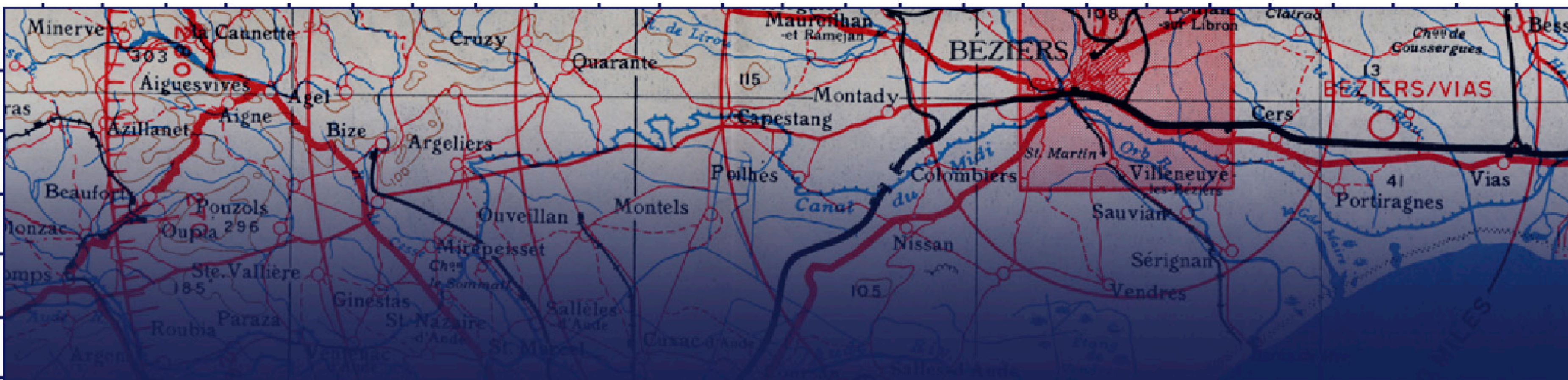


TIME *and* NAVIGATION

The Untold Story of Getting From Here to There

Andrew Johnston
Smithsonian National Air and Space Museum

Time and Navigation:
The Untold Story of Getting From Here to There.

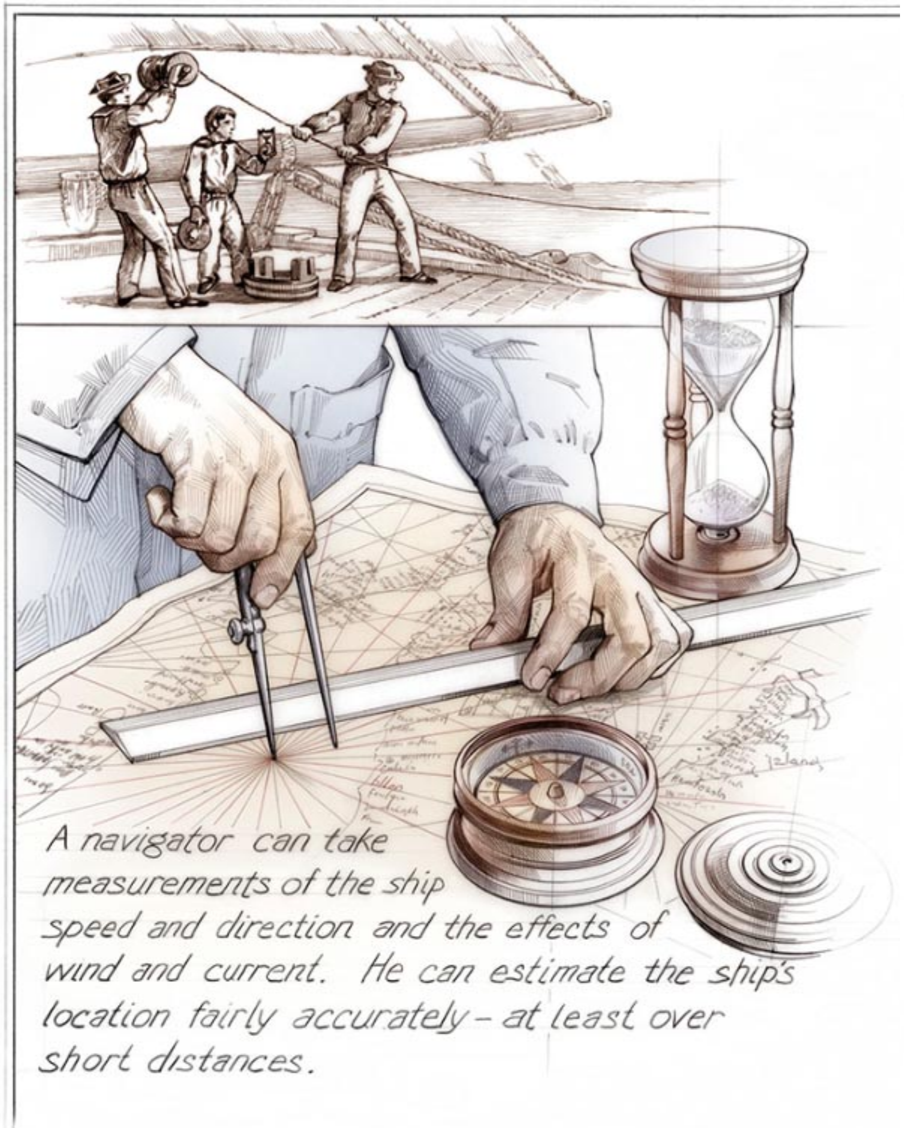
An enduring connection between determining time and position.

