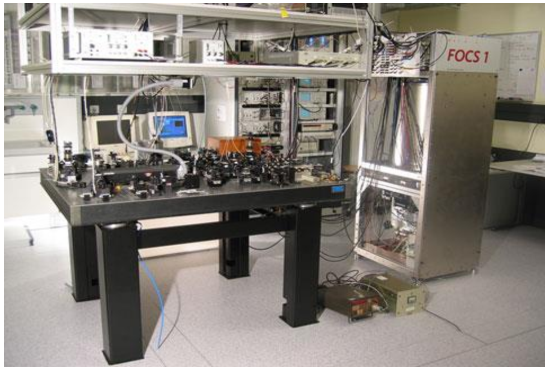
Differential GPS (DGPS)

- An enhancement to GPS which provides improved location accuracy (from 15 m down to 1 - 3 cm)
- DGPS Uses a network of fixed ground-based reference stations that broadcast the difference between the positions indicated by GPS and their known fixed positions, thereby allowing receivers to correct their location estimate
- Widely used in military and civilian applications (e.g., autonomous vehicles in transport and smart agriculture

GPS Spoofing and GPS Jamming

- **GPS spoofing** is when a counterfeit radio signal is transmitted to a receiver antenna to override a legitimate GPS satellite signal
- **GPS jamming** drowns out the signals from GPS satellites, rendering the receiver unable to calculate its position or time accurately
- Both are a form of cyberattack perpetrated by bad actors attempting for example to steer off course
  - freight ships (→ pirate attacks)
  - drones and precision-guided bombs (→Ukraine conflict)

FYI: Atomic Clocks



- A clock whose timekeeping mechanism is based on the interaction of electromagnetic radiation with the excited states of certain atoms
- They are the most accurate time and frequency standards known, and are used as primary standards for international time distribution services
- More explanations: https://www.timeanddate.com/time/how-do-atomic-clocks-work.html

GMT, UTC and TAI

- GMT (Greenwich Mean Time)
  - This original time standard set at the Royal Observatory in Greenwich is based on astronomical observations
  - It is based on the mean solar time at the Prime Meridian (0° longitude), and less precise than modern atomic time standards
- TAI ("temps atomique international")
  - TAI is a high-precision time standard based entirely on ~400 atomic clocks across 60+ locations
- UTC (Coordinated Universal Time)
  - The current primary global time standard
  - It combines the high precision of TAI with occasional leap seconds to stay in sync with the Earth's rotation
    - The Earth's rotation slows down. To keep UTC aligned with mean solar time, we add leap seconds to account for these variations
    - E.g., the time of a full year (as measured today) covered 400 days 300 million years ago

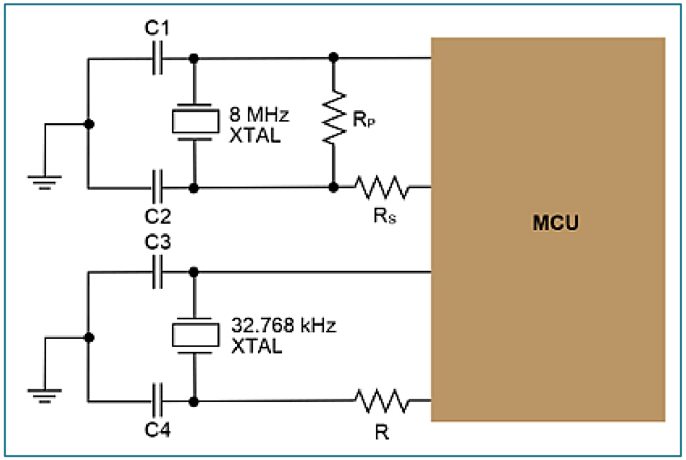
UTC versus TAI, and Adding a Leap Second

2016-12-31 23:59:59 UTC = 2017-01-01 00:00:36 TAI
2016-12-31 23:59:60 UTC = 2017-01-01 00:00:36 TAI
2017-01-01 00:00:00 UTC = 2017-01-01 00:00:37 TAI

