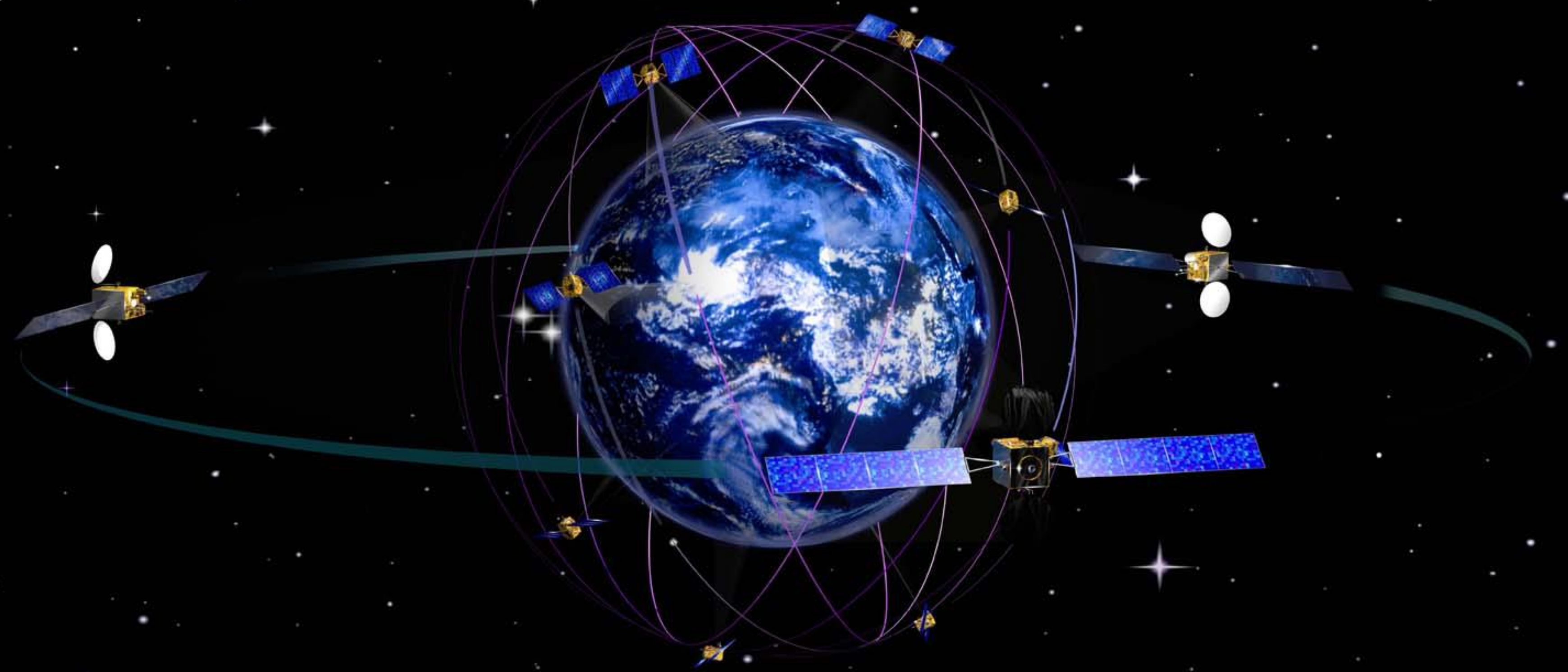
Satellite Communications
– RRY100 –



2024 Study Period 1

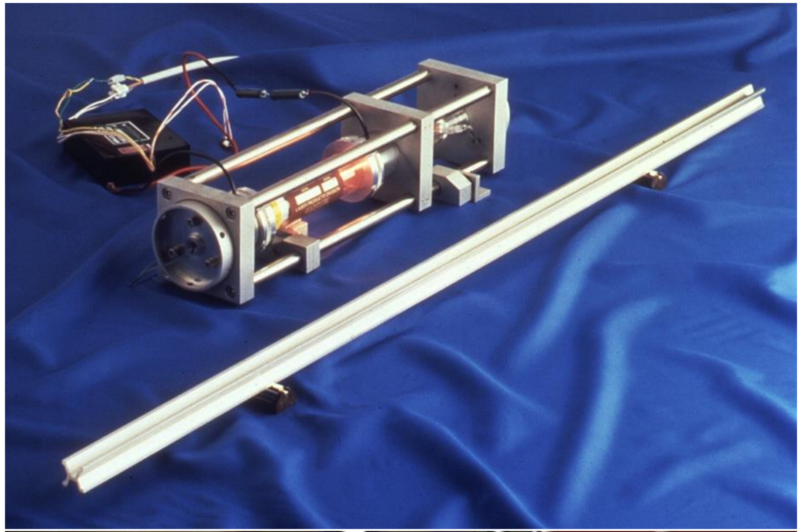
Guest lecturer: Jan Johansson

Lecture-13: SatCom / SatNav and Time and Frequency

RISE Research Institutes of Sweden

AstaZero – autonomous transport and safety

AWITAR
EMC – antennas and communication



National Metrology Institute

Today’s Lecture

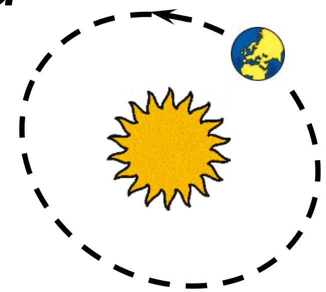
- The definition of the SI-second
- Time scales
- International time keeping
- Atomic clocks and their characterization

- Requirements for time and frequency
- Time and frequency distribution systems
- Time in GNSS
- Time transfer using GNSS (with examples)

How long is a Second?

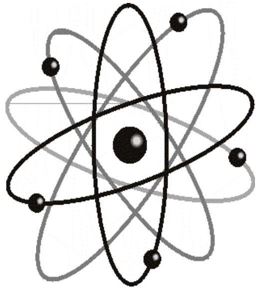
#1: Earth based

- Before 1956: *Mean Solar Second*
  - – 1 second = One *Mean Solar Day* / 86,400
  - – Dependent on Earth rotation – not stable
- Between 1956 and 1967: *Ephemeris second*
  - – 1 second = One *Tropical year for 1900 /* 31,556,925.9747
  - – The Ephemeris second is more stable in the long term but difficult to measure and verify



How long is a Second?

#2: The atomic era



- From 1967 to present: *Atomic Second*
  - Based on radiations in the caesium 133 atom
    - Counting periods of electromagnetic radiation locked to an atoms resonant frequency
    - When an atom changes energy level, it either radiates or absorbs energy with a specific frequency
  - 1 second = “the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom”
    - The number of periods was chosen so as to make the atomic second equal to the ephemeris second

Time scales in general

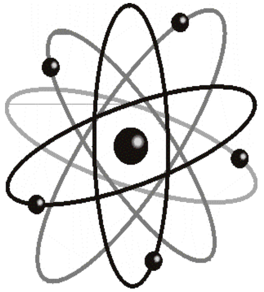
- A time scale has:
  - an arbitrary initial start time, and
  - a time scale unit that accumulates time
- Usually:
  - a day contains 86,400 seconds, and
  - a year contains 365 days
- Leap years and Leap Seconds occur
- International time scales “starts” from the zero meridian (Greenwich)
  - 00:00:00 at midnight
- National official time depends on time zone

Time scales: UT1

- Universal time scale UT1
  - Based on the Earth's rotation around its axis and the *mean solar second*
  - GMT (Greenwich Mean Time)
    - Official international time from 1884
    - Based on UT1

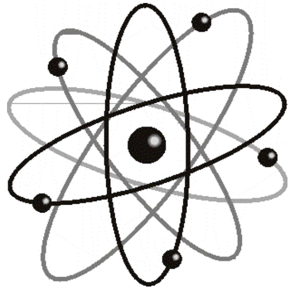
Time scales: TAI

- Atomic Time Scale TAI
  (International Atomic Time)
  - Based on the *Atomic second and atomic clocks*
  - Independent on the rotation of the Earth
  - TAI $\approx$ UT1 January 1, 1958
  - TAI $\approx$ UT1 + 37 s in 2022

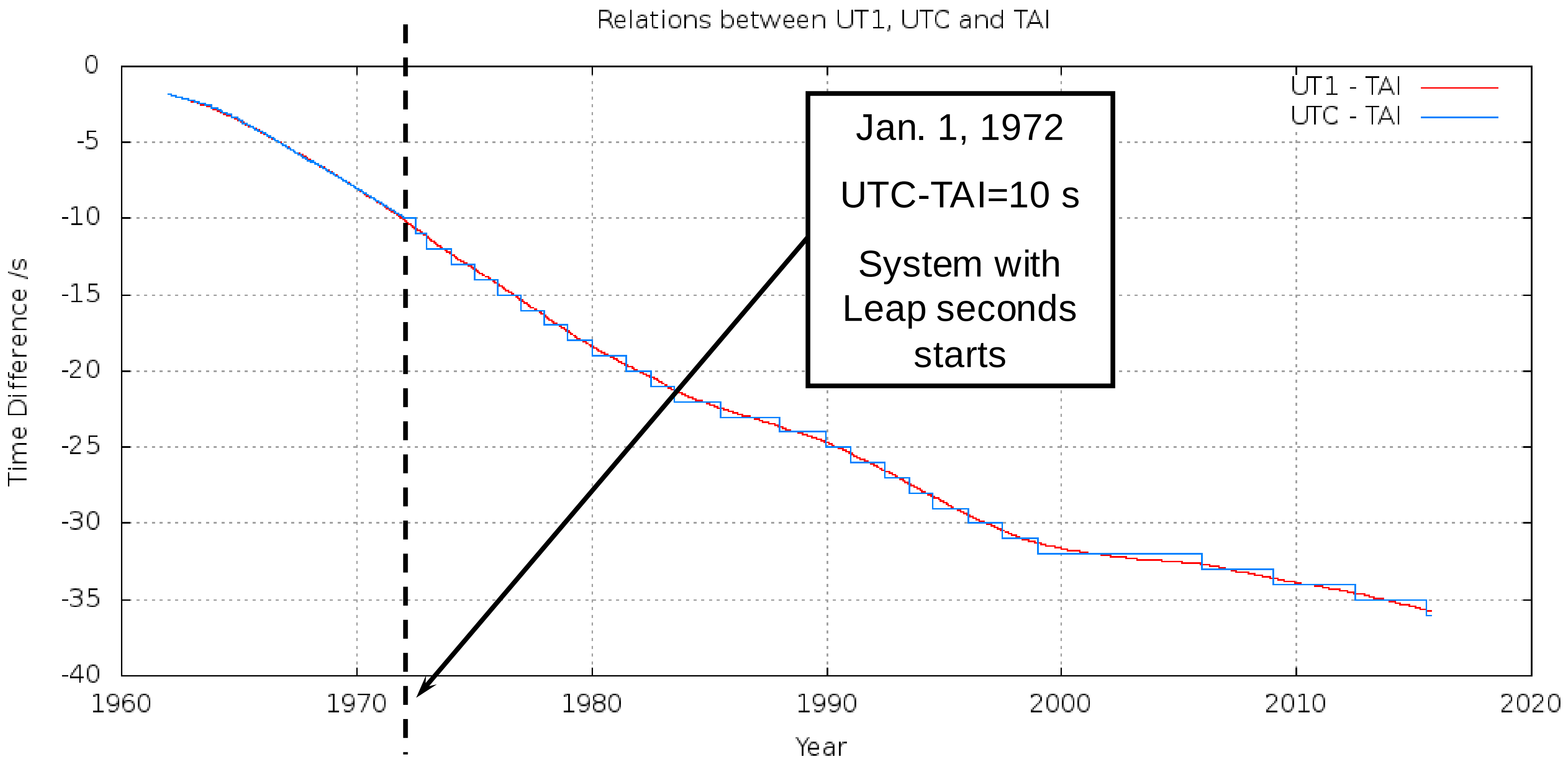


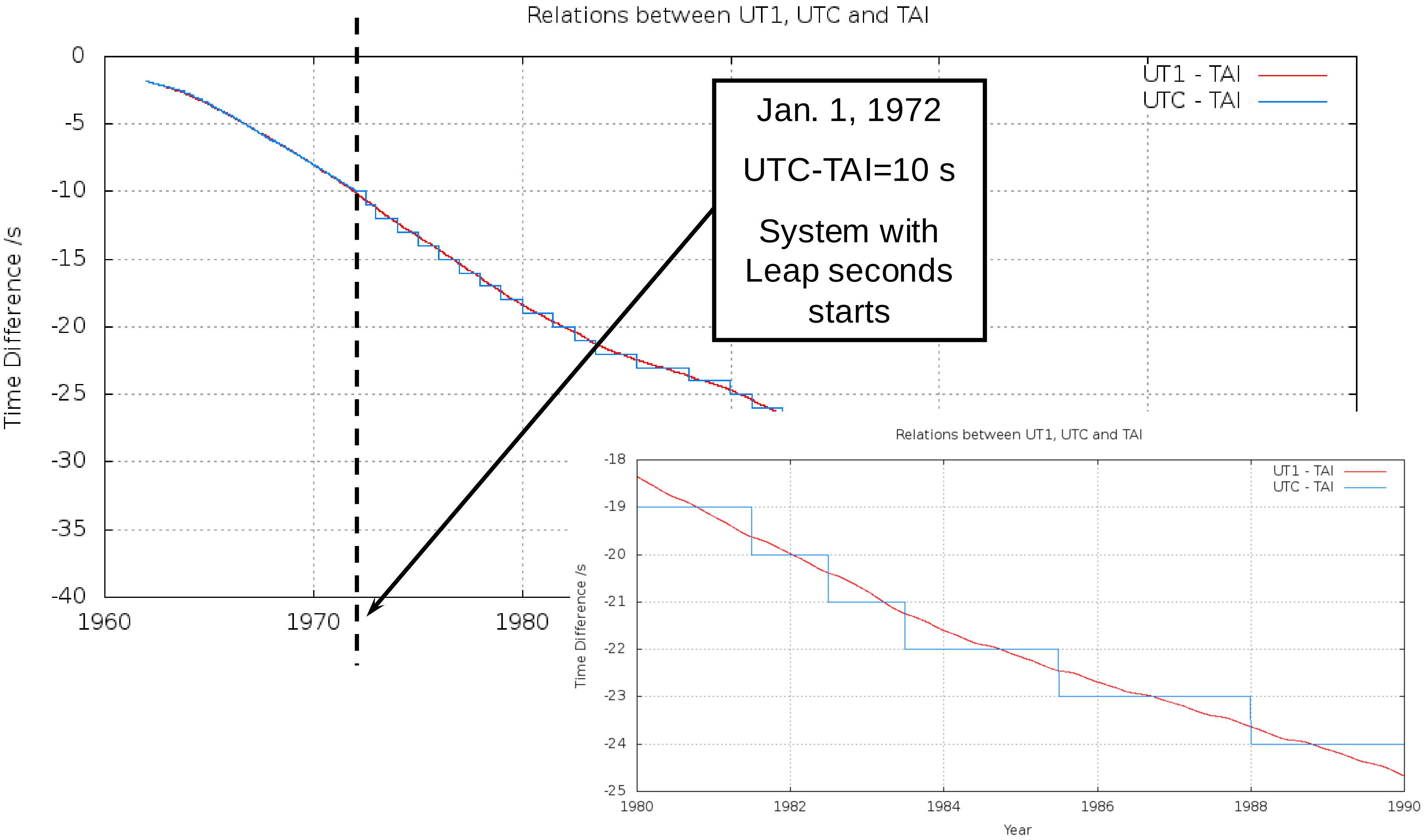
Time scales: UTC

- Universal time scale UTC (Coordinated Universal Time)
  - Based on the Atomic second but ***follows the rotation of the Earth*** and defined as
    - UTC - TAI = N seconds (N integer)
    - | UTC - UT1 | < 0.9 seconds; UT1 - UTC = DUT1
    - N is also called ***leap seconds***
  - Leap seconds are introduced to make UTC follow the Mean Solar Day
  - Official international time since 1972

