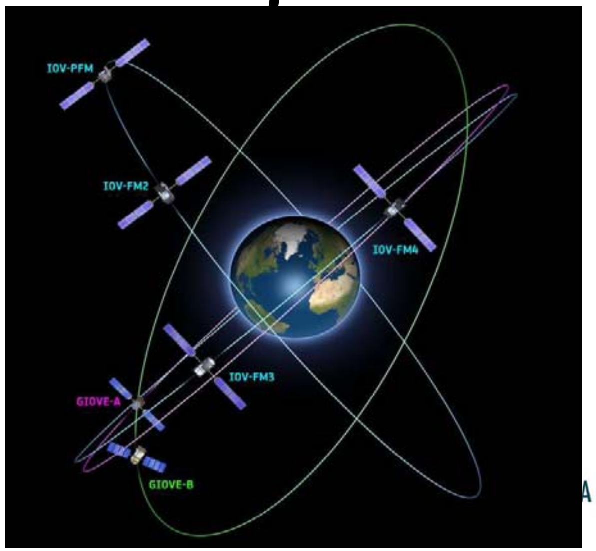
Metrology: from physics fundamentals to quality of life

July 2016

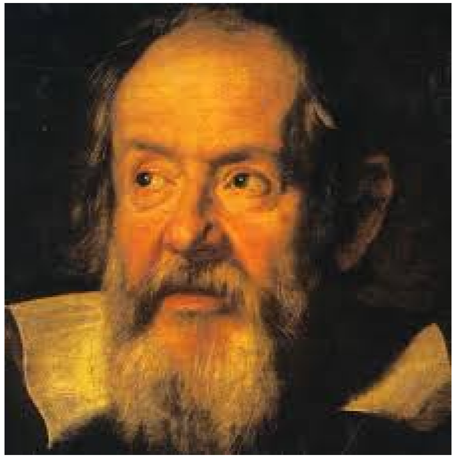
International School of Physics

Precise time scales and navigation systems

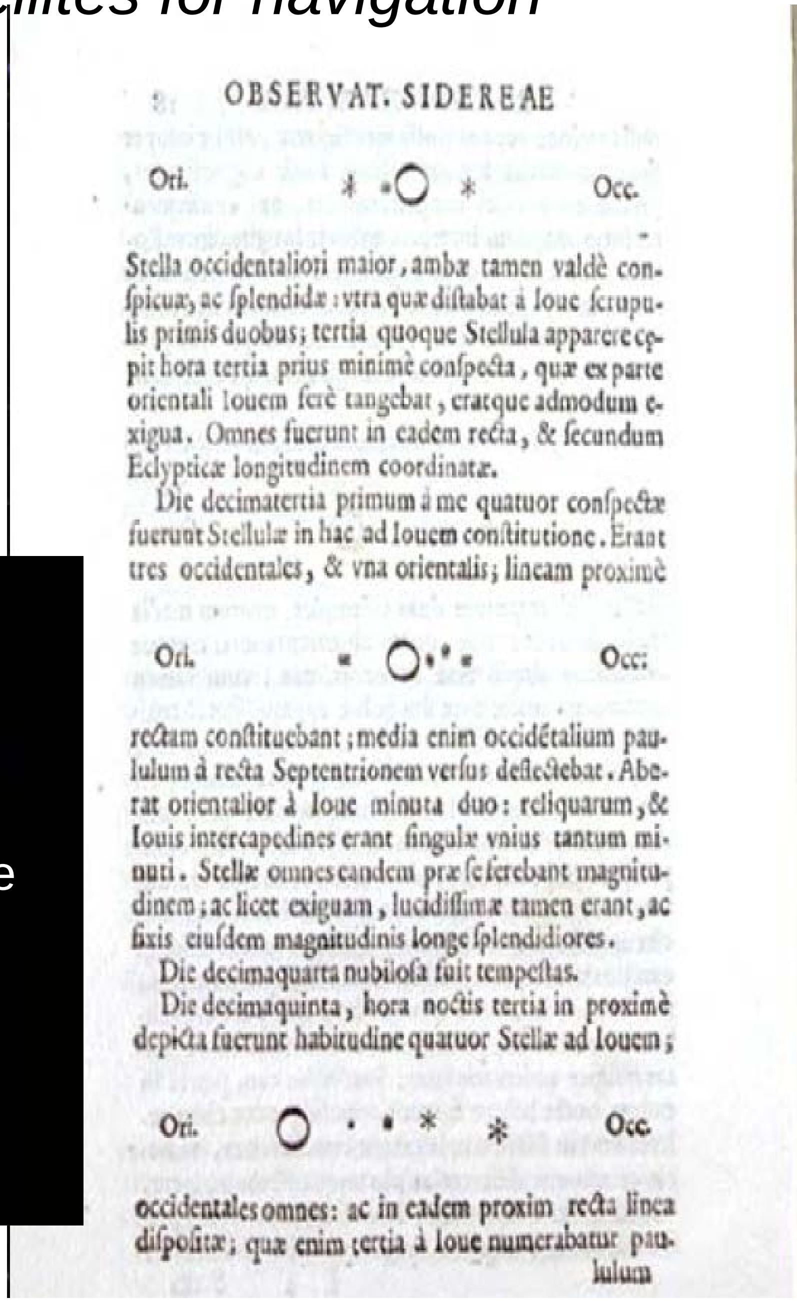


Patrizia Tavella
Istituto Nazionale Ricerca Metrologica
Torino Italy

In 1612 Galileo wrote a letter to the King of Spain, proposing the use of the Juppiter satellites for navigation



"….these stars display conjunctions, separations, eclipses, and other precise configurations…more than 100 a year…and they are so unique, identifiable, and so exact that nobody, of medium intelligence, is not able to use them to estimate the longitude and the position of the ship based on the ephemerids I have computed for the next years to come."
Sept 7th, 1612



OBSERVAT. SIDEREAE

Ori. Occ.

Stella occidentaliori maior, ambæ tamen valdè conſpicuæ, ac ſplendidæ: vtra quæ diſtabat à Ioue ſcrupulis primis duobus; tertia quoque Stellula apparere cœpit hora tertia prius minimè conſpecta, quæ ex parte orientali Iouem ferè tangebat, eratque admodum exigua. Omnes fuerunt in eadem recta, & ſecundum Eclypticæ longitudinem coordinatæ.

Die decimatertia primum à me quatuor conſpectæ fuerunt Stellulæ in hac ad Iouem conſtitutione. Erant tres occidentales, & vna orientalis; lineam proximè

Ori. Occ:

rectam conſtituebant; media enim occidētalium paululum à recta Septentrionem verſus deflectebat. Aberat orientalior à Ioue minuta duo: reliquarum, & Iouis intercapedines erant ſingulæ vnius tantum minuti. Stellæ omnes eandem præ ſe ferebant magnitudinem; ac licet exiguam, lucidiſſimæ tamen erant, ac fixis eiuſdem magnitudinis longe ſplendidiores.

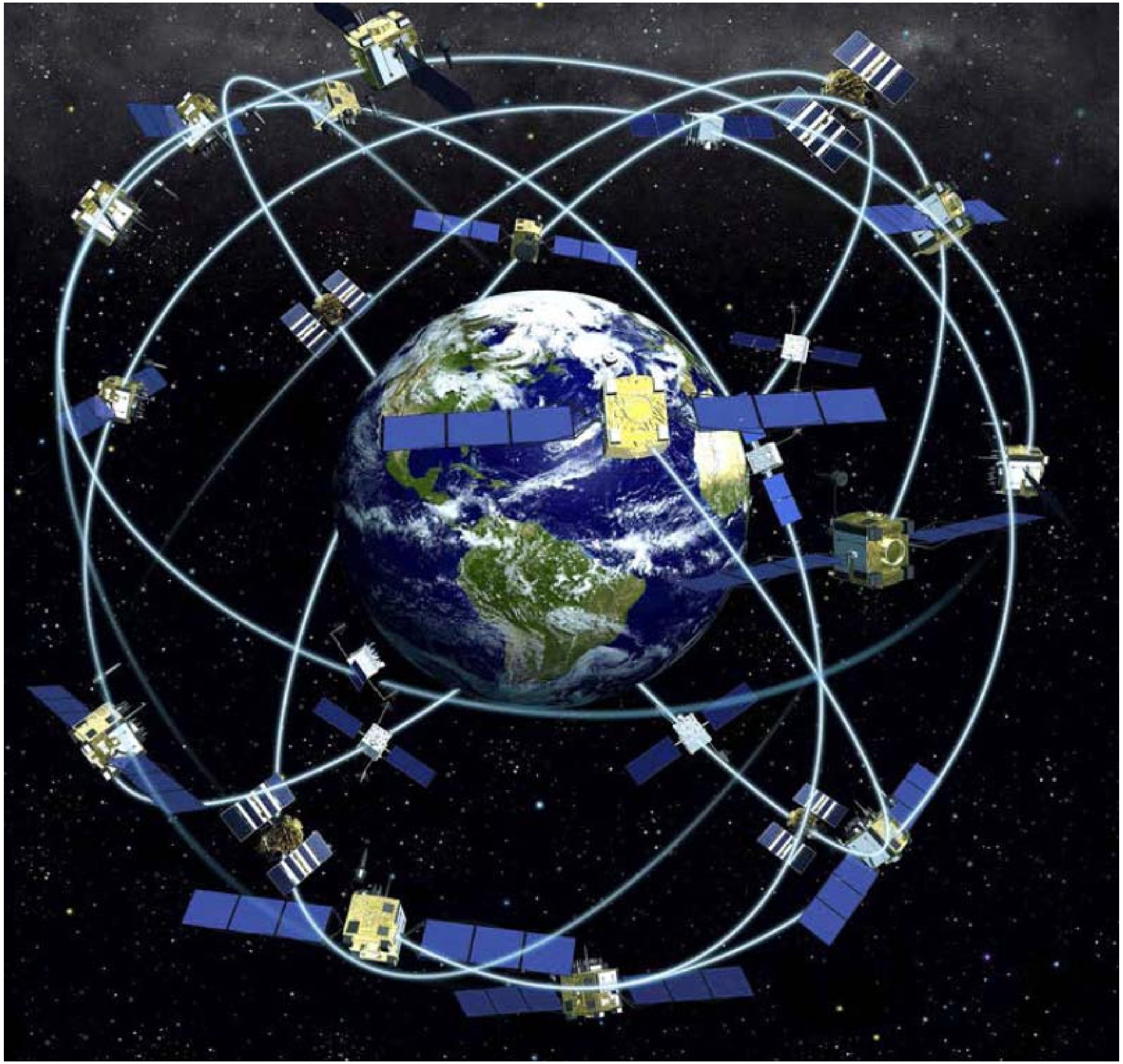
Die decimaquarta nubiloſa fuit tempeſtas.

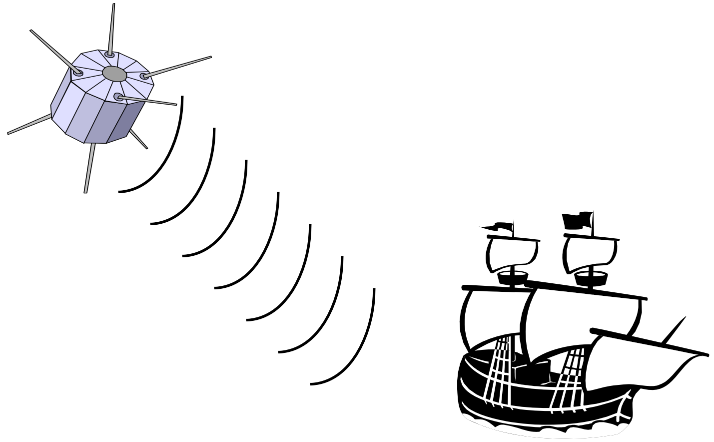
Die decimaquinta, hora noctis tertia in proximè depicta fuerunt habitudine quatuor Stellæ ad Iouem;

Ori. Occ.

occidentales omnes: ac in eadem proxim recta linea diſpoſitæ; quæ enim tertia à Ioue numerabatur paululum

Navigation by "moon" observation



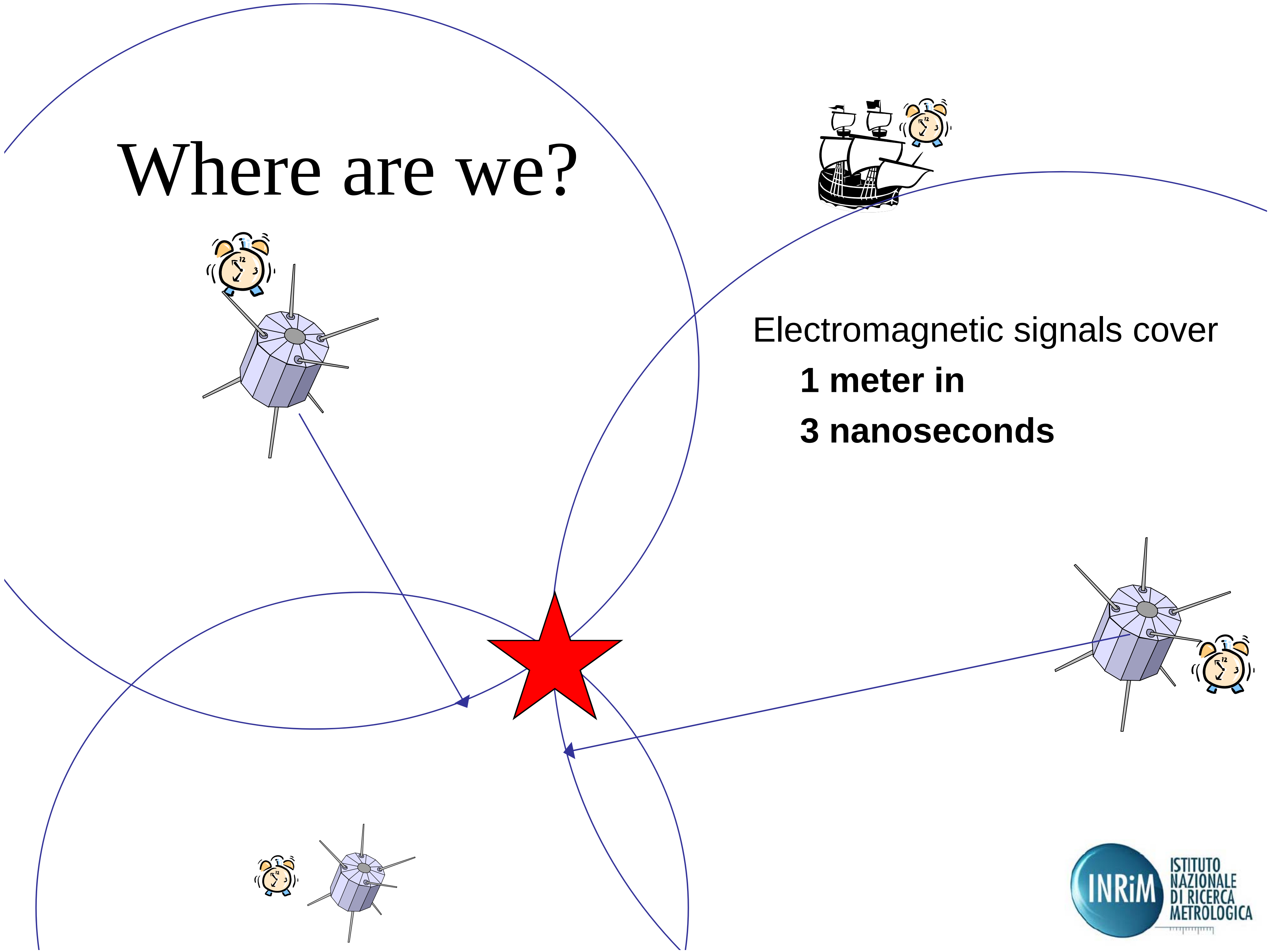


In spherical navigation

position is estimated by measuring ***distance*** from 3 known fixed points

the ***distance*** measurement are measurement of the flight ***time*** of an electromagnetic signal

Where are we?



Electromagnetic signals cover

1 meter in

3 nanoseconds

We therefore need:

good clocks (on Ground and in Space)

good clock synchronisation system

good reference time scale

good algorithms for clock evaluation

in timekeeping and navigation

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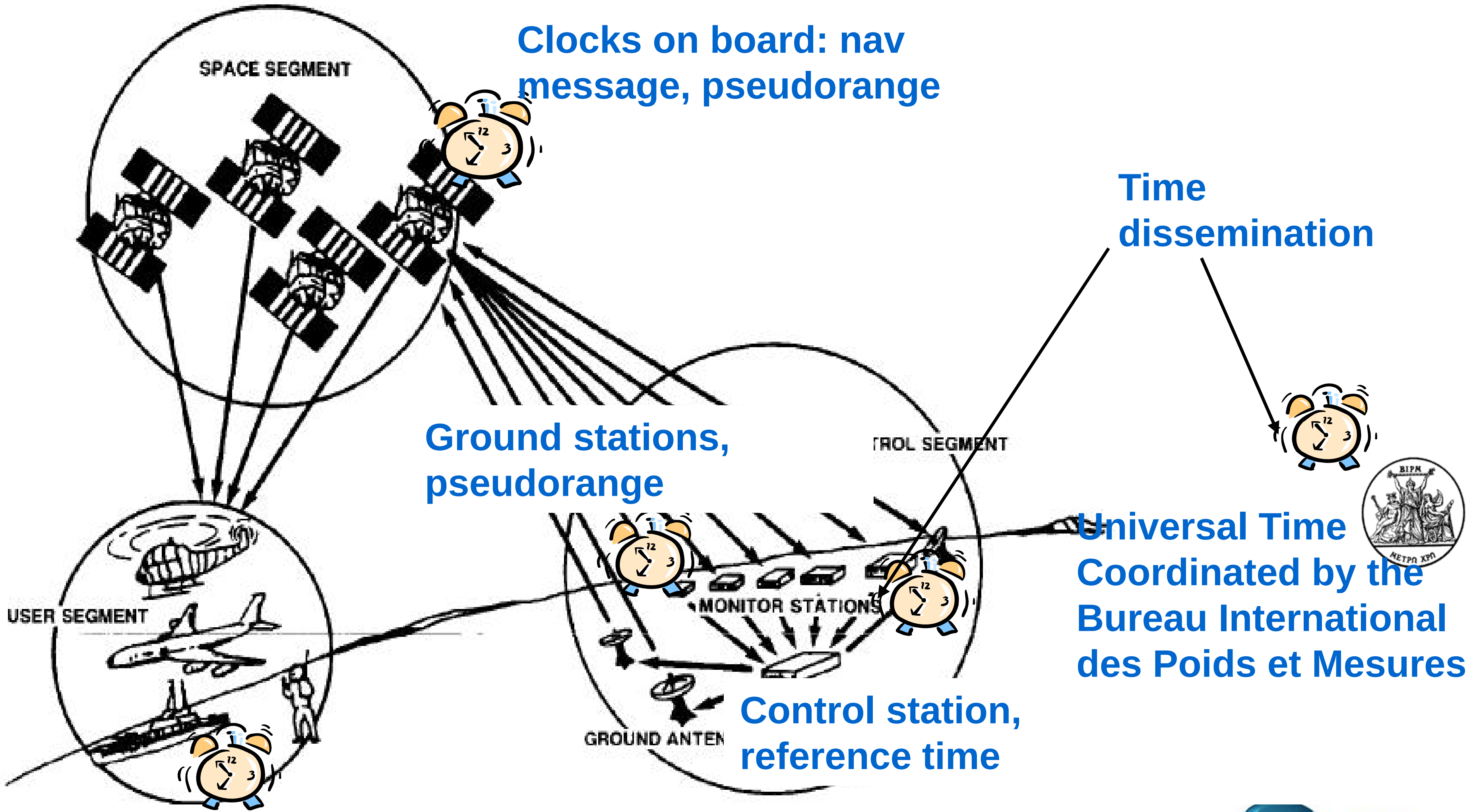
GNSS: Where are the clocks and why?