“If you want to know where you are, you need a reliable clock.“

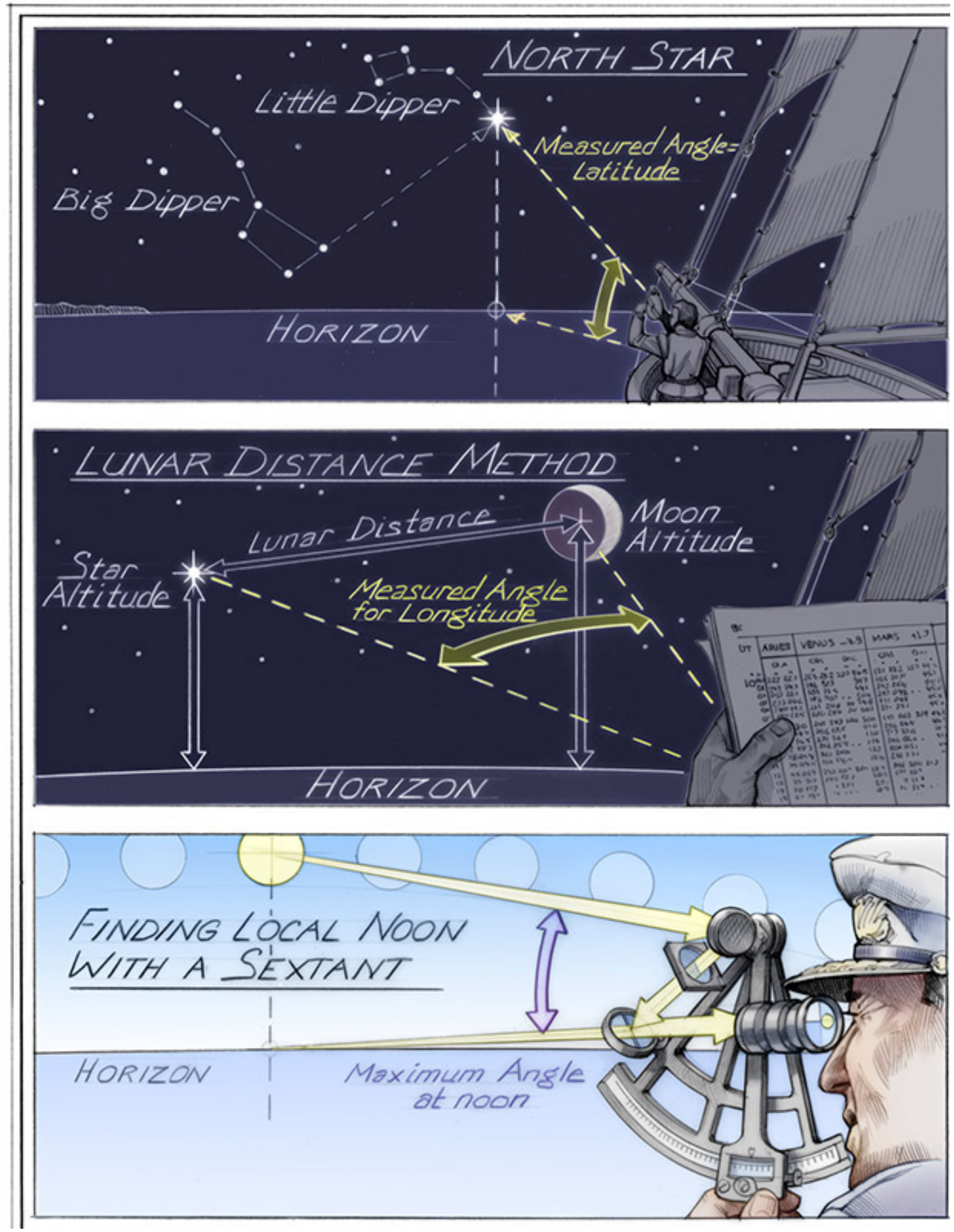
WELCOME TO

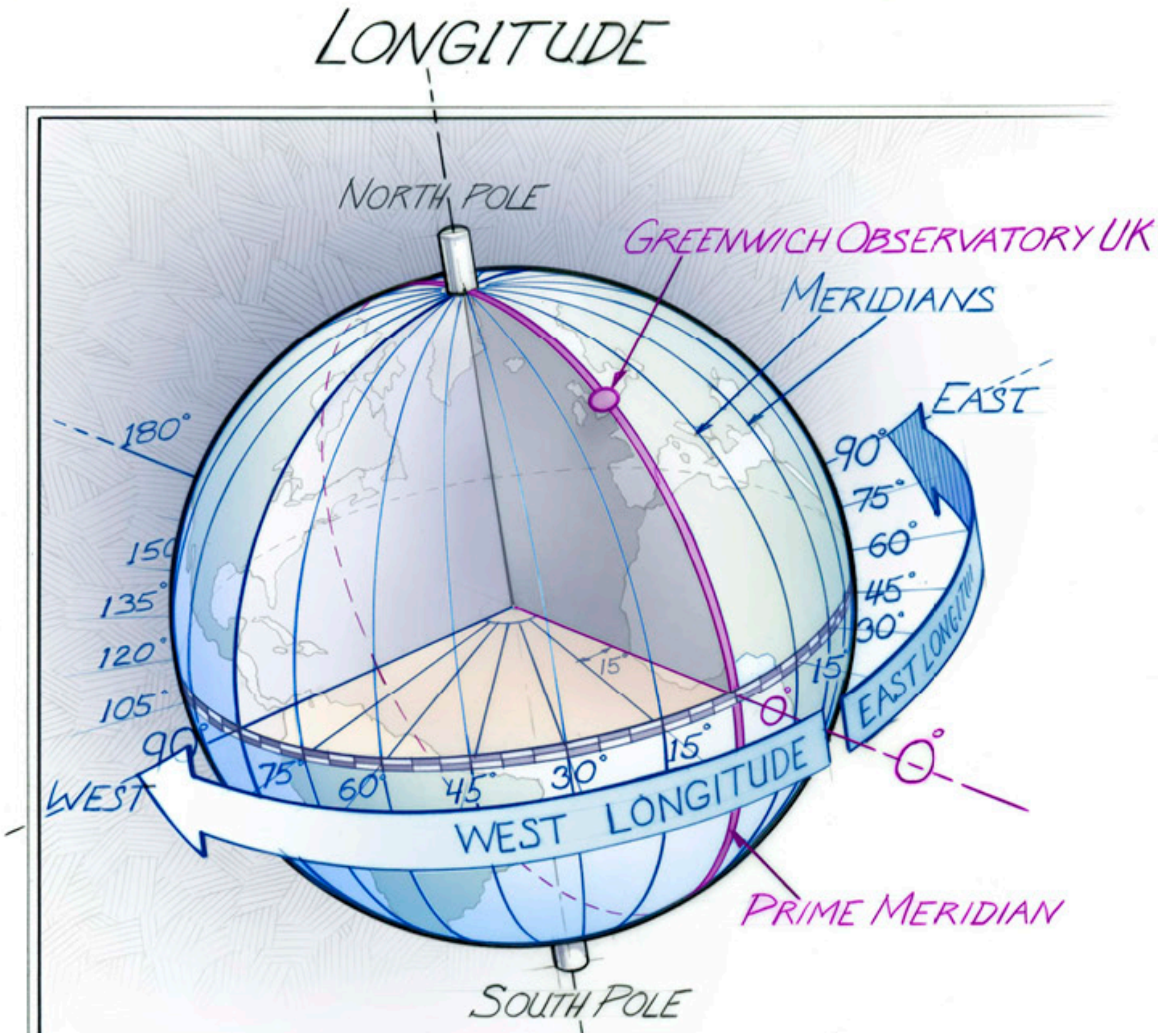
TIME *and* NAVIGATION

DEAD RECKONING AT SEA

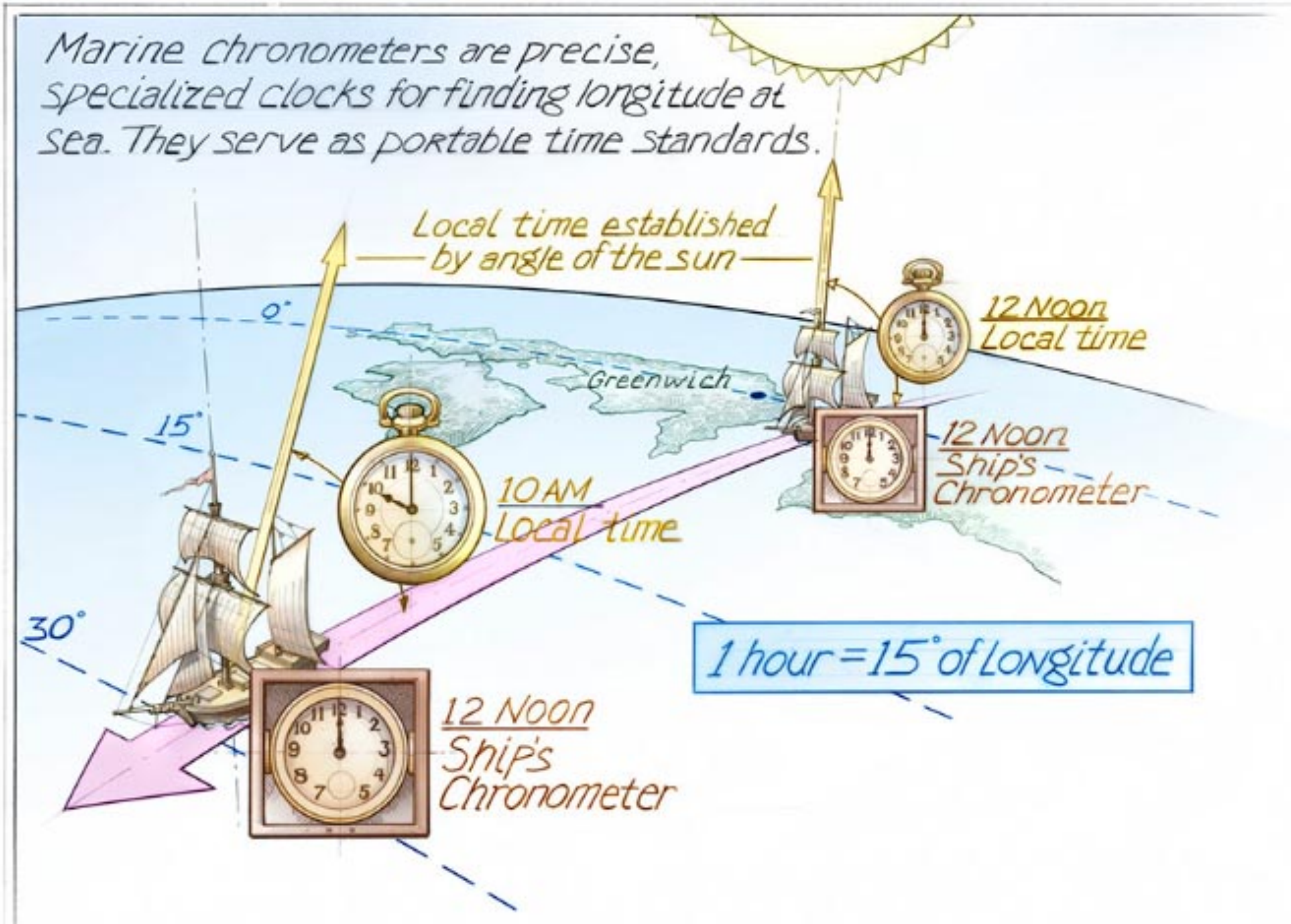


CELESTIAL NAVIGATION AT SEA

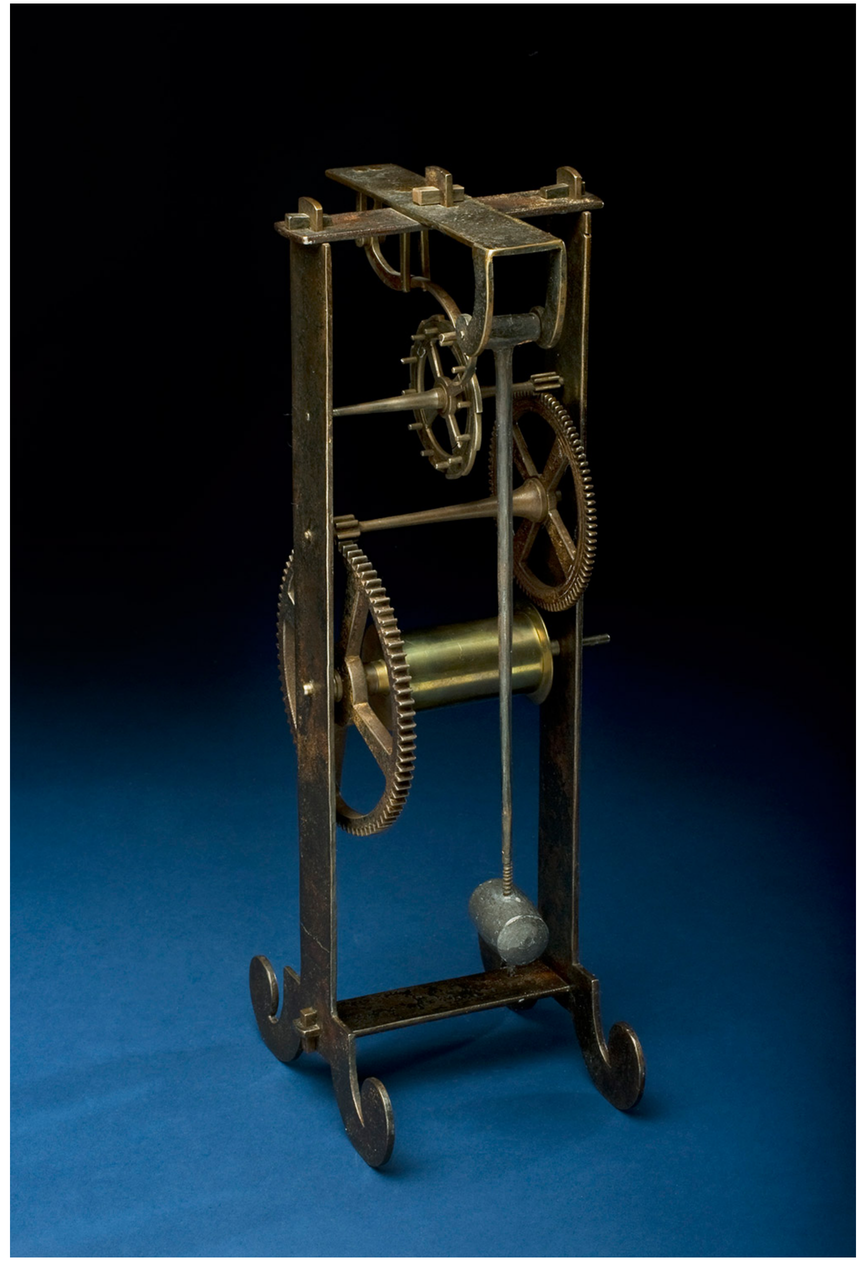



LONGITUDE
NORTH POLE
GREENWICH OBSERVATORY UK
MERIDIANS
EAST
180°
90°
75°
60°
45°
30°
15°
150
135°
120°
105°
90°
WEST
75°
60°
45°
30°
15°
0°
WEST LONGITUDE
0°
PRIME MERIDIAN
SOUTH POLE

USING A MARINE CHRONOMETER

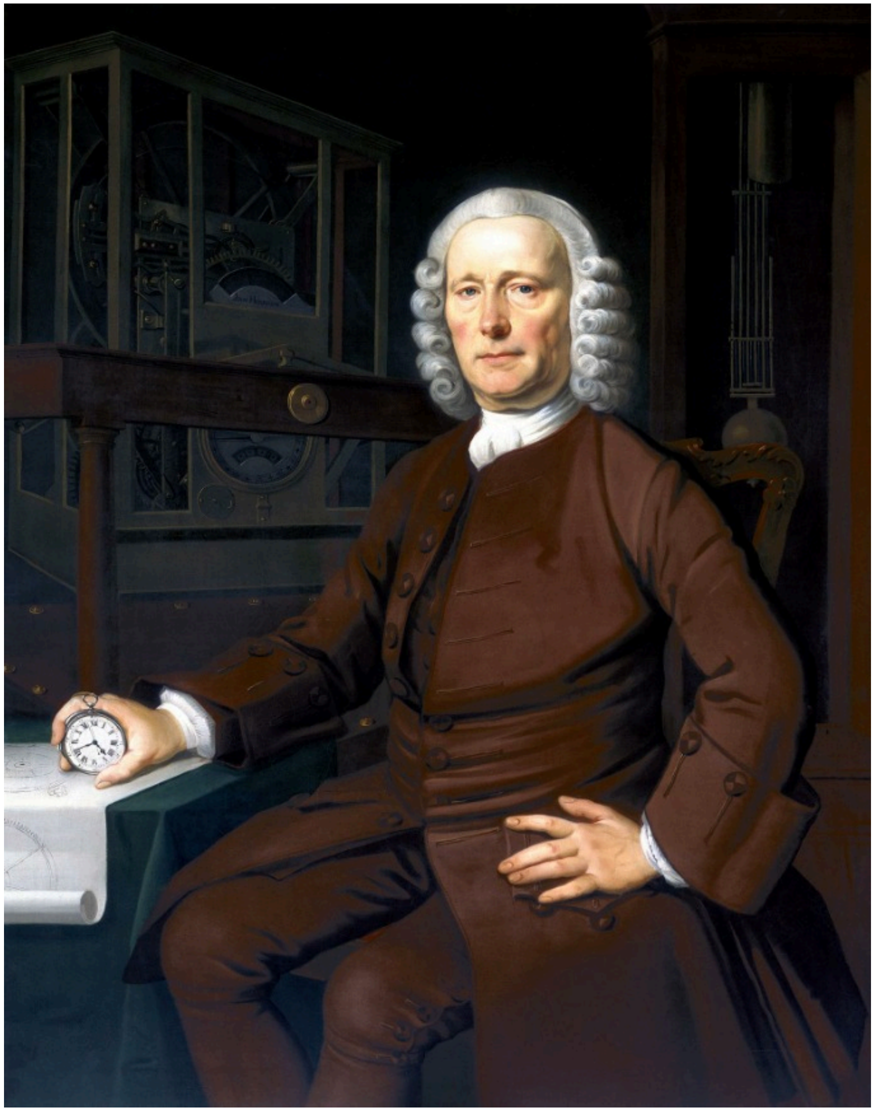


Replica of Galileo's Giovilabio



Replica of Galileo Pendulum Clock Design from 1642

Navigation at Sea



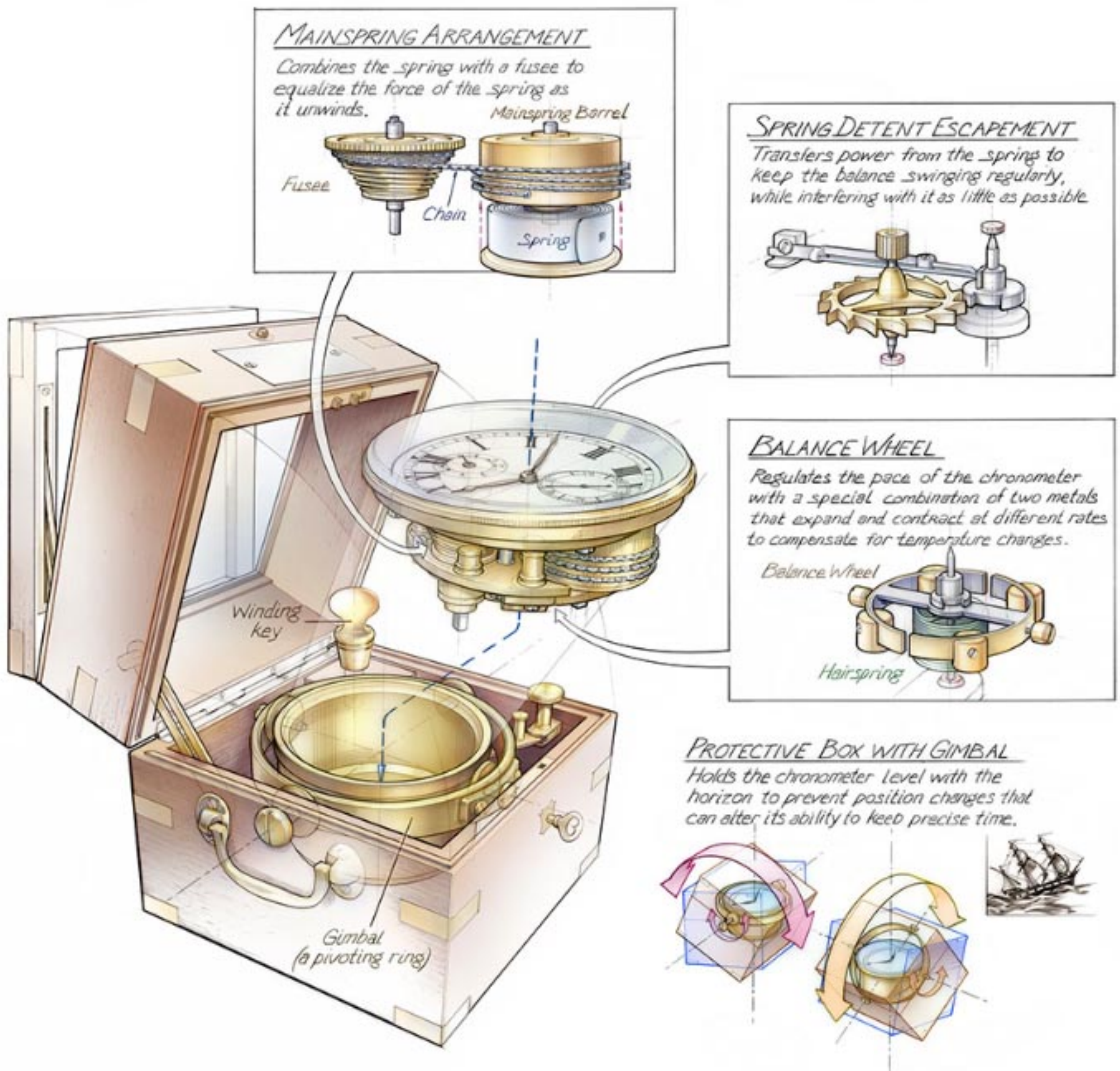
John Harrison, five clocks 1735-1772.
(portrait 1766)