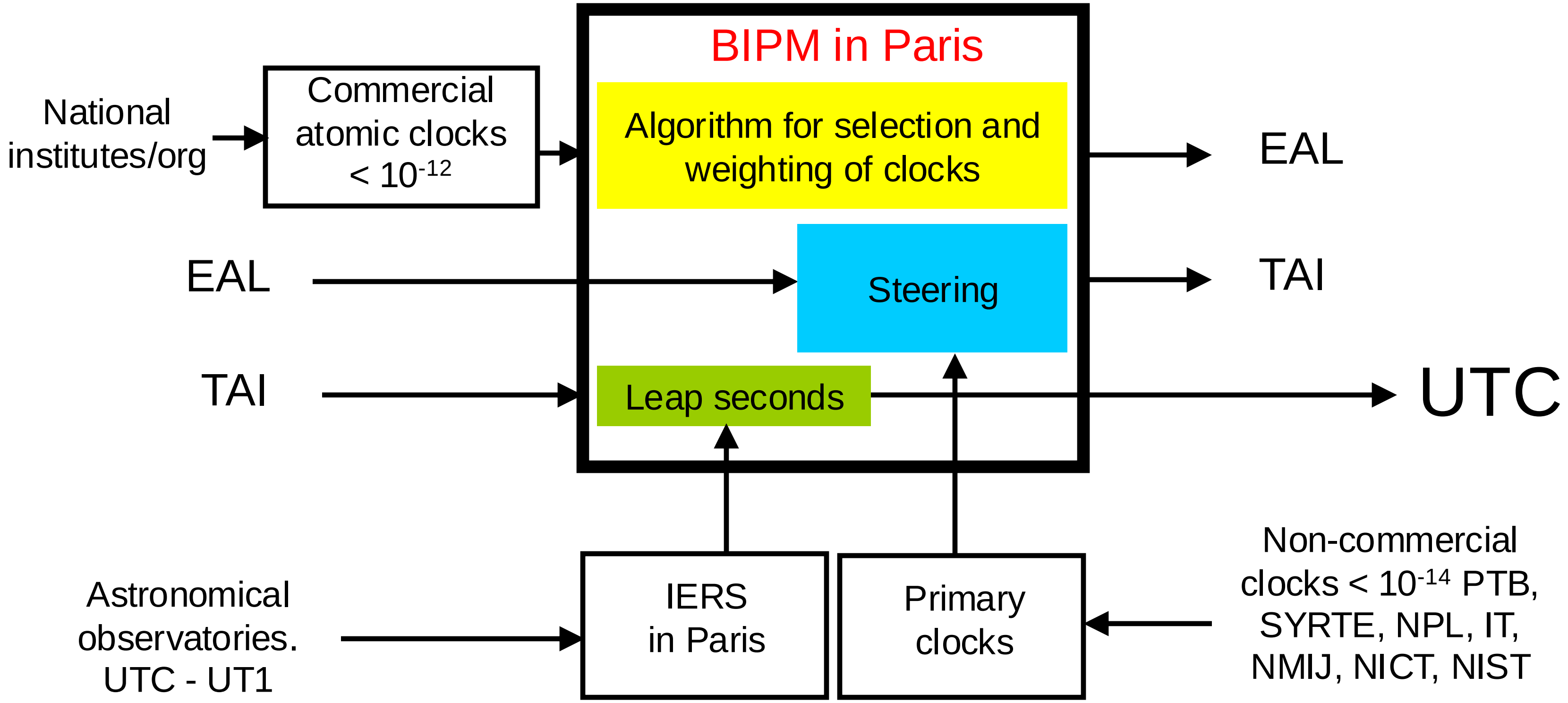


Relations between UT1, TAI and UTC




Relations between UT1, UTC and TAI
Time Difference /s
0
-5
-10
-15
-20
-25
-30
-35
-40
1960
1970
1980
UT1 - TAI
UTC - TAI
Jan. 1, 1972
UTC-TAI=10 s
System with Leap seconds starts
Relations between UT1, UTC and TAI
Time Difference /s
-18
-19
-20
-21
-22
-23
-24
-25
1980
1982
1984
1986
1988
1990
Year
UT1 - TAI
UTC - TAI

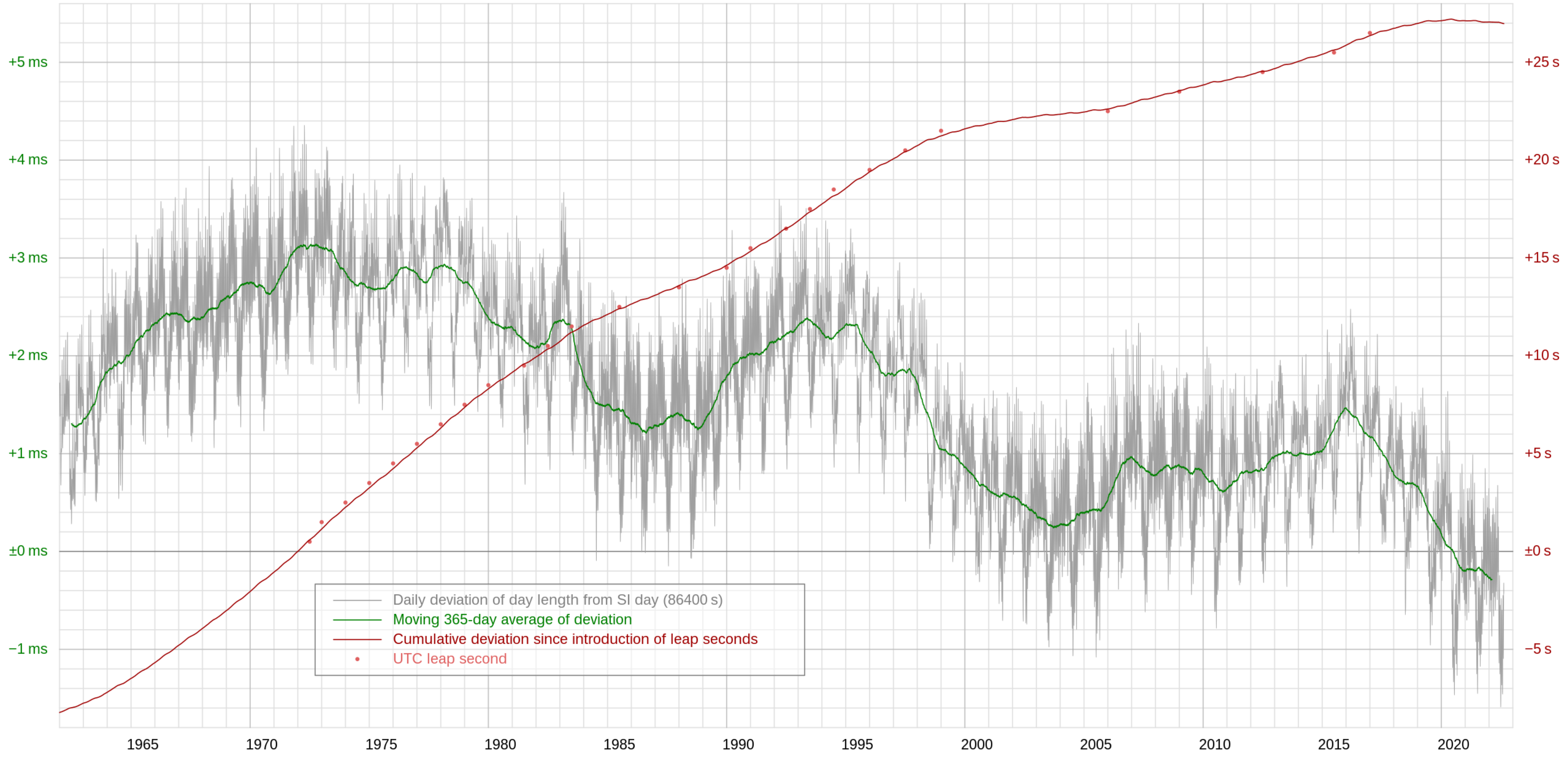
BIPM calculates UTC



BIPM is the International Bureau of Weights and Measures

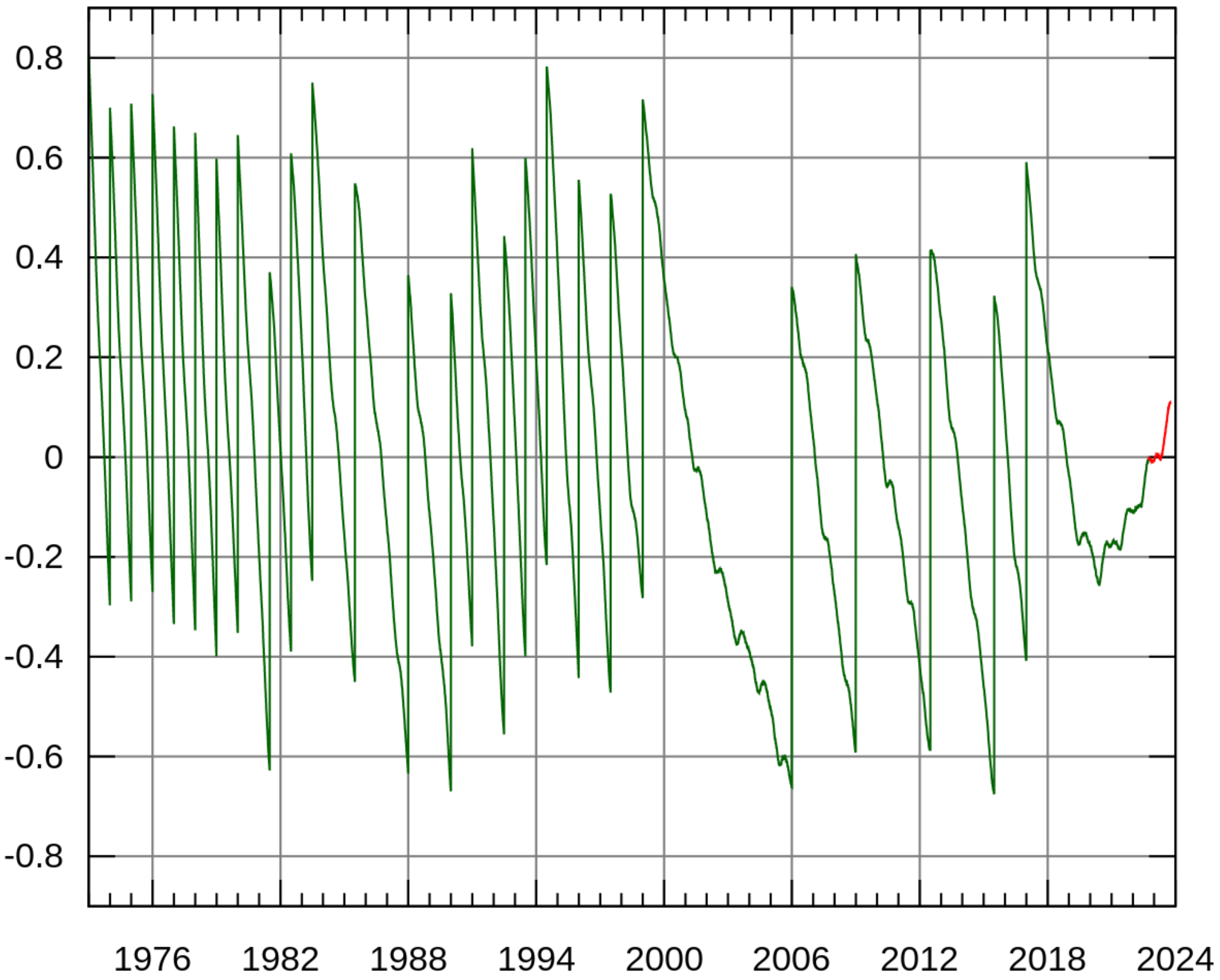
IERS is the International Earth Rotation and Reference System Service

EAL (*É*chelle *A*tomique *L*ibre, free atomic time scale)



http://maia.usno.navy.mil/

UT1 - UTC

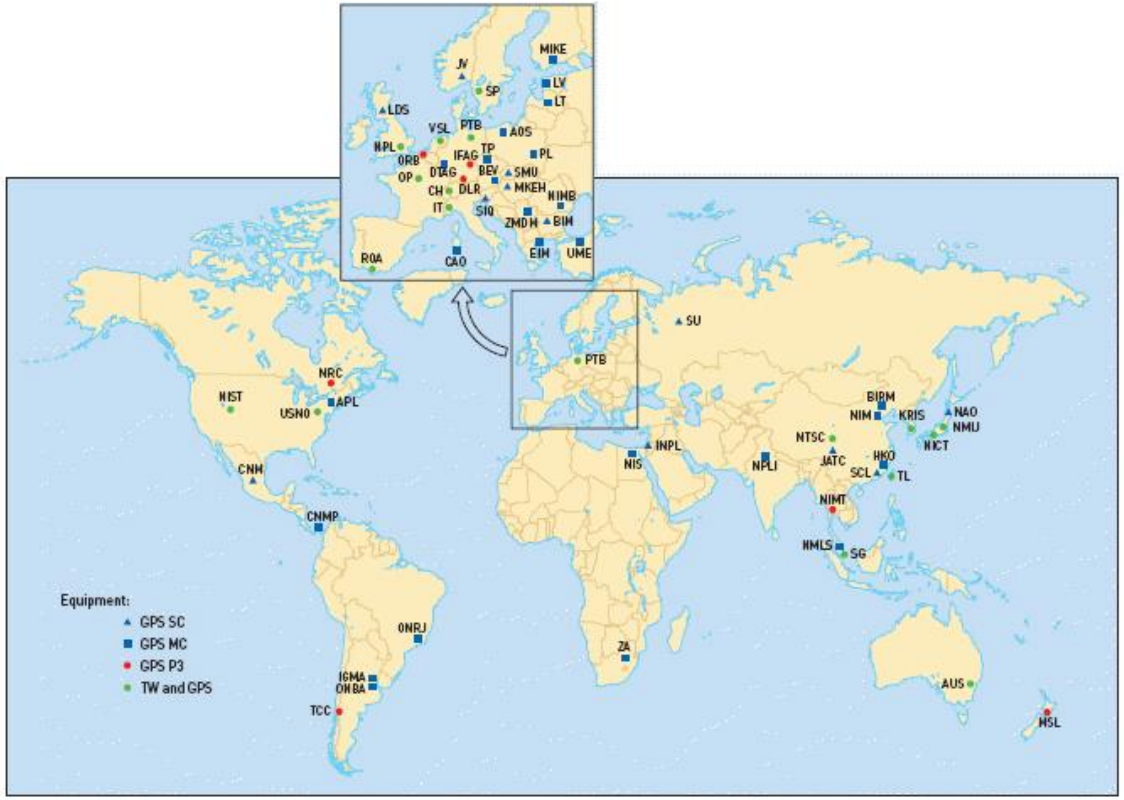


http://maia.usno.navy.mil/

...in more detail...