Clocks on board: nav message, pseudorange

Time dissemination

Ground stations, pseudorange

Universal Time Coordinated by the Bureau International des Poids et Mesures

Control station, reference time

User clocks estimated as additional unknown

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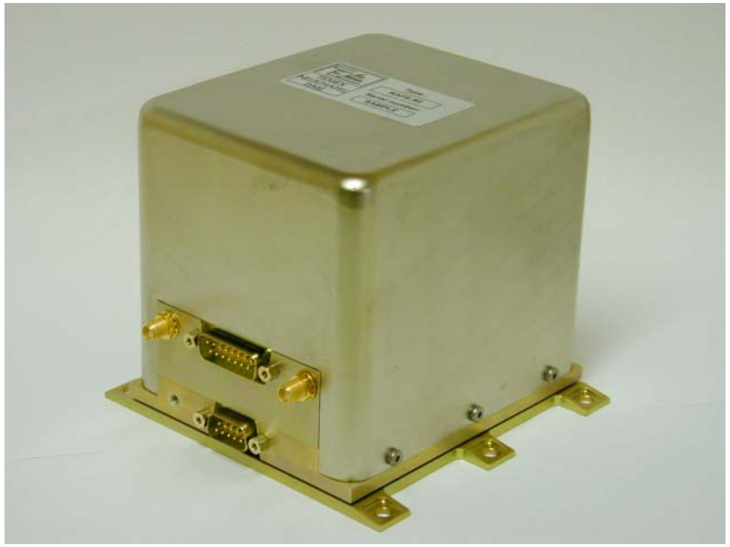
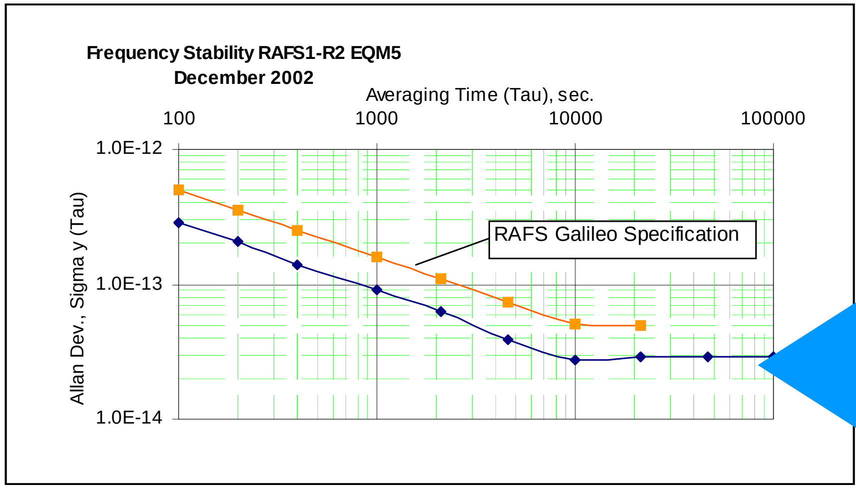
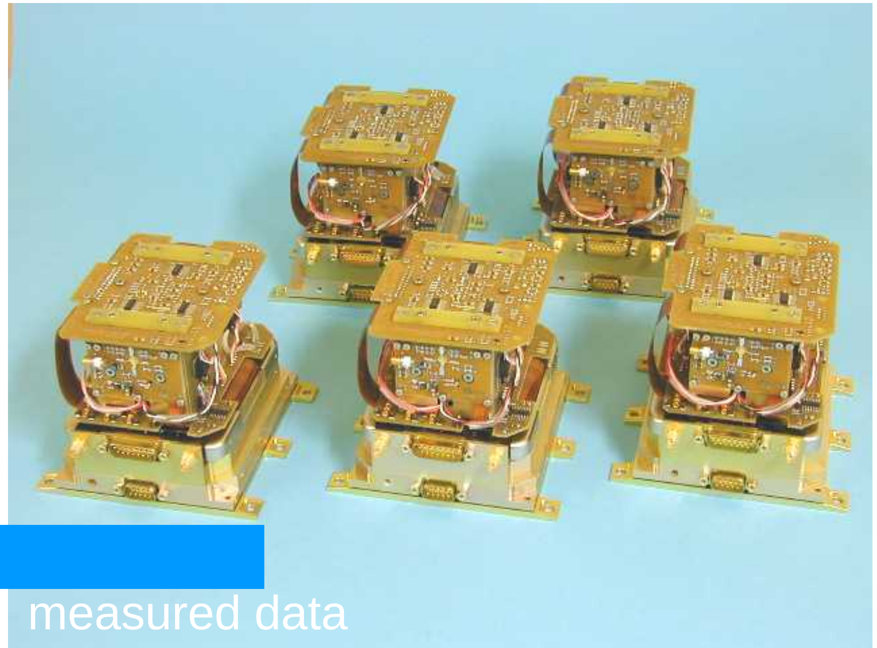
Galileo clocks: space



Space Rubidium Atomic Frequency Standard (RAFS)

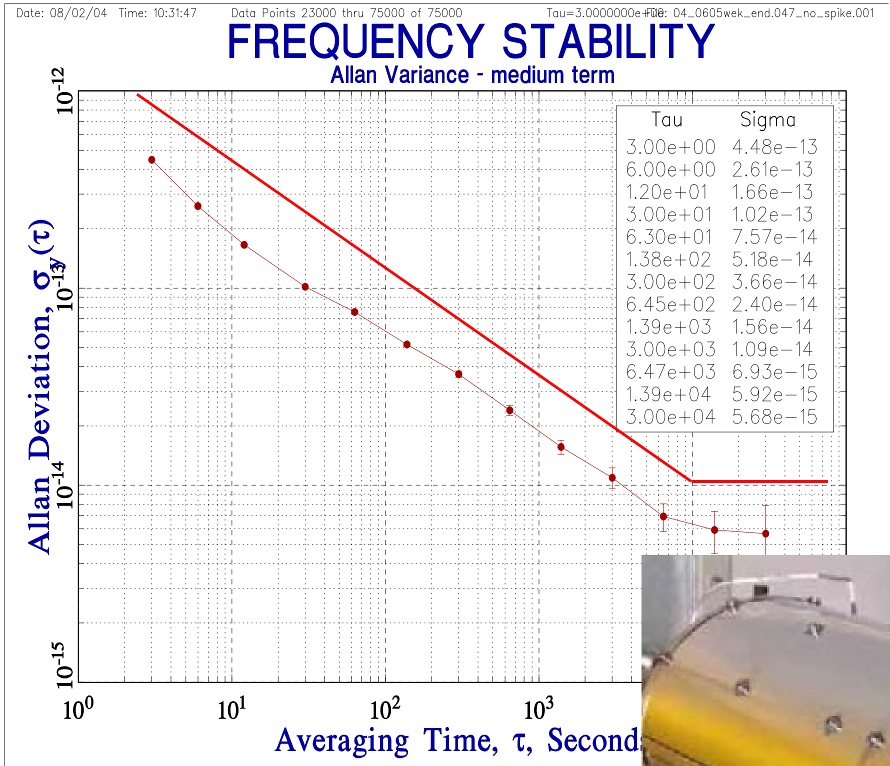


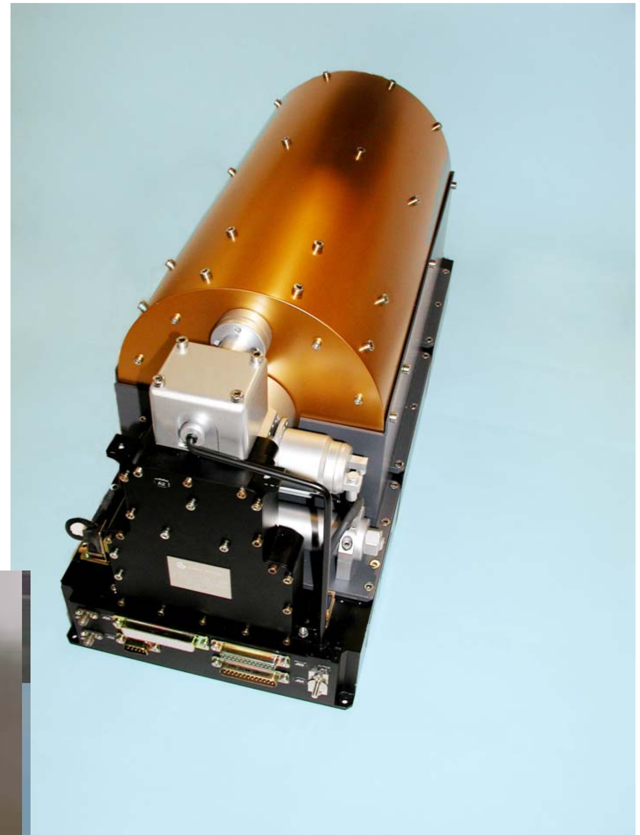


measured data

Galileo clocks: space

FIRST Space H-Maser Atomic Clocks





Galileo clocks: ground

Ground Clocks inside the Control Centres

2 Active H maser

4 Cesium beam clocks

Cryogenic cesium Fountain INRIM ITCsF2

Relative accuracy $2x10^{-16}$

Laser cooling 1 μK;

Cryogenic structure 89 K;

Italian realization of the definition of the second

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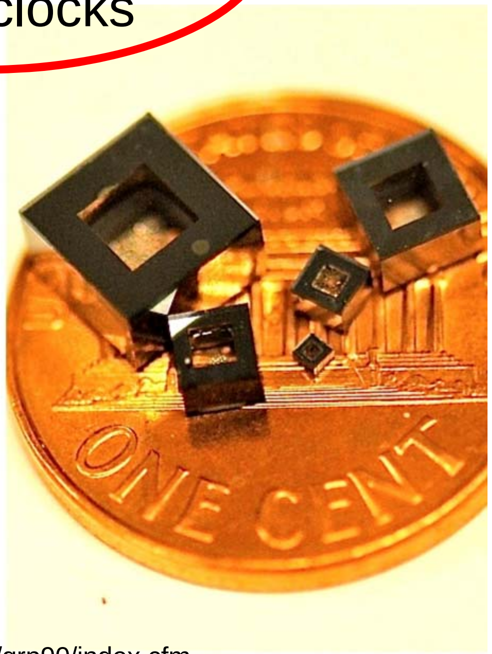
Miniaturized atomic clocks

Next generation

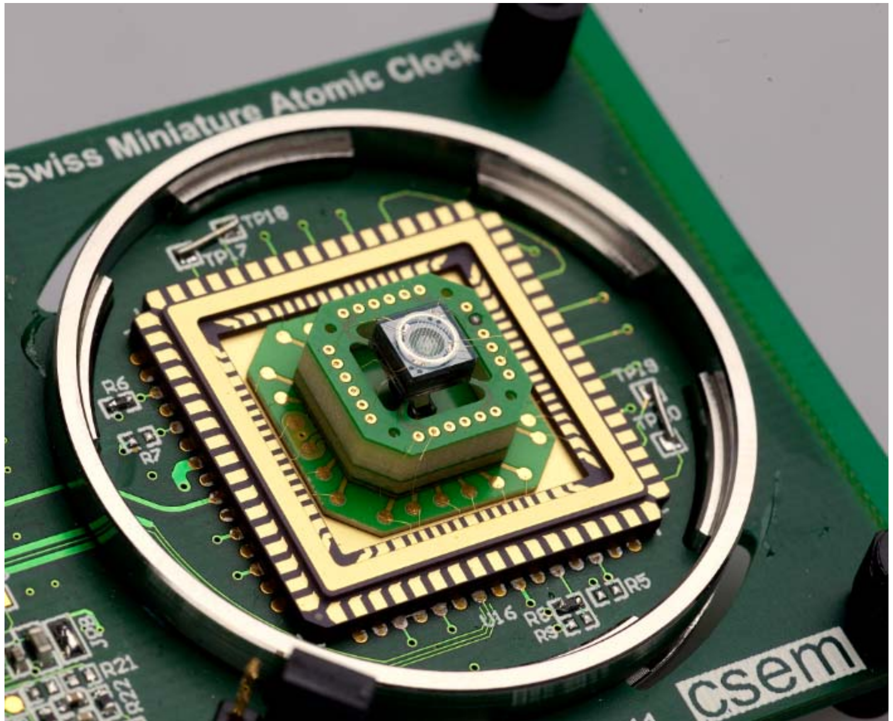
Ground clocks



http://www.nist.gov/pml/div688/grp90/index.cfm

New conception of miniaturized clocks is leading towards atomic clocks of a few mm dimension

They could be implemented in GNSS receivers to improve the positioning (altitude estimate), reduce the noise of the phase measures, allowing holdover navigation …



Close-up on the physics package of the Swiss Miniature Atomic Clock , 24x24 mm^2

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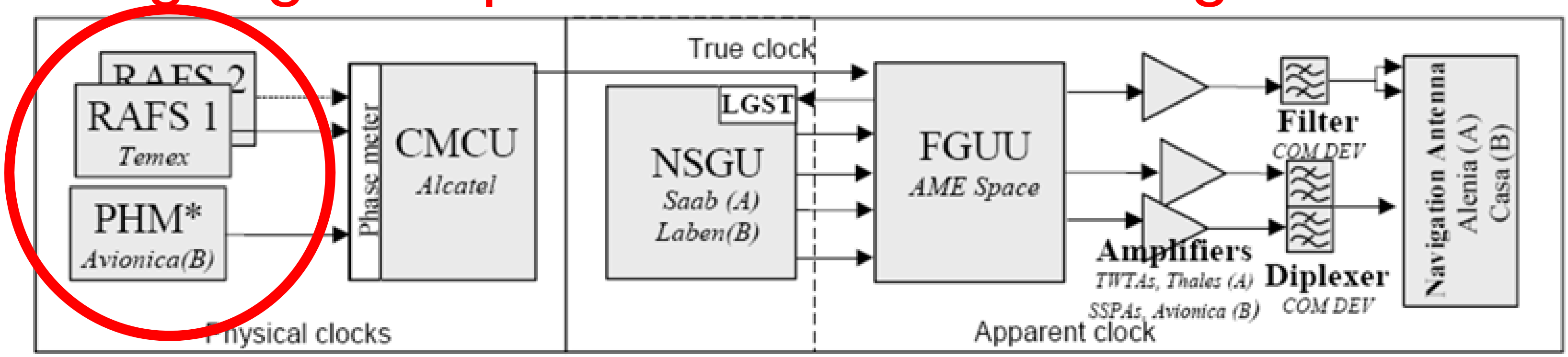
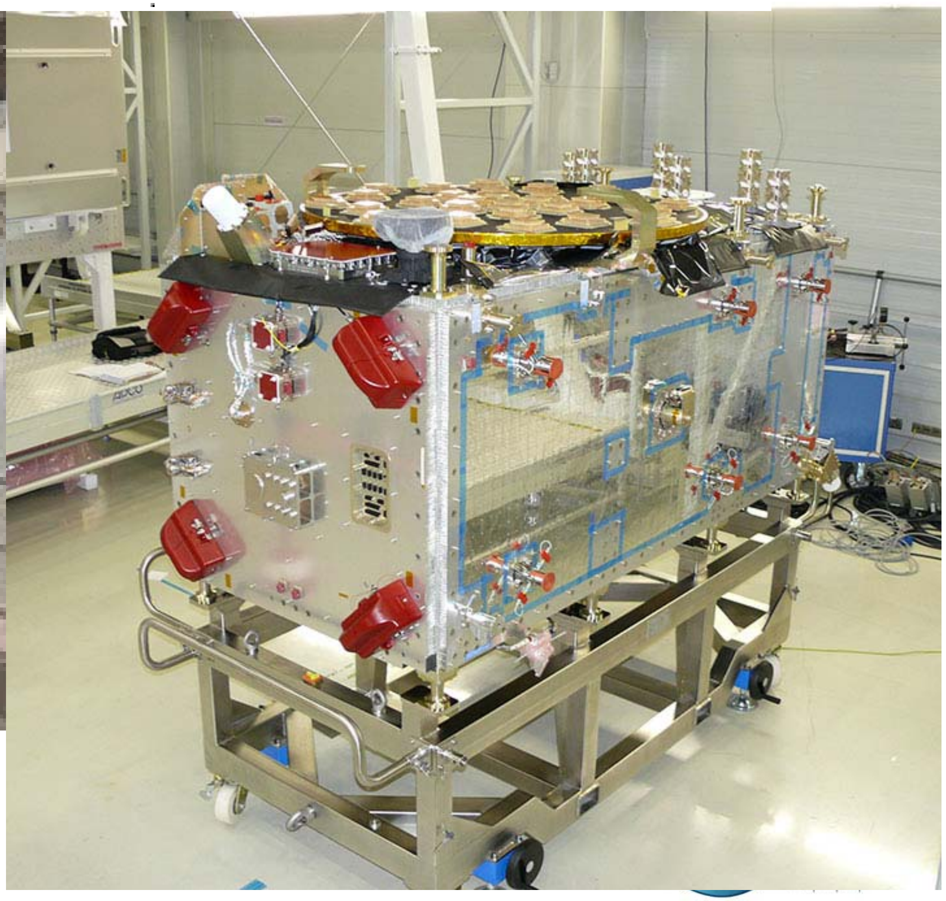
Having a good space clock is not enough…





http://www.gpsworld.com/first-galileo-foc-satellite-heads-to-testing/

Relativity effects

With atomic clock on board

relativistic effect are common routine

Travelling clock are slowing down

Clock at high altitude are going faster

The relative effect is 10^{-13} / km

3 microsec / year for one km in altitude

On board GPS/Galileo at 20000 km

The effect is about 4 10^{-10} which means

40 microseconds in a day

corresponding to about 10 km error in positioning in one day

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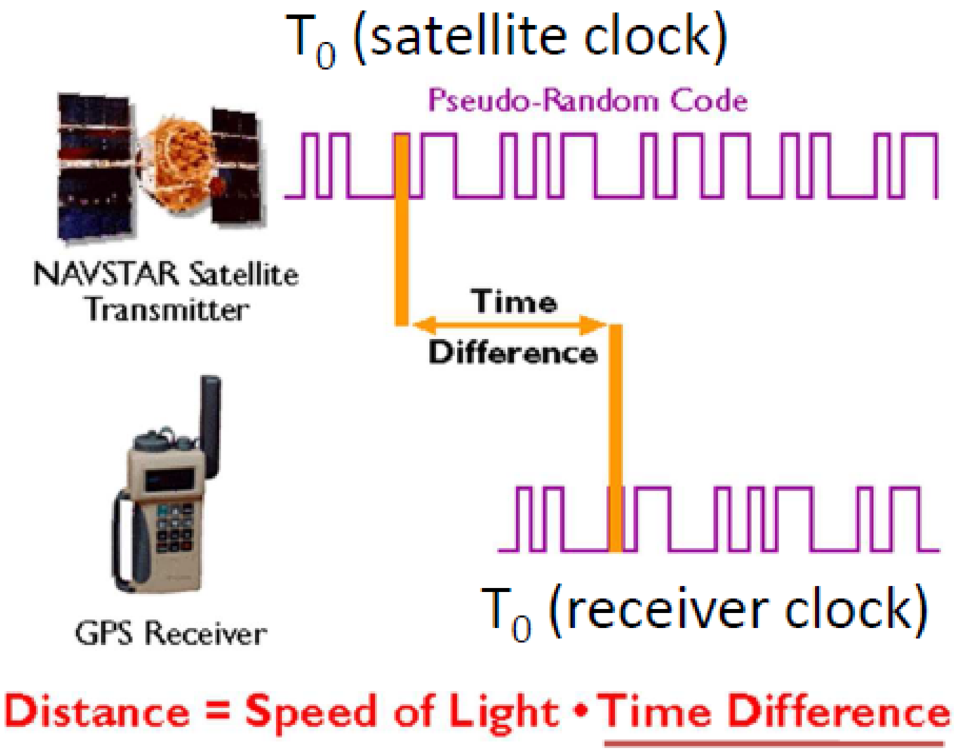
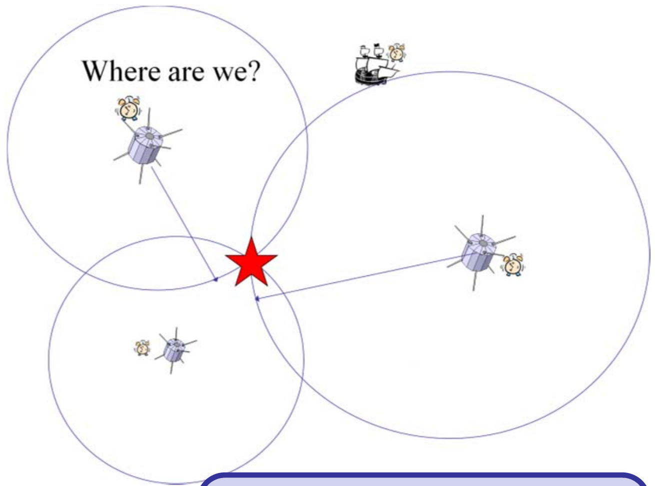
The clock signal is emitted from space and then measured on ground