- As of today, the difference between TAI and UTC is 37 seconds, with TAI being ahead of UTC by this amount
- The last time, a leap second was added, was in December 31st 2016

Computer Clocks

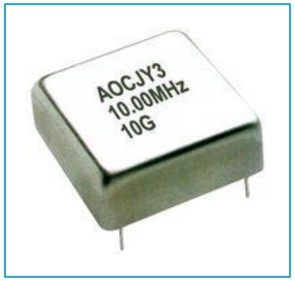
- Most commonly consist of quartz crystal and a counter
- Crystal oscillates at defined rate (Hz)
  - generates a consistent tick
  - increments a software counter
- Counter value
  - translated to time standard e.g. UTC
- Crystal *Quality* described by *accuracy & stability*



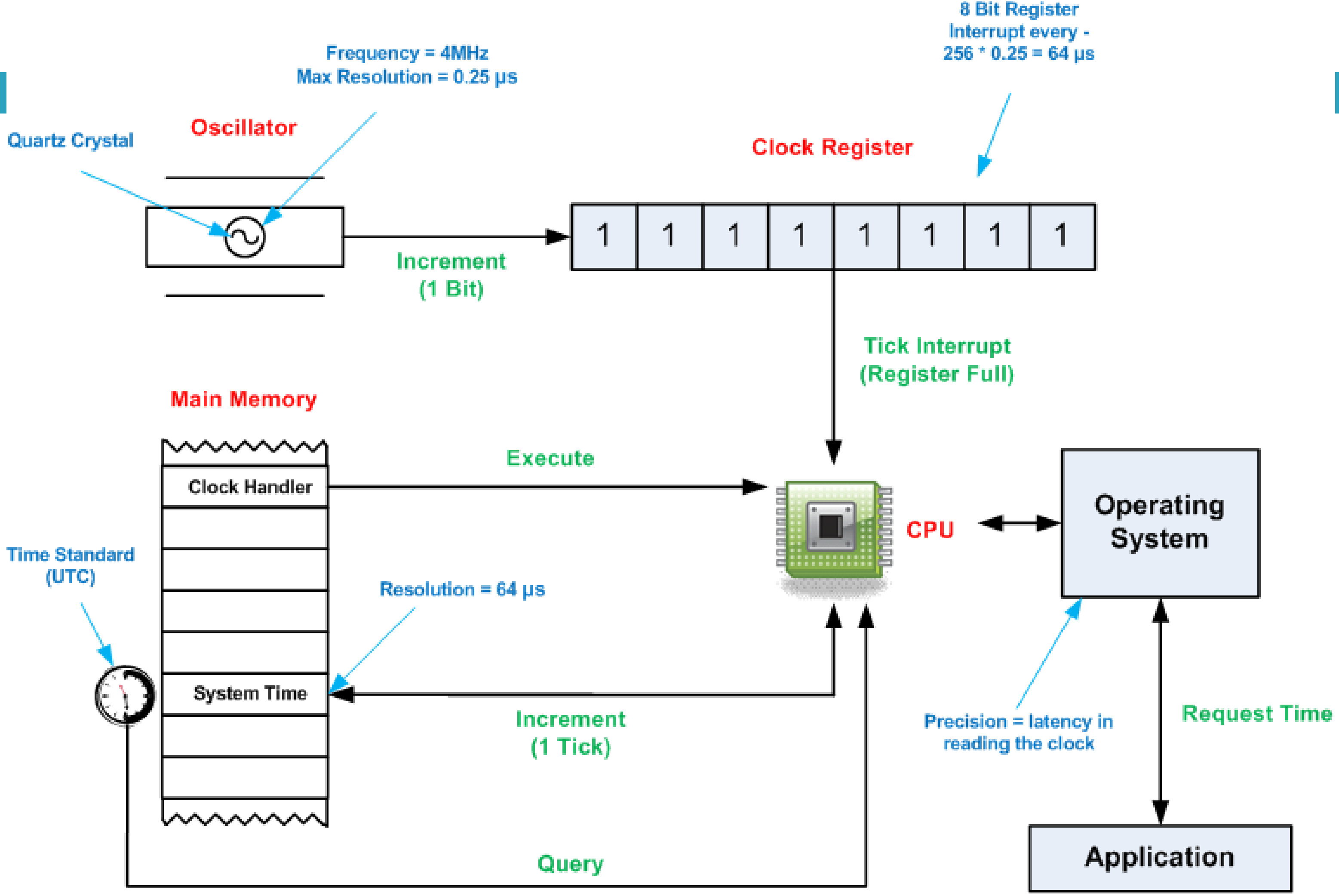
Crystal Quality

- *Accuracy* relates to how close the crystal frequency is to its rated value
- *Stability* relates to how frequency *varies over time, as crystal is influenced by parameters such as:*
  - **Temperature,** e.g. frequency may change by 2 ppm / degree Celsius
  - Ageing, usually only significant over long timescales
  - DC power variations
- Obviously a crystal with poor quality results in a poor computer clock

Crystal Options for a Computer Clock



- Off-the-shelf 20 Cent oscillator
  - Gives you a clock accuracy of +/- 2000 ms / day
- Temperature Compensated Crystal Oscillator (TCXO)
  - Gives you a clock accuracy of +/- 100 ms / day
- Oven Controlled Crystal Oscillator (OCXO)