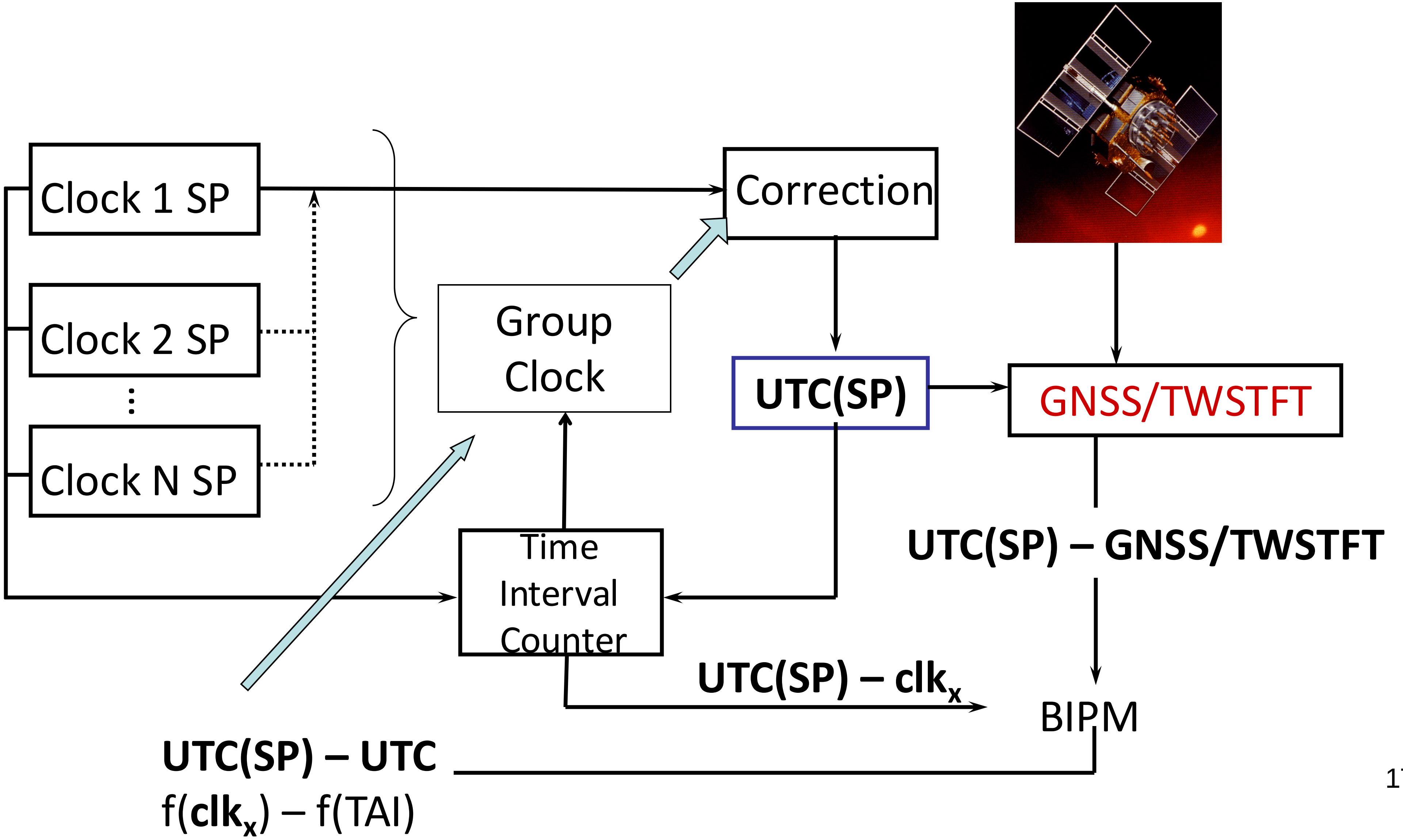
- To calculate UTC, BIPM relies on time differences between clocks located worldwide
- These differences are calculated by using so called Time Links between institutes
- The Time Links are based on satellite techniques such as GNSS, often called Time Transfer Techniques
- These are described in Part 2 of this lesson

National institutes contributing to TAI and UTC



- Around 70 national institutes and organisations contribute to TAI and UTC
- Each institute realises its own version of UTC, UTC(k), and makes this time scale available to different users of time
- BIPM calculates the time difference UTC – UTC(k) which is published monthly in the BIPM Circular T

Swedish National Time Scale UTC(SP)



Atomic clocks

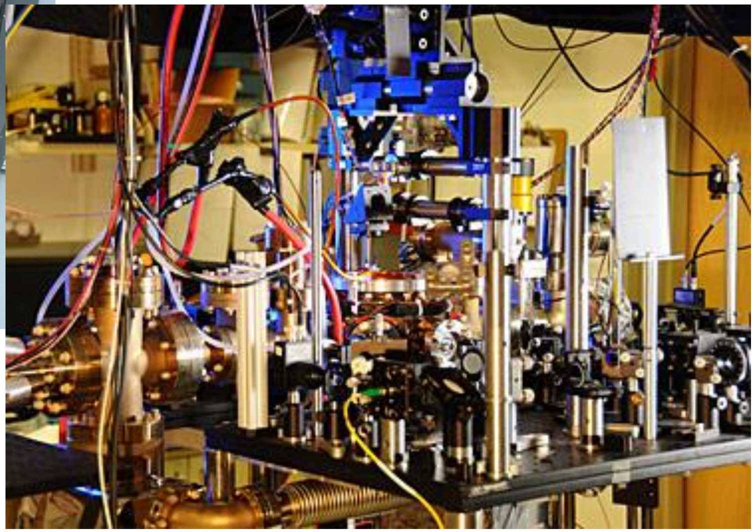
Commercial
Caesium clock

Commercial
Hydrogen maser

Small Rubidium clock

Caesium fountain clock

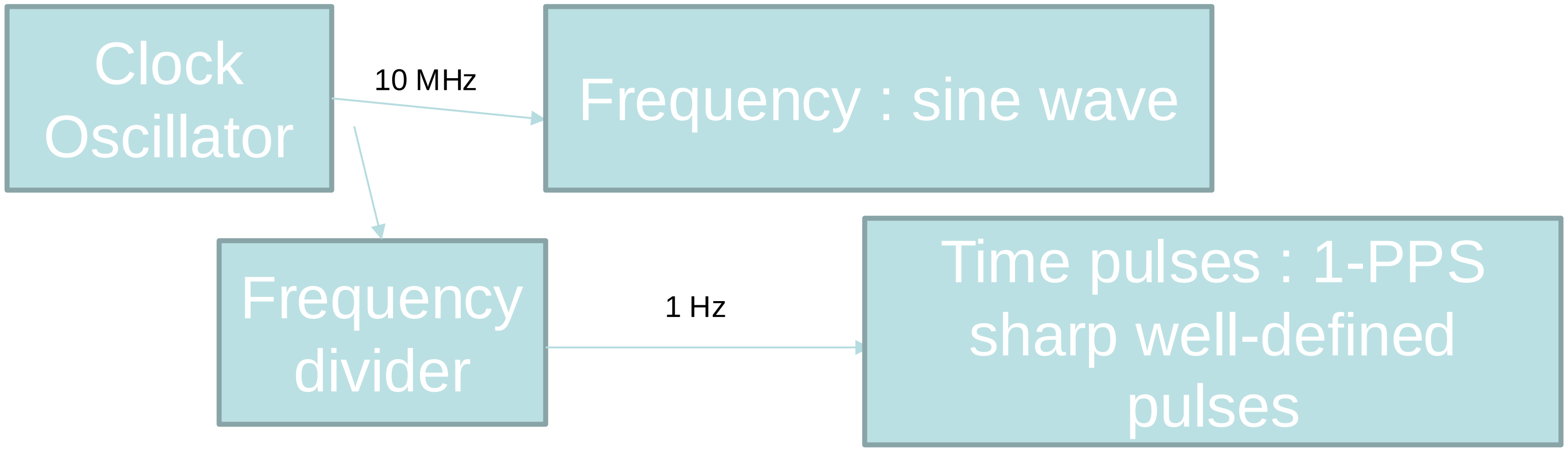
Ytterbium optical clock



Characteristics of Atomic clocks

- Commercial Caesium clocks
  - Accurate but not very stable (50 kEuro)
  - Used for calculation of EAL
- Hydrogen masers
  - Very stable but not accurate
  - Commercially available but expensive (100-200 kEuro)
  - Used for calculation of EAL
- Caesium fountain clocks
  - Very accurate and stable
  - Laboratory clocks, very expensive and complicated to build
  - Used to steer TAI to the SI second
- (Small) Rubidium clocks
  - Moderate accuracy and stability
  - Cheap (< 2 kEuro), used in a variety of industrial applications
- Optical clocks
  - The future of time keeping
  - Today only a few exists, very expensive complicated to build

Atomic Clock: Time and Frequency



- Frequency and Time used for “in-house” reference signals
- Time pulses from Clocks are also used to build Time scales
- Compare different clocks using measurement techniques
  - closely located clocks (within a lab) often by time interval counters (1-PPS)
  - remote clocks by time transfer techniques such as GNSS (1-PPS and Sine waves)

End of Part 1

Today's Lecture

- The definition of the SI-second
- Time scales
- International time keeping
- Atomic clocks and their characterization

- Requirements for time and frequency
- Time and frequency distribution systems
- Time in GNSS
- Time transfer using GNSS (with examples)

Requirements for Time and Frequency

Requirement	Examples	Time	Frequency
Everyday Life	Wristwatches, stop watches, parking meters, musical pitch, tuning forks, computers, servers, etc.	1 s/day to minutes/hour	0.1 to 1E-6
Financial Markets	Stock market time stamps, Computer-based trading	1 μs to a few seconds	NA
Broadcasting	AM/FM radio, TV Carries, Short-wave	NA	1E-5 to 1E-6
Electric Power Distribution	Generation control, Event recorders, Fault detection, Phasor measurements for assessing network conditions	1 μs to 10 ms	NA
Telecommunication Systems	Land-based Telephone, Mobile phones networks, Wireless networks	NA	5E-6 to 1E-11 Stratum 3 to 1
Calibration Laboratories	Time, Frequency, Voltage, Length, Flow, etc.	< 100 ns	<1E-12
Radio Navigation	Clocks for Loran-C, GNSS	NA	< 1E-13
Science	Remote comparisons of clocks, time transfer, fundamental physics, etc.	< 1 ns	< 1E-15

Lombardi (NIST), Measure vol. 1 No. 3, 2006

Sensor fusion

- Increased update frequency
- Navigation in difficult environments such as indoors and tunnels
- Increased robustness

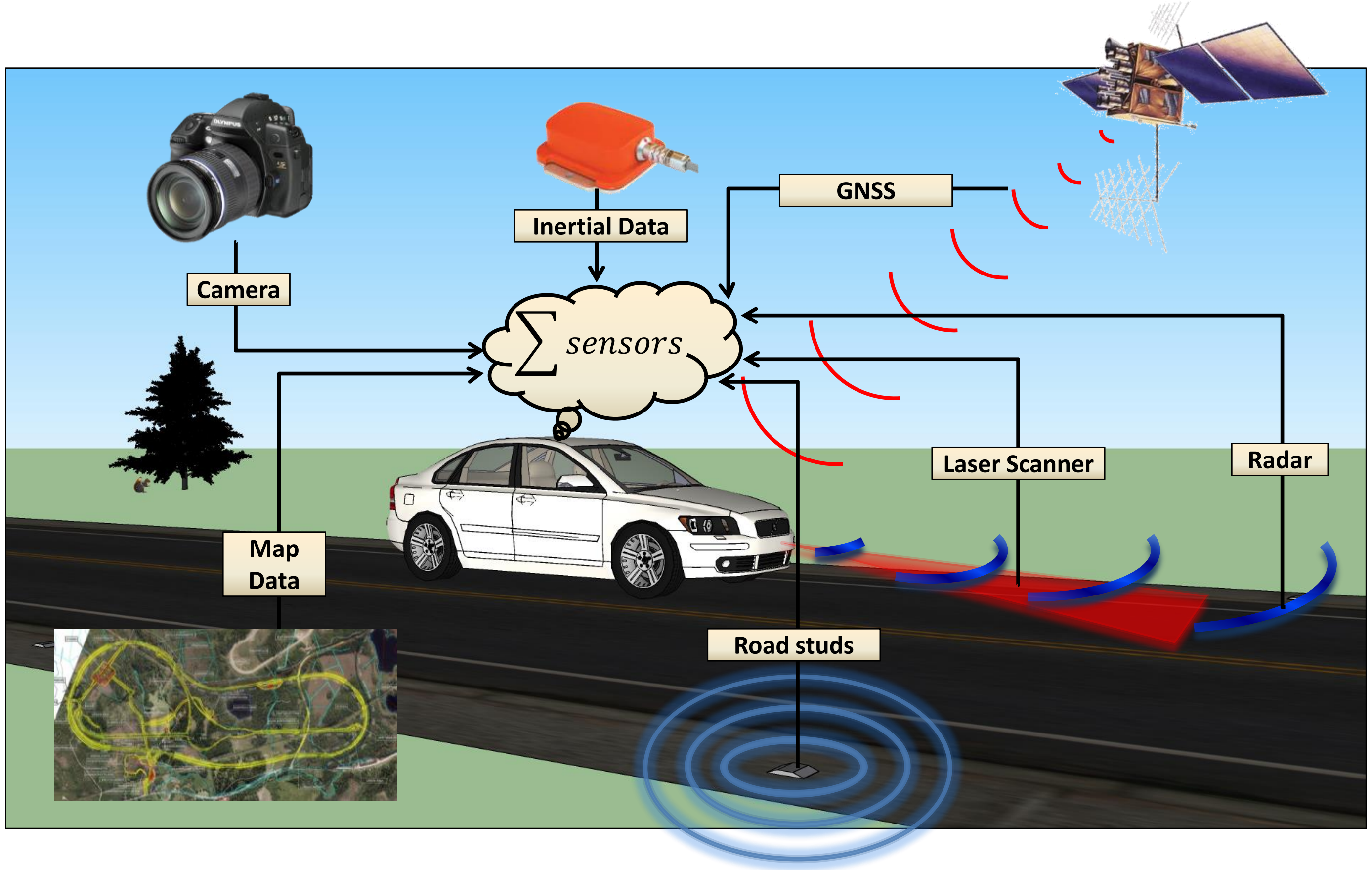
• GNSS provides position, velocity, acceleration and time

• Accelerometer provides acceleration

• Gyro provides angles

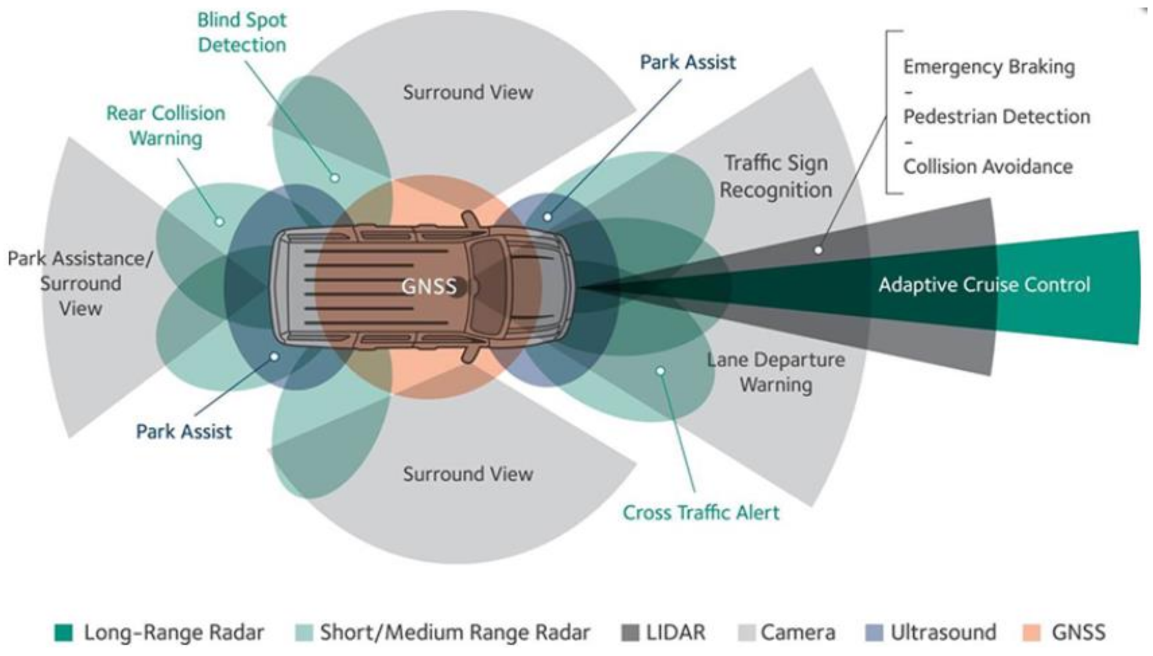
• CAN bus provides speed

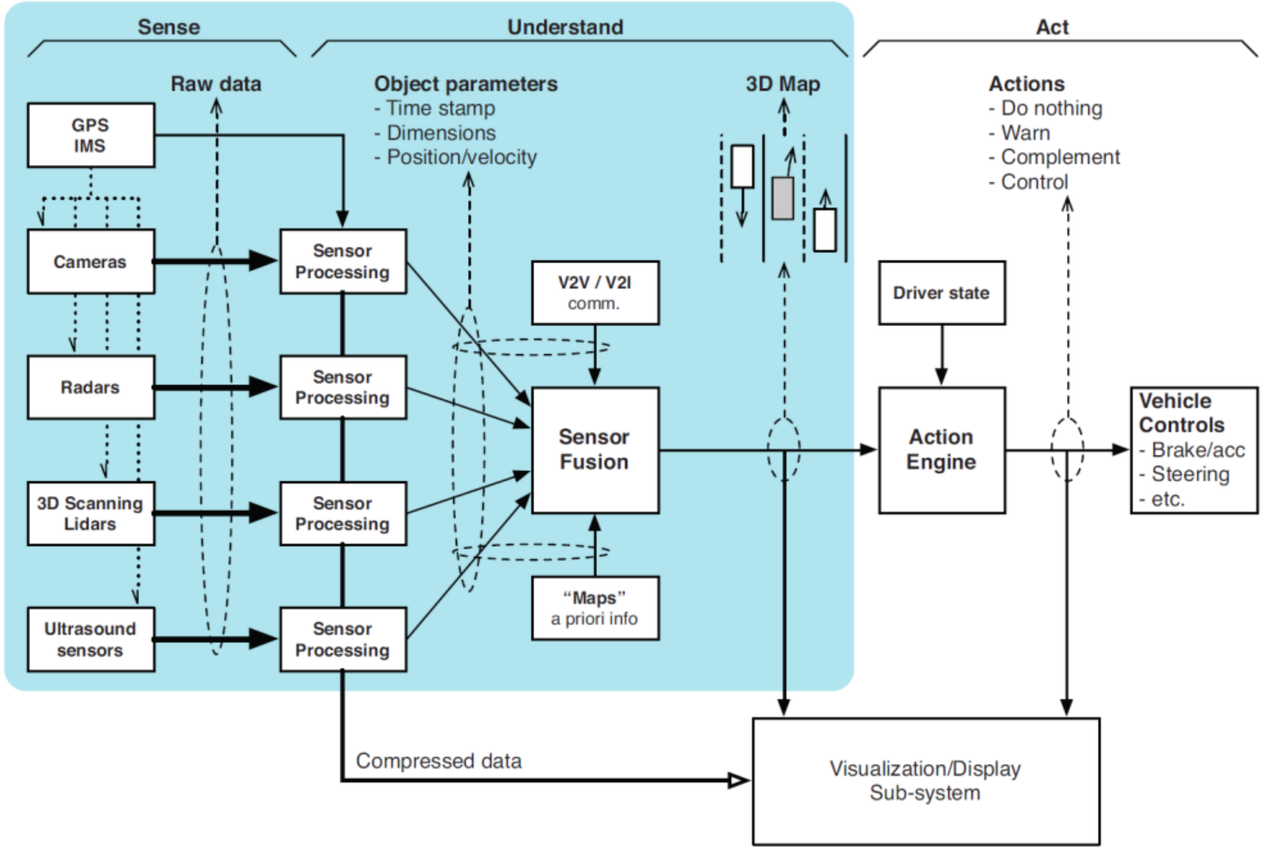
Measurements are combined through sensor fusion in a Kalman filter



Technologies for autonomous vehicles

- The car need sensors for decsision making based on indata.
- Sensor Data Fusion and Machine Learning need information about the quality of input data.



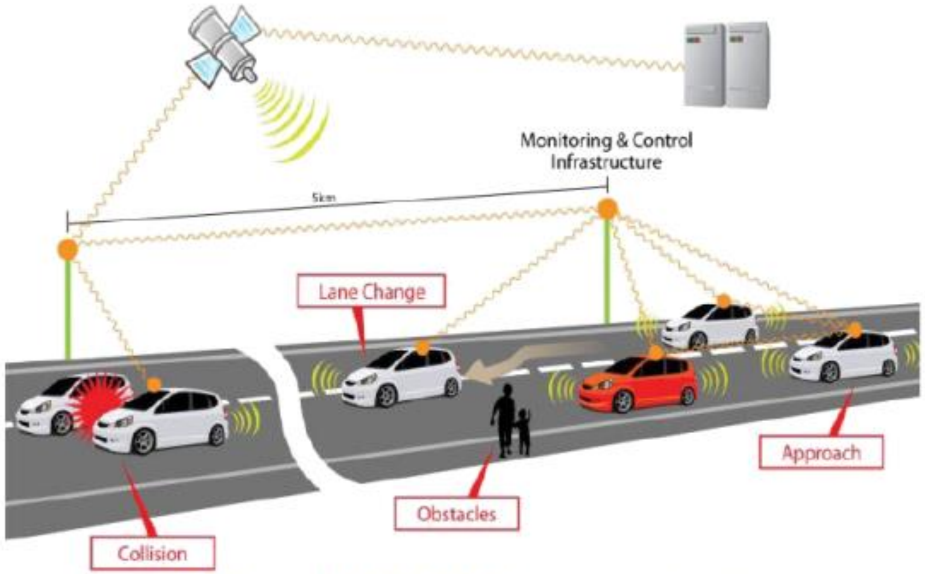


ETSI C-ITS

Vehicle to Vehicle (V2V) communication

(Courtesy of autoevolution)

Vehicle to Infrastructure (V2I) communication



V2V and V2I-I2V Communications
(Courtesy of Embedded System Technology)

Communication protocol is based on IEEE 802.11p

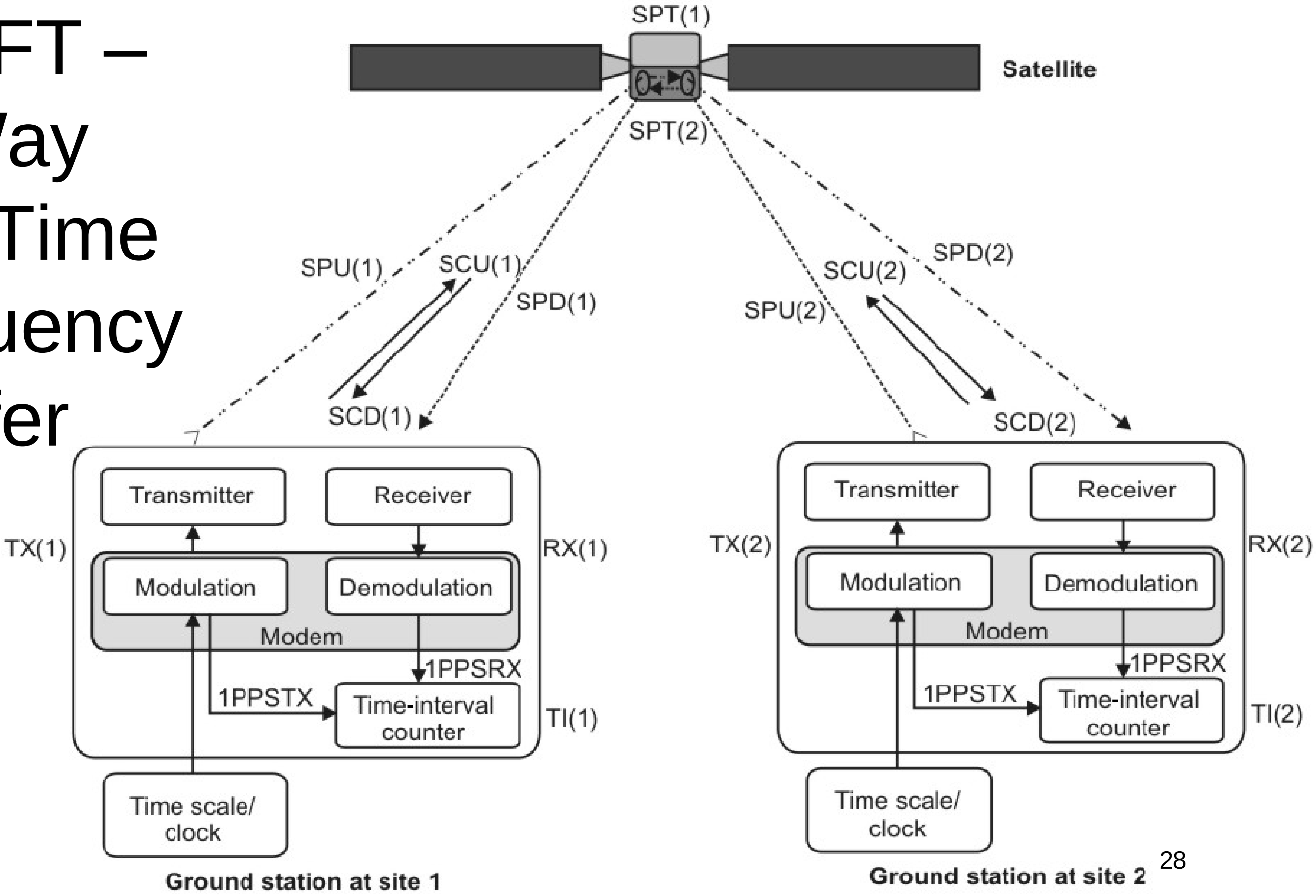
Ref: http://www.autoevolution.com/news/gm-begins-testing-of-vehicle-to-vehicle-communication-in-ann-arbor-48560.html
Ref: http://en.wikipedia.org/wiki/IEEE_802.11p
Ref:http://www.uwicore.umh.es/files/paper/2012_international/uwicore_IEEE_Communications_802.11p%20vehicle%20to%20infrastructure%20communications%20in%20urban%20environments.pdf

Time and Frequency distribution

Method	Baseline length	Time	Frequency
Speaking Clock	National	< 1 s	NA
Network Time Protocol (NTP)	Worldwide	1 to 50 ms	NA
Precise Time Protocol (PTP)	Local networks or campus	1 μs to 1 ms	NA
Short- and Long wave transmitters	Regional/Continental	1 μs to 10 ms	1E-6 to 1E-12
GNSS	Worldwide	< 1 ns	< 1E-15
TWSTFT (Time and Frequency transfer over geostationary satellites)	Inter-continental	< 1 ns	< 1E-15
Optical Fibres	Continental	NA	< 1E-18

Accuracy often dependent on observation time

TWSTFT – Two-Way Satellite Time and Frequency Transfer



TWSTFT – some equations

- Ku or X-band
- RF carrying BPSK modulation of PRN codes
- Unique PRN codes for each station => CDMA

The difference of the time scale at station 2 from the time scale at station 1, TS(1) – TS(2), is determined as follows:

The TIC reading at station 1 is:

$$TI(1) = TS(1) - TS(2) + TX(2) + SPU(2) + SCU(2) + SPT(2) + SPD(1) + SCD(1) + RX(1),$$

and that at station 2 is:

$$TI(2) = TS(2) - TS(1) + TX(1) + SPU(1) + SCU(1) + SPT(1) + SPD(2) + SCD(2) + RX(2).$$

Thus

$$TI(1) - TI(2) = 2\ TS(1) - 2\ TS(2) + TX(2) - TX(1) + SPU(2) - SPU(1) + SPT(2) - SPT(1) + SPD(1) - SPD(2) + RX(1) - RX(2) + SCD(1) - SCU(1) - SCD(2) + SCU(2).$$

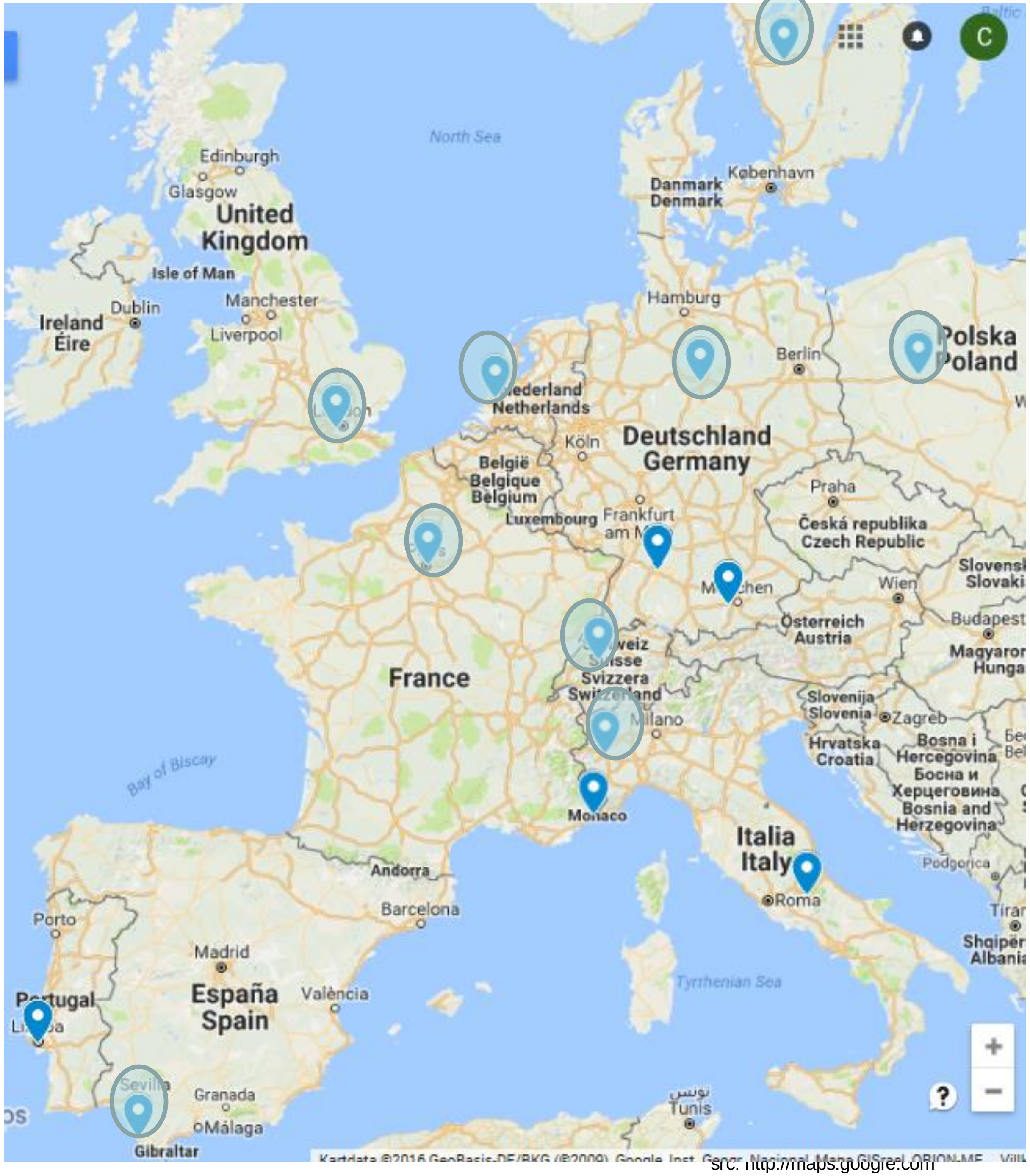
The time-scale difference is then given by the so-called two-way equation:

$$\begin{aligned}
TS(1) - TS(2) = &+ 0.5\ [TI(1)] && \text{(= TIC reading at station 1)}\\
&- 0.5\ [TI(2)] && \text{(= TIC reading at station 2)}\\
&+ 0.5\ [SPT(1) - SPT(2)] && \text{(= Satellite delay difference)}\\
&- 0.5\ [SCD(1) - SCU(1)] && \text{(= Sagnac correction for station 1)}\\
&+ 0.5\ [SCD(2) - SCU(2)] && \text{(= Sagnac correction for station 2)}\\
&+ 0.5\ [SPU(1) - SPD(1)] && \text{(= Up/down difference at station 1)}\\
&- 0.5\ [SPU(2) - SPD(2)] && \text{(= Up/down difference at station 2)}\\
&+ 0.5\ [TX(1) - RX(1)] && \text{(= Transmit/receive difference at station 1)}\\
&- 0.5\ [TX(2) - RX(2)] && \text{(= Transmit/receive difference at station 2),}
\end{aligned}$$

where the last seven terms are corrections for non-reciprocity. Apart from the satellite delay difference SPT, the corrections can in principle be grouped in corrections per station.

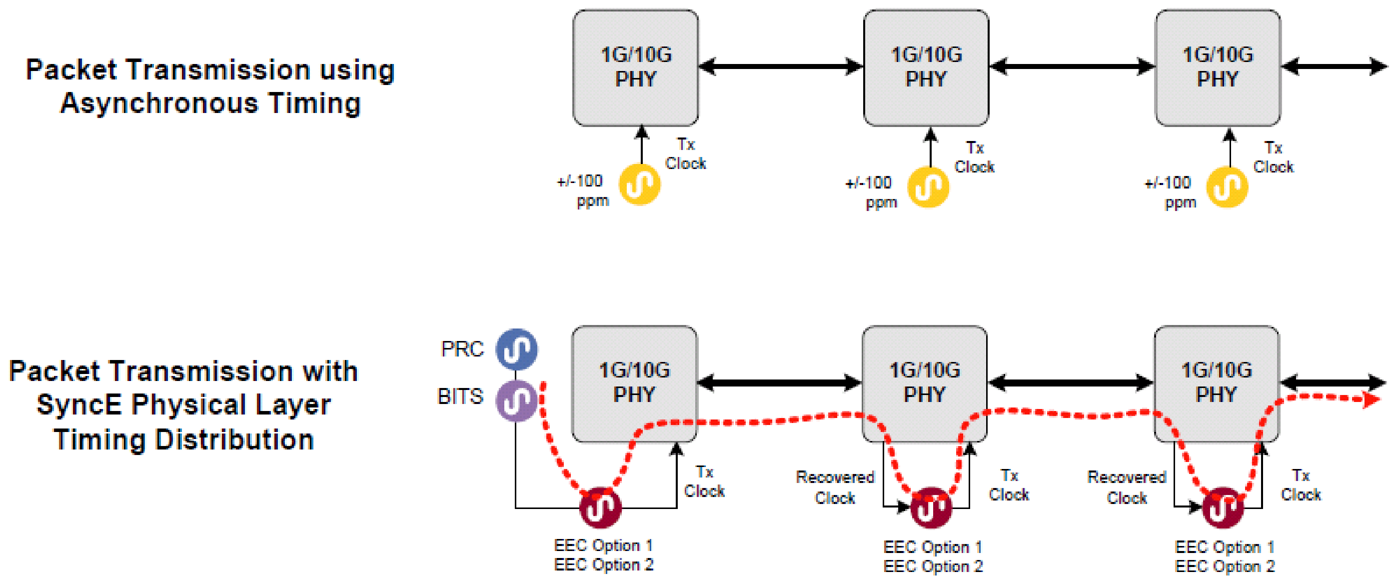
The Active European Network

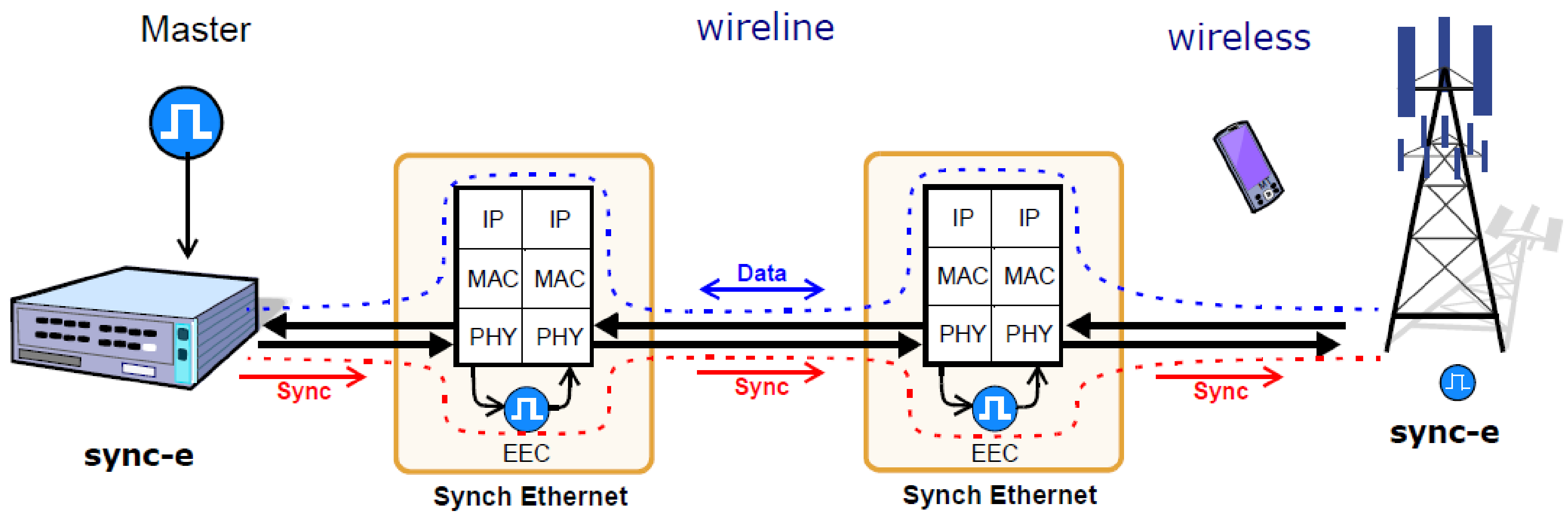
- **10** NMI ROA, IPQ, NPL, OP, VSL, PTB, CH, INRIM, AOS, RISE/SP
- **5** associate laboratories
  OCA, PTF1, PTF2, TIM, LTFB



src: http://maps.google.com

Optical fiber ...





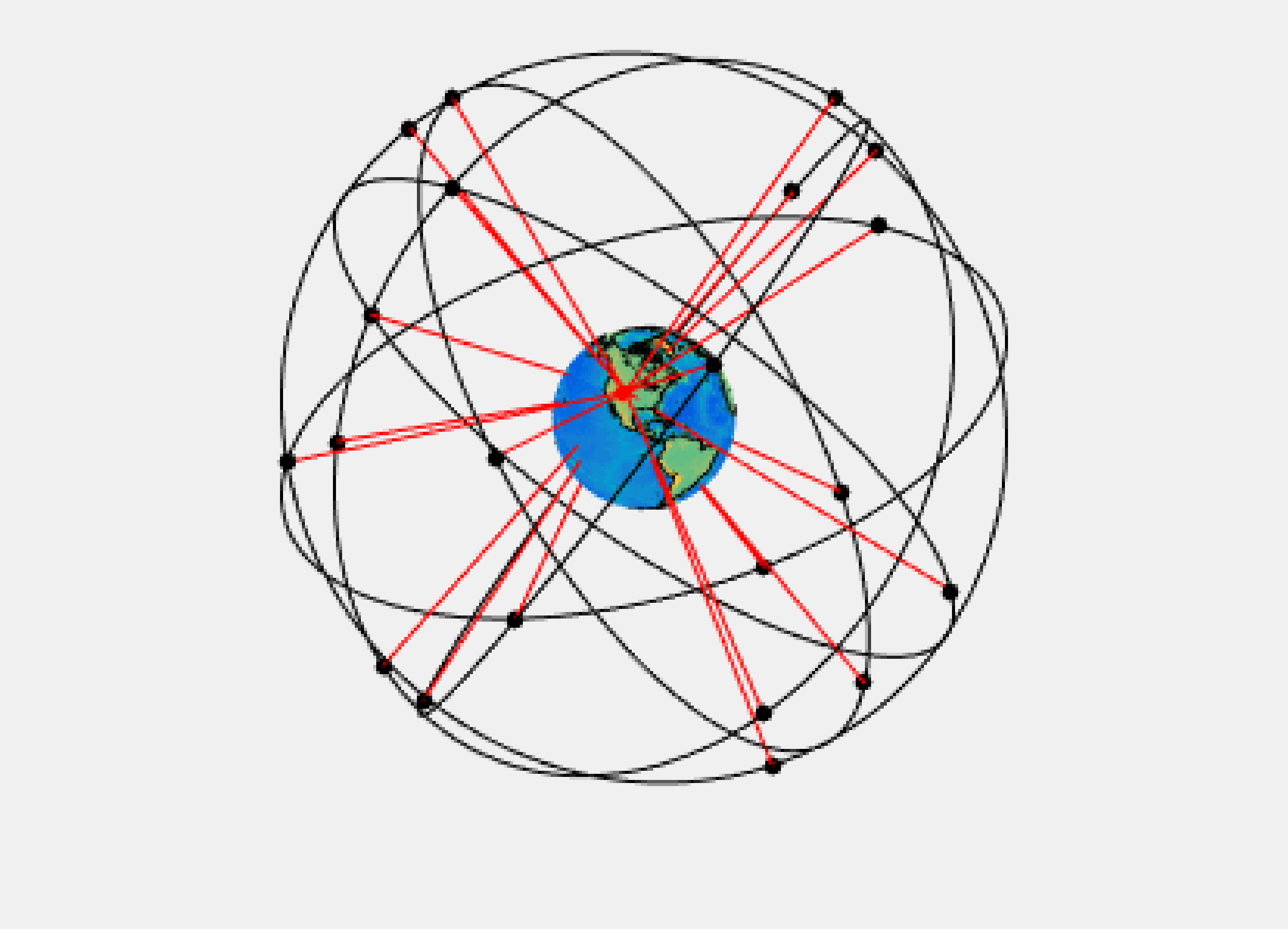
https://en.wikipedia.org/wiki/Synchronous_Ethernet

Present GNSS

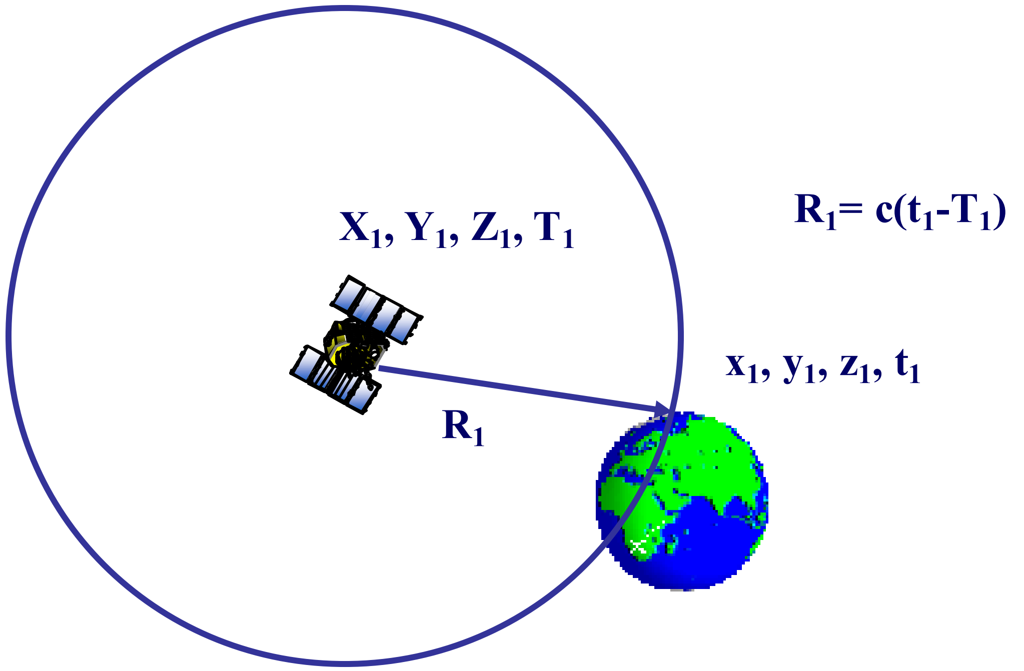
	Country	Region	First launch	Approximate number of satellites	Operational
GPS	USA	Global	1978	32	1995
GLONASS	Russia	Global	1982	30 (24)	2011 (?)
Beidou	China	Global	2000	30	2023
Galileo	Europe, EU	Global	2011	30 (23)	2025
QZSS	Japan	Regional	2010	7	2020
IRNSS	India	Regional	2013	7	2016

Satellite-based navigation

- GNSS – Global Navigation Satellite Systems
- GPS, Glonass, Galileo och Beidou consists of ≈ 30 satellites each
- All satellites at an altitude of ≈ 20 000 km
- All systems broadcast similar signaler and can be used together.
- Nanosecond & millimeter



Why Time in GNSS?



- The calculation of R_1 is based on a time interval measurement
- T_1 (satellite time) and t_1 (receiver time) must be in the same time reference frame and must be synchronized – 30 meter is 100 nanoseconds
- This synchronization offset must be calculated using a 4th satellite
- T_1 is related to GNSS-time

GNSS-time summary

	Definition / UTC-offset 2019	Clock reference	Steered to	Accuracy
GPS	TAI - 19 s / 18 s	Satellite and tracking station clocks	UTC(USNO)	≈10 ns
GLONASS	UTC / 0 s	Several H-masers	UTC(SU)	<100 ns
Galileo	TAI - 19 s / 18 s	Several H-masers	Average of 5 UTC(k) labs	≈10 ns

Difference between GNSS-times published in navigation messages

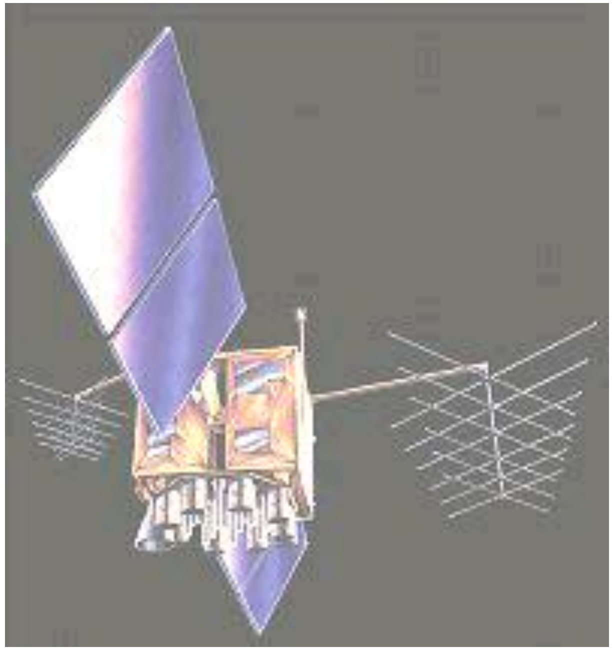
Atomic clocks onboard the satellites

- Each GNSS-satellite has several atomic clocks onboard
- The signals sent from the satellites are based on these clocks
  - The frequency (carrier) of the signal
  - The time reference
- Each clock has its own time
  - The difference between the “clock-time” and the GNSS-time is calculated by the tracking stations and transmitted/uploaded to the satellites
  - The difference is for a user included in the Navigation message
- The satellites contain Caesium clocks (mainly older satellites), Rubidium clocks, and H-maser clocks (Galileo)

Time and Frequency transfer using GNSS

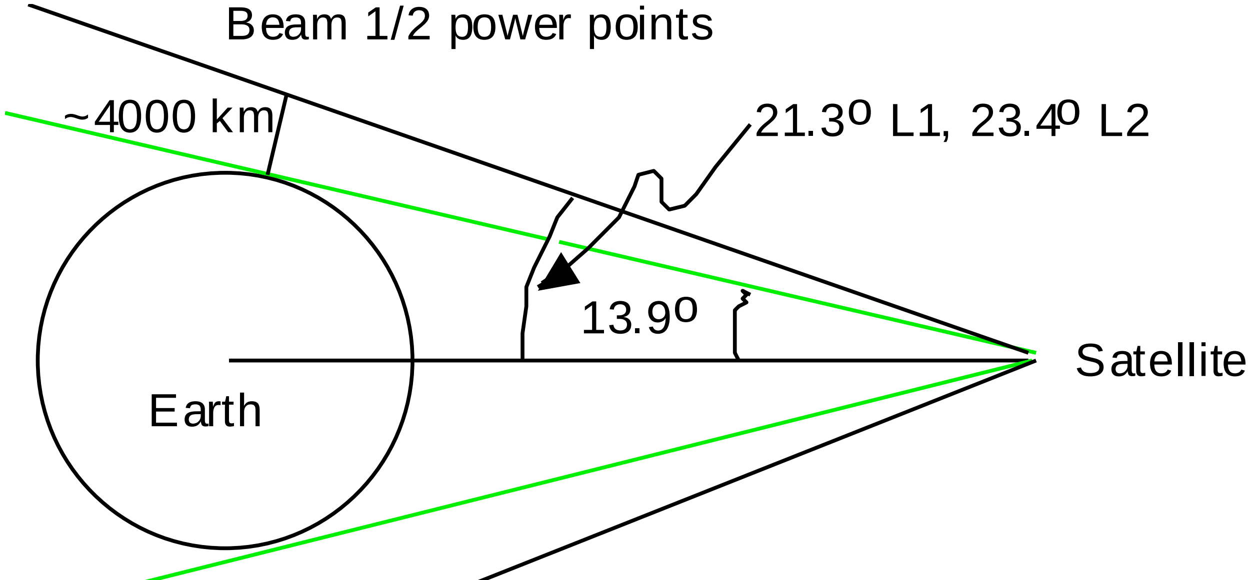
- Example applications
  - International Time scale and Clock comparisons
  - Synchronization of telecom networks
  - Characterization of electric power networks
  - Synchronization of computers and IT-systems
- In principle two GNSS Time Transfer techniques exists
  - Direct comparisons to GNSS-time
  - The use of GNSS-time as a temporary reference

Satellite Coverage



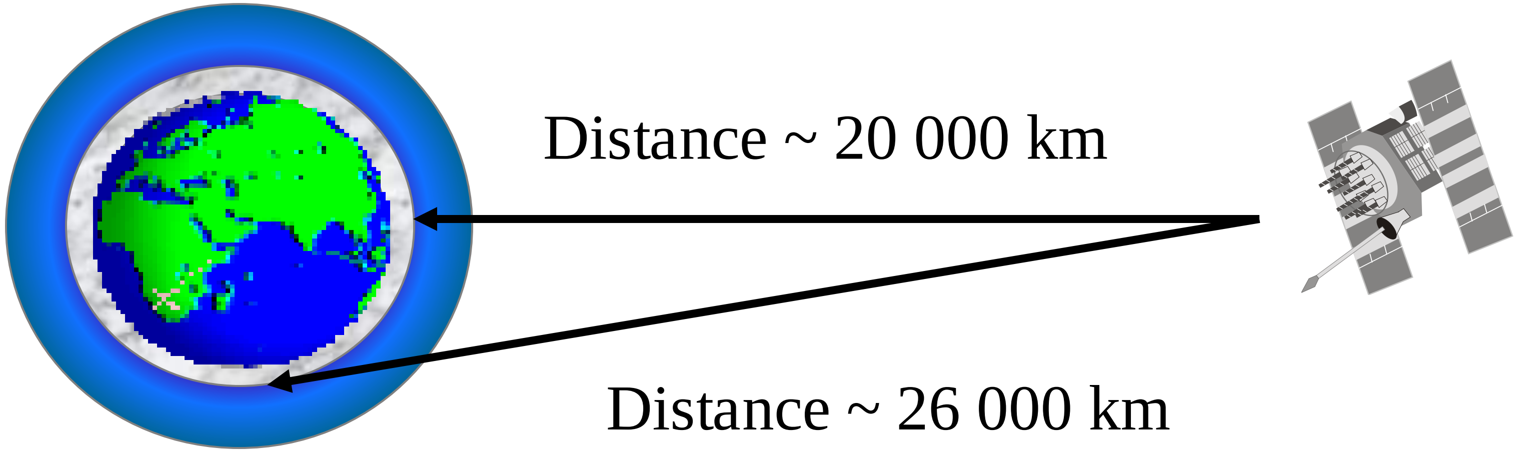
Block IIR satellite
(1,100 kg)

- The GPS satellites point their transmission antenna to the center of the Earth.
- Main beam at L1 is 21.3^o half width, at L2 23.4^o (due to lower frequency)

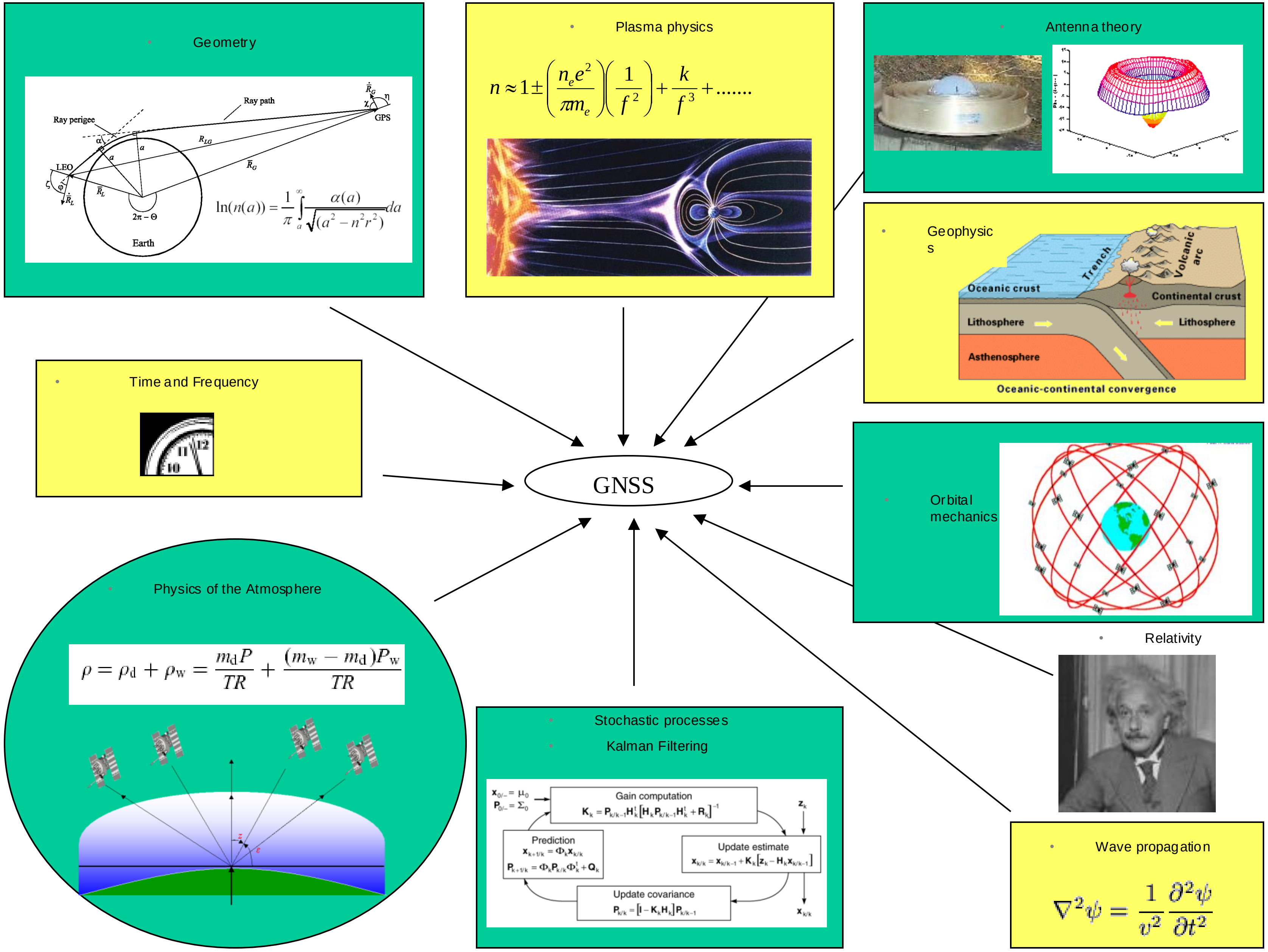


GNSS signals are weak!!!

Satellite power: $P_T = 27$ W
Antenna Gain: $G_T \sim 10$ dBi
Transmitted power ~ 250 W



Received power (minimum):
$P_R = 10^{-16}$ W = -130 dBm = -160 dBW


Geometry
Ray path
Ray perigee
GPS
LEO
Earth
$\ln(n(a)) = \frac{1}{\pi}\int_a^\infty \frac{\alpha(a)}{\sqrt{(a^2 - n^2r^2)}}da$
Plasma physics
$n \approx 1 \pm \left(\frac{n_e e^2}{\pi m_e}\right)\left(\frac{1}{f^2}\right) + \frac{k}{f^3} + \ldots\ldots$
Antenna theory
Geophysics
Oceanic crust
Trench
Volcanic arc
Continental crust
Lithosphere
Lithosphere
Asthenosphere
Oceanic-continental convergence
Time and Frequency
GNSS
Orbital mechanics
Relativity
Physics of the Atmosphere
$\rho = \rho_d + \rho_w = \frac{m_d P}{TR} + \frac{(m_w - m_d)P_w}{TR}$
Stochastic processes
Kalman Filtering
Gain computation
Prediction
Update estimate
Update covariance
Wave propagation
$\nabla^2\psi = \frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2}$

GNSS interferen… s

- GNSS signals … …r whic…
  can easily b…
- Wider fr…
- Increa… …onal …
  - … …al
  - …cipat…
  - …onc… …ons
    R… …nterfe…
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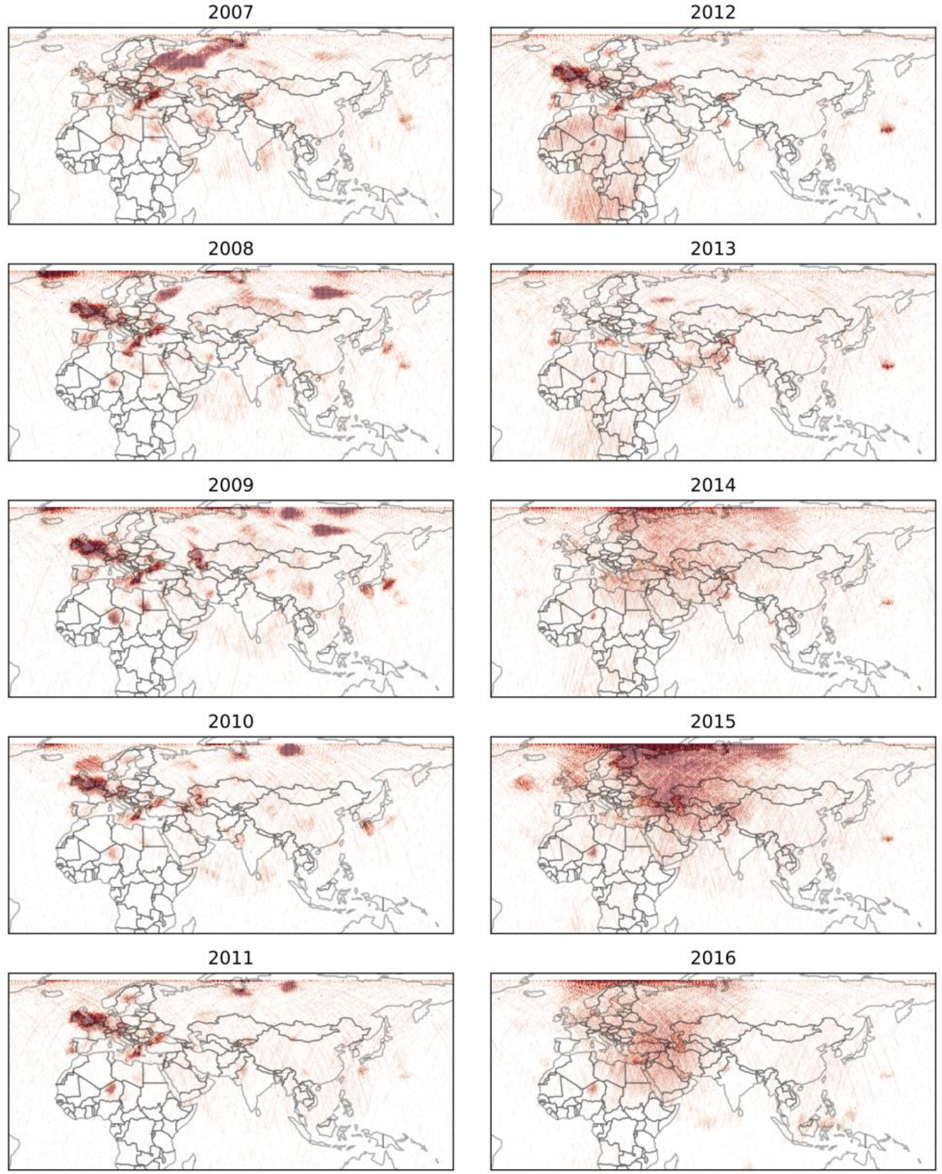
  - …
    - … – Dis…
    - … …ing – … …sition

https://safetyfirst.airbus.com/gnss-interference/

- **Temporal variations of RFI over Europe, Asia, Africa**
- **Russia-Ukraine conflict effect visible in 2014-2016**
  - **Roberts M et al 2021**



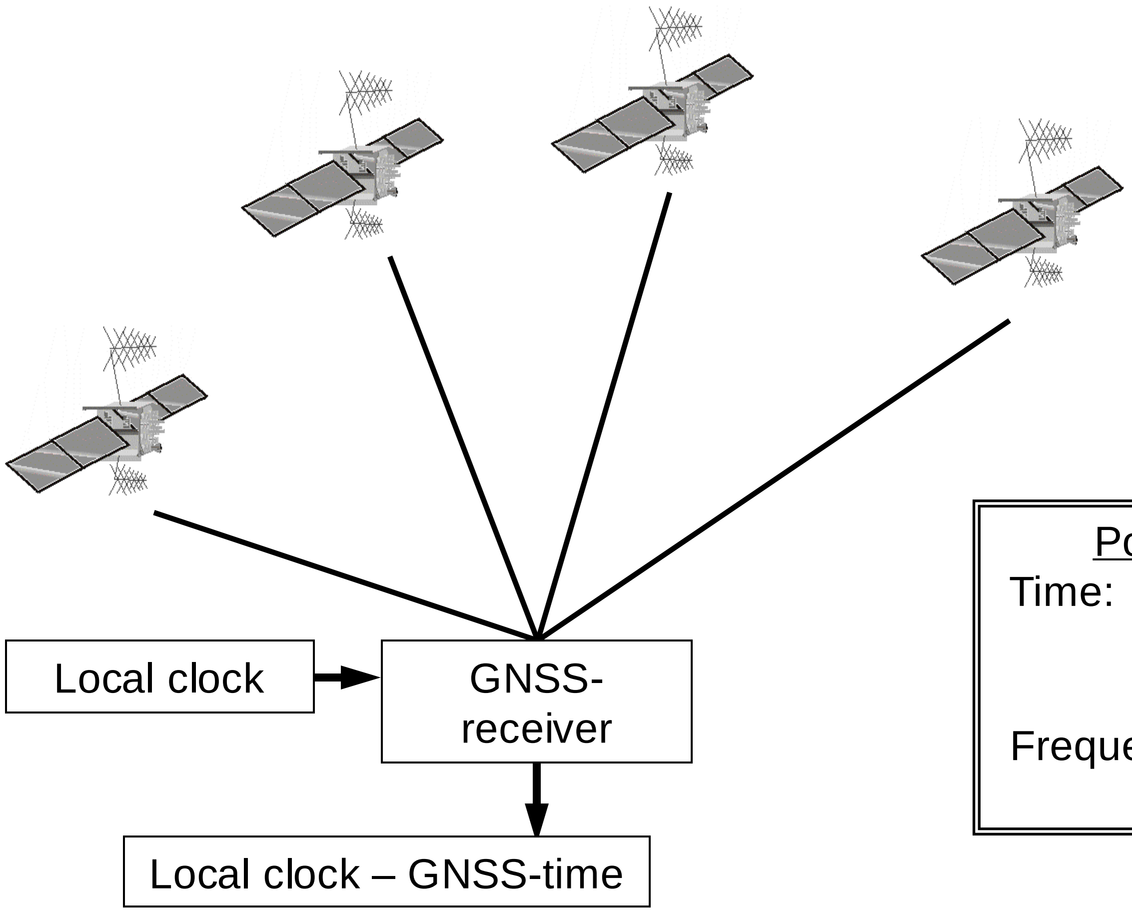
The GNSS receiver

Enough for positioning applications. Internal oscillator represents receiver time

GNSS-Time

External clock signals for timing applications 10 MHz sine and 1-PPS. “Replaces” the internal oscillator. All observations timed by external clock

One-Way GNSS time transfer using P3 code data in real time



In principle, only one satellite is necessary if the position of the receiver is known to within about 1 meter

<u>Potential accuracy relative to UTC:</u>

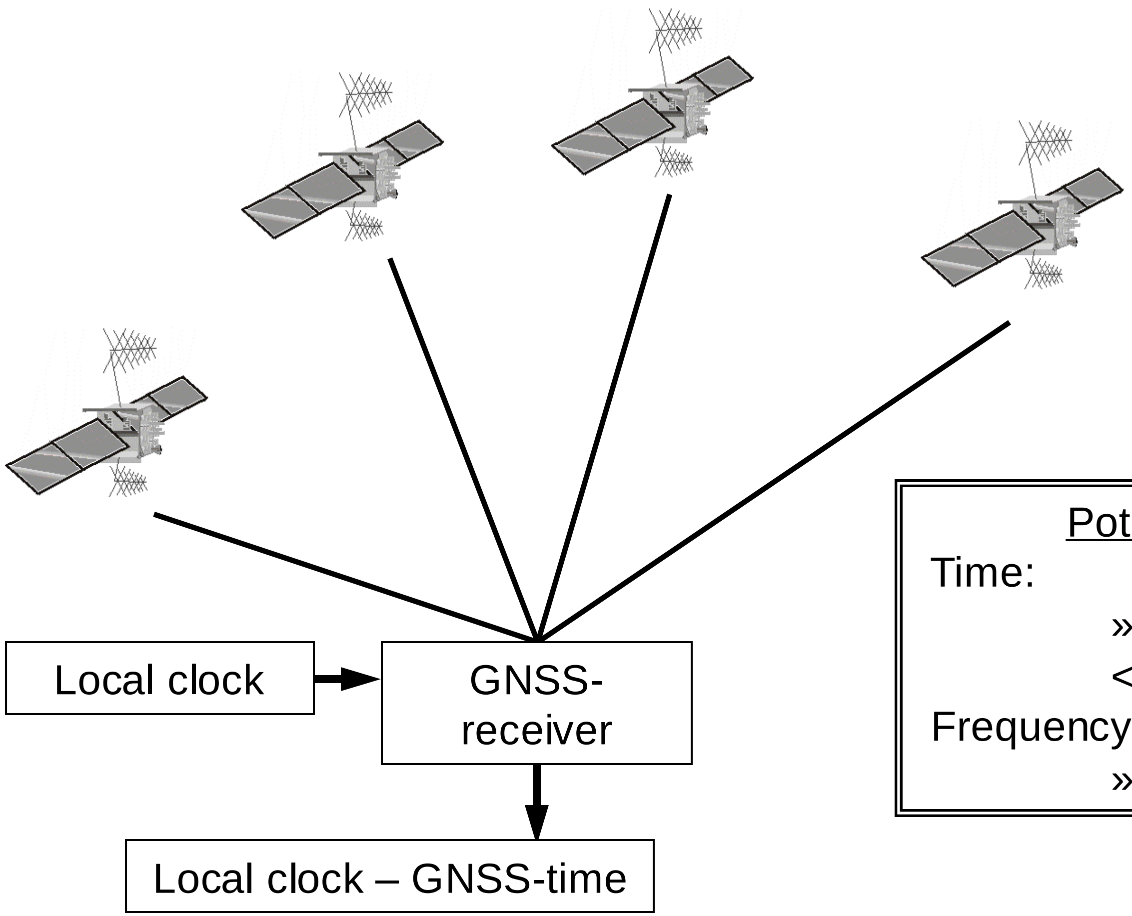
Time:

- » 50 ns in real-time and
- < 10 ns averaged over 1 day

Frequency:

- » 1E-13 averaged over 1 day

One-Way GNSS time transfer using carrier phase and P3 code data (PPP)



Requires precise, estimated satellite orbits and clocks. Accuracy depends on chosen orbits and clocks.

<u>Potential accuracy relative to UTC:</u>

Time:

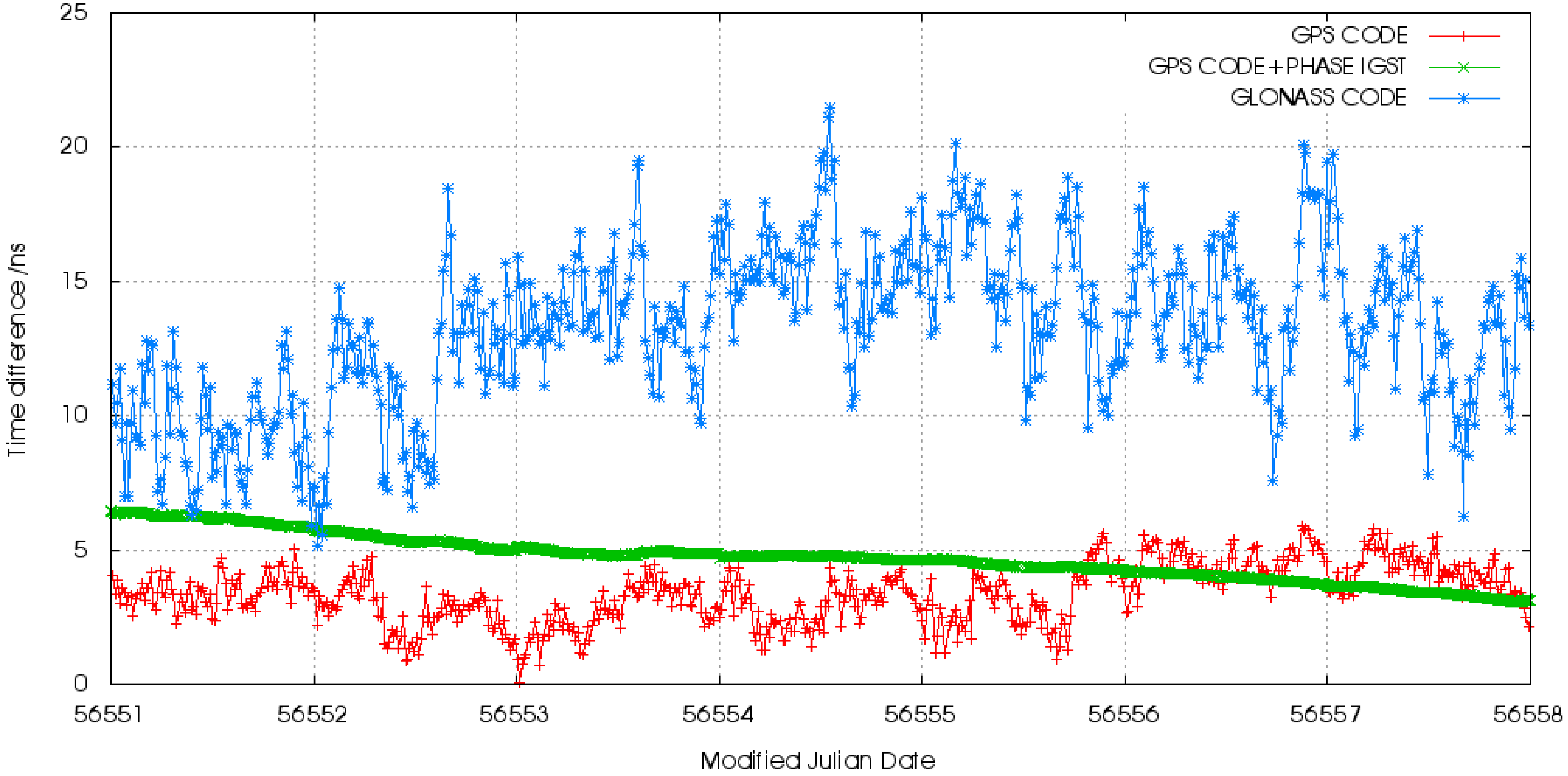
» 50 ns in real-time and

< 10 ns averaged over 1 day

Frequency:

» 1E-15 averaged over 1 day

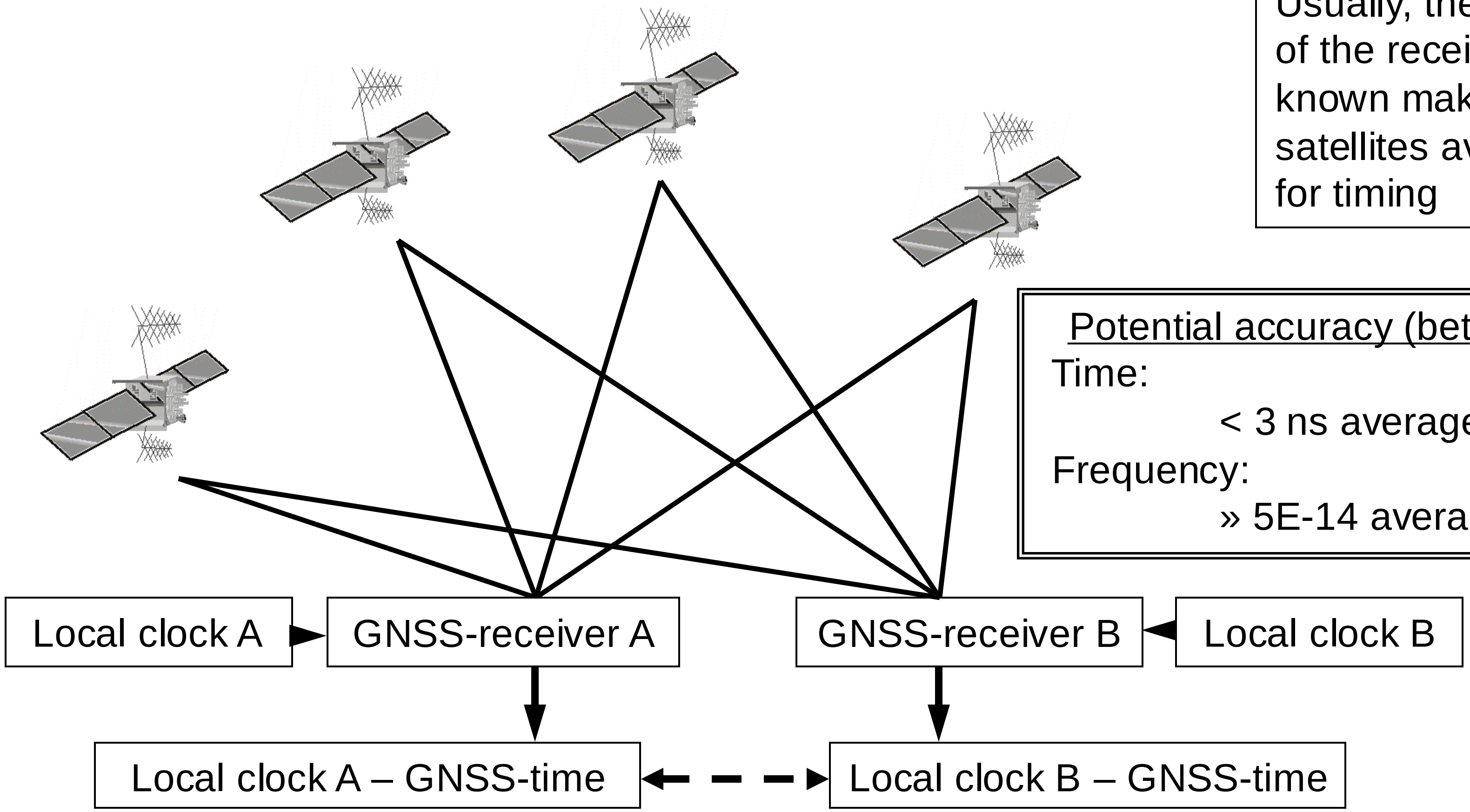
One-Way GNSS time transfer: Local Clock – GNSS/IGS-time



IGS is a provider of accurate satellite orbits and clocks

Common-View GNSS time transfer using P3 code data

Usually, the position of the receivers are known making all satellites available for timing



<u>Potential accuracy (between clocks):</u>

Time:

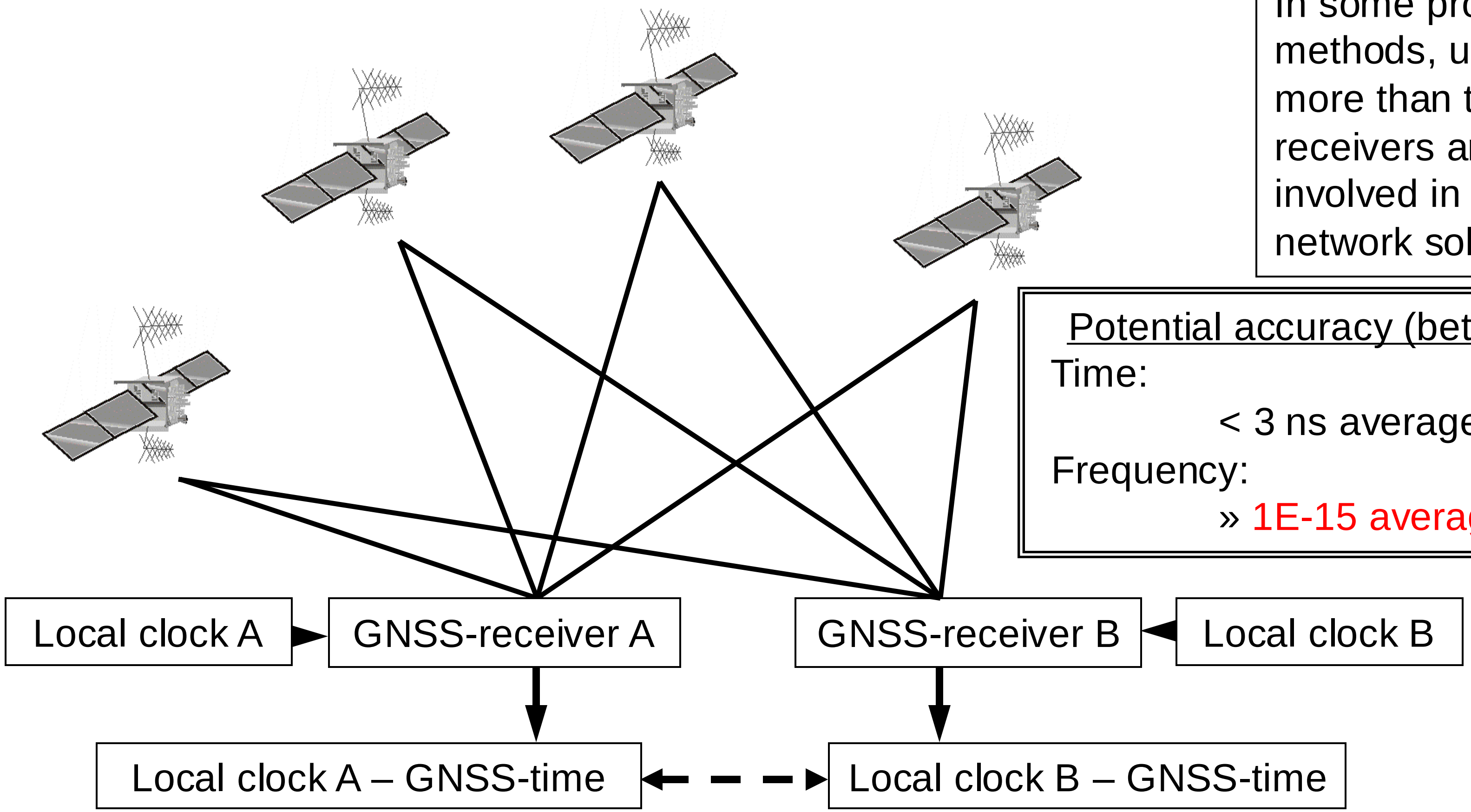
< 3 ns averaged over 1 day

Frequency:

» 5E-14 averaged over 1 day

Data transfer and computations gives Clock A - Clock B (GNSS-time is cancelled)

Common-View GNSS time transfer using carrier phase and P3 code data



In some processing methods, usually more than two receivers are involved in a network solution

<u>Potential accuracy (between clocks):</u>

Time:

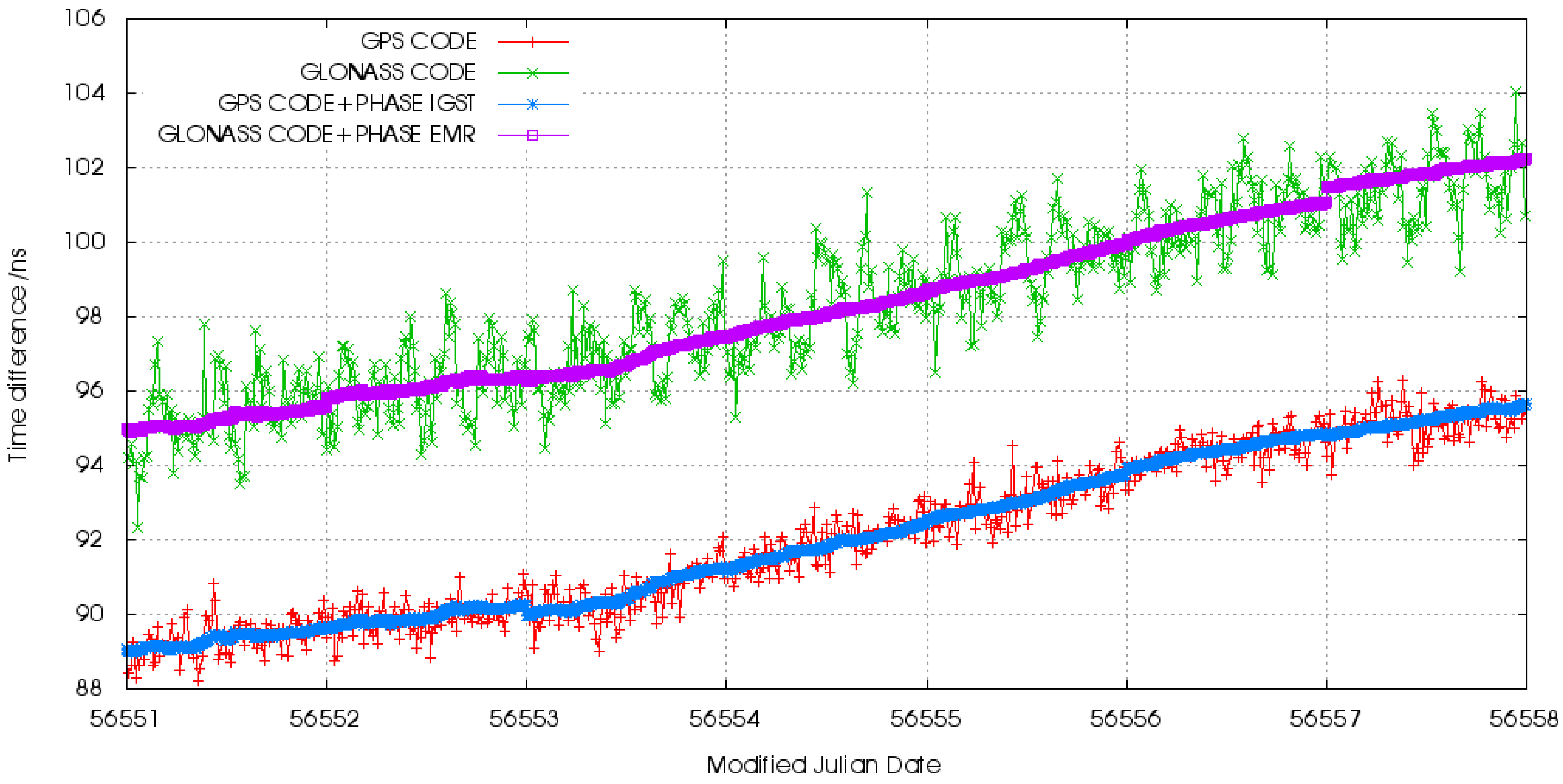
< 3 ns averaged over 1 day

Frequency:

» 1E-15 averaged over 1 day

Data transfer and computations gives Clock A - Clock B (GNSS-time is cancelled)

Common-View GNSS time transfer: Clock A – Clock B



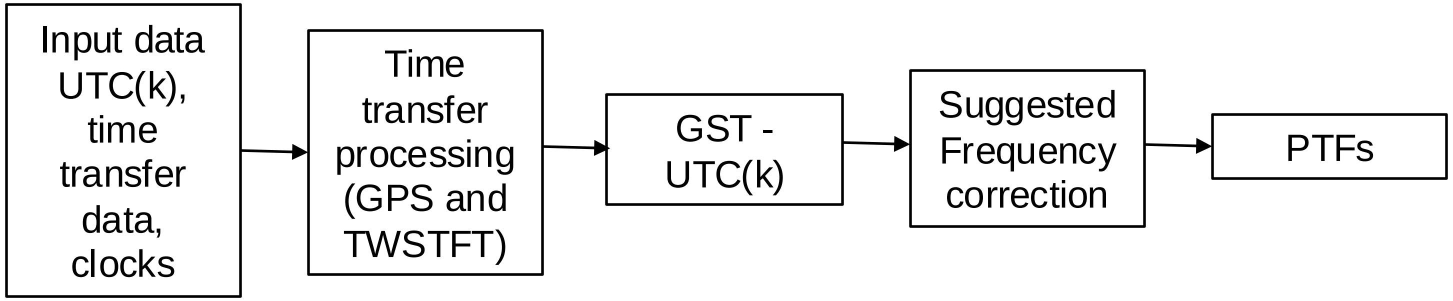
IGS and EMR are providers of accurate satellite orbits and clocks

Time Transfer Example: Characterisation of GST

- The new European Navigation system **Galileo** is presently being implemented
- **GST** – Galileo System Time is used as reference for all signal transmissions
- **PTF**s (Precise Timing Facilities) - contains ensemble of clocks where GST is physically realized on ground
  - PTF1 in Fucino, Italy
  - PTF2 in Oberpfaffenhofen, Germany
  - At any time, one PTF is the master and the other is the slave/backup
  - Each contains 2 Hydrogen masers (HM) and 4 Caesium clocks
  - Normally, one maser is defined as reference and steered towards UTC

Time Transfer Example: Characterisation of GST

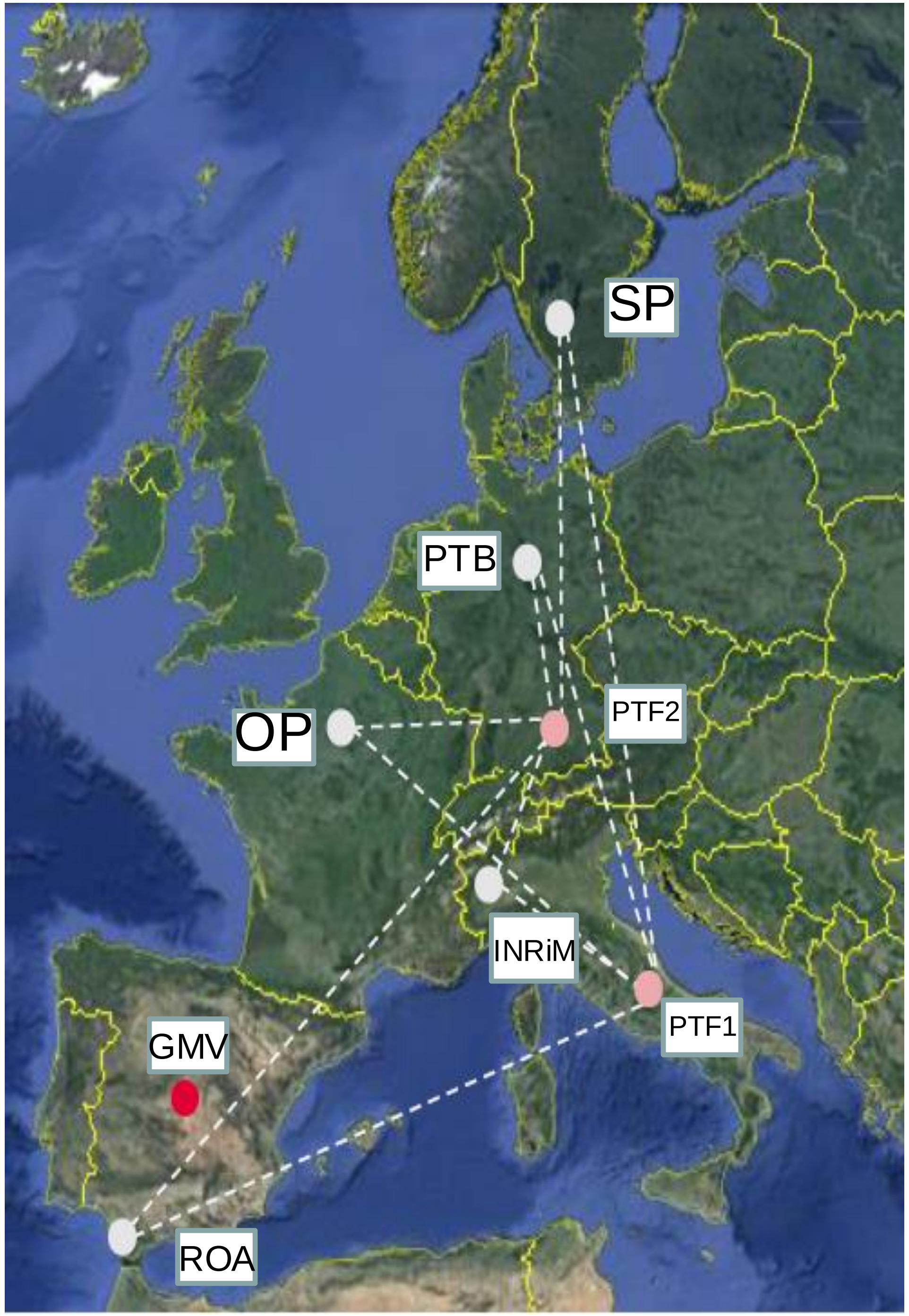
- **TVF** (Time Validation Facility) – entity in charge of steering GST to keep it close to UTC.
  TVF relies on to separate entities
  - **TSP** (Time Service Provider), located at GMV, Spain
  - **ATSP** (Alternative Time Service Provider), located at RISE (SP), Sweden



Note: Time transfer by *GPS* and *TWSTFT* to calculate GST

Time Transfer Example: Characterisation of GST

- Processing of **time transfer** measurements provided by
  - **PTF**s
  - **Five national timing laboratories maintaining UTC(k)**:
    - INRiM, Italy
    - OP, France
    - PTB, Germany
    - ROA, Spain
    - RISE, Sweden
  - **TSP** calculates GST relative to an average of UTC(k)
  - **ATSP** uses a Kalman-filter based time scale algorithm to relate GST to UTC
    - ATSP may be combined with TSP, used for validation or as a backup



End of Part 2

Summary of Today's Class

- The definition of the SI-second
- International and National Time scales and their usage
- Different atomic clocks and their characterization
- (Accuracy, stability and the Allan Deviation)
- General requirements for time and frequency
- Examples of time and frequency distribution systems
- Why time and atomic clocks are important in GNSS
- Examples of time transfer using GNSS