GNSS Code measurement

Courtesy of
P.Defraigne, ORB



range equations



Information from satellite

Unknowns

$$P_{rec,1}^{sat} = c\left[(t_{rec} - t_{sat1})\right] = |\,\mathbf{x}_{sat1} - \mathbf{x}_{rec}\,|$$

$$P_{rec,2}^{sat} = c\left[(t_{rec} - t_{sat2})\right] = |\,\mathbf{x}_{sat2} - \mathbf{x}_{rec}\,|$$

$$P_{rec,3}^{sat} = c\left[(t_{rec} - t_{sat3})\right] = |\,\mathbf{x}_{sat3} - \mathbf{x}_{rec}\,|$$

x_{rec} = receiver position

x_{sat} = satellite position

t_{rec} = receiver clock

t_{sat} = satellite clock

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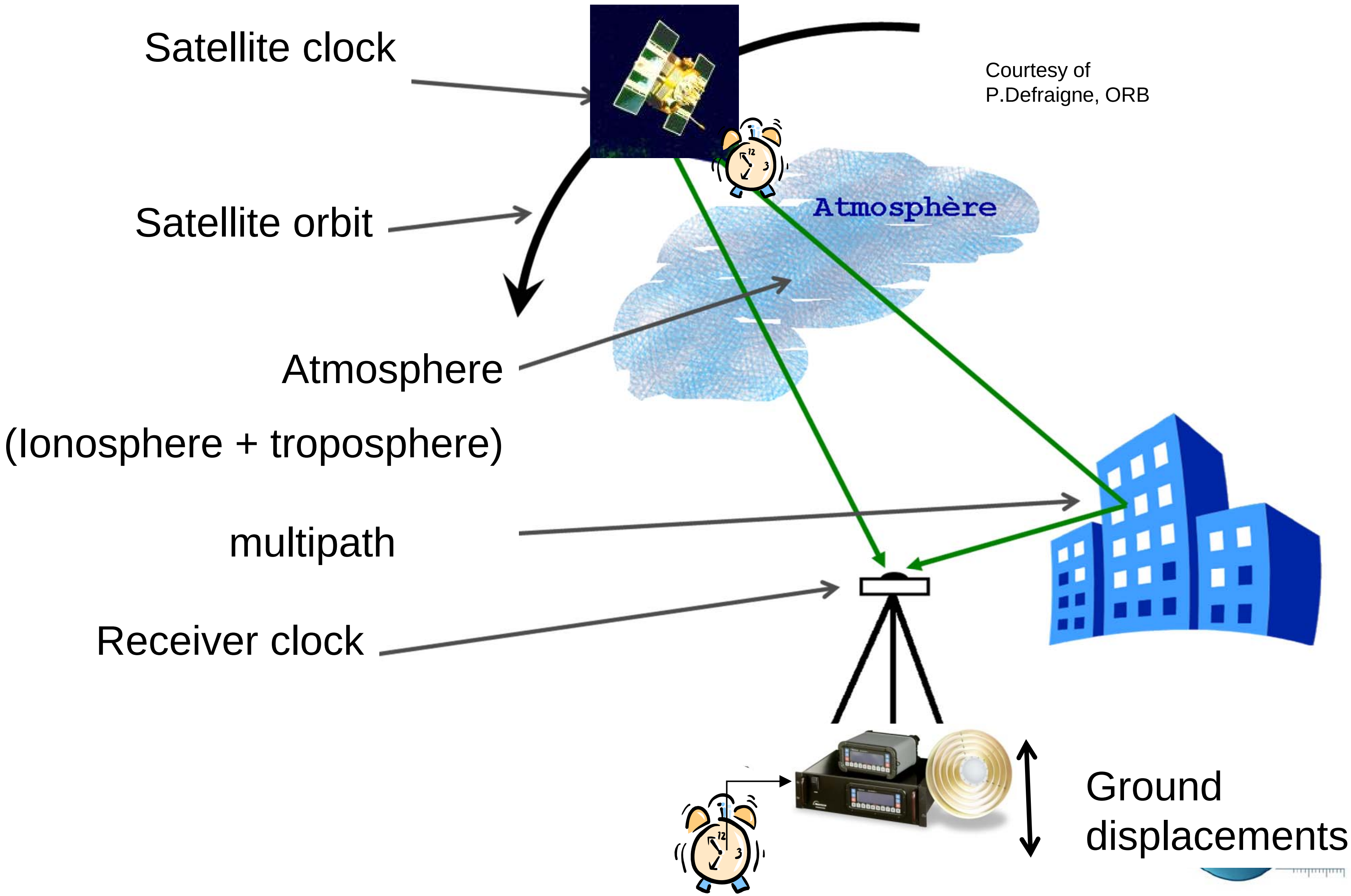
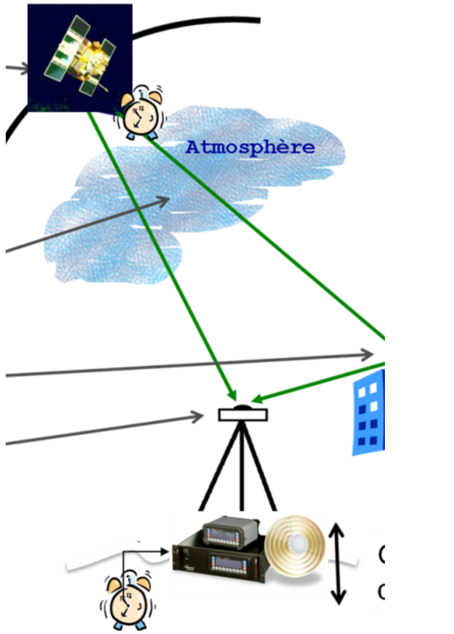
From space clock to ground receiver



Observation equations



Range :

$$P^{sat}_{rec,1} = c\left[(t_{rec} - t_{sat1})\right] = |\,\mathbf{x}_{sat1} - \mathbf{x}_{rec}\,|$$

Unknowns to be estimated

Pseudorange :

Clock error versus t_{ref}

$$P^{sat}_{rec,1} = c\left[(t_{rec} - t_{sat})\right] =$$

$$|\,\mathbf{x}_{sat} - \mathbf{x}_{rec}\,| + c\left[(t_{rec} - t_{ref}) - (t_{sat} - t_{ref})\right] + I_{rec,1} + Tr + \delta_{rec,1} + \varepsilon_{rec,1},$$

iono

tropo

Hardware delay

Information from satellite

x_{rec} = receiver position
x_{sat} = satellite position

t_{rec} = receiver clock
t_{sat} = satellite clock

t_{ref} = reference time

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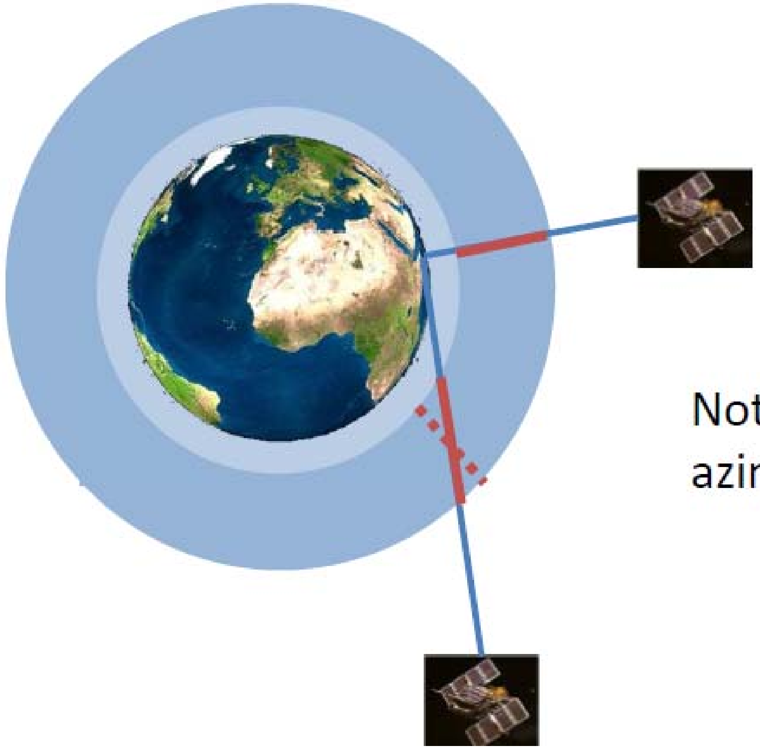
The ionosphere is due to the to solar radiation, which ionizes the atoms and molecules in the upper atmosphere, producing a sea of ions and free electrons

Ionosphere

Layer of electrons and electrically charged atoms and molecules that surrounds the Earth, 50 km → ~1000 km.



Effects on GNSS signal :

- 0-15 m at high elevation
- Up to 45 m at low elevation

Not same iono for different azimuth-elevation

Solar flares shape ionosphere

NASA [*https://archive.org/details/CIL-10104*](https://archive.org/details/CIL-10104)

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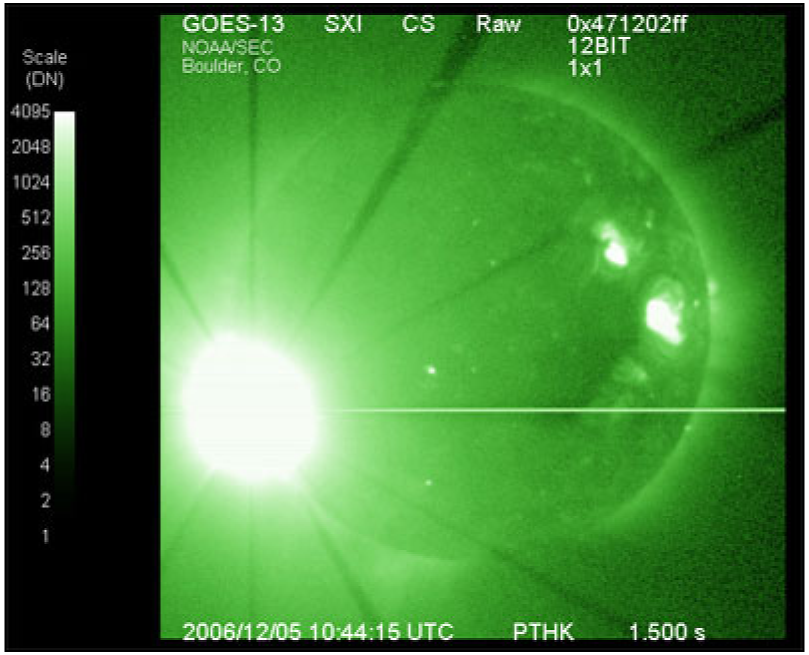
GPS significantly impacted by powerful solar radio burst

NOAA NEWS RELEASE
Posted: April 4, 2007

During an unprecedented solar eruption last December, researchers at Cornell University confirmed solar radio bursts can have a serious impact on the Global Positioning System (GPS) and other communication technologies using radio waves. The findings were announced Wednesday in Washington, D.C., at the first Space Weather Enterprise Forum‹an assembly of academic, government and private sector scientists focused on examining the Earth's ever-increasing vulnerability to space weather impacts.



A satellite image of the Dec. 5, 2006, solar flare that caused the following day's intense radio burst that affected GPS systems. Credit: NOAA

https://www.ras.org.uk/news-and-press/news-archive/157-news2010/1776-space-storms-could-threaten-the-uk-power-grid

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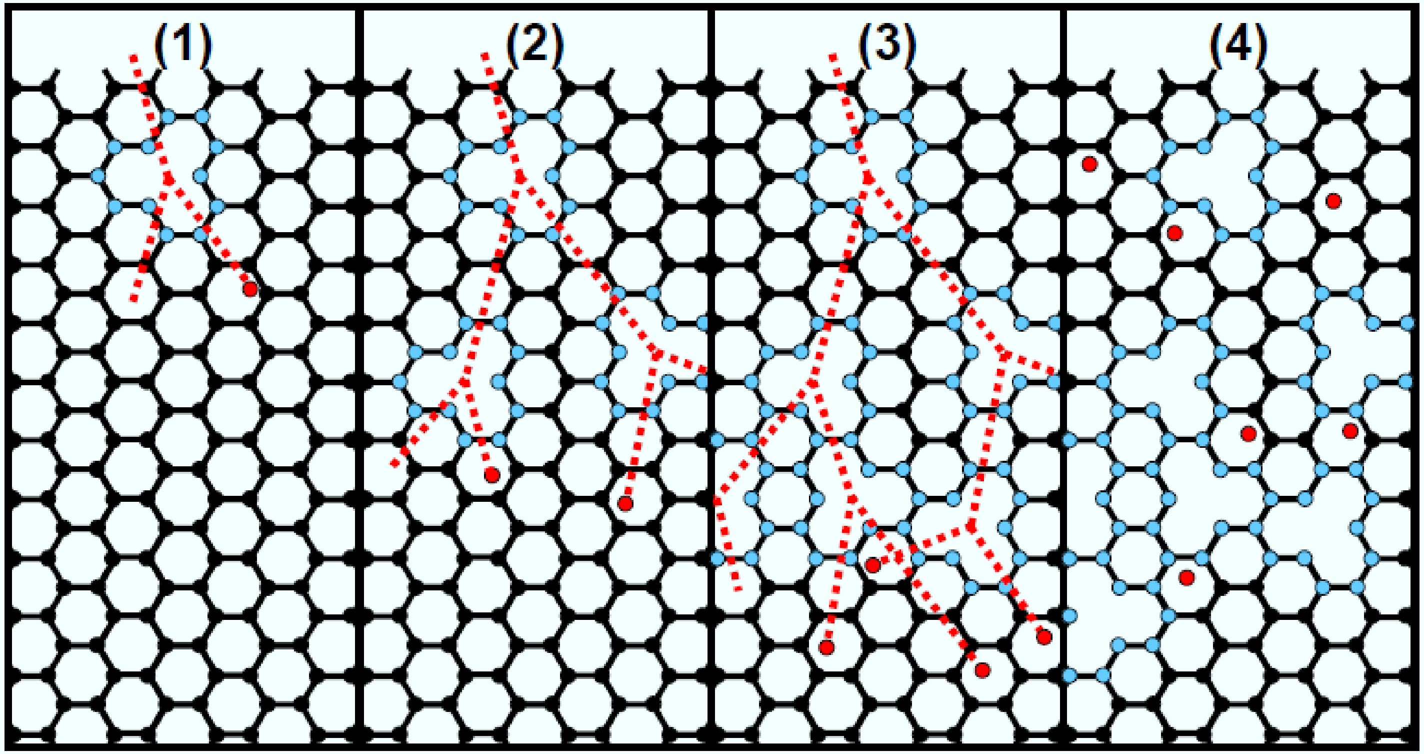
Solar flare effect on quartz clocks

Neutron Damage



A fast neutron can displace about 50 to 100 atoms before it comes to rest. Most of the damage is done by the recoiling atoms. Net result is that each neutron can cause numerous vacancies and interstitials.