  - Gives you a clock accuracy of 10 µsec / day
- **Other Options:**
  1. Atomic clock ($50,000 - $100,000)
  2. GNSS receiver (based on atomic clock), but doesn’t work indoors
  3. DCF77 radio receiver, but only works reliably in central Europe
     1. DCF77 is a German longwave time signal and standard-frequency radio station (both time signal and frequency generation are linked to an atomic clock)
  4. Software-based approach (later)


Frequency = 4MHz
Max Resolution = 0.25 μs
8 Bit Register
Interrupt every -
256 * 0.25 = 64 μs
Quartz Crystal
Oscillator
Clock Register
1
1
1
1
1
1
1
1
Increment
(1 Bit)
Tick Interrupt
(Register Full)
Main Memory
Execute
Clock Handler
CPU
Operating System
Time Standard
(UTC)
Resolution = 64 μs
System Time
Increment
(1 Tick)
Precision = latency in
reading the clock
Request Time
Query
Application

Clock Handler Pseudo Code

- Consider the following data structure to hold time:
- `timespec` structure (counts seconds and nanoseconds)

  -
    ```
    struct timespec{
      time_t tv_sec;
      time_t tv_nsec;
      }
    ```
- `time_t` is simply an integer type (32 or 64 bits)
- In many OS `timespec` structure specifies the number of seconds and nanoseconds since the base time of 00:00:00 GMT, 1 January 1970

Clock Handler Pseudo Code