Chronometer, Thomas Mudge Jr. Number 14 (1802)

Navigation at Sea

Bond Chronometer (1812)

Chronometer Movement,
John Roger Arnold
(about 1825)

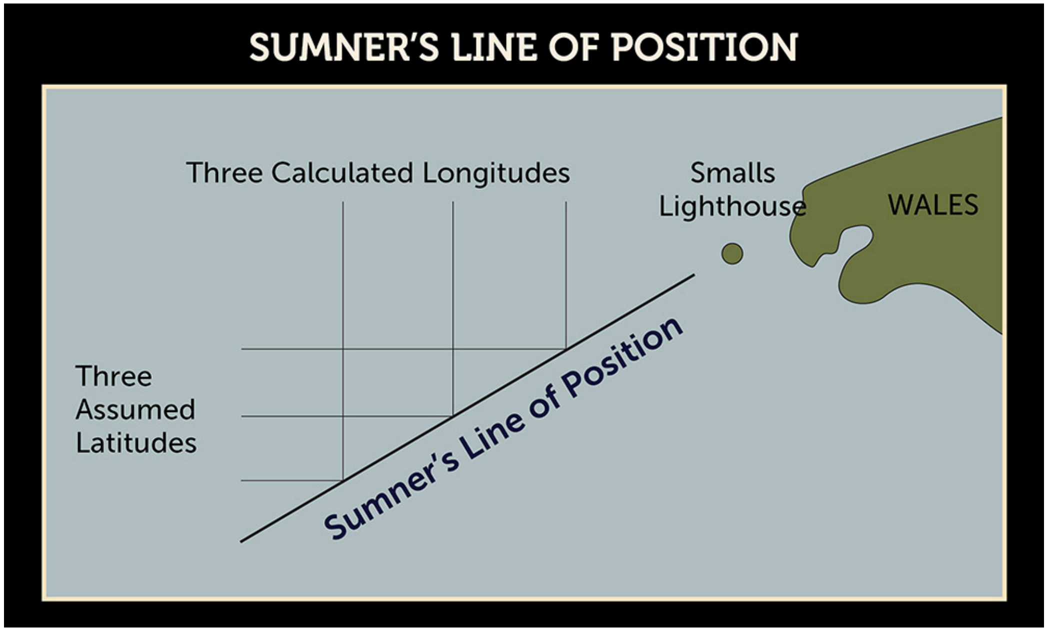

MAINSPRING ARRANGEMENT
Combines the spring with a fusee to equalize the force of the spring as it unwinds.
Mainspring Barrel
Fusee
Chain
Spring
SPRING DETENT ESCAPEMENT
Transfers power from the springs to keep the balance swinging regularly, while interfering with it as little as possible
BALANCE WHEEL
Regulates the pace of the chronometer with a special combination of two metals that expand and contract at different rates to compensate for temperature changes.
Balance Wheel
Hairspring
Winding key
Gimbal (a pivoting ring)
PROTECTIVE BOX WITH GIMBAL
Holds the chronometer level with the horizon to prevent position changes that can alter its ability to keep precise time.

Navigation at Sea

Ramsden Dividing Engine (1775)

Sextant, Jesse Ramsden
(after 1775)

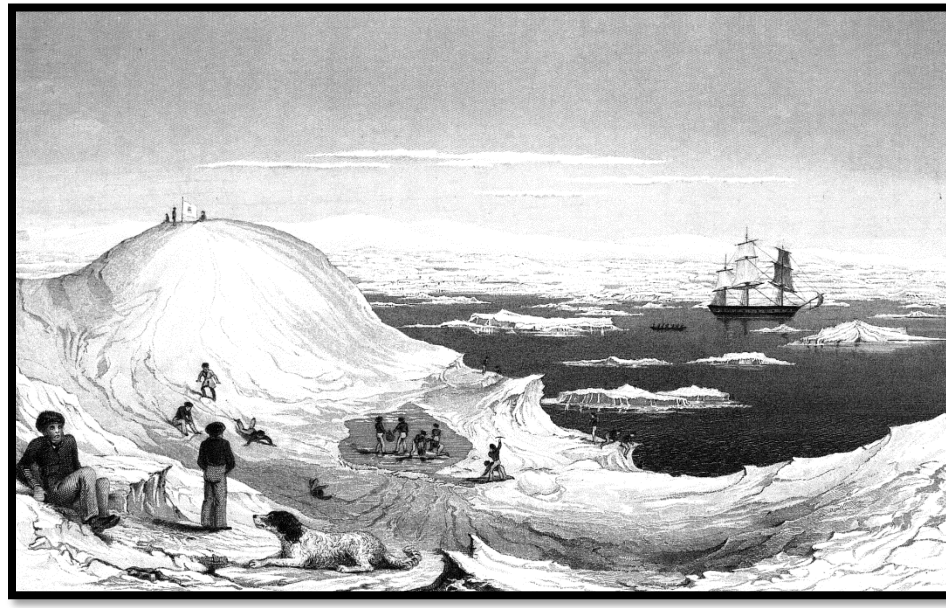
Navigation at Sea

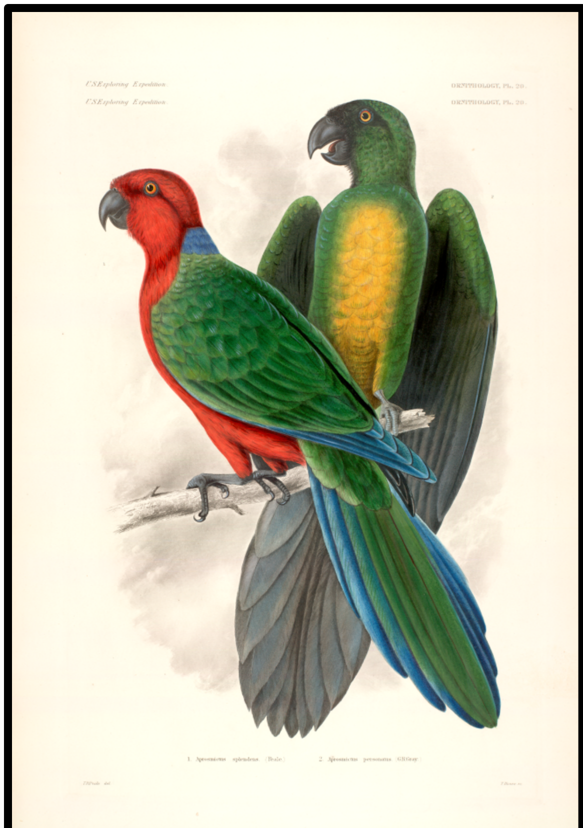


Thomas Sumner's line of constant altitude (voyage 1838, published 1843)

Navigation at Sea

United States Exploring Expedition
(Pacific Ocean 1838-1842)





Flying Cloud
(New York – San Francisco 1854)

Synchronizing the World

Scales for time and location moved from local to global.

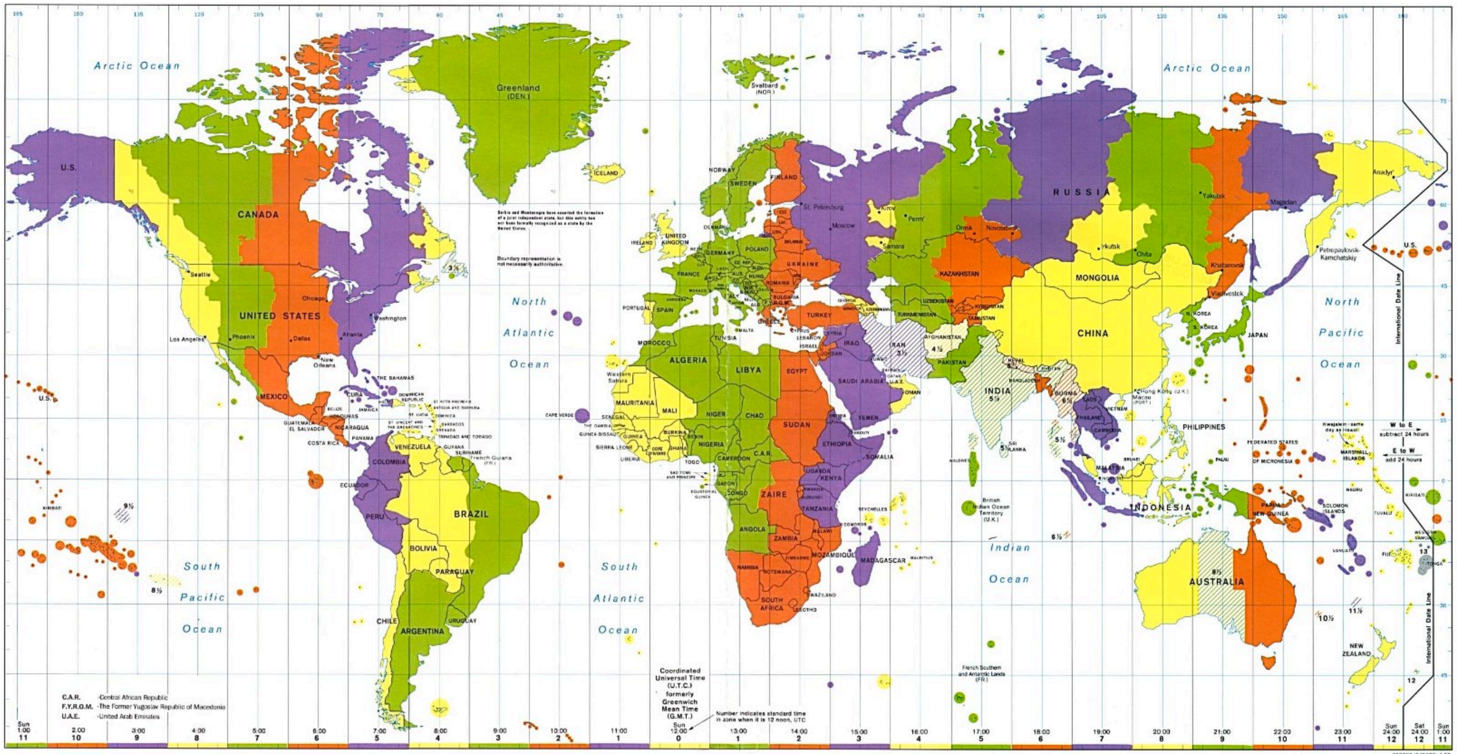
Railroad Time: Great Western Railway to Greenwich time (1840), US Railway Time (1883)

US Meridian in DC: Jefferson Pier Stone (1804), Old Naval Observatory (1850)

Geographical Congress (1881) - International Geodesic Conference, Rome (1883)
International Meridian Conference, Washington DC (1884)
Prime Meridian Contested: Selected Greenwich by vote of 22-1 (2 abstentions)

Time Zones proposed by Sandford Fleming in 1879 and again at 1884 Conference

Map shows current time zones. Each zone defined at national and local level.