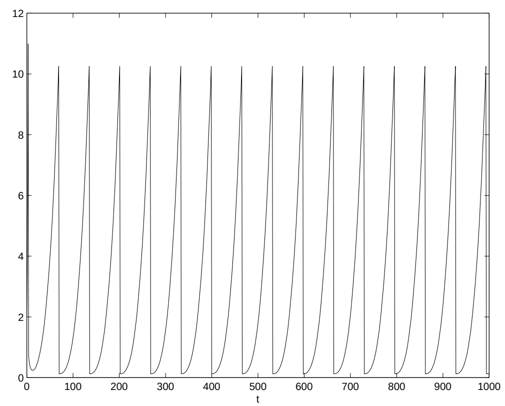
J. Vig, PTTI 2004, Tutorial, http://www.umbc.edu/photonics/Menyuk/Phase-Noise/Vig-tutorial_8.5.2.2.pdf

Algorithms

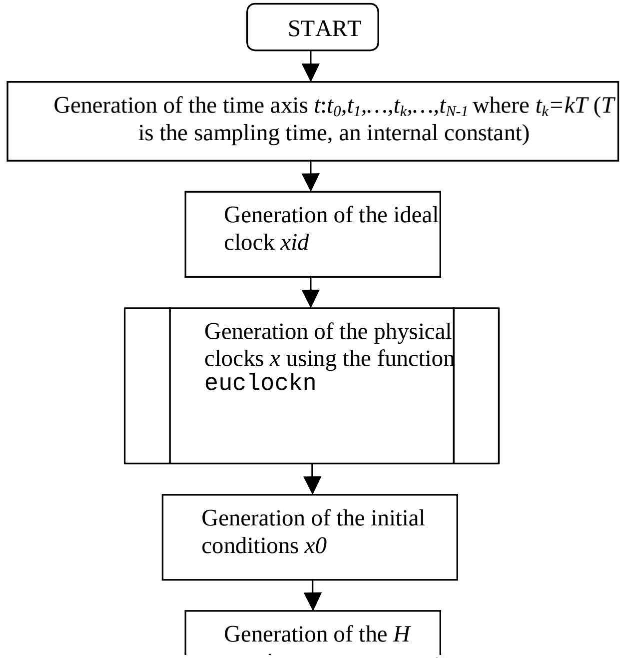
$$x_i = TA(t) - h_i(t) = \sum_{j=1}^{N} w_j \left[h_j'(t) + x_{ij}(t)\right]$$

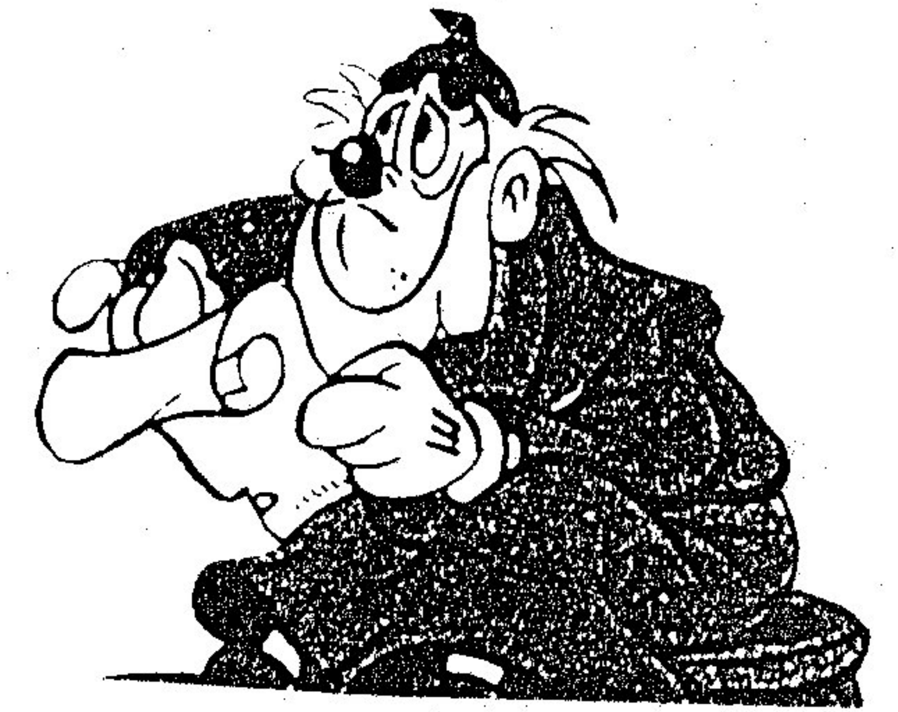
$$w_i = \frac{1}{\sum_{k=1}^{N} \frac{1}{\langle \varepsilon^2{}_k(\tau) \rangle}} \cdot \frac{1}{\langle \varepsilon^2{}_i(\tau) \rangle}$$

$$\begin{cases} x_i(t) = \sum_{j=1}^{N} w_j \left[\hat{x}_i(t) + x_{ij}(t)\right] \\ x_{ij} = x_j(t) - x_i(t) \end{cases}$$



Kclock: Flow Chart





$$P_{rec,1}^{sat} = c\left[(t_{rec} - t_{sat})\right] =$$

Satellite clock error =offset versus the Ref time

$$|\mathbf{x}_{sat} - \mathbf{x}_{rec}| + c\left[(t_{rec} - t_{ref}) - (t_{sat} - t_{ref})\right] + I_{rec,1} + Tr + \delta_{rec,1} + \varepsilon_{rec,1},$$

1. t_{ref} is the System *Ref*erence Time to be defined from the *ensemble* of space/ground clocks (as any national ref time scale)
   - GPS time is a paper time scale estimated with a Kalman filter and *steered* versus UTC(USNO),
   - Galileo System Time is a weighted average of the ground clocks steered versus UTC
2. The offset t_{sat} - t_{ref} is estimated by a complex algorithm using the same pseudorange measures and estimating orbits and clocks (Kalman filter in case of GPS, Batch least square in case of Galileo, …)
3. The real time offset t_{sat} - t_{ref} transmitted to the user is a prediction based on previous measures

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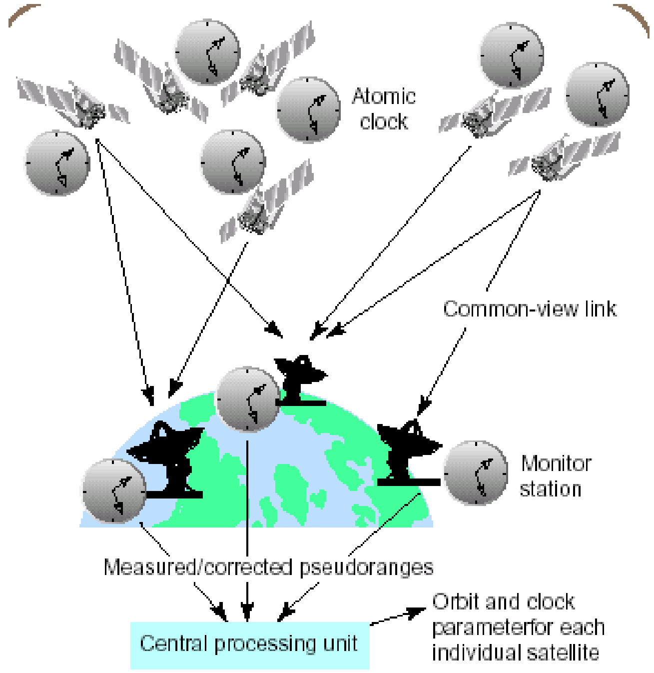
$$P_{rec,1}^{sat} = c\left[(t_{rec} - t_{sat})\right] =$$
$$|\mathbf{x}_{sat} - \mathbf{x}_{rec}| + c\left[(t_{rec} - t_{ref}) - (t_{sat} - t_{ref})\right] + I_{rec,1} + Tr + \delta_{rec,1} + \varepsilon_{rec,1},$$

Predicted clock error

Predicted clock offsets (and predicted orbits) are estimated on ground and uploaded to the satellite

They are transmitted to the user as part of the navigation message and should be valid for a certain period in the future (GPS needs one day validity, Galileo plans 100 minutes validity, …)

The uploaded navigation message contains

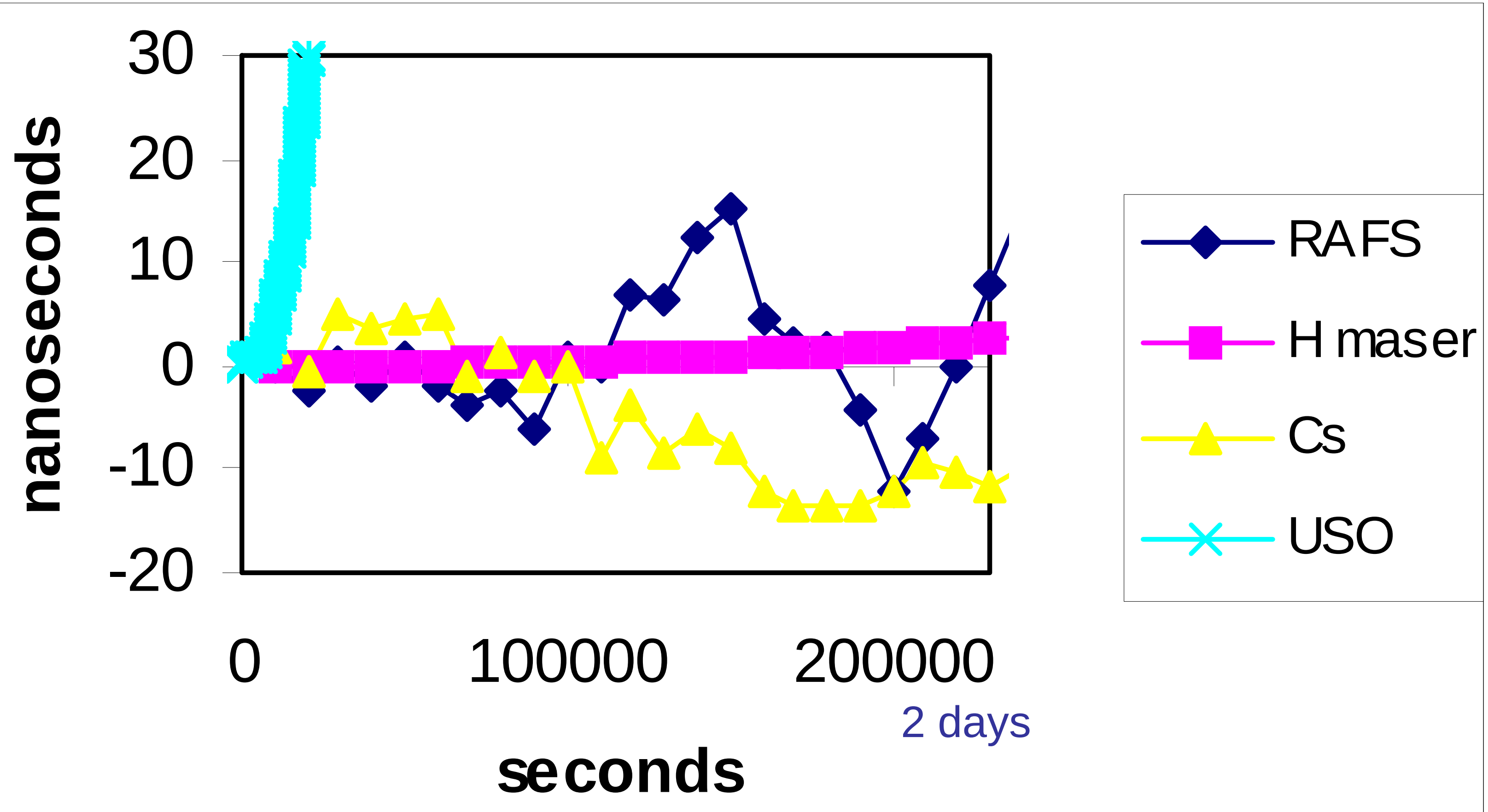


predictions

orbit prediction, clock prediction...

After synchronisation, any clock accumulate an error

Galileo requirement for maximum offset = 1.5 ns



Rubidium

Cesium clock

Ultra Stable Oscillator (quartz)

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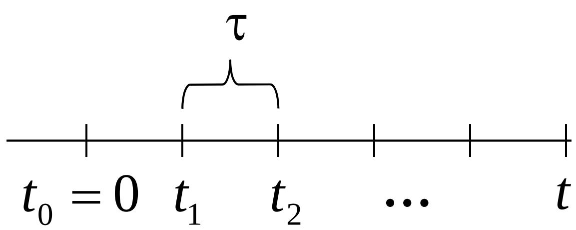
The clock signal affected by White and Random Walk frequency noises plus deterministic drifts can be handled exactly with **stochastic differential equations.**

Iterative solution useful for simulations, filter, …



Phase deviation

$$X_1(t_{k+1}) = X_1(t_k) + X_2(t_k)\tau + a\frac{\tau^2}{2} + \sigma_1 \mathrm{W}_{1,k}(\tau) + \sigma_2 \int_{t_k}^{t_{k+1}} W_2(s)ds$$

Freq component

$$X_2(t_{k+1}) = X_2(t_k) + a\,\tau + \sigma_2 \mathrm{W}_{2,k}(\tau)$$

correlated processes

with initial conditions $\begin{cases} X_1(0) = x_0 \\ X_2(0) = y_0 \end{cases}$

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Stochastic processes helps the clock prediction

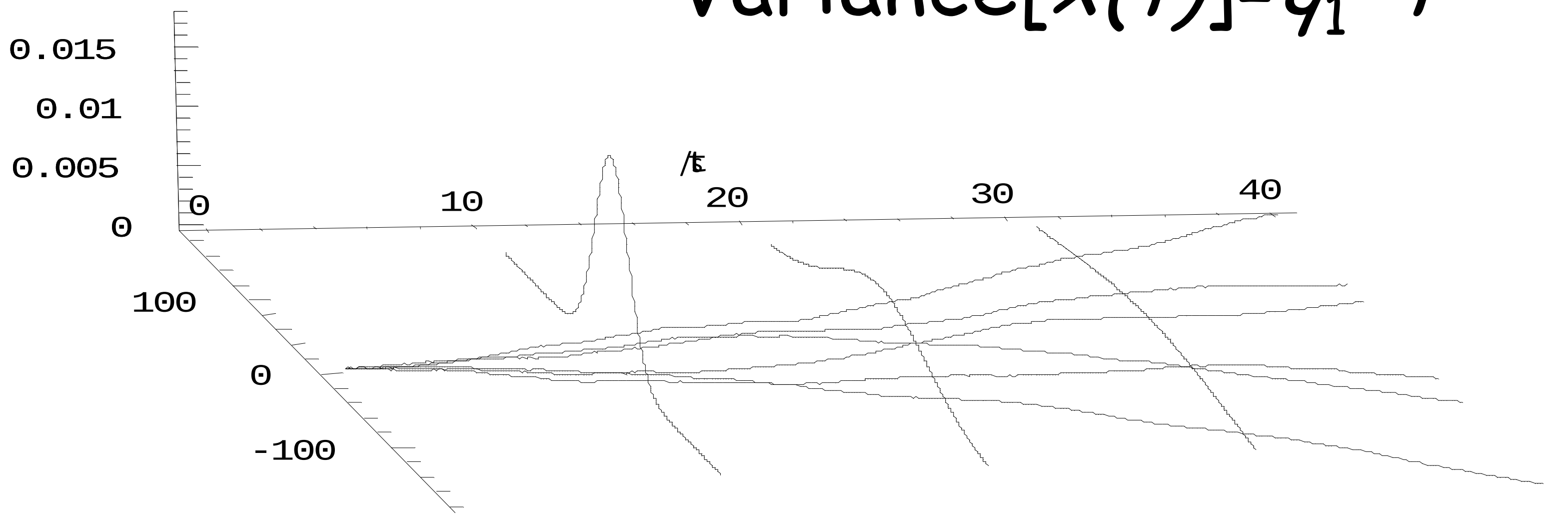
Example: White frequency noise → Random walk of phase *x(t)*

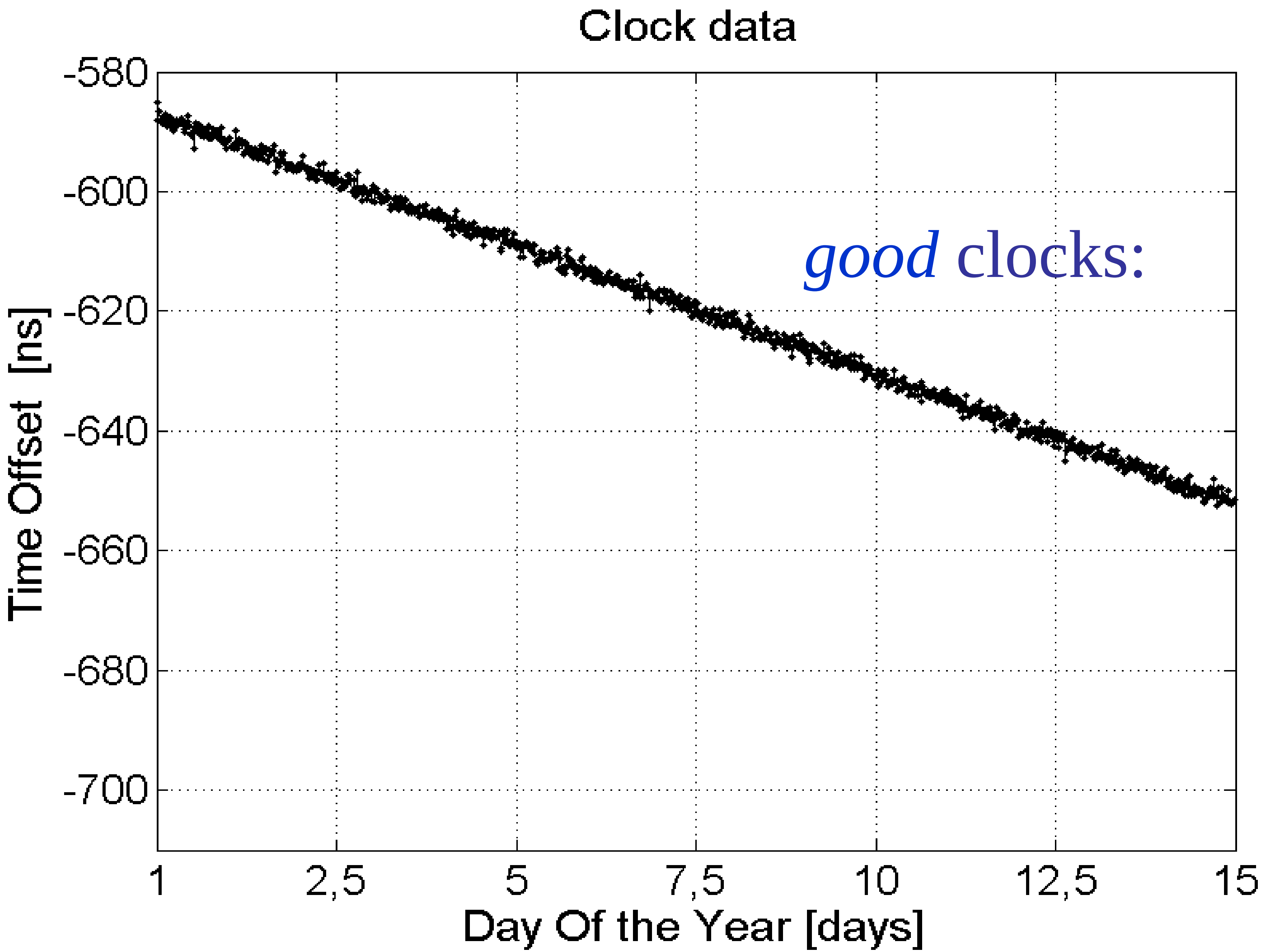
At time *t* after synchronisation, the time error *x(t)* is described by a Gaussian probability density with