```
…
// Global variable to store time
struct timespec Master_clock;
…
#define CLOCK_TICK_INCREMENT         64000
#define ONE_SECOND_IN_NANO_SEC       1000000000
…
void init_time_struct(struct timespec *clock) {
         clock->tv_sec = 0;
         clock->tv_nsec = 0;
}
…
__interrupt void clock_handler() {
         Master_clock.tv_nsec += CLOCK_TICK_INCREMENT;
         while (Master_clock.tv_nsec >= ONE_SECOND_IN_NANO_SEC) {
                   Master_clock.tv_nsec -= ONE_SECOND_IN_NANO_SEC;
                   Master_clock.tv_sec++;
         }
}
```

Clock Accuracy and Clock Resolution

- Let $C(t)$ be a perfect (or true) clock providing a time reference
- A clock $C_i(t)$ is called **correct** at a time t if $|C_i(t) - C(t)| < e$ with a tolerable error e
- **Accuracy** (sometime called **clock uncertainty**) describes the maximum deviation over time of a clock $C_i(t)$, *i.e. for* t_0 *and* t_1 *with* $t_1 > t_0$:

$$|[C(t_1) - C(t_0)] - [C_i(t_1) - C_i(t_0)]| < max$$

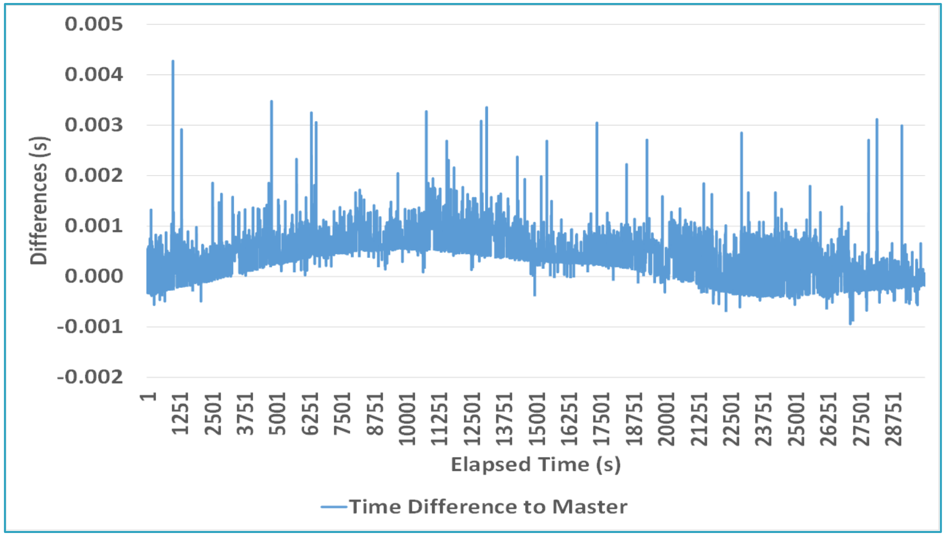
  - E.g., the Huygens pendulum clock had a clock uncertainty of approx. 5 minutes after one month of operation
- The smallest possible increase of time *provided by a clock* is called **resolution**
  - E.g., clocks with hands (hours, minutes, seconds) would have a resolution of 1 second

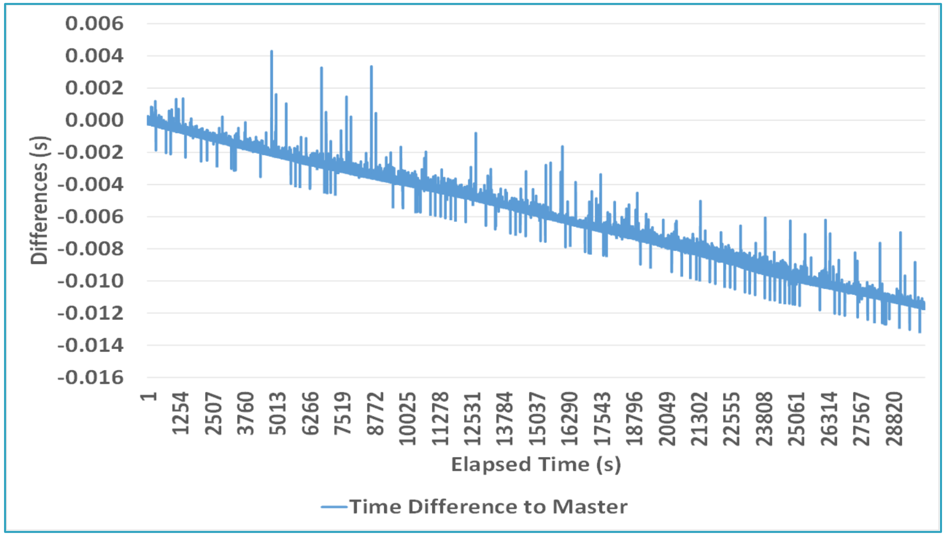
Clock Offset and Clock Skew

- **Offset** is the actual difference between the time reported by clock C_i, i.e. C_i (t), and the true clock (e.g., UTC) at true time t
  - There is also the *relative offset* between clocks C_1 and C_2: $C_1(t) - C_2(t)$
- **Skew** is the difference in the (tick) frequency between clock C_i and a true clock
  - Expressed in ppm
    - E.g. +/-12 ppm skew results in +/- 1 sec offset per day