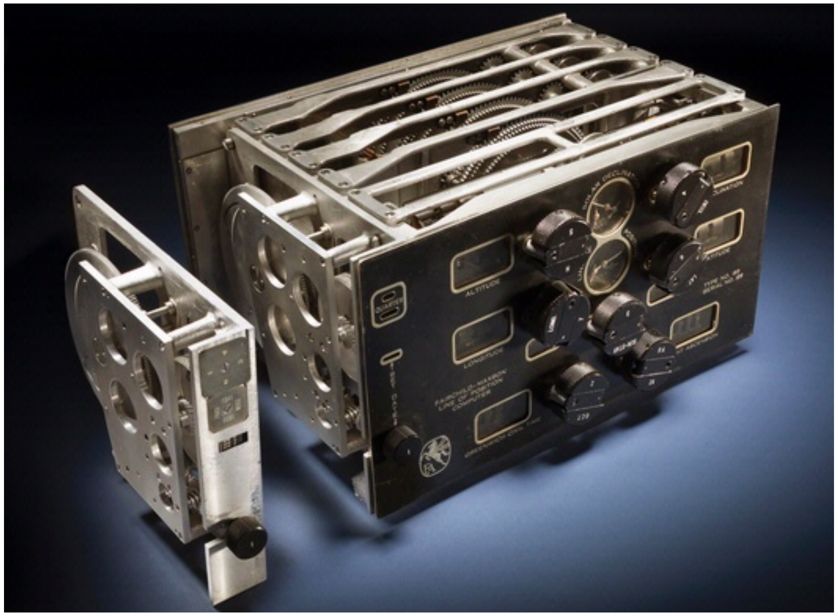


Navigation in the Air

NC-4 by Ted Wilbur
(Atlantic crossing 1919)

Lockheed Vega *Winnie Mae*
(around the world in 1931, 1933)

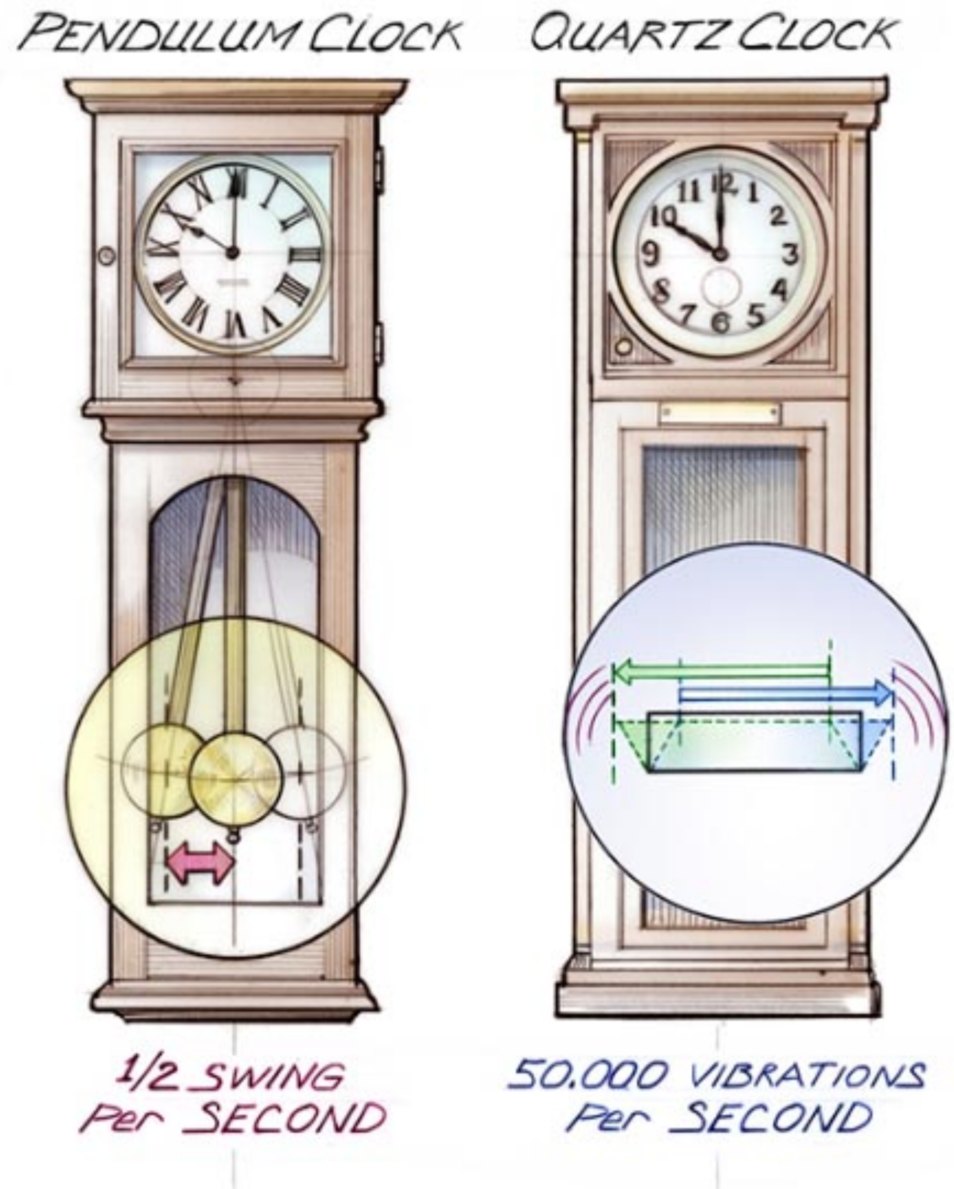
Navigation in the Air

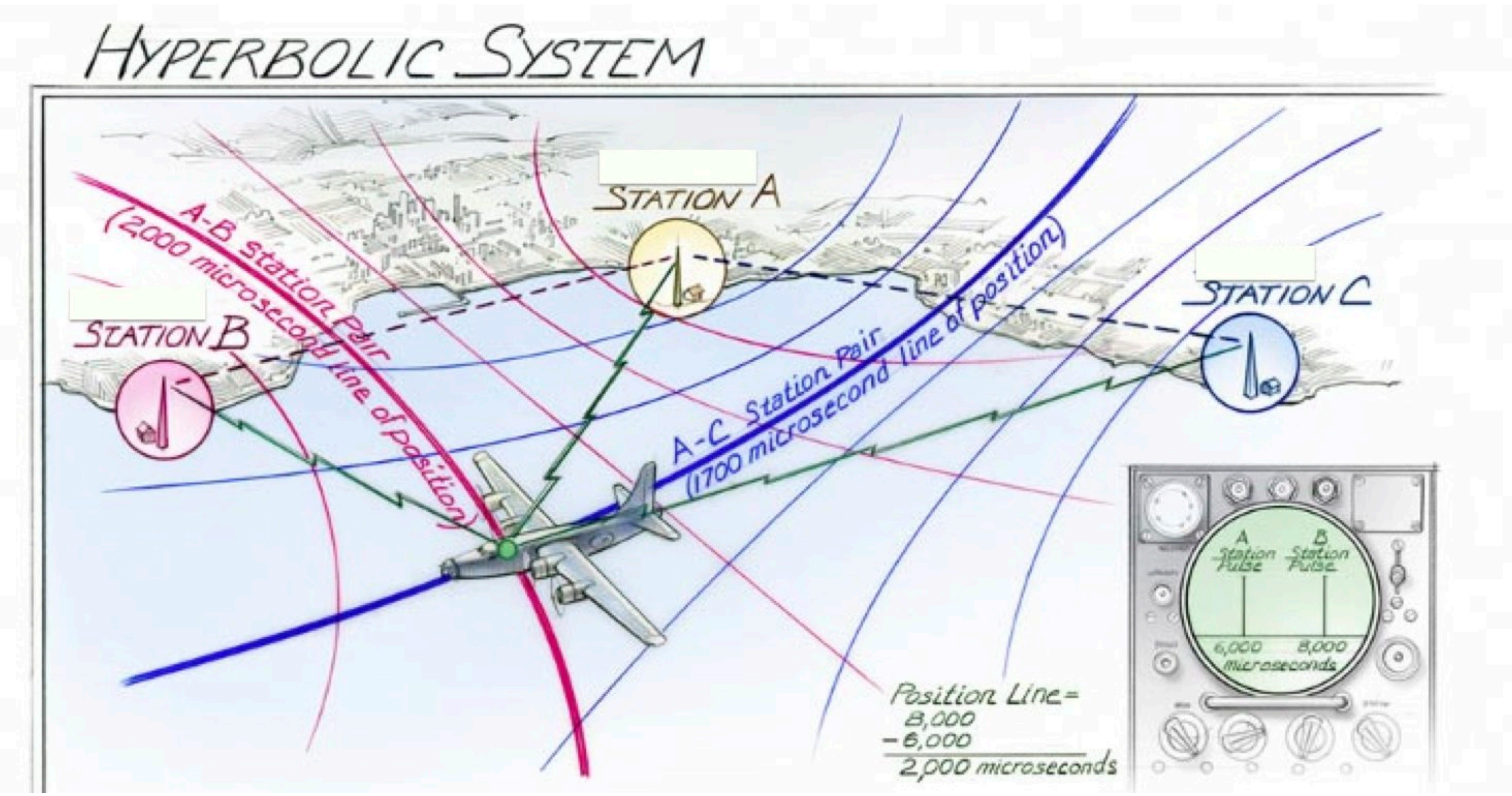


Fairchild-Maxson
Line of Position Computer (1938)

Richie Compass from *Winnie Mae*
(recovered 1935 after Post & Rogers crash)

Navigation in the Air

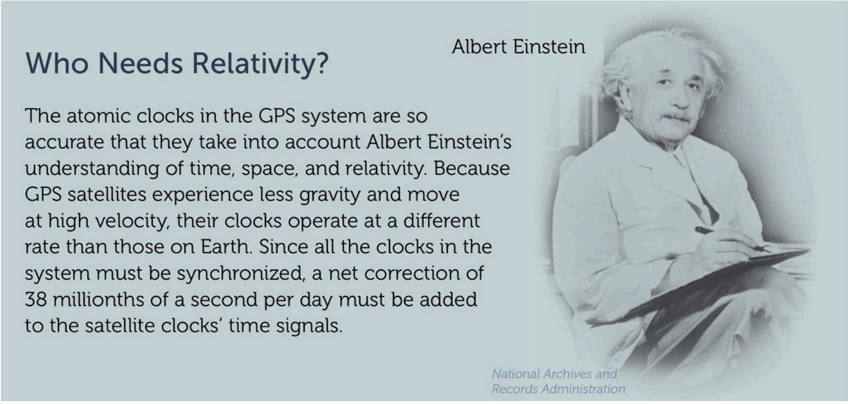

PENDULUM CLOCK
QUARTZ CLOCK
1/2 SWING
Per SECOND
50.000 VIBRATIONS
Per SECOND



HYPERBOLIC SYSTEM
STATION A
STATION B
STATION C
A-B Station Pair
(2000 microsecond line of position)
A-C Station Pair
(1700 microsecond line of position)
A Station Pulse
B Station Pulse
6,000
8,000
microseconds
Position Line =
8,000
-6,000
2,000 microseconds

Synchronizing the World

Global Time Scales, but with expanding range of applications.
How to define time scale for specific needs?



Rotation of the Earth
Local Solar Time
Universal Time - UT1 and UT2 (smoothed UT1)

Movement of Celestial Bodies
Ephemeris Time
1950 – revolution of Earth around Sun (IAU)
Relativistic Scales
1977 - Correction applied for clock altitudes
1979 - Terrestrial Dynamical Time (Earth center) and Barycentric Dynamical Time (Sun center)

Atomic Time
1955 – Greenwich Atomic (GA)
1956 – USNO A.1 scale related to ET, master clock updated to match UT2
1957 - NIST Boulder NBS-A followed A.1, NBS-UA offset to UT2 and broadcast on WWV

Synchronizing the World

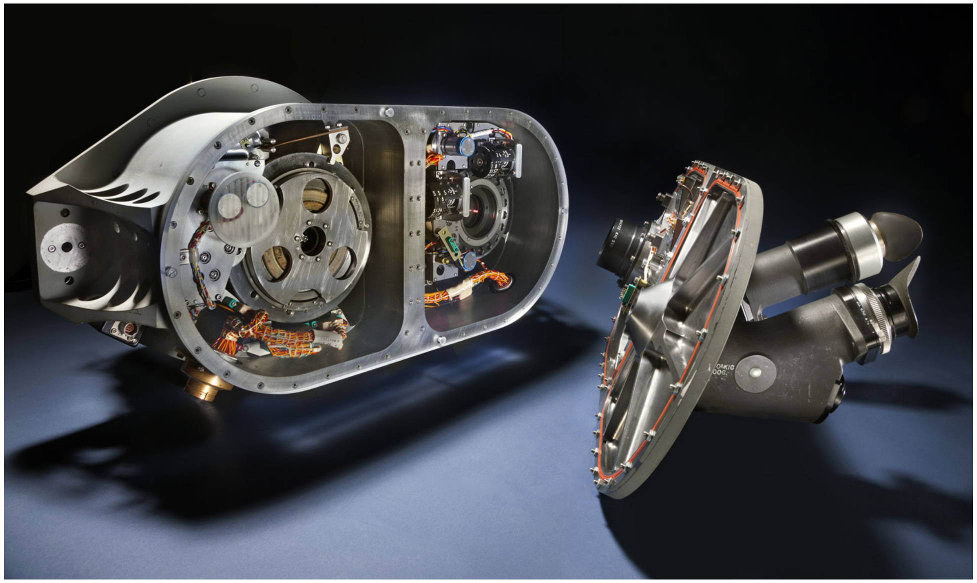
Who sets the time? Would it continue to follow Earth rotation? Differences between celestial time and atomic time are not new.

1959 – International Radio Consultative Committee (CCIR) studies time standard
1960 – Labs in US and UK coordinate time
1960 - International Time Bureau (BIH) mean atomic time (AM, A3) and Δ UT2
1960 – SI second defined by Ephemeris Time
1963 – UTC formalized and adopted by CCIR: included 100ms steps to match UT2
1966 – CCIR experiment: Stepped Atomic Time (SAT) – 0.1s of UT2 with 200ms steps
1967 – SI second defined by Cesium 133
1968 – Leap seconds proposed

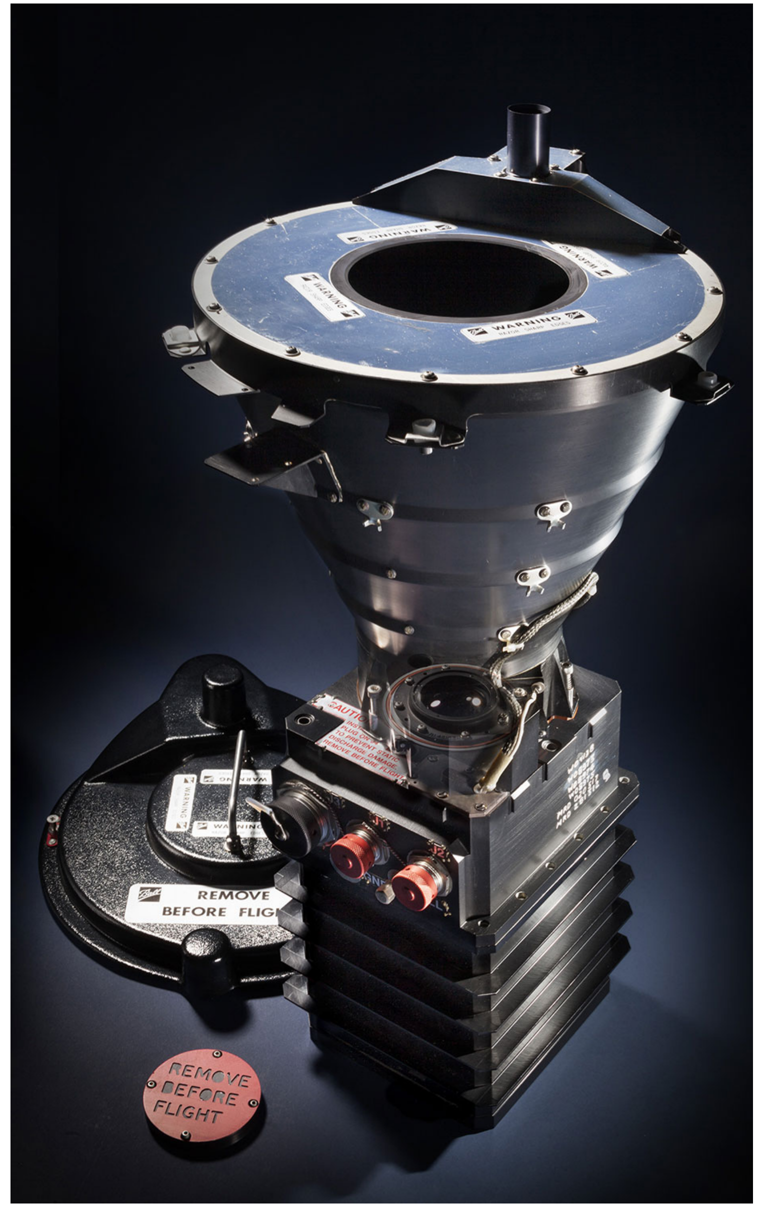
1971 – International Atomic Time (TAI) – extension of BIH time (A3)
1972 – UTC altered: Approximates UT1 instead of UT2 - Leap seconds adopted

1987 – International Bureau of Weights and Measures (BIPM) maintains UTC, TAI
1987 - International Earth Rotation Service (now International Earth Reference Systems Service) forecasts DUT1 and announces leap seconds

Navigation in Space



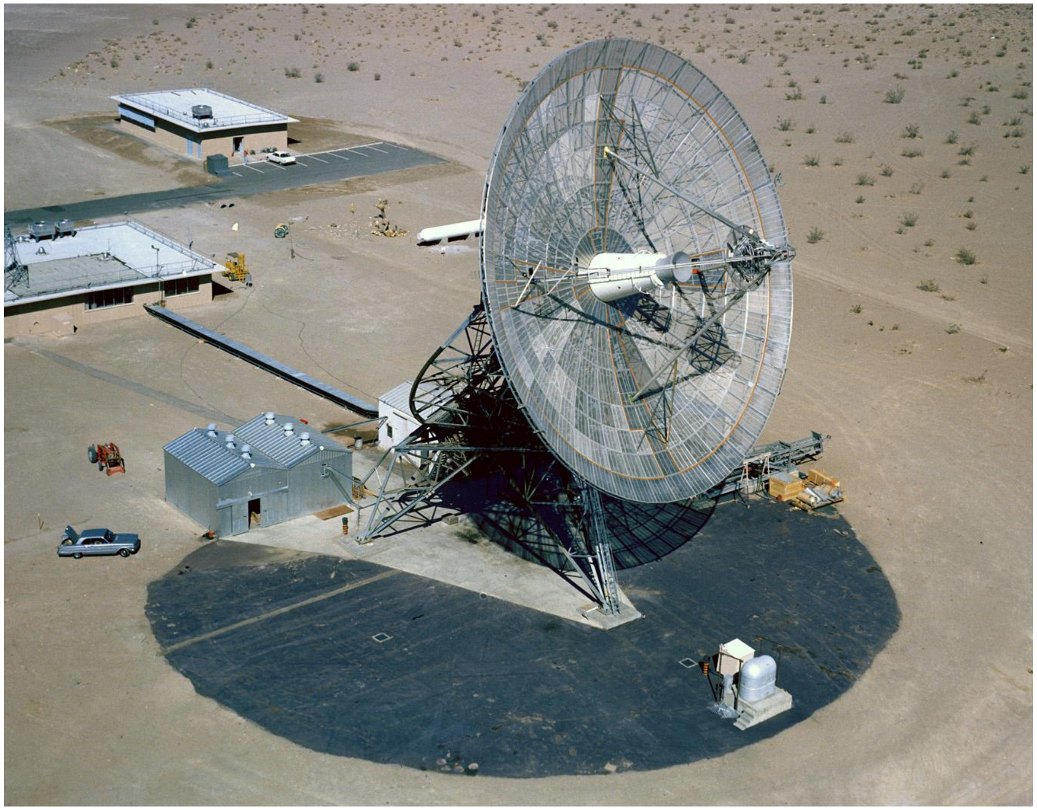
Apollo Sextant (1968)



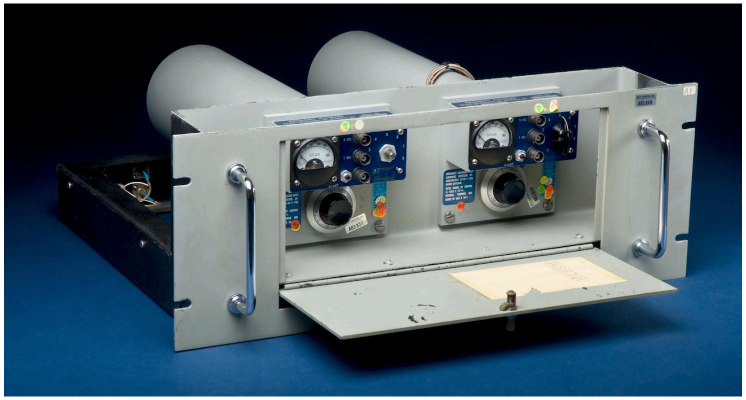
Space Shuttle star tracker (1981)

Navigation in Space

Pioneer 4 (1959)



26 m antenna at Goldstone



Quartz Oscillator (1961)

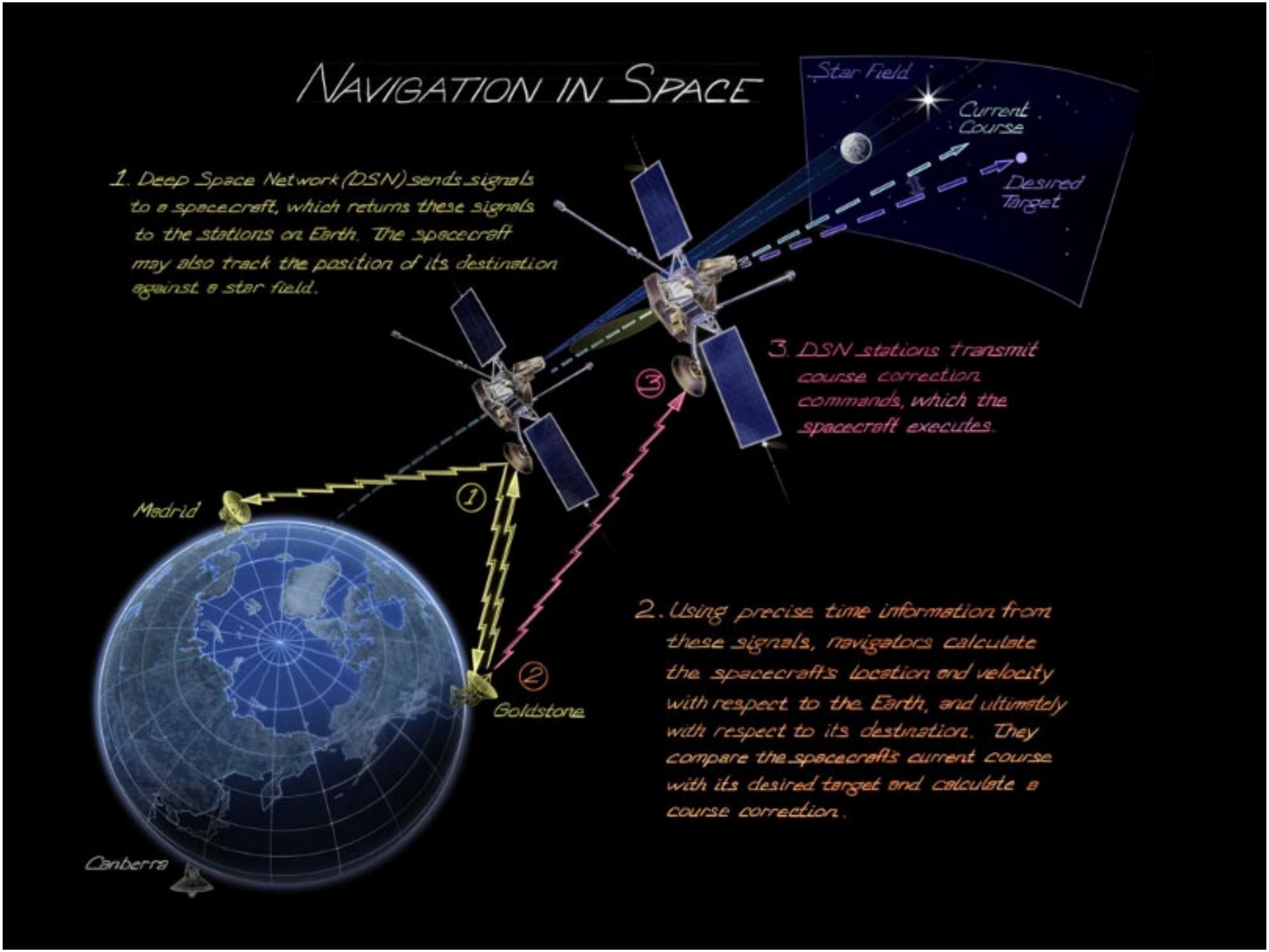
Velocity precision improved from 10m/sec to 50mm/sec

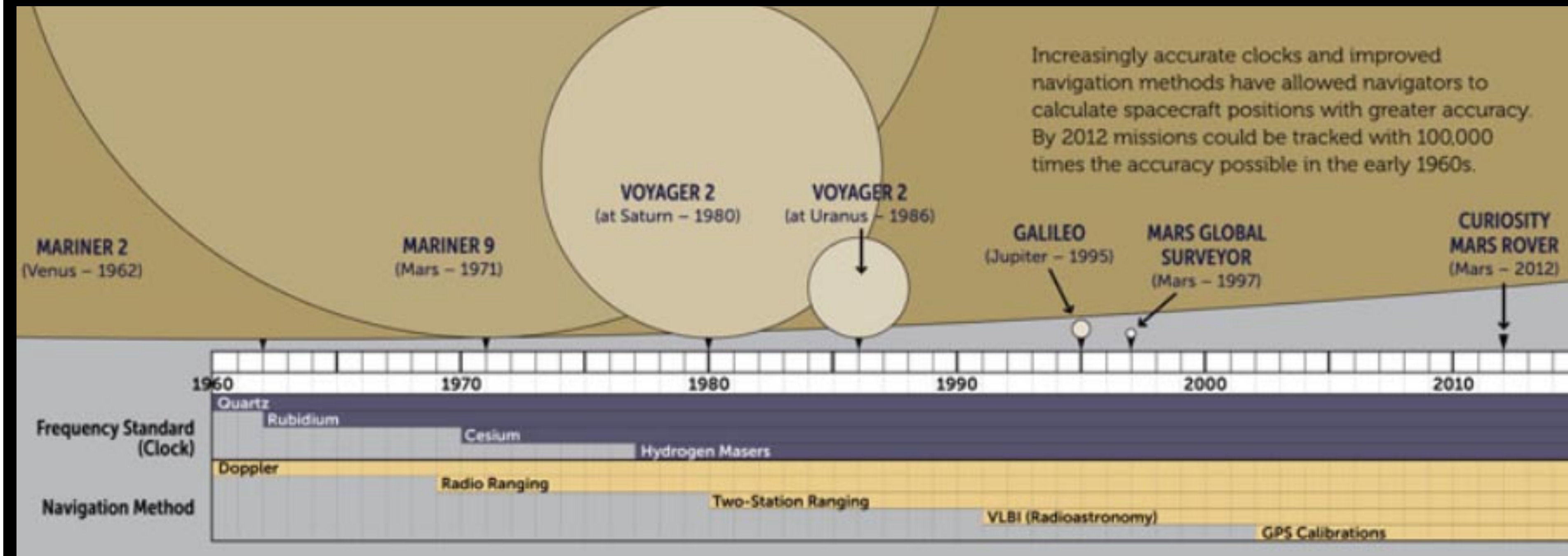
1962 Atomic clocks: 5mm/sec

Navigation in Space

70 m antenna at Goldstone

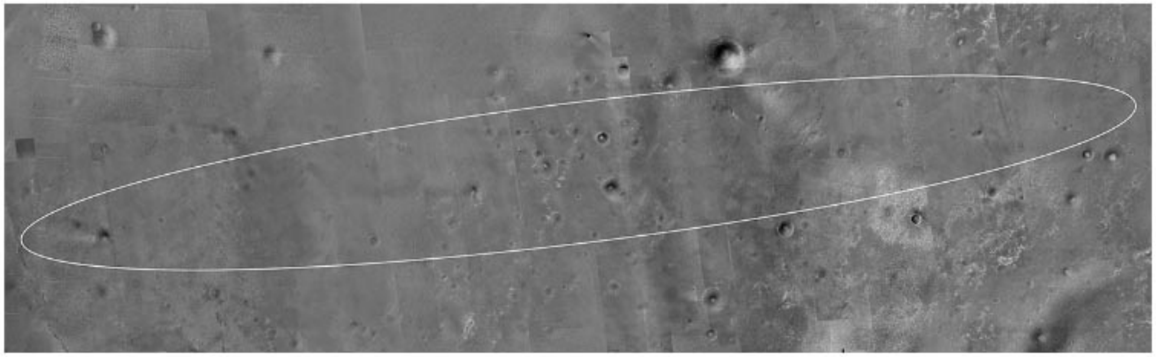
Mariner 10 (1973)

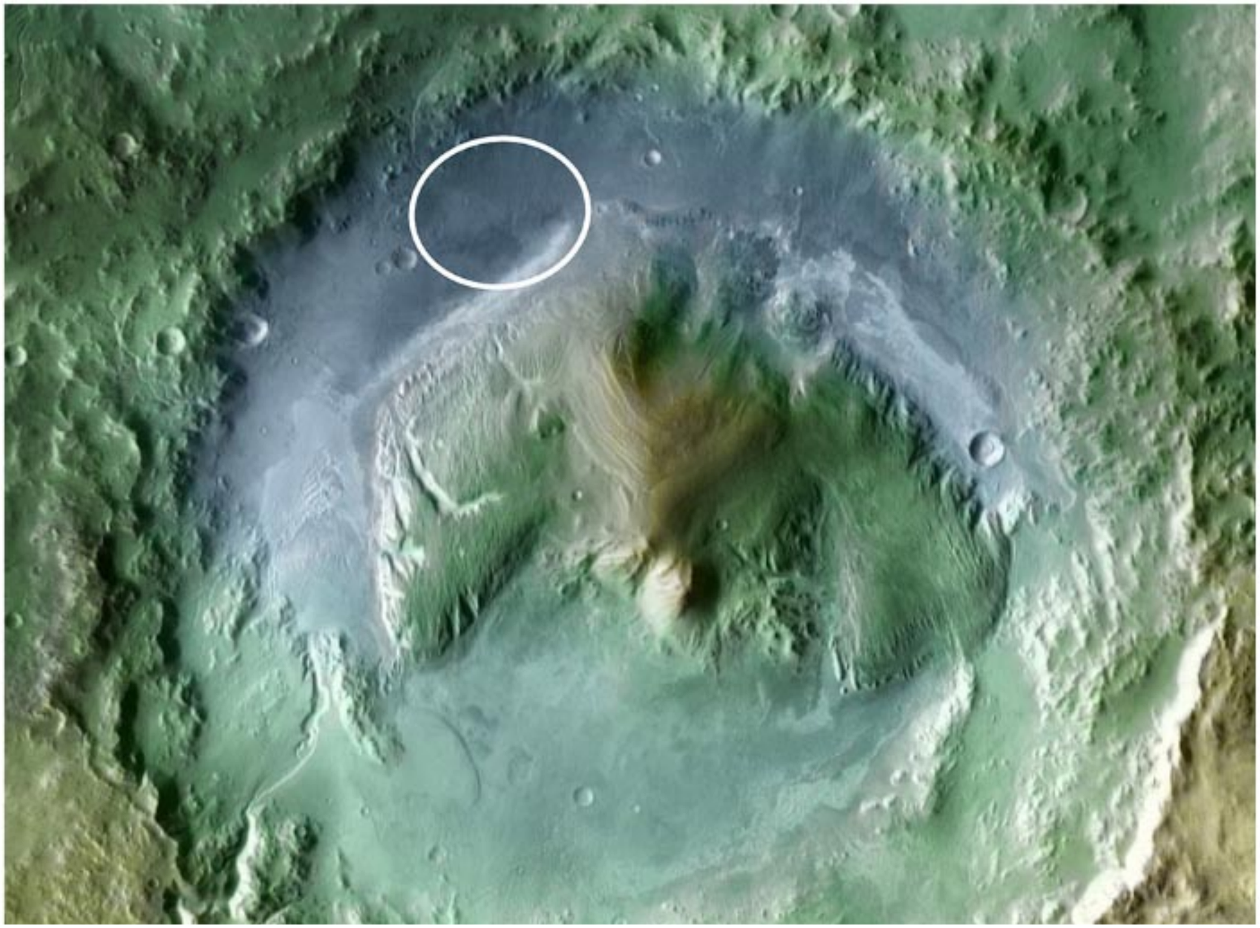

NAVIGATION IN SPACE
Star Field
Current Course
Desired Target
1. Deep Space Network (DSN) sends signals to a spacecraft, which returns these signals to the stations on Earth. The spacecraft may also track the position of its destination against a star field.
3. DSN stations transmit course correction commands, which the spacecraft executes.
2. Using precise time information from these signals, navigators calculate the spacecraft's location and velocity with respect to the Earth, and ultimately with respect to its destination. They compare the spacecraft's current course with its desired target and calculate a course correction.
1
2
3
Madrid
Goldstone
Canberra



Increasingly accurate clocks and improved navigation methods have allowed navigators to calculate spacecraft positions with greater accuracy. By 2012 missions could be tracked with 100,000 times the accuracy possible in the early 1960s.
MARINER 2
(Venus – 1962)
MARINER 9
(Mars – 1971)
VOYAGER 2
(at Saturn – 1980)
VOYAGER 2
(at Uranus – 1986)
GALILEO
(Jupiter – 1995)
MARS GLOBAL SURVEYOR
(Mars – 1997)
CURIOSITY MARS ROVER
(Mars – 2012)
1960
1970
1980
1990
2000
2010
Frequency Standard (Clock)
Quartz
Rubidium
Cesium
Hydrogen Masers
Navigation Method
Doppler
Radio Ranging
Two-Station Ranging
VLBI (Radioastronomy)
GPS Calibrations

MER Landing Ellipse (2004)

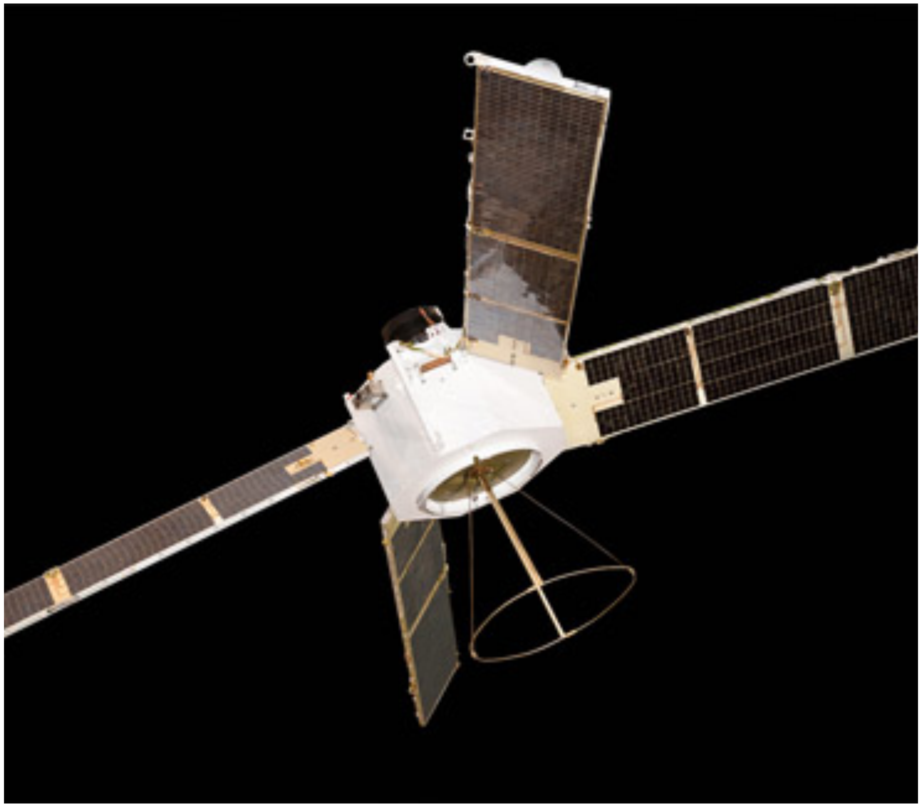




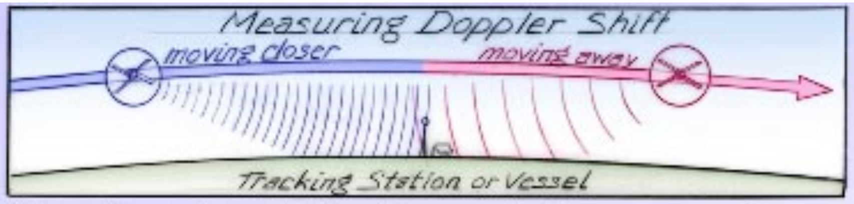
MSL Landing Ellipse (2012)

Satellite Navigation

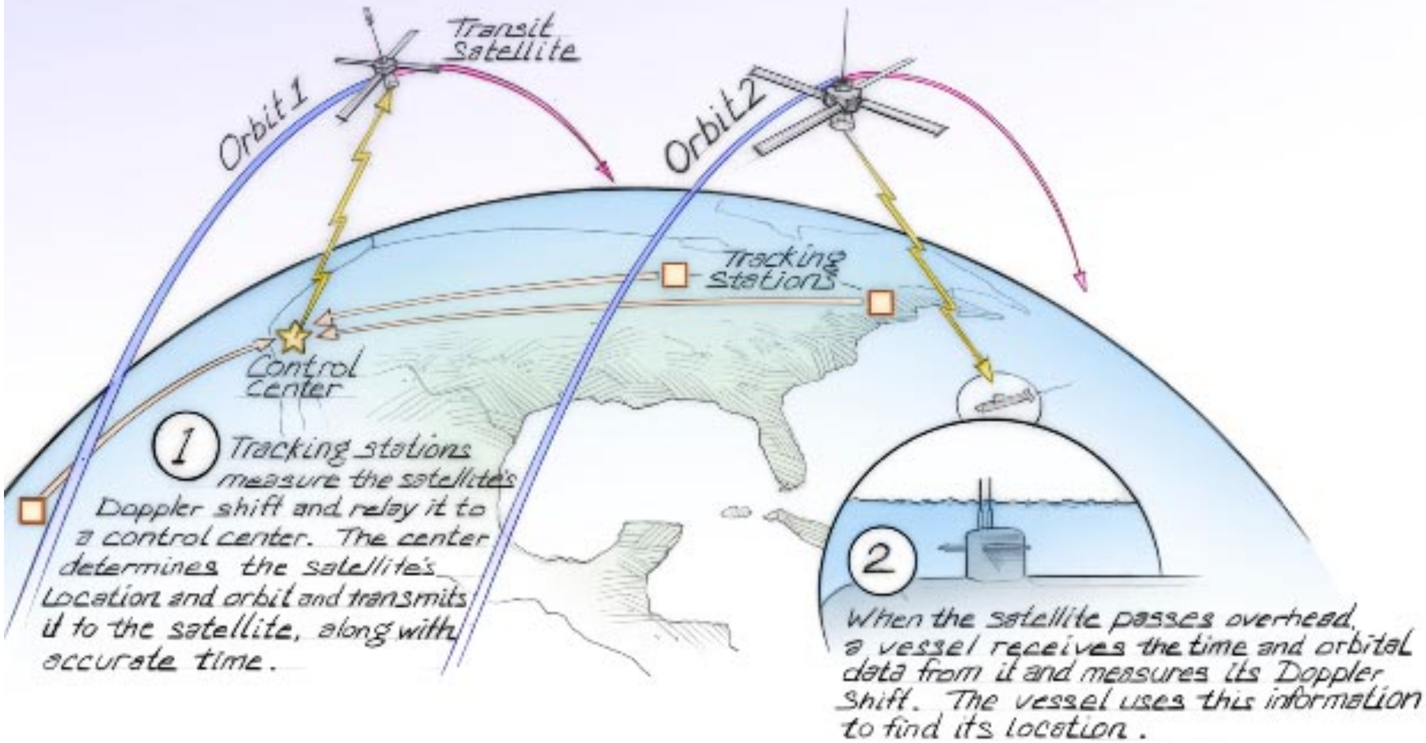
Second Transit satellite (1960)



Transit 5A satellite (1970s)



The Doppler shift of signals from a moving satellite is used to determine the satellite's orbit compared to the location of the tracking station. By then inverting the process, a vessel can locate itself compared to the satellite's known location.



Satellite Navigation

SINS from USS Alabama

Satellite Navigation

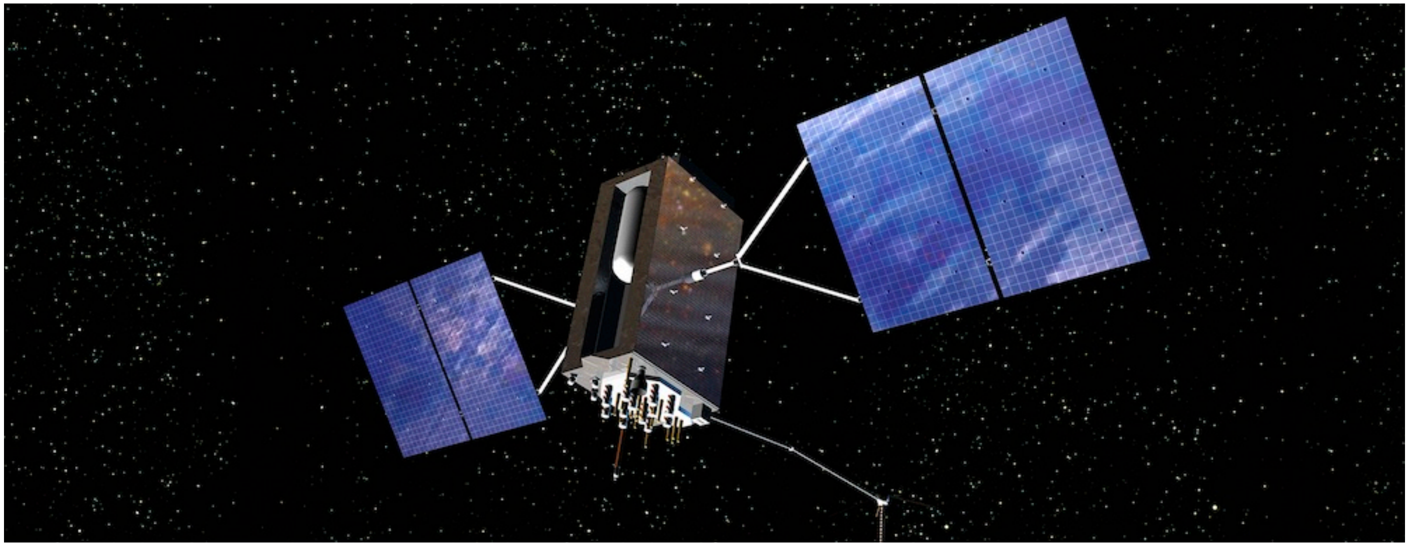
NTS-2 satellite (1977)

Satellite Navigation

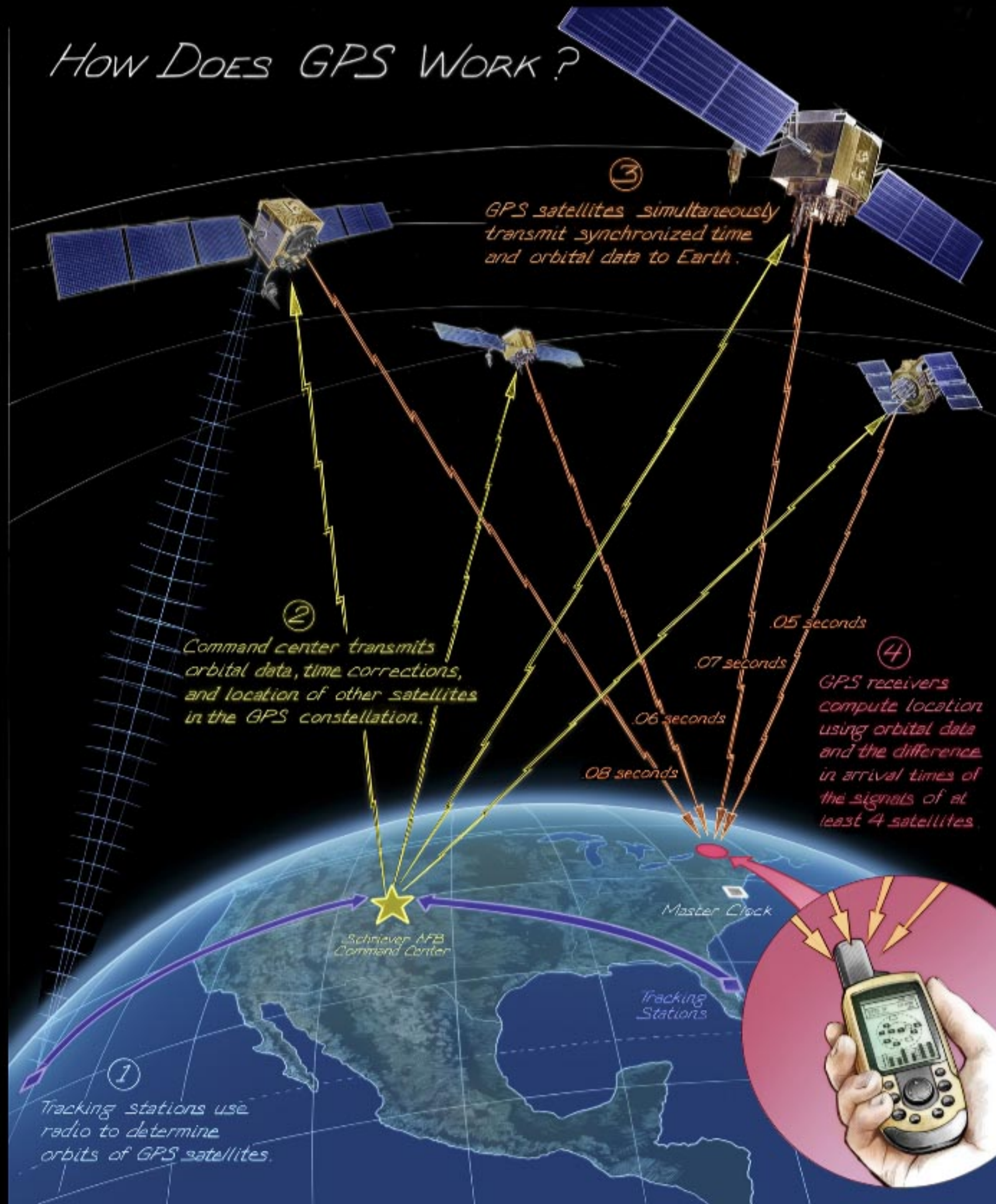
Small Diameter Bomb

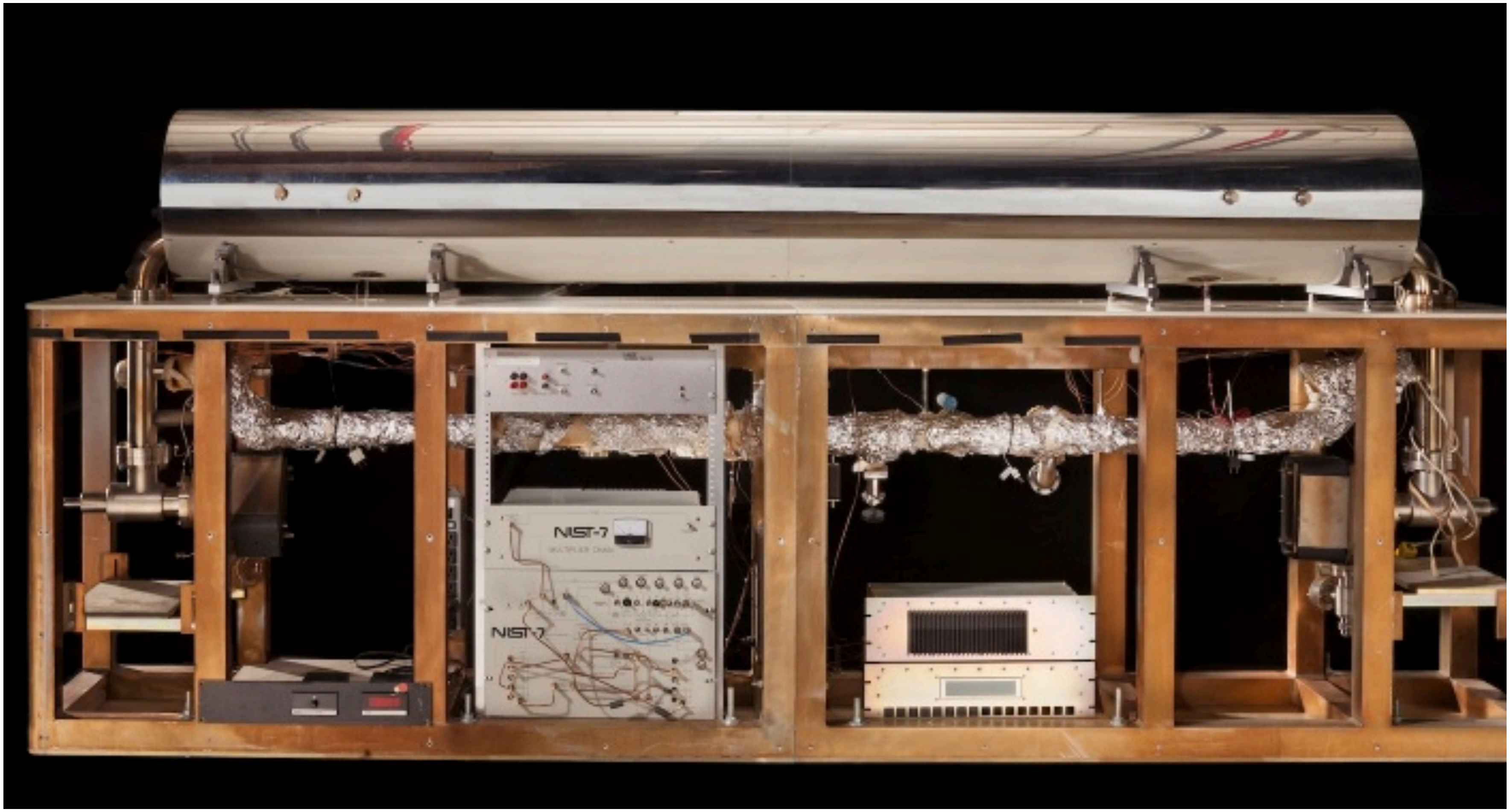
T-Hawk

Navigation for Everyone



GPS Time maintained at Schriever AFB to match USNO time.



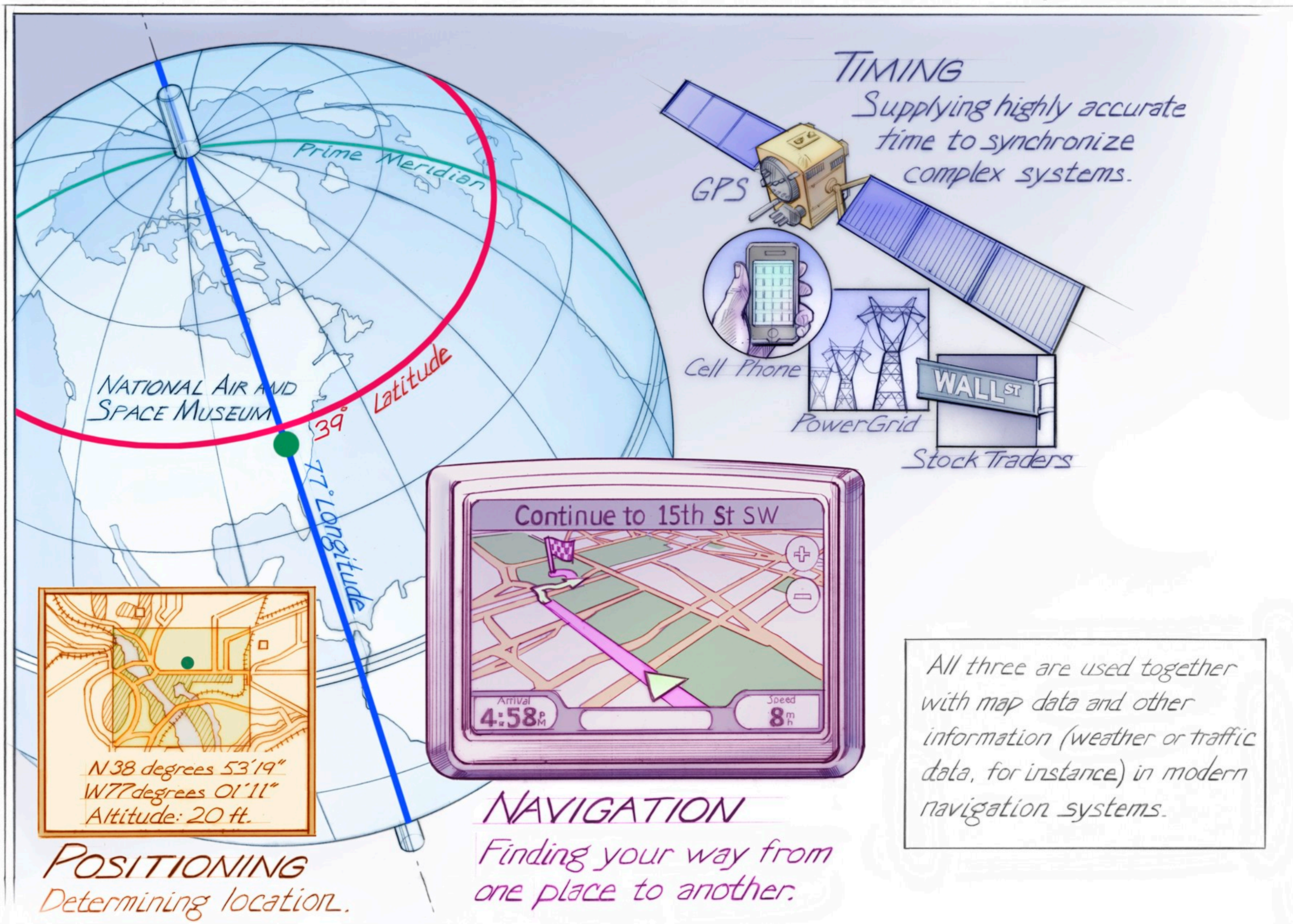


NIST-7 Atomic clock

Navigation for Everyone

Stanley (2005)

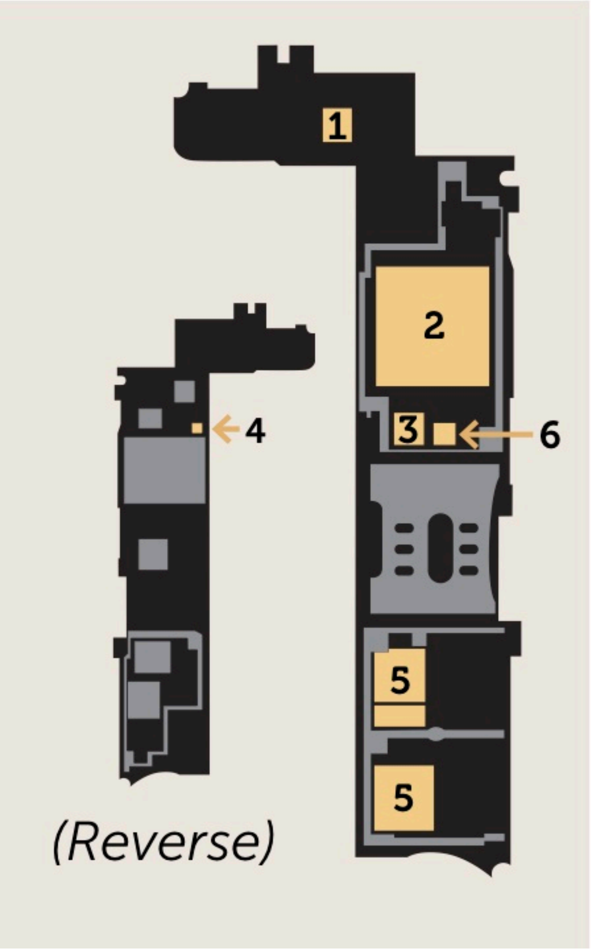
PNT (Positioning, Navigation, and Timing)



Navigation for Everyone

John Sullivan   Roy Bardole   Eva González

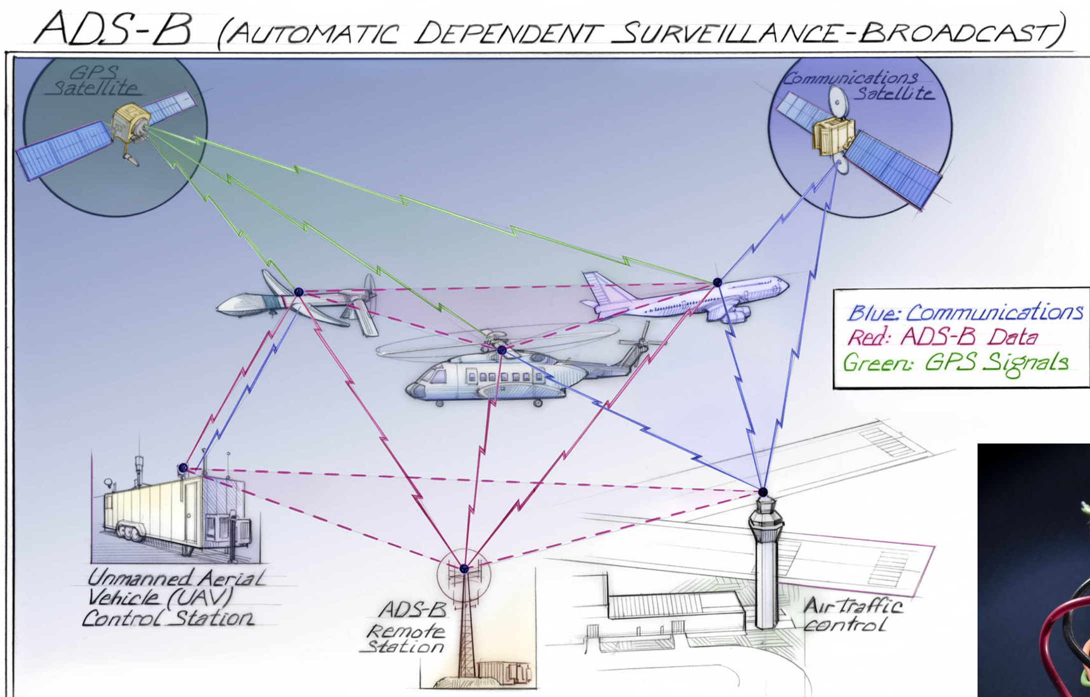
Navigation for Everyone



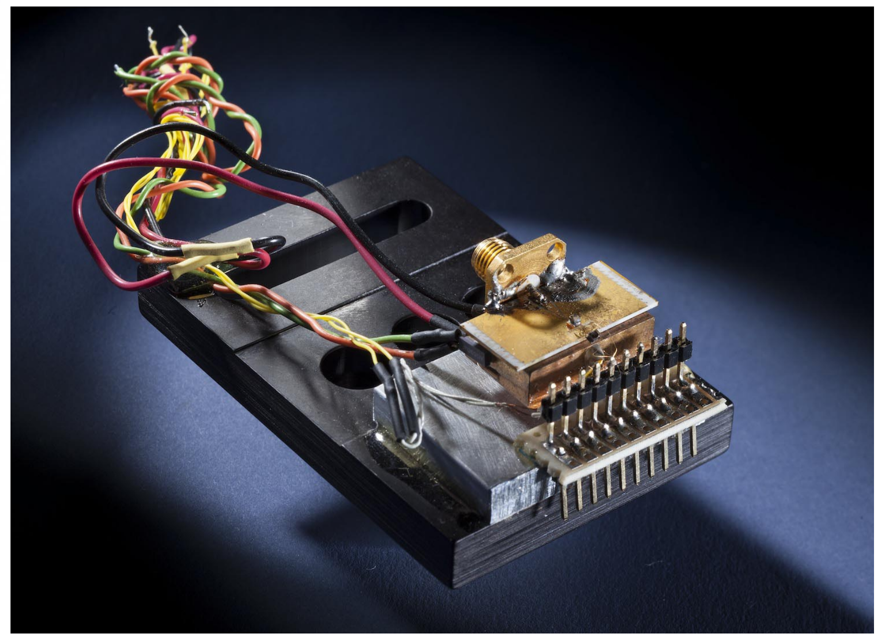
1 GPS receiver
2 Processor (computer)
3 Three-axis gyroscope
4 Magnetic compass
5 Radio receivers
6 Three-axis accelerometer

Seiko Epson Digital Assistant (1997)

Looking Ahead



How can navigation be more robust?
International systems, multiple sources: Ground-based backup, integrated precision time



Chip-Scale atomic clock

Looking Ahead

Future Time: Global Time, Local Implications

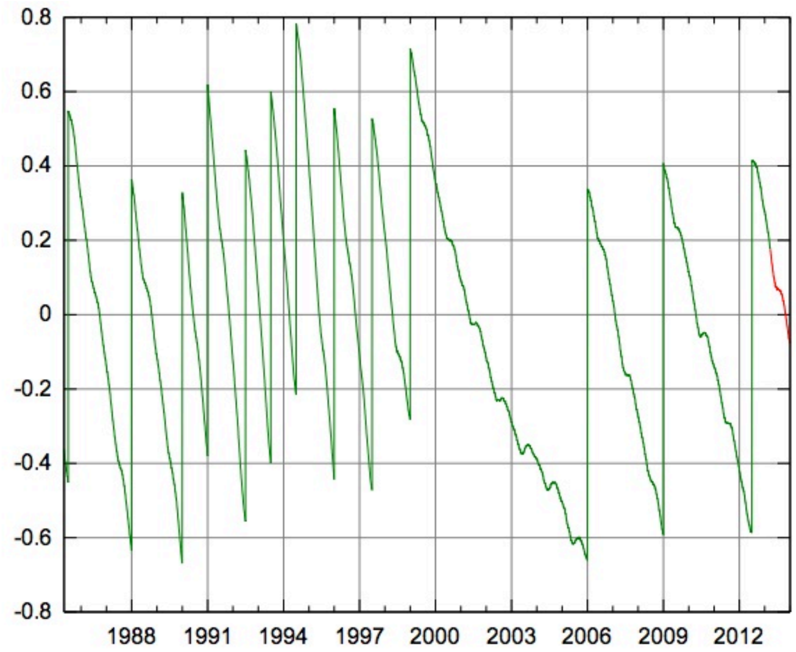
Multiple communities with diverse viewpoints rely on precise time services.
UTC by itself is not a perfect solution for either celestial or radio navigation.

TAI – UTC now 35 seconds apart:
10 seconds in 1972, 25 leap seconds.

DUT1 = UT1 – UTC
Broadcast by WWV

Each GNSS has its own time scale.
Leap seconds in GPS message.
GLONASS impact in the past.
Future impact could increase.

Keep UTC as basis of civil time?
Rename UTC? Eliminate TAI?



Future of Leap Seconds?
2008 – ITU working party submits recommendation to stop leap seconds
2012 – ITU postpones decision to 2015 conference in Geneva

Behinds the Scenes at Time and Navigation

DSN Frequency Standard

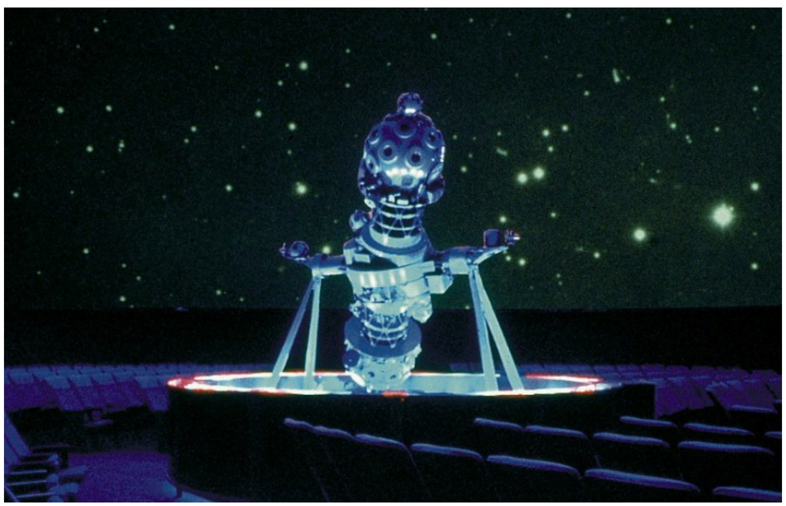
Working atomic clock

Time and Navigation open to the public at the National Air and Space Museum

Please visit web site:
timeandnavigation.si.edu

More information:
Andrew Johnston
JohnstonA@si.edu

Come visit the Einstein Planetarium!
Tuesday 10:00



Phoebe Waterman Haas Public Observatory (Wed.-Sun.)
Explore the Universe Gallery