gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

Lecture 4

GNSS Time Reference Systems and Frames

Professors: Dr. J. Sanz Subirana, Dr. J.M. Juan Zornoza
and Dr. Adrià Rovira García

Contents

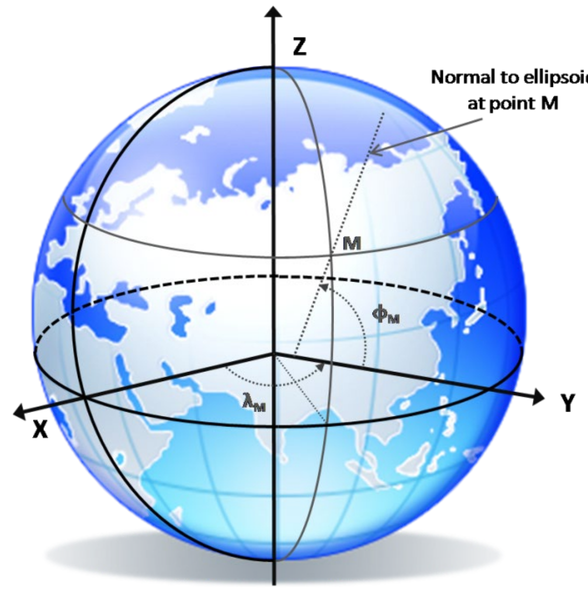
1. Introduction

The next three fields are the heart of positioning and navigation system:

- Geodesy (study of shape and size of Earth and mapping of it is surface)
- Timekeeping (art and science of measuring time)
- Astronomy and astronautics

Which is my position?

How do we determine the coordinates of a point in a system, in a map?



http://gnss.be/systems/tutorial.php

❖ It took about two thousand years to accomplish this goal.

❖ Now we can specify the position of a point on Earth with **millimetre-level** accuracy.

Contents

2.1 Reference Systems and Frames

Satellite coordinates and users' receivers must be expressed in a well defined reference. Therefore an **accurate definition and determination is essential to ensure precise positioning** in GNSS.

❑ Distinction must be made between two terms

- **Reference System:** Theoretical definition, including models and standards for its implementation *[generally only one system].*
- **Reference Frame:** Practical implementation, through observations and a set of reference coordinates (a set of fundamental stars for space-fixed frames or fiducial stations for a Earth-fixed frames) *[usually many frames].*

❑ Two main kinds of reference systems are used in GNSS

- **Space-fixed** or inertial systems, in which the positions of stars are fixed or almost fixed.

  ➔Suitable for satellite motion.

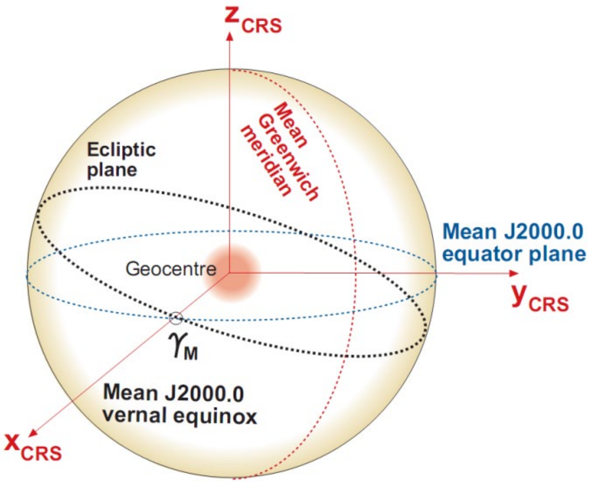
- **Earth-fixed** systems, co-rotating with the Earth, in which terrestrial points can be expressed conveniently on the Earth's surface.

  ➔Suitable for user position.

2.1 Reference Systems and Frames: Space-fixed

- ***Conventional Celestial Reference System (CRS)*** (also called Conventional (quasi)-Inertial System, CIS). It is considered to be inertial over short periods of time.

- **Origin**: Earth's centre of mass, or geocentre.
- **X-axis** points in the direction of the mean vernal equinox. at the J2000.0 epoch.
- **Z-axis** is orthogonal to the plane defined by the mean equator at the J2000.0 epoch.
- **Y-axis** is orthogonal to the former axes, so the system is right-handed oriented.



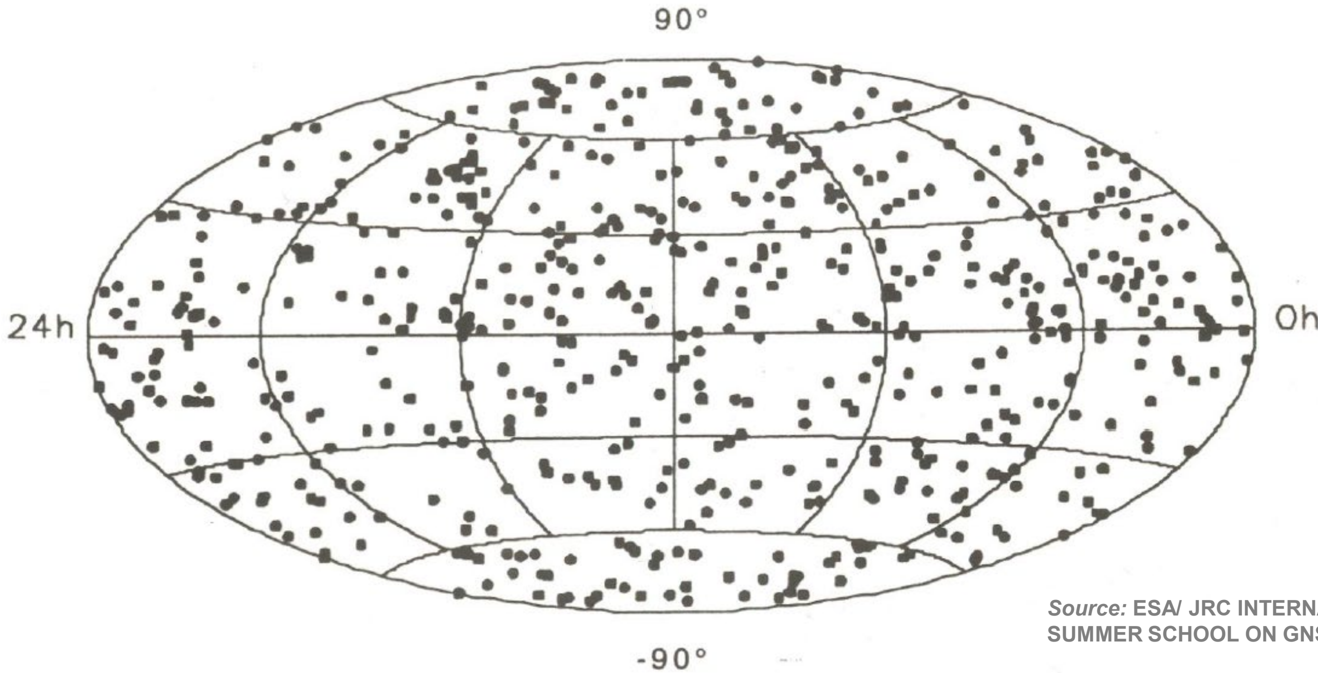
Note: The Mean Equator and Equinox J2000.0 were defined by the International Astronomical Union (IAU) agreements in 1976. (the former reference epoch was 1950.0).

❖ Practical implementation: **Celestial Reference Frame (CRF)**

2.1 Reference Systems and Frames: Space-fixed

International Celestial Reference Frame (ICRF)

It is determined from a set of precise coordinates of extragalactic radio sources (i.e. it is fixed with respect to distant objects of the Universe).

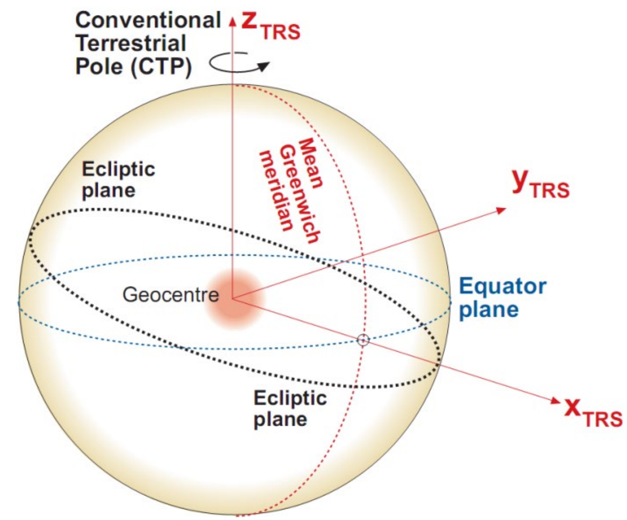


Source: ESA/ JRC INTERNATIONAL SUMMER SCHOOL ON GNSS 2014

The current realization contains over 500 extragalactic objects, mostly quasars and galactic nuclei.

2.1 Reference Systems and Frames: Earth-fixed (co-rotating)

- ***Conventional Terrestrial Reference System. (TRS). Earth-Centred, Earth-Fixed (ECEF).***



- **Origin** in Earth's centre of mass.
- **Z-axis** is identical to the direction of Earth's axis of rotation as defined by the **CTP *(Conventional Terrestrial Pole)***
- **X-axis** intersection of equatorial plane (orthogonal to Z-axis) with the mean **Greenwich meridian**.
- **Y-axis** is orthogonal to both of them (right-handed oriented system).

Note: The Earth's CTP was defined as the average of the poles from 1900 to 1905, by the Bureau Internat.de l'Heure

❖ Practical implementation: ***Conventional Terrestrial Reference Frame(CRF)***

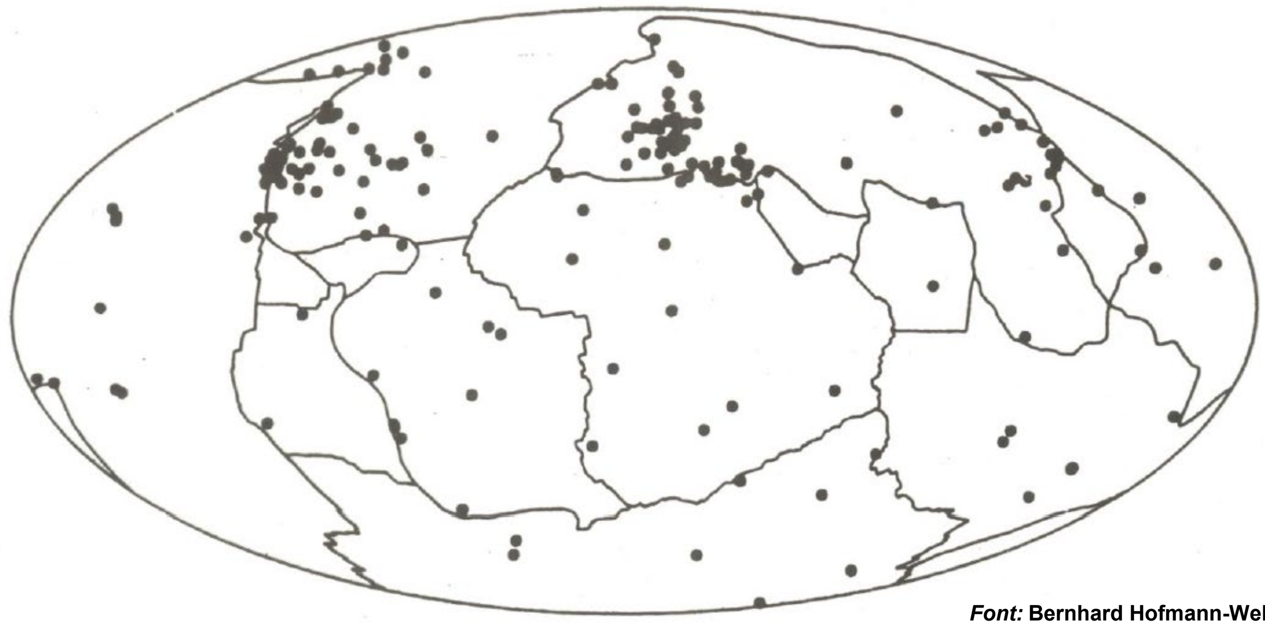
Examples of TRF:

- International Terrestrial Reference Frame (ITRF), introduced by International Earth Rotation and Reference Systems Service (IERS), (ITRF98, ITRF99, etc.).
- *GPS World Geodetic System 84 (WGS-84), Galileo Terrestrial Reference Frame …*

2.1 Reference Systems and Frames: Earth-fixed (co-rotating)

International Terrestrial Reference Frame (ITRF)

It is determined through the coordinates of a set of sites on Earth serving as reference points.



Font: **Bernhard Hofmann-Wellenhof**
Graz University of Technology

The current realization of the ITRF gives coordinates of some 200 sites with an accuracy of 1 to 3 cm, and site velocities within 2 to 5 mm/year. It samples twelve tectonic plates.

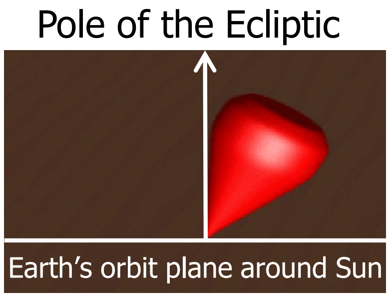
Contents

2.2 Transformations between Celestial and Terrestrial Frames

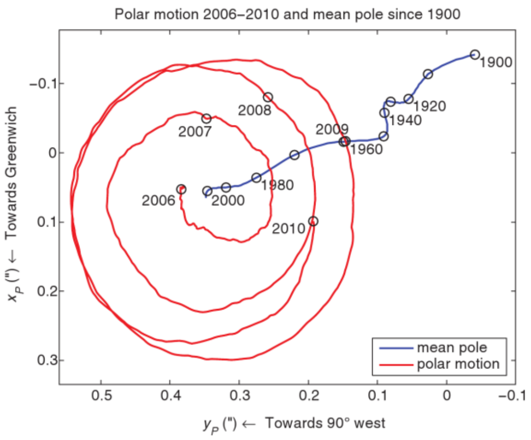
Instantaneous Earth's Rotation Axis: **[Celestial Ephemeris Pole (CEP)]**

CRF ←— Precession + Nutation —→ **CEP** ←— Pole movement + Earth rotation —→ TRF

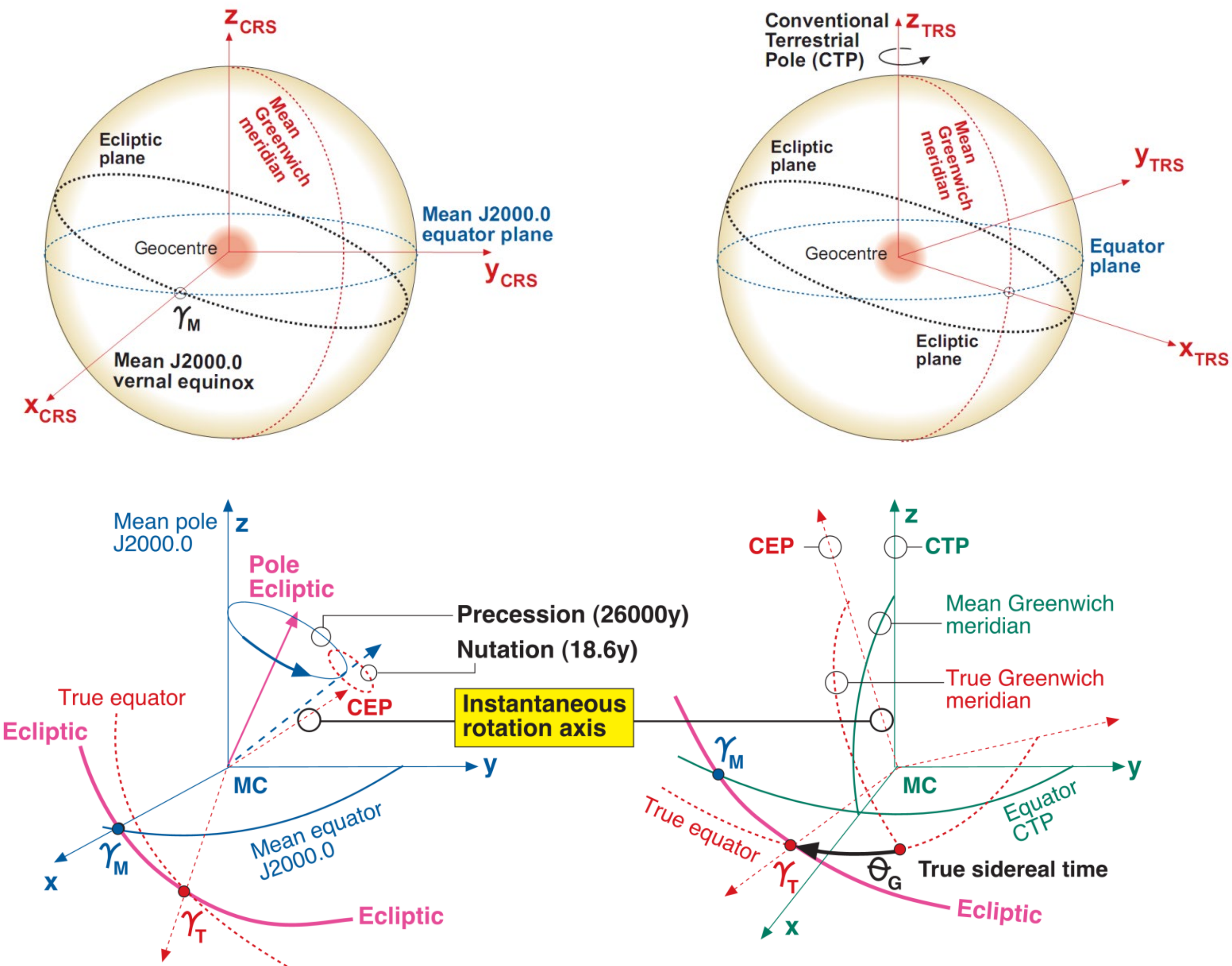
- **Precession and Nutation (forced rotation)**:
  Instantaneous Earth's rotation axis is not kept fixed in space (in relation to so-called `fixed stars´), but it rotates about the pole of the ecliptic.
  This movement is due to the effect of the gravitational attraction of the Moon and the Sun and major planets.
  Period: Precession: 26 000 years. Nutation: 18,6 years.



- **Pole movement (free rotation):**
  Earth's crust is not keep fixed in relation to the instantaneous Earth's rotation axis. Moreover, the rotation velocity is not constant, but changes slowly
  These effects are due to structure of Earth's distribution of mass and its variation.
  Pole movement Period: 430 sidereal days.



CRF ← Precession + Nutation → **CEP** ← Pole movement + Earth rotation → **TRF**



CELESTIAL REFERENCE FRAME (CRF)