  - There is also the *relative skew* between clocks C_1 and C_2 : $C_1'(t) - C_2'(t)$
- In **clock synchronisation** offset and skew of a clock C_i in relation to a time reference are to be reduced below a nominal tolerance

Offset, Skew and Drift of typical Embedded Systems Clocks

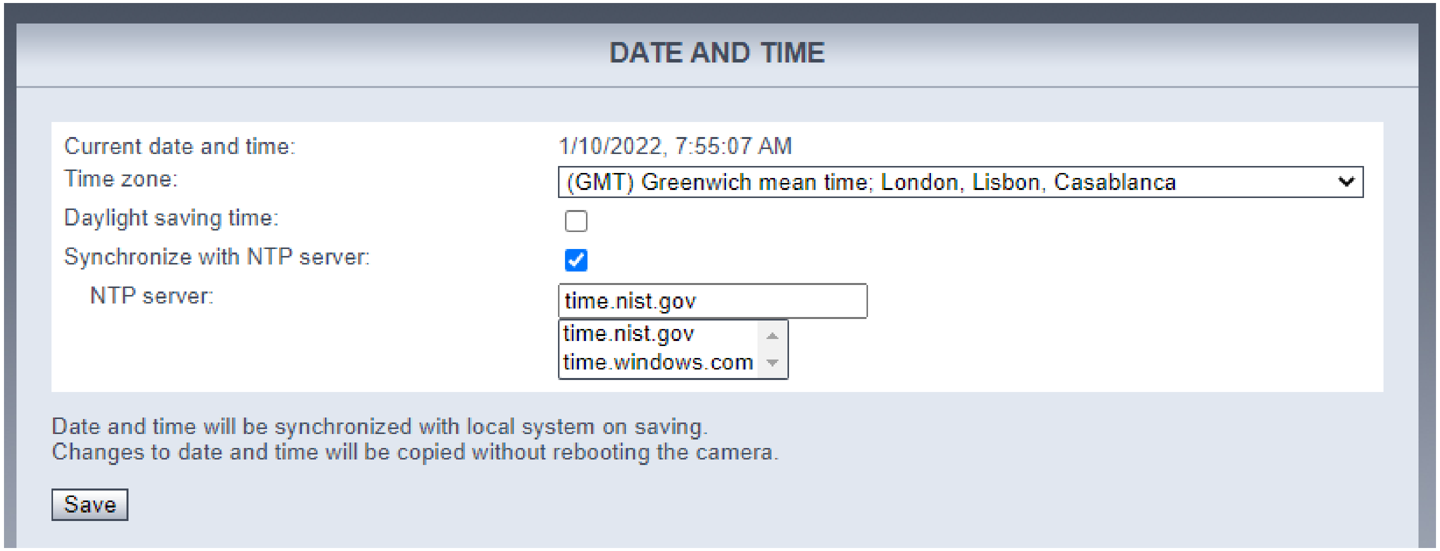
- The diagrams shows the results of two experiments, where the clock offset of two embedded systems' clocks were determined over a 24 hours period; an accurate time reference (UTC) was based for the calculations
- Top: The clock of a Raspberry Pi 4 shows an oscillating clock offset resulting from a variable skew, which points to a temperature-induced stability problem of its oscillator (i.e. night-day room temperature changes)
- Bottom: The clock of an Intel Galileo shows a linearly increasing clock offset (12 ms offset after just 24 hours of operation) and therefore constant skew, resulting from an oscillator with good stability but poor accuracy





Outlook for next Lecture

- Consider an in-door network-connected security camera system that records, timestamps and processes video frames
- The camera’s quartz oscillator is useless for timestamping
- GPS doesn’t work because it is an in-door camera
- Therefore, **network-based time synchronisation** is used (see also the configuration screen below)
- Such time synchronisation protocols are covered in the next lecture



DATE AND TIME

Current date and time: 1/10/2022, 7:55:07 AM
Time zone: (GMT) Greenwich mean time; London, Lisbon, Casablanca
Daylight saving time: ☐
Synchronize with NTP server: ☑
NTP server: time.nist.gov
time.nist.gov
time.windows.com

Date and time will be synchronized with local system on saving.
Changes to date and time will be copied without rebooting the camera.