Diffusion coefficient linked to Allan Deviation
$q_1 t = AVAR(t) \cdot t^2$

$$E[x(t)]=0$$

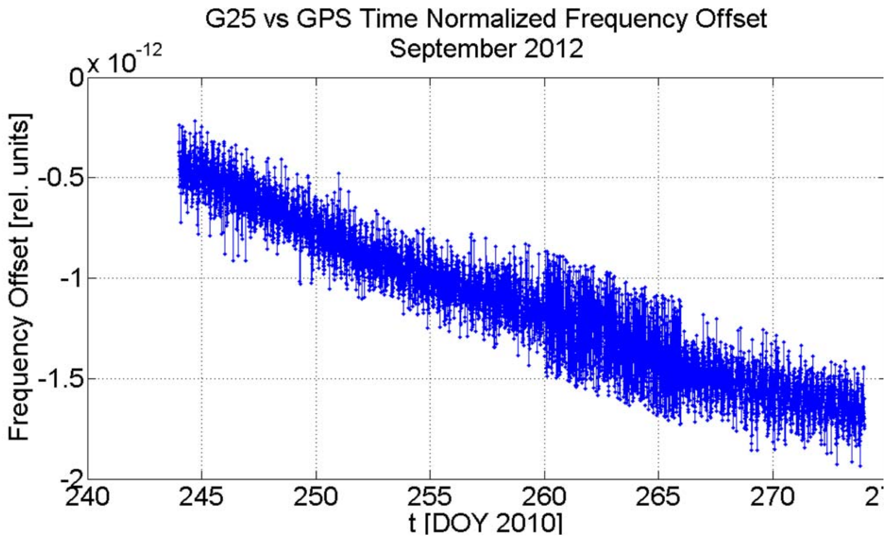
$$Variance[x(t)]=q_1 \cdot t$$

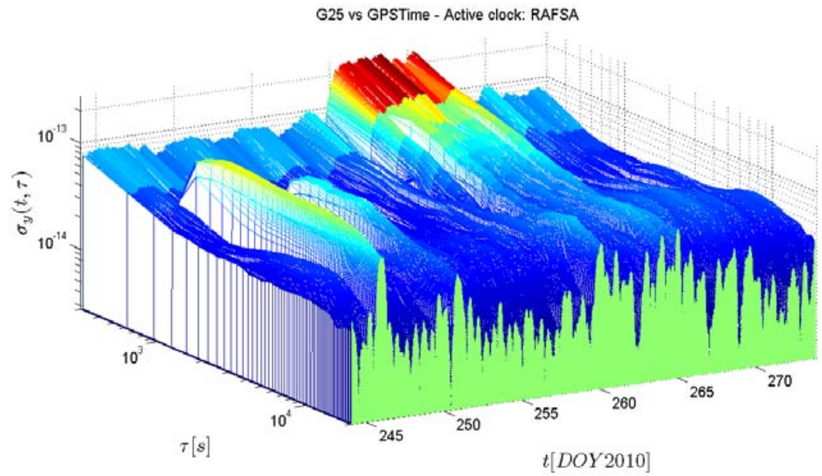


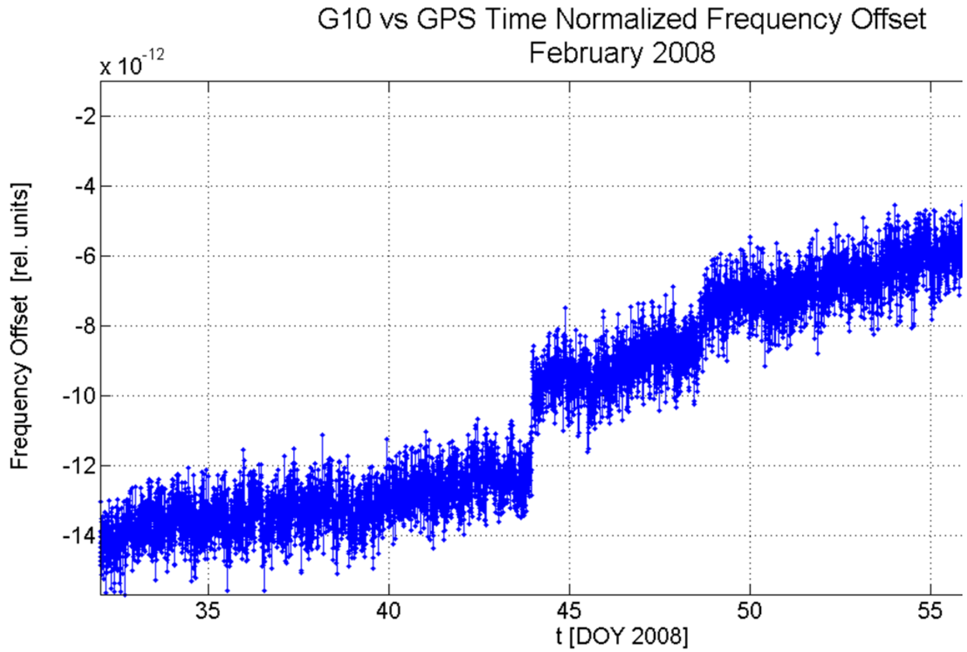


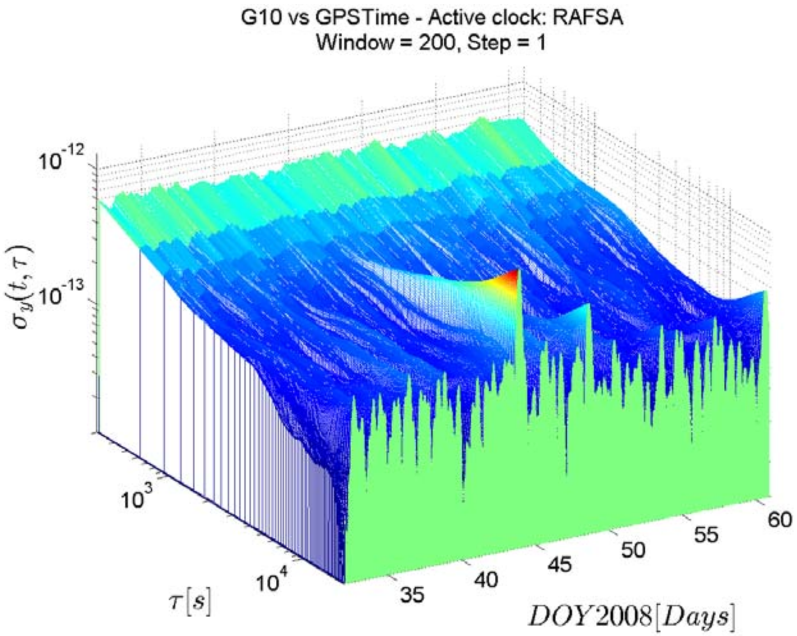
Clock data
-580
-600
-620
-640
-660
-680
-700
Time Offset [ns]
1
2,5
5
7,5
10
12,5
15
Day Of the Year [days]

good clocks:



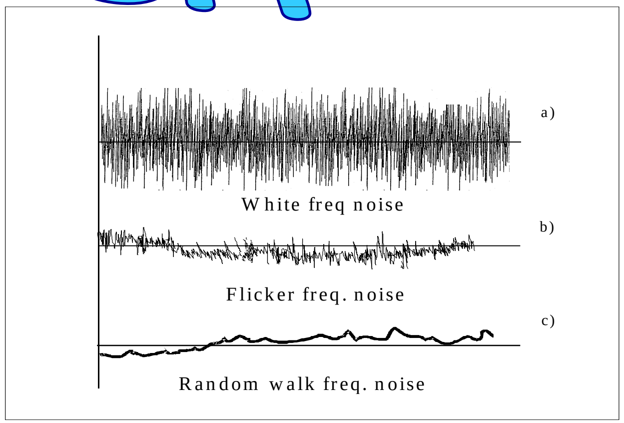






L. Galleani, P. Tavella IEEE FCS/ EFTF 2013 Prague

GNSS Reference time dissemination



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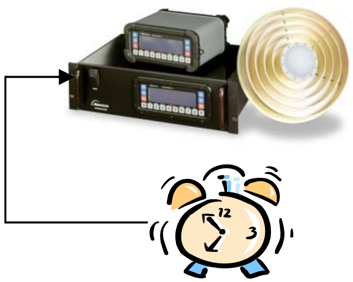
$$P_{rec,1}^{sat} = c\left[(t_{rec} - t_{sat})\right] =$$

$$|\mathbf{x}_{sat} - \mathbf{x}_{rec}| + c\left[(t_{rec} - t_{ref}) - (t_{sat} - t_{ref})\right] + I_{rec,1} + Tr + \delta_{rec,1} + \varepsilon_{rec,1},$$

The User clock error =offset versus the Ref time is estimated by the receiver



- GNSS receiver and its antenna
  - Timing receiver
  - Fixed (and known) location
- External frequency reference for receiver
  - Atomic clocks (H-maser, Cesium…)
  - Physical time scale

the difference Local clock – GPS time = $(t_{rec} - t_{ref})$ is estimated

Signals-in-space (SIS) transmitted by the GNSS satellites contains also a prediction of $(UTC_{SIS} - t_{ref})$ as for example the predicted $(\text{UTC(USNO)} - \text{GPStime})_{SIS}$

$(t_{rec} - t_{ref}) - (UTC_{SIS} - t_{ref})$ allows to estimate Local clock – UTC_{SIS}

The timing user can get UTC_{SIS} from GNSS

A navigation system is also a mean for

UTC time dissemination

What is the Universal Time Coordinated?

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For centuries

The time was given by the rotating Earth

on which we set the clock

From 1967

The time is given by atomic clock

used to study Earth rotation

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Along centuries...

Universal Time

- day and night are the "natural" time unit
- it was observed that during the year the length of day changes but the "Mean Solar Day" was deemed constant and Universal
- Universal Second = 1/86400 of rotational day (Mean Solar Time)
- 1884 Greenwich reference meridian
- 1925 International Astronomical Union fixes the beginning of the mean solar day at h. 00 and defines the Universal Time

Universal Time

the rotation rate is constant?

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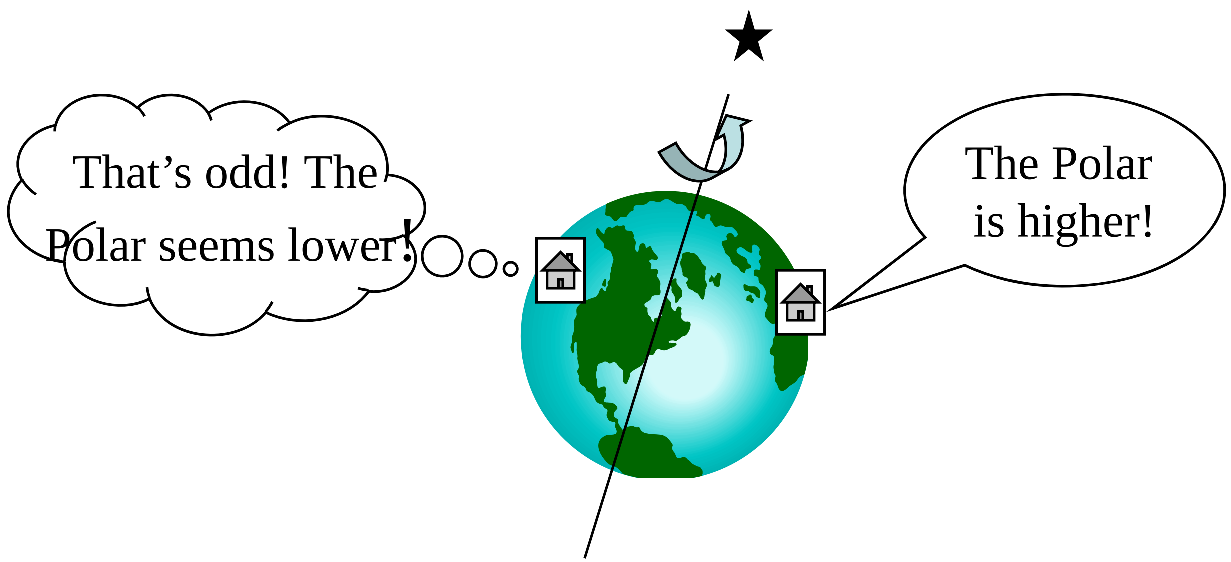
Polar motion

Suspected around 1850 from astronomers



Polar motion can be measured but is not predictable

Polar motion, 1995-1998
Solid line : mean pole displacement,

About
10 m

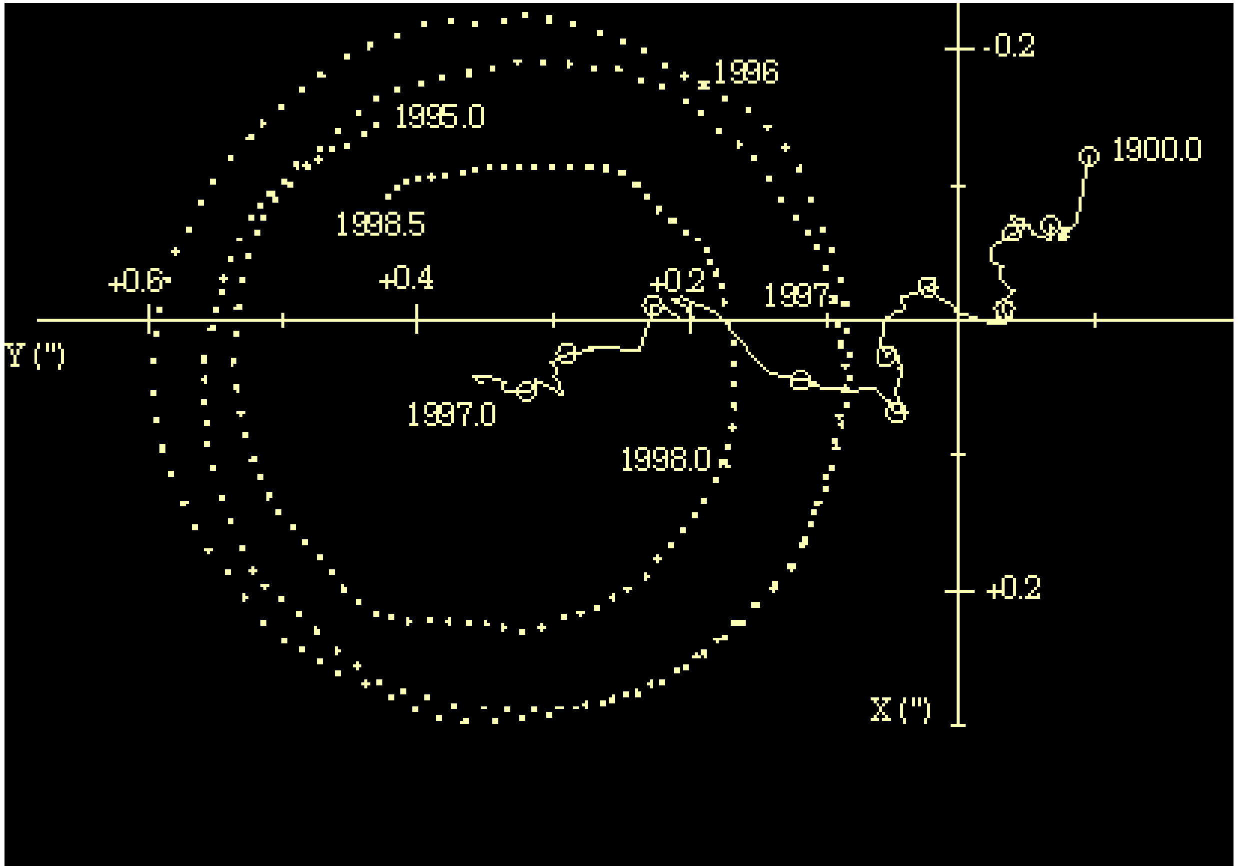


Figure O-1 : Polar motion, 1995-1998. Raw value of Table O-4.
Solide line: mean pole displacement, 1900-1997

http://www.iers.org *International Earth Rotation and Reference Systems Service*

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Seasonal variation: in summer we spin faster

- A. Scheibe, 1936 in Berlin
- N. Stoyko, 1936 in Paris (BIH)

with crystal clock the day was measured shorter of about 1.2 ms

Variations in the duration of the day

http://www.iers.org

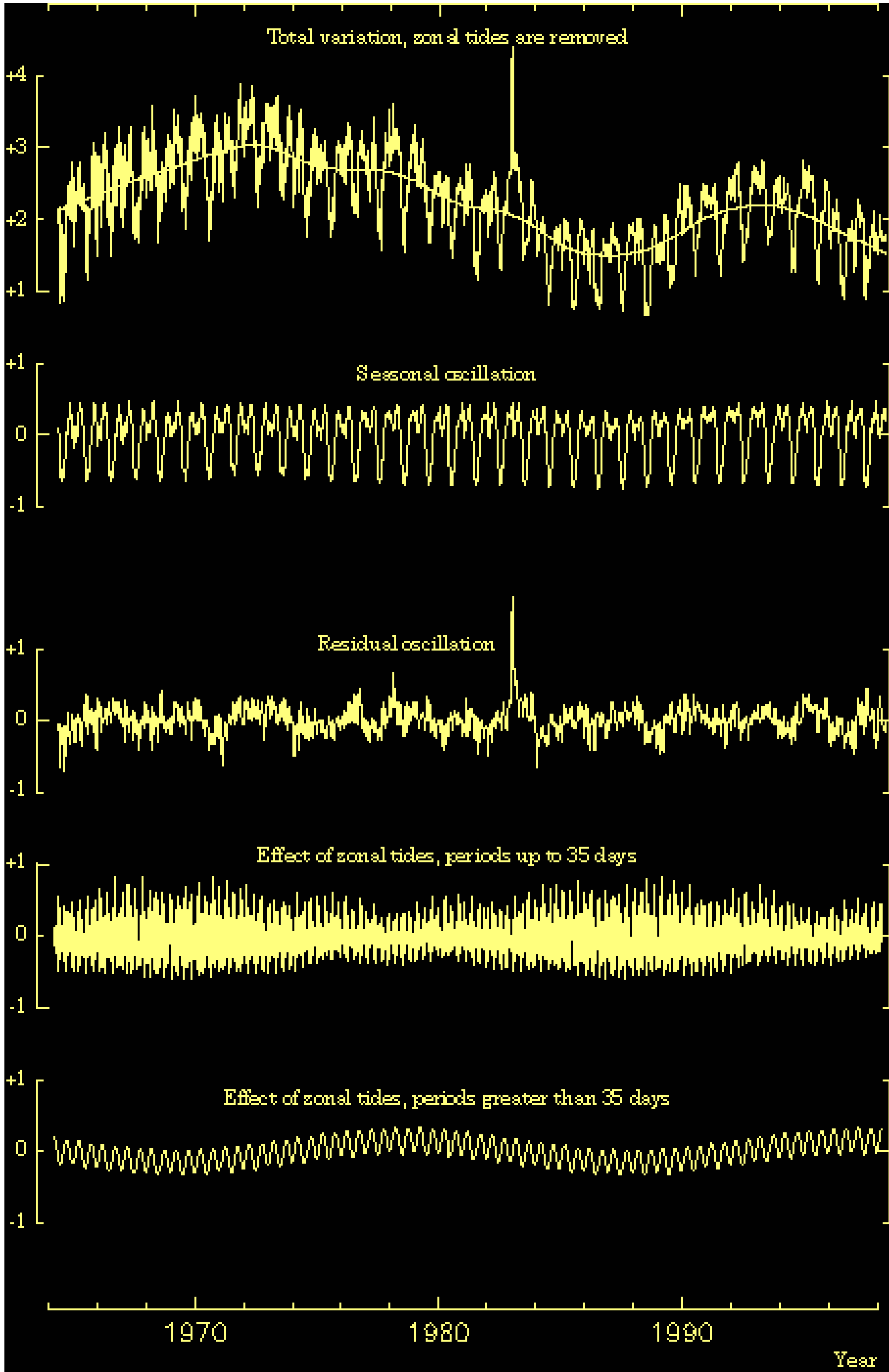
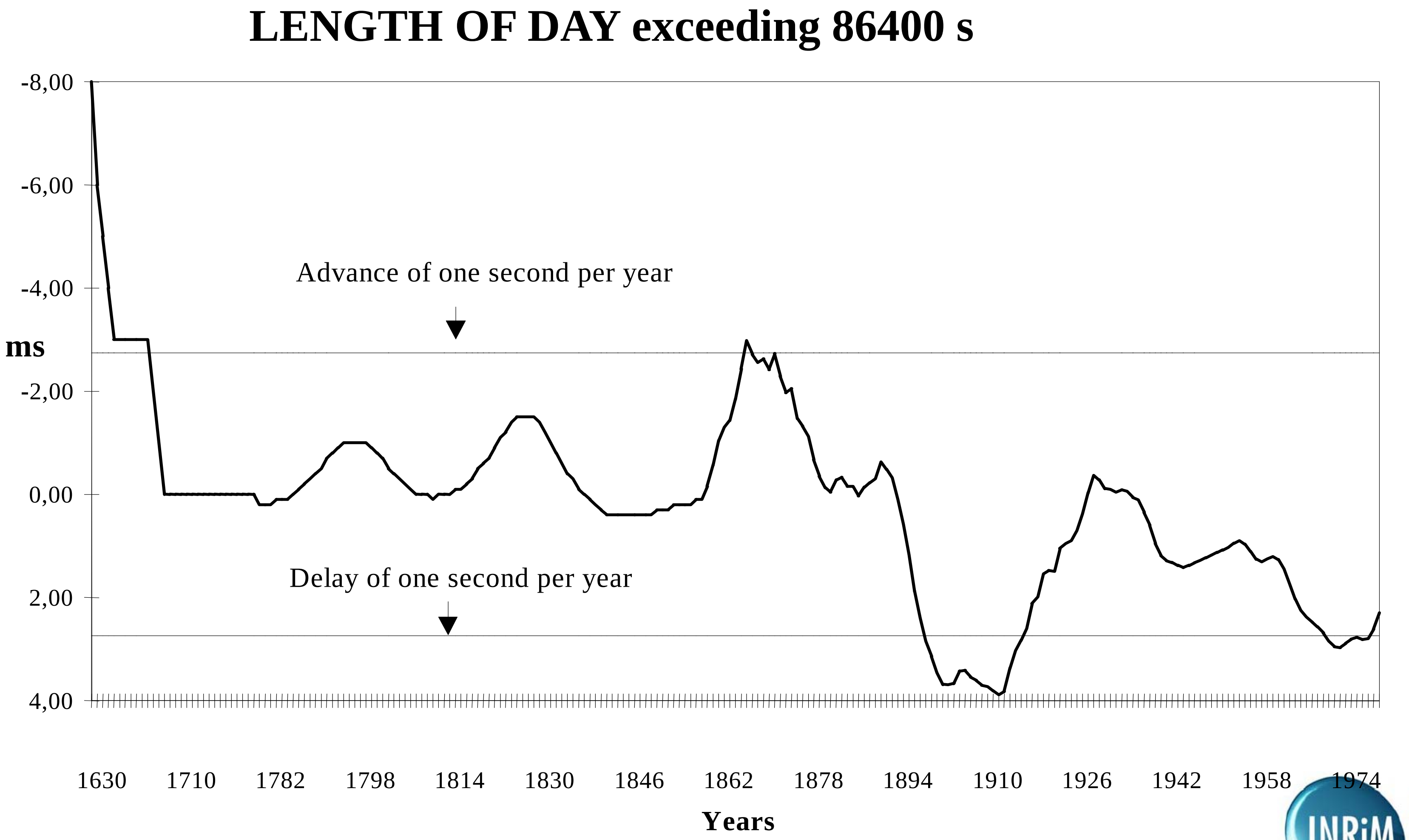


Figure II-5: Variations in the duration of the day

Secular slowing down



The Universal Time was improved

UT = Universal Time scale

UT1 = Universal Time corrected by polar motion

UT2 = Universal Time scale corrected by seasonal variations

…. (UT not GMT!)

…in 1960

• the "revolution" of the Earth around the Sun is constant.

•Measuring the longitude of the Sun and using the equation of the apparent Sun orbit

• The new time scale: Ephemeris Time starts from h. 0 UT of January 1st, 1900.

Ephemeris Time

• Time unit is the Ephemeris Second = 1/31 556 925.9747 of the tropical year on day **January 0, 1900**

• any new definition of the Second has to be in agreement with the previous one. For continuity with UT, this is the duration of the second in 1900

that duration!

in 1960 this duration was already shorter than 1/86400 of the Mean Solar Day

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…in 1967

Atomic Time

- Atomic Second = 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Cs 133 atom

- First comes the second, then the time scale: in 1971: Temps Atomique International TAI, International Atomic Time

- TAI starts from h. 0 UT of January 1st, 1958.

- The length of the atomic second is in agreement with the Ephemeris second

therefore shorter than 1/86400 of the Mean Solar Day

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So far we have learnt that the Atomic Second is, by definition,

shorter than the **current** Rotational Second (Universal Time)

because it was defined in agreement with

the duration of the Rotational Second in 1900 and

the Earth is (slowly!) slowing down

The International Astronomical Union recommends time scales and reference frames for the different applications in Geocentric or Solar System Barycentric frames. On the Earth or in the vicinity (50000 km) the reference time scale (1991) is the

Terrestrial Time

The Terrestrial Time is a coordinate time scale defined in a geocentric reference frame (centered at the centre of the Earth), with scale unit the SI second as realised on the rotating geoid, i.e. differing by a constant rate with respect to a geocentric clock.

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The International Atomic Time

is an optimal realisation of the Terrestrial Time
other realisation are for example TT(BIPM), some TA(k)

But which is **now** the angular position of the **EARTH?**

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Some users need to know the relationship between the Universal Time UT1 (rotational) and the Atomic Time

Coordinated

in 1975

The Universal Coordinated Time (UTC) is a trade-off defined with the same time unit as TAI but with insertion of additional leap second

TAI-UTC = n seconds $\qquad$ $n = 0, \pm 1, \pm 2, \ldots$

Universal Time UT0, UT1, UT2,….

$|UT1 - UTC| < 0.9$ s

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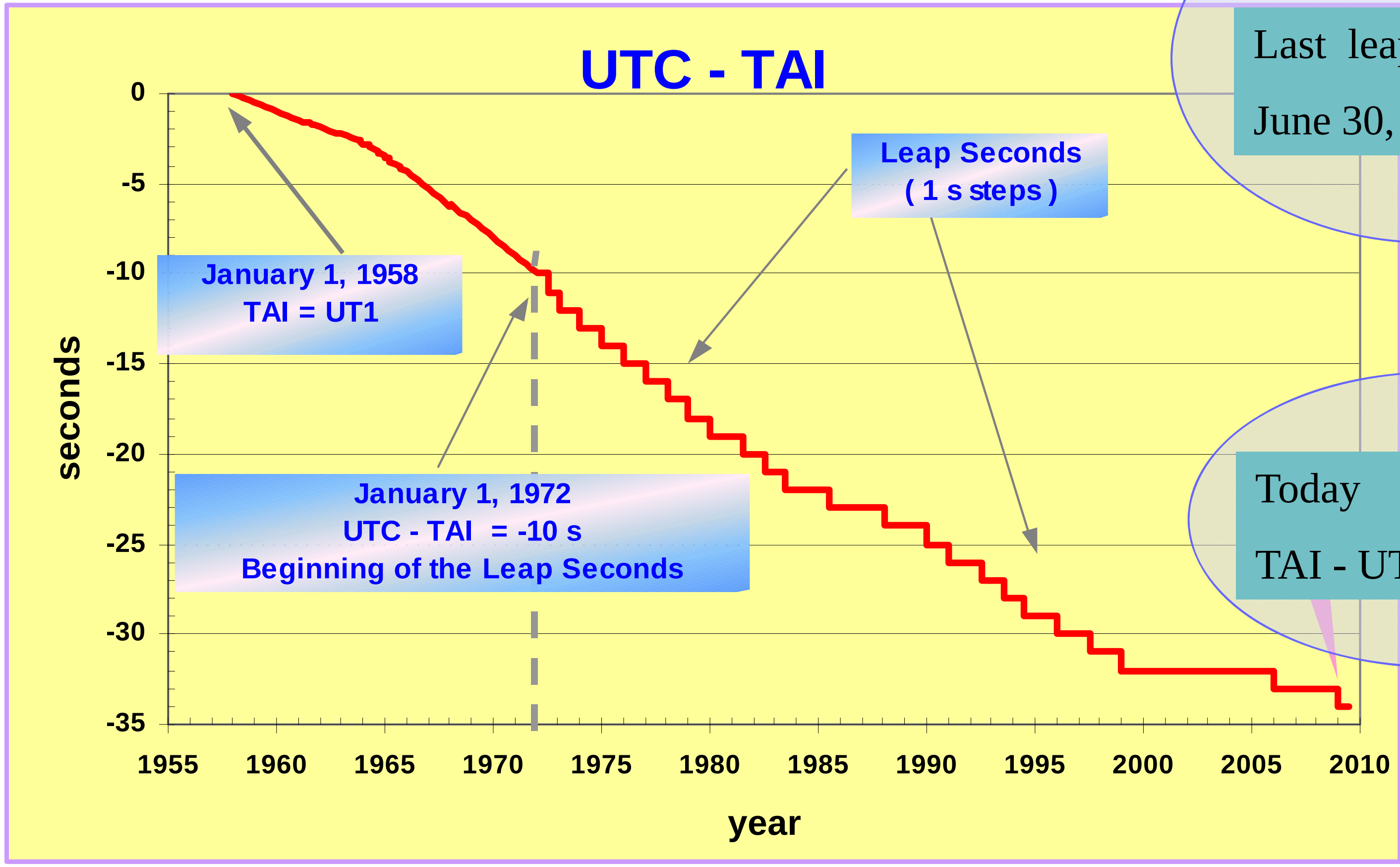
Universal Coordinated Time and leap seconds



Last leap second

June 30, 2015

Today

TAI - UTC = 36 s

Universal Time Coordinated

is computed at the BIPM in different steps:

EAL = Echelle Atomique Libre = weighted mean of all atomic clocks in the world

TAI = Temps Atomique International = EAL plus frequency steering to maintain the TAI second in agreement with the definition of the second of the International System (SI). This is obtained through the evalation of primary frequency standards

UTC = Universal Time Coordinated = TAI with the addition of leap second to remain close to the rotating Earth

The Universal Time Coordinated is the ultimate time reference (also with a «rapid» version) and it is available

in deferred time

Local time scale UTC(k) are realised by national laboratories

in real-time

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Leap seconds are useful or annoying?

- Idea first raised in public in 1999

INNOVATION

GPS and Leap Seconds

Time to Change?

Dennis D. McCarthy, U.S. Naval Observatory
William J. Klepczynski, Innovative Solutions International

Since ancient times, we have used the Earth's rotation to regulate our daily activities. By noticing the approximate position of the sun in the sky, we knew how much time was left for the day's hunting or farming, or when we should stop work to eat or pray. First sundials, water clocks, and then mechanical clocks were invented to tell time more precisely by essentially interpolating from noon to noon.

As mechanical clocks became increasingly accurate, we discovered that the Earth does not rotate ...

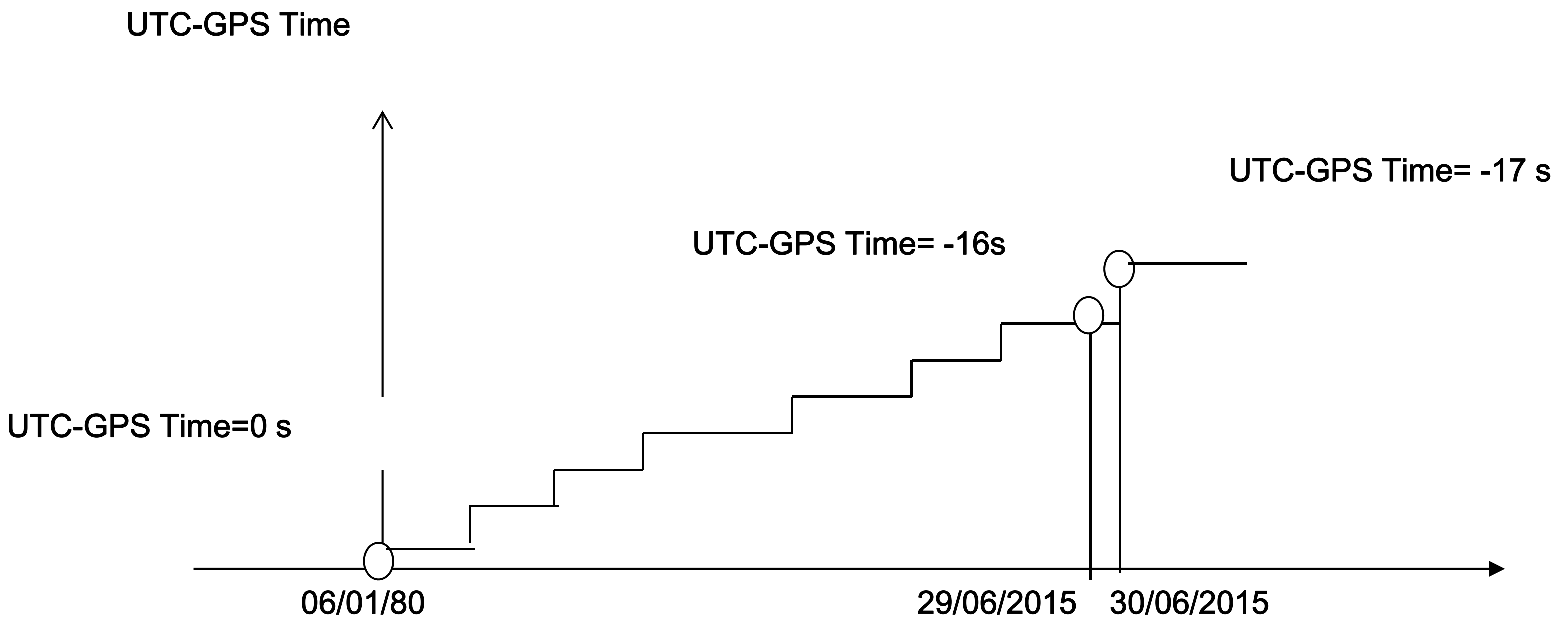
Just as leap years keep our calendar approximately synchronized with the Earth's orbit about the Sun, leap seconds keep precise clocks in synchronization with the rotating Earth, the traditional "clock" that humans have used to determine time. Coordinated Universal Time (UTC), created by adjusting International Atomic Time (TAI) by the appropriate number of leap seconds, is the uniform time scale that is the basis of most civil timekeeping in the world. The concept of a leap second was introd...

... seconds. While resetting the GLONASS clocks, the system is unavailable for navigation service because the clocks are not synchronized. If worldwide reliance on satellite navigation for air transportation increases in the future, depending on a system that may not be operational during some critical areas of flight could be a difficulty. Recognizing this problem, GLONASS developers plan to significantly reduce the ...

Source:
GPS World
Nov 1999

Global Positioning System: navigation and timing services

GPS time was set in agreement with UTC on h. 00 Jan 6, 1980

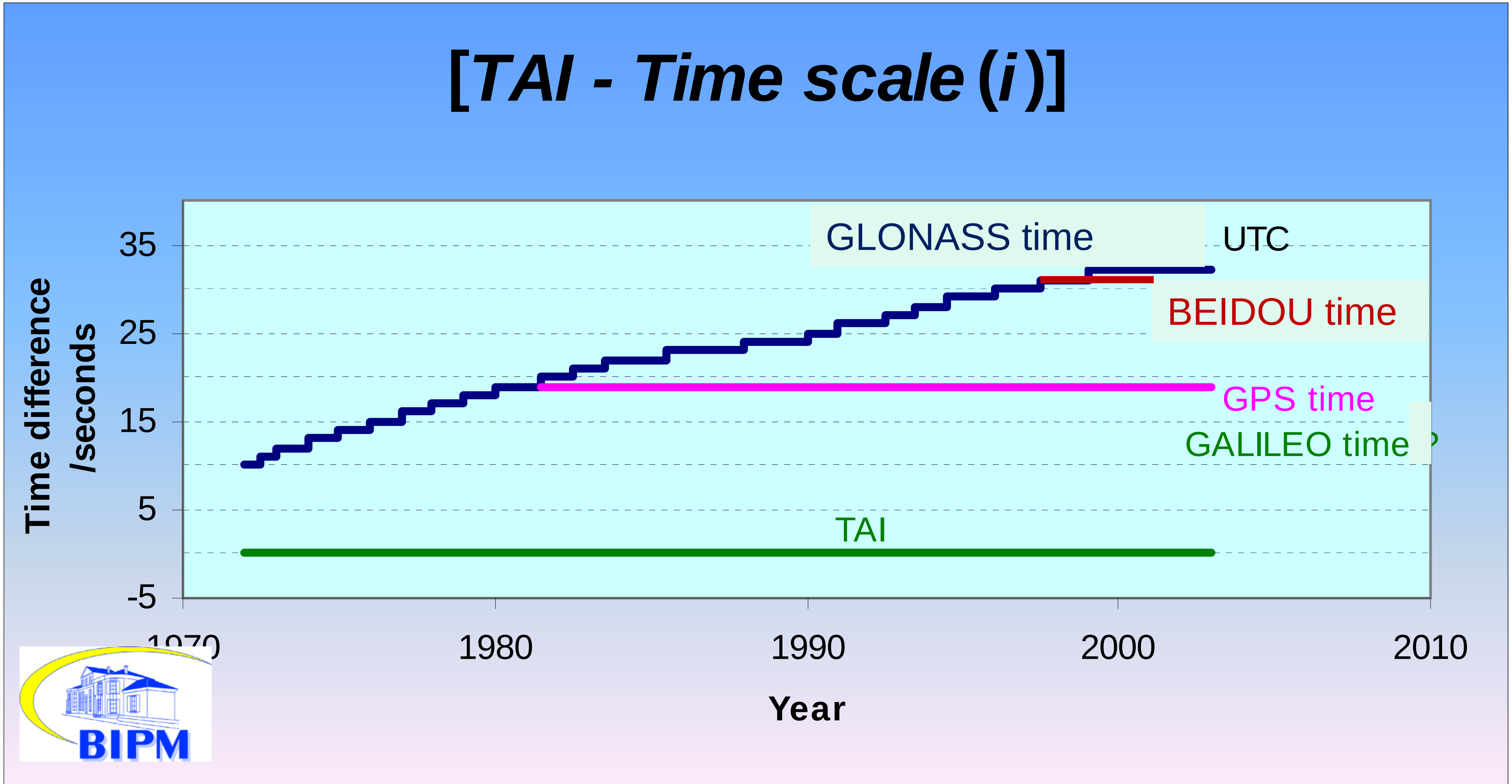


The accumulate time difference between UTC

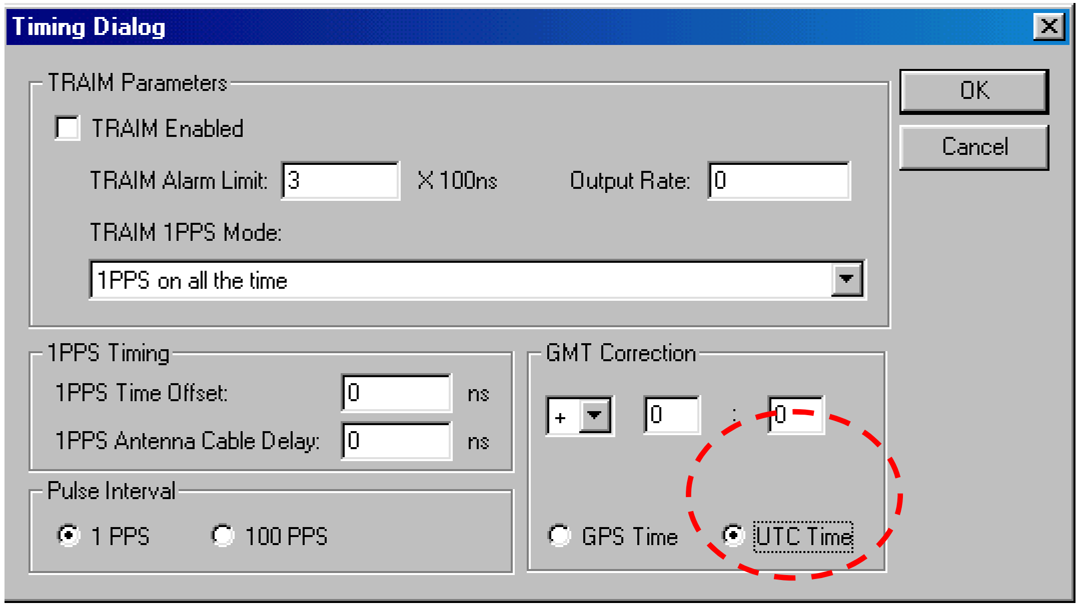
and GPS time is now of 17 seconds. GPS time is ahead 17 s

Leap seconds in Global Navigation Satellite System time scales

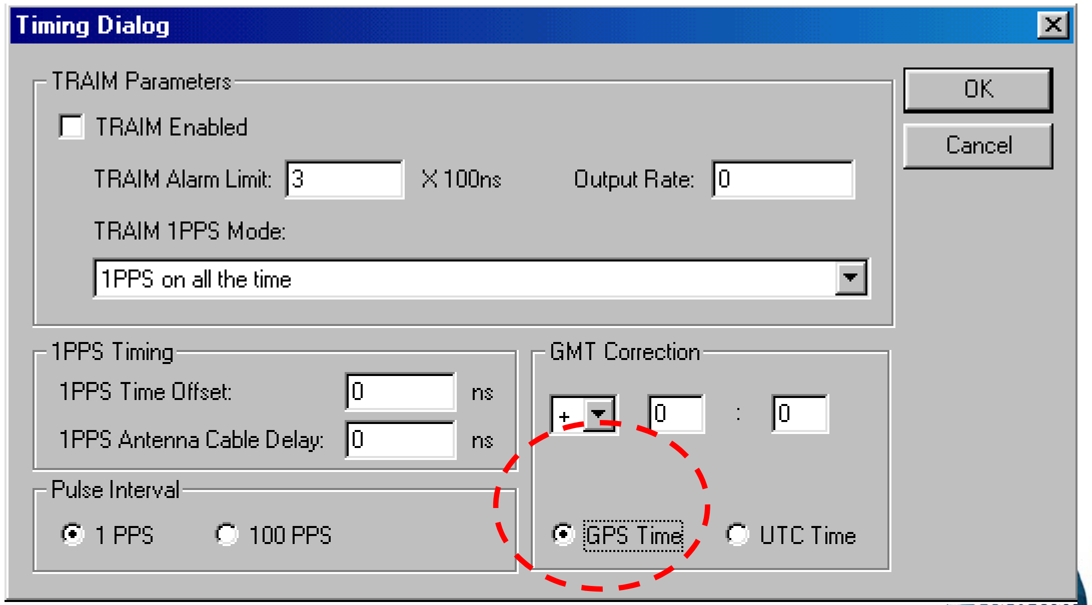
GNSS prefer not to apply leap seconds (except GLONASS), their time scale is easily available all over the world inside the navigation message, reference time scales differ from seconds, source of CONFUSION!!!



Timing from a MOTOROLA GPS receiver



UTC or GPS time can be chosen as reference time



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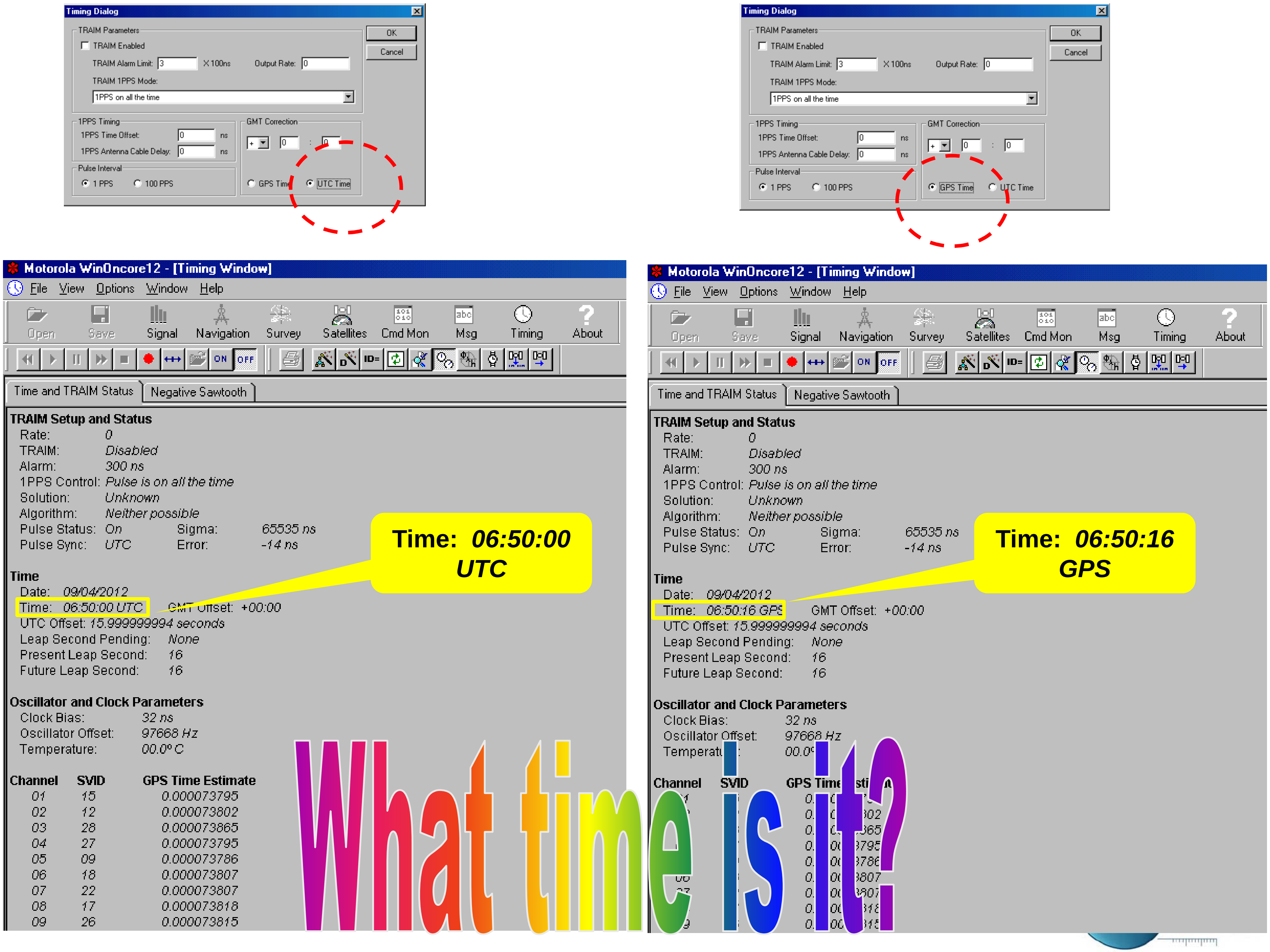
Timing Dialog
TRAIM Parameters
TRAIM Enabled
TRAIM Alarm Limit: 3 X 100ns
Output Rate: 0
TRAIM 1PPS Mode:
1PPS on all the time
1PPS Timing
1PPS Time Offset: 0 ns
1PPS Antenna Cable Delay: 0 ns
GMT Correction
Pulse Interval
1 PPS
100 PPS
GPS Time
UTC Time
OK
Cancel
Motorola WinOncore12 - [Timing Window]
File View Options Window Help
Open Save Signal Navigation Survey Satellites Cmd Mon Msg Timing About
Time and TRAIM Status
Negative Sawtooth
TRAIM Setup and Status
Rate: 0
TRAIM: Disabled
Alarm: 300 ns
1PPS Control: Pulse is on all the time
Solution: Unknown
Algorithm: Neither possible
Pulse Status: On Sigma: 65535 ns
Pulse Sync: UTC Error: -14 ns
Time
Date: 09/04/2012
Time: 06:50:00 UTC
GMT Offset: +00:00
UTC Offset: 15.999999994 seconds
Leap Second Pending: None
Present Leap Second: 16
Future Leap Second: 16
Oscillator and Clock Parameters
Clock Bias: 32 ns
Oscillator Offset: 97668 Hz
Temperature: 00.0° C
Channel SVID GPS Time Estimate
01 15 0.000073795
02 12 0.000073802
03 28 0.000073865
04 27 0.000073795
05 09 0.000073786
06 18 0.000073807
07 22 0.000073807
08 17 0.000073818
09 26 0.000073815
Time: 06:50:00
UTC
Time: 06:50:16 GPS
GMT Offset: +00:00
Time: 06:50:16
GPS
What time is it?

Leap seconds are useful or annoying? The current proliferation of time scales is generating confusion and possible danger

ITU
INTERNATIONAL TELECOMMUNICATION UNION
RADIOCOMMUNICATION STUDY GROUPS

Special Rapporteur Group 7A
(SRG 7A) on the
Future of the UTC Time Scale

Several international organisations created working groups to evaluate this issue. In November 2015 **ITU General Assembly** decided not do change till 2022. ITU would continue to be responsible for the dissemination of time signals via radiocommunication and BIPM for establishing and maintaining the second of the International System of Units (SI) and its dissemination through the reference time scale.

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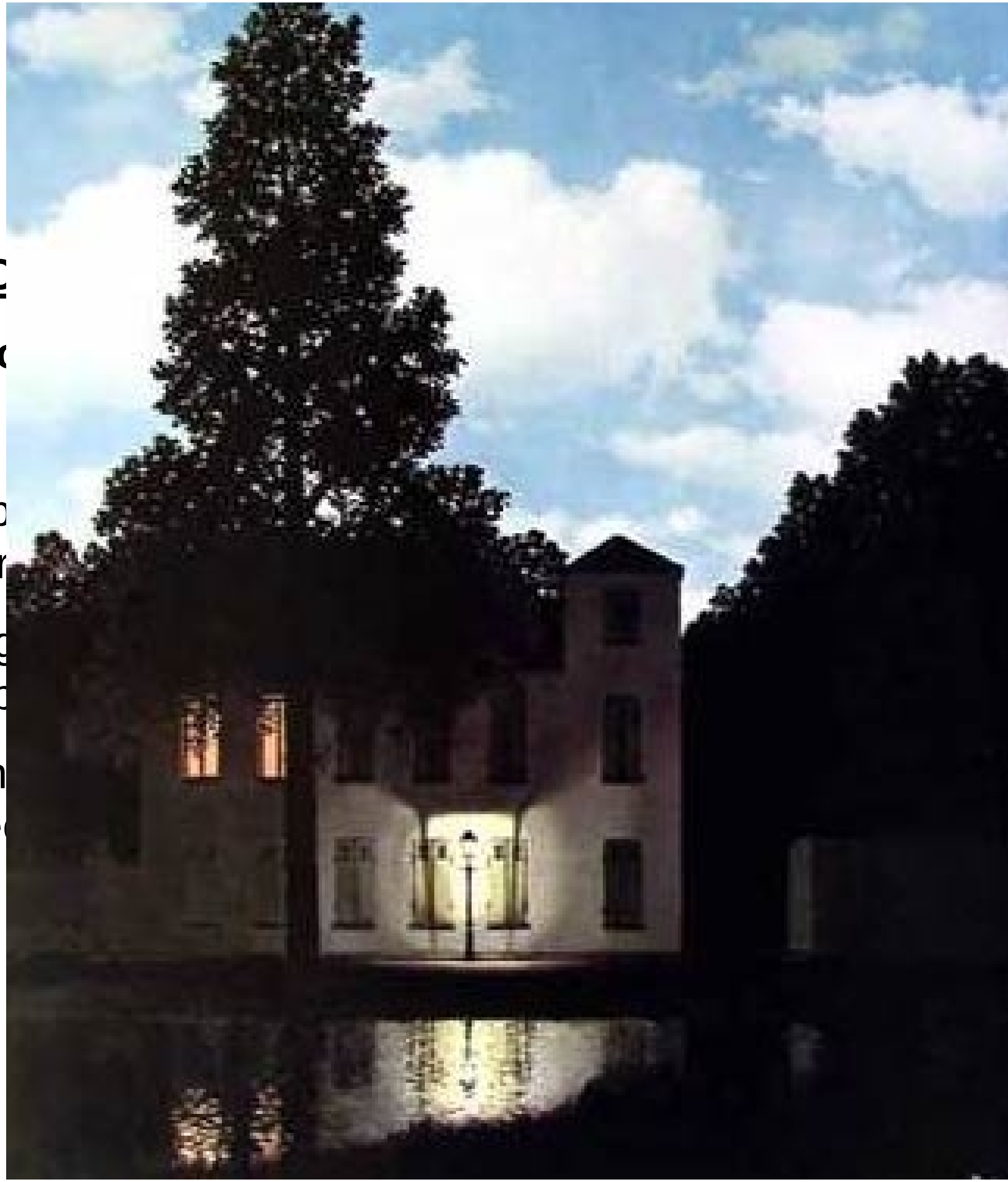
BIPM press release 13 C

The proposed redefinitio

Today, leap seconds keep
phase with the slightly var

The possibility of dropping
misconceptions in the pop

There are an increasing n
second causes serious te



Further lecture…

The proposed redefinition of Coordinated Universal Time, UTC

There is a need to set out clearly the reasons for the change and what is involved. This is the **purpose of what follows:**

The international character of the world's time scale

The measure of time and its unit the second are matters of international cooperation. Up until the middle of the 20th century, time scales were based on astronomical observations of the rotation of the Earth and the movement of the Earth in its orbit round the Sun. These had been within the purview of astronomers for centuries and, since the 1920s, had been the concern of the International Astronomical Union (IAU). With the invention of the atomic clock in 1955, however, everything began to change. By then, the irregular rate of rotation of the Earth and the practical difficulties in the realization of ephemeris time, based on the period of the Earth's orbit round the Sun, made it necessary to move to a time scale based on the atomic clock. ....

http://www.bipm.org/utils/en/pdf/Press_Release_UTC_13October.pdf

UTC for the 21st century

November 2011 at The Royal Society at Chicheley Hall,

Organised by Dr Terry Quinn and Dr Felicitas Arias

http://royalsociety.org/events/2011/utc-21-century/

Metrologia

Special issue on "modern time scales" 48 (2011) S121–S124

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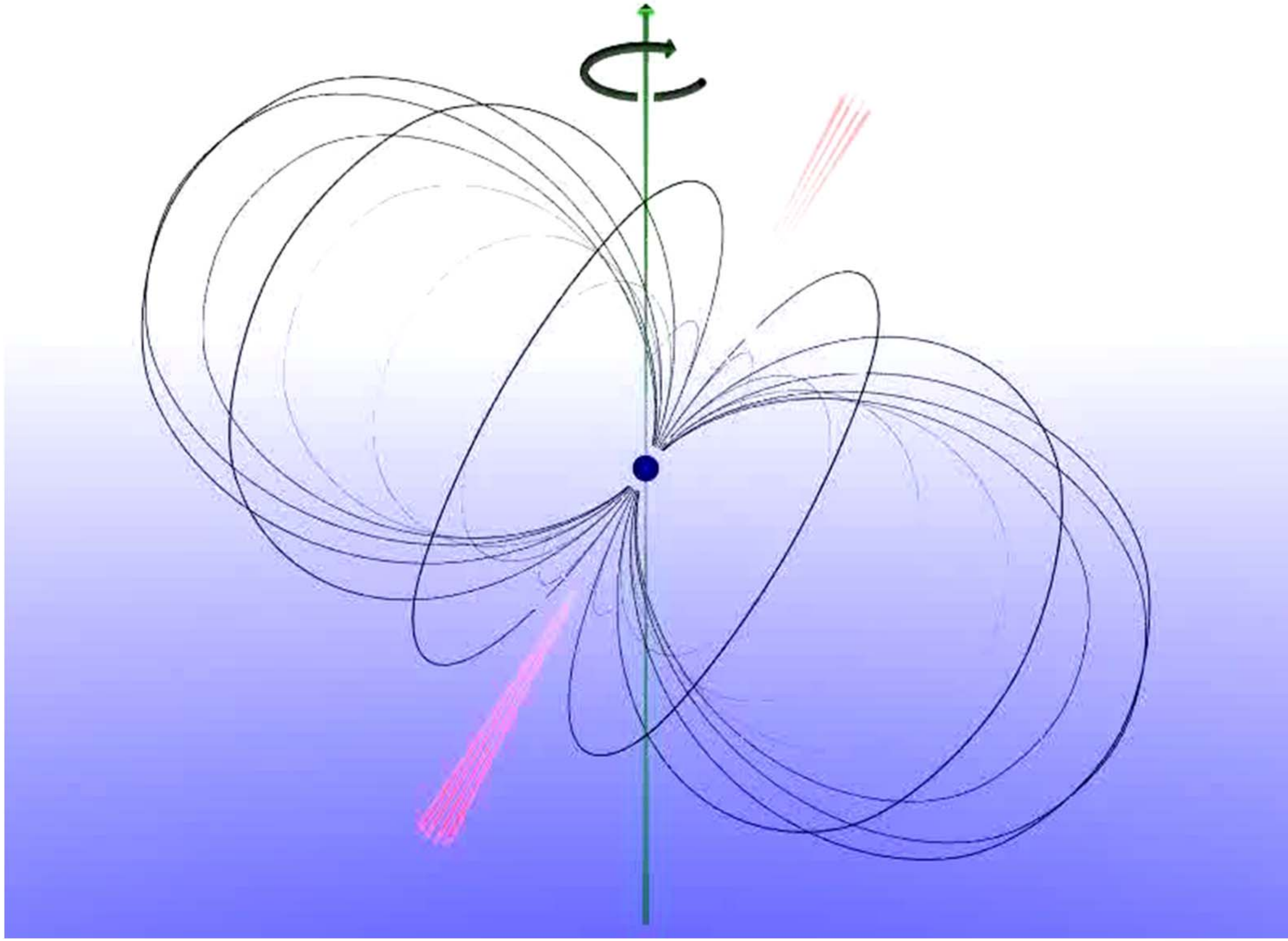
Time and navigation will return in space?

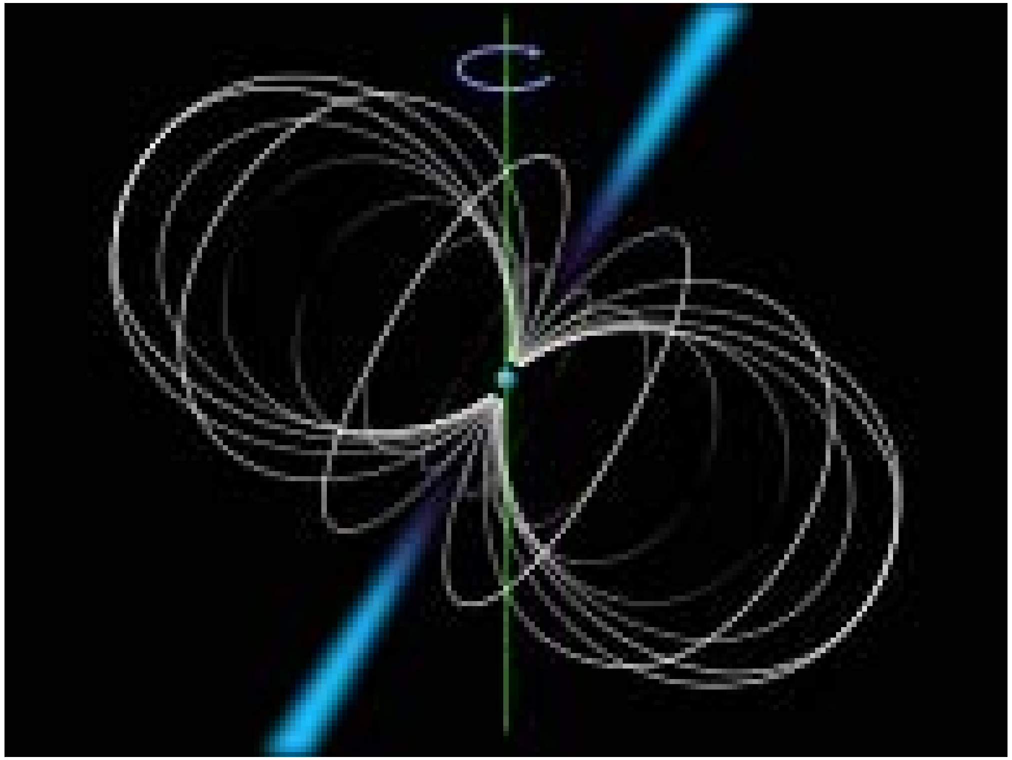
Pulsar: a rotating star

A clock in space?



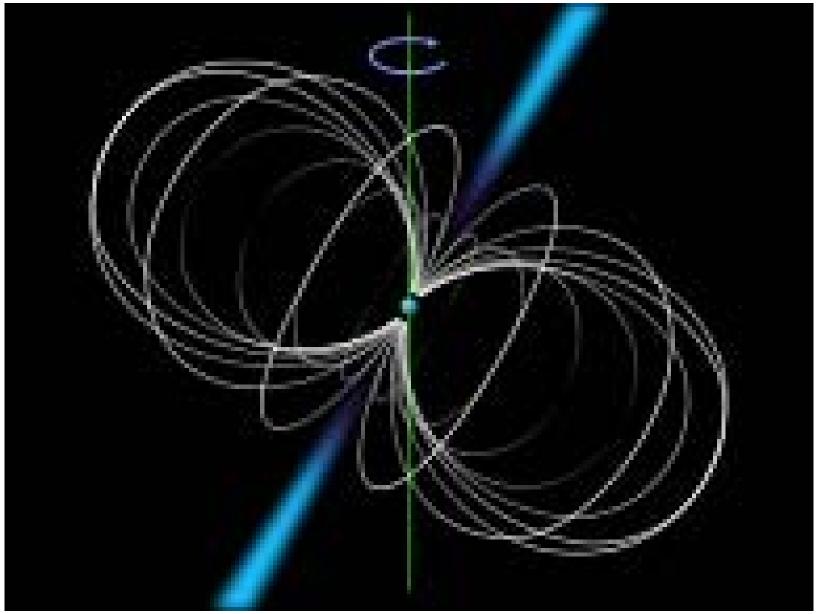
TUTO
IONALE
ICERCA
ROLOGICA

Pulsar



- Neutron star
- 20 km as diameter
- 1,4 time the solar mass
- in our Galaxy, thousand light years apart
- some spinning with millisecond period
- emitting radiowave as a lighthouse

Pulsar



- The rotation is highly stable
- Every millisecond we see a radio pulse

Is it a “clock”?

Many different difficulties:

- The rotation period is slowing down
- The pulse has to cross 10^{16} km of interstellar region
- The Earth is a rotating observatory

But...

Pulsar

Nobel Prize to Taylor and Hulse for gravitational wave detection (1993)

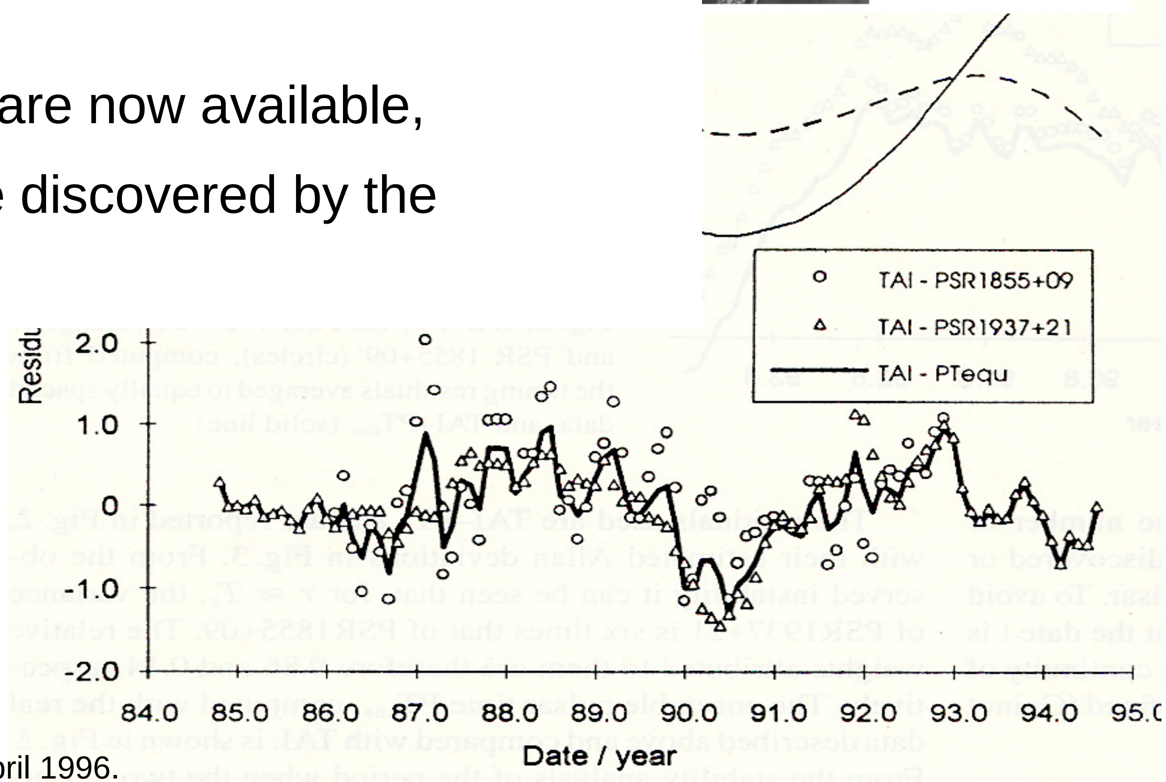
some ideas on the long term instabilities of atomic clocks

Pulsar is the hot topic:

new decades of observations are now available,

tens of millisec pulsars will be discovered by the

Square Kilometer Array

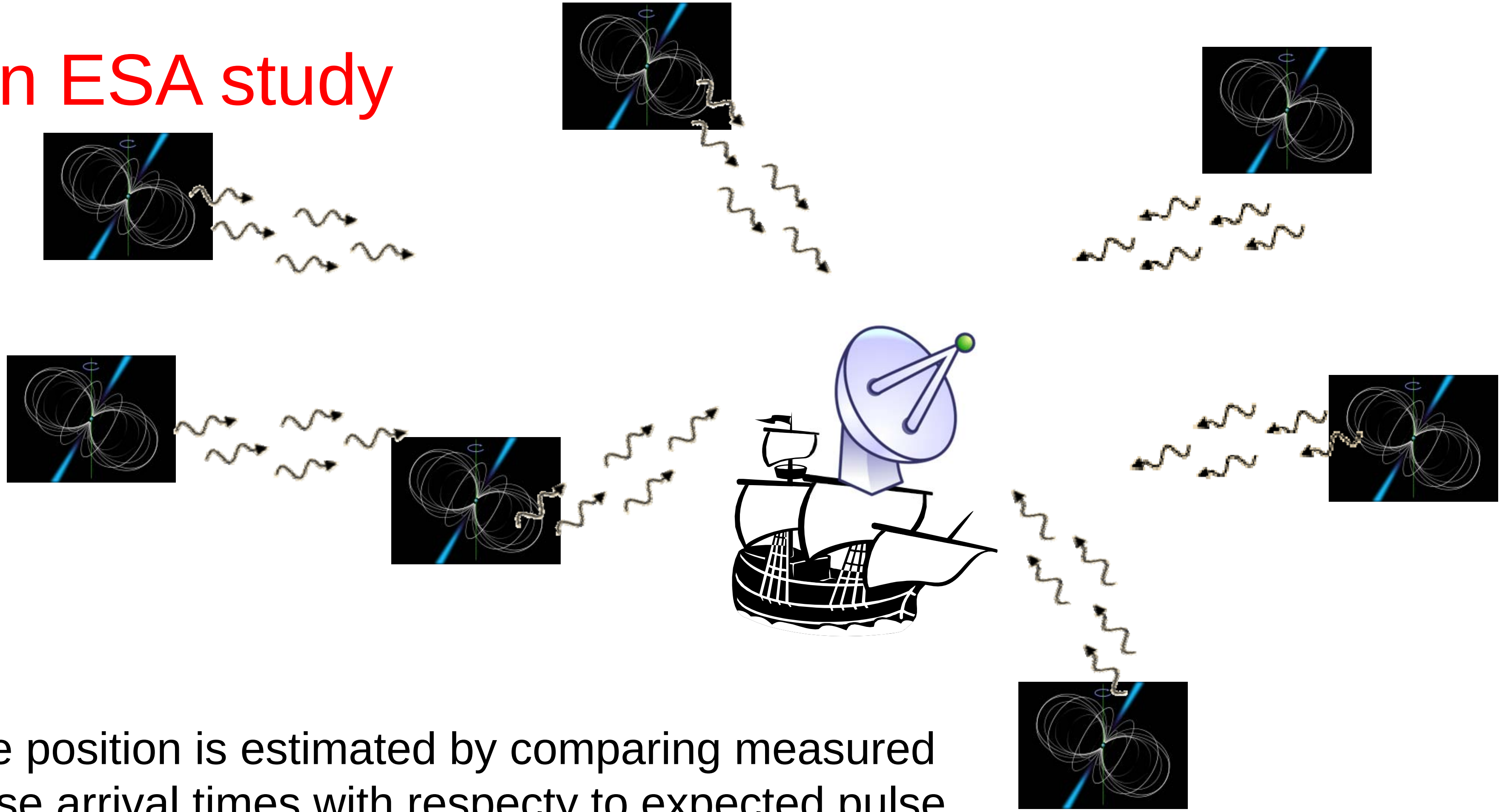


G. Petit, Astronomy and Astrophysics 308, April 1996.

R. Breton et al Science 4 July 2008, A. Papitto, Nature 09/2013

Pulsars for extraterrestrial space navigation?

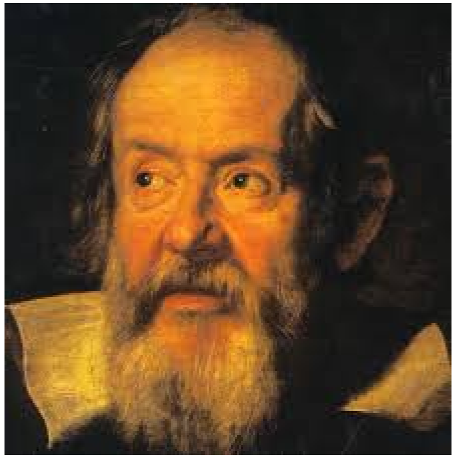
an ESA study



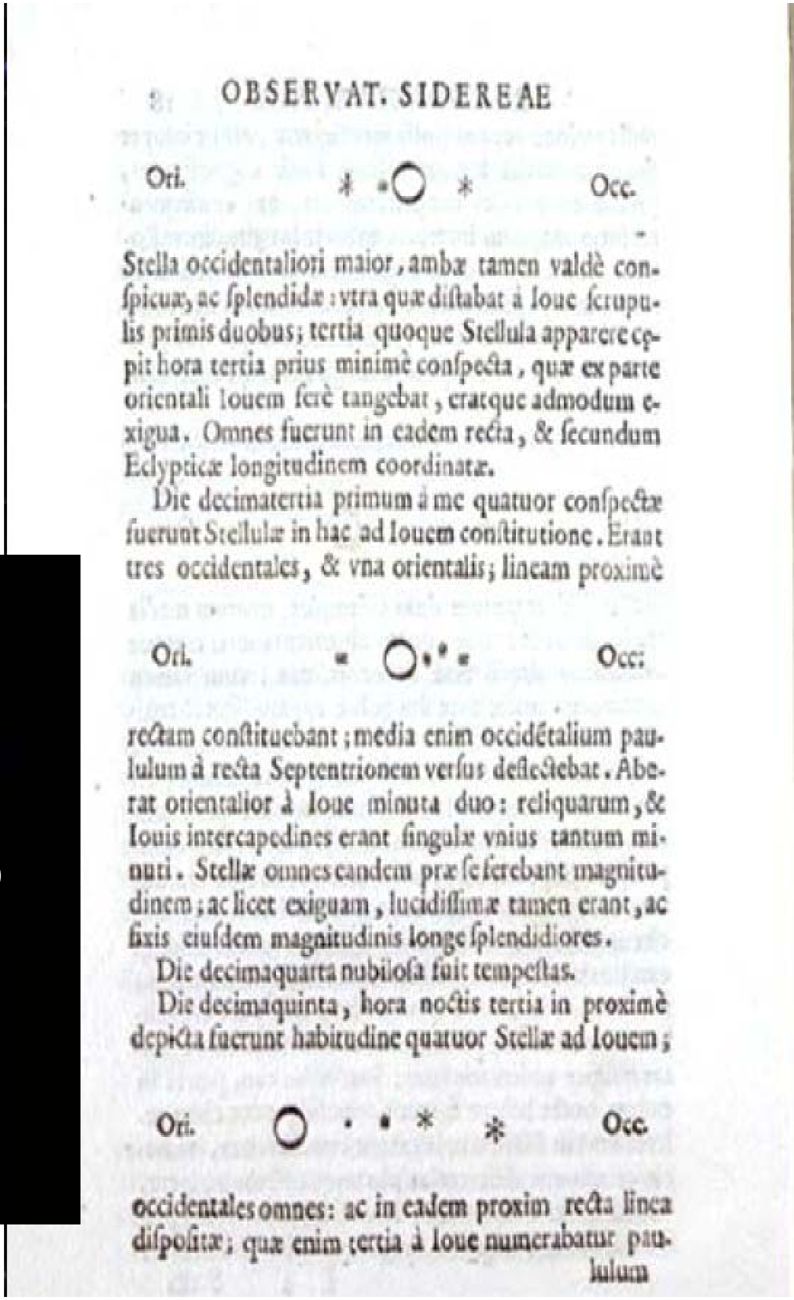
The position is estimated by comparing measured pulse arrival times with respecty to expected pulse arrival times using information from a pulsar database

Josep Sala et al, https://www.esa.int/gsp/ACT/doc/EVENTS/InnovativeSystemWorkshop2/ACT-ART-Bridge2Space-Sala.pdf

The letter to the King of Spain in 1612 still alive…



These stars display conjunctions, separations, eclipses, and other configurations…more than 100 a year…and they are so unique, identifiable, and so exact that nobody, of medium intelligence, is not able to use them to identify the longitude and the position of the ship based on the ephemerids I have computed for the next years to come.



OBSERVAT. SIDEREAE

Ori. Occ.

Stella occidentaliori maior, ambæ tamen valdè conspicuæ, ac splendidæ: vtra quæ distabat à Ioue scrupulis primis duobus; tertia quoque Stellula apparere cępit hora tertia prius minimè conspecta, quæ ex parte orientali Iouem ferè tangebat, eratque admodum exigua. Omnes fuerunt in eadem recta, & secundum Eclypticæ longitudinem coordinatæ.

Die decimatertia primum à me quatuor conspectæ fuerunt Stellulæ in hac ad Iouem constitutione. Erant tres occidentales, & vna orientalis; lineam proximè

Ori. Occ:

rectam constituebant; media enim occidétalium paululum à recta Septentrionem versus deflectebat. Aberat orientalior à Ioue minuta duo: reliquarum, & Iouis intercapedines erant singulæ vnius tantum minuti. Stellæ omnes eandem præ se ferebant magnitudinem; ac licet exiguam, lucidissimæ tamen erant, ac fixis eiusdem magnitudinis longe splendidiores.

Die decimaquarta nubilosa fuit tempestas.

Die decimaquinta, hora noctis tertia in proximè depicta fuerunt habitudine quatuor Stellæ ad Iouem;

Ori. Occ.

occidentales omnes: ac in eadem proxim recta linea dispositæ; quæ enim tertia à Ioue numerabatur paululum

CA

Mostafa Fatemi

Mayo Cinic, USA
reveal email address
January 1, 2016 through June 30, 2017.
"Medical Ultrasound Technology: From Pulse

After an introduction on the trend of diagno
ultrasound radiation force. Next, the result
applications will be presented.

Patrizia Tavella

Istituto Nazionale Ricerca Metrologica INRI
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July 1, 2015 through December 31, 2016
"Precise Time Scales and Navigation Systen

View their reports

Susan Trolier-McKinstry

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"Piezoelectric Films for Microelectromechani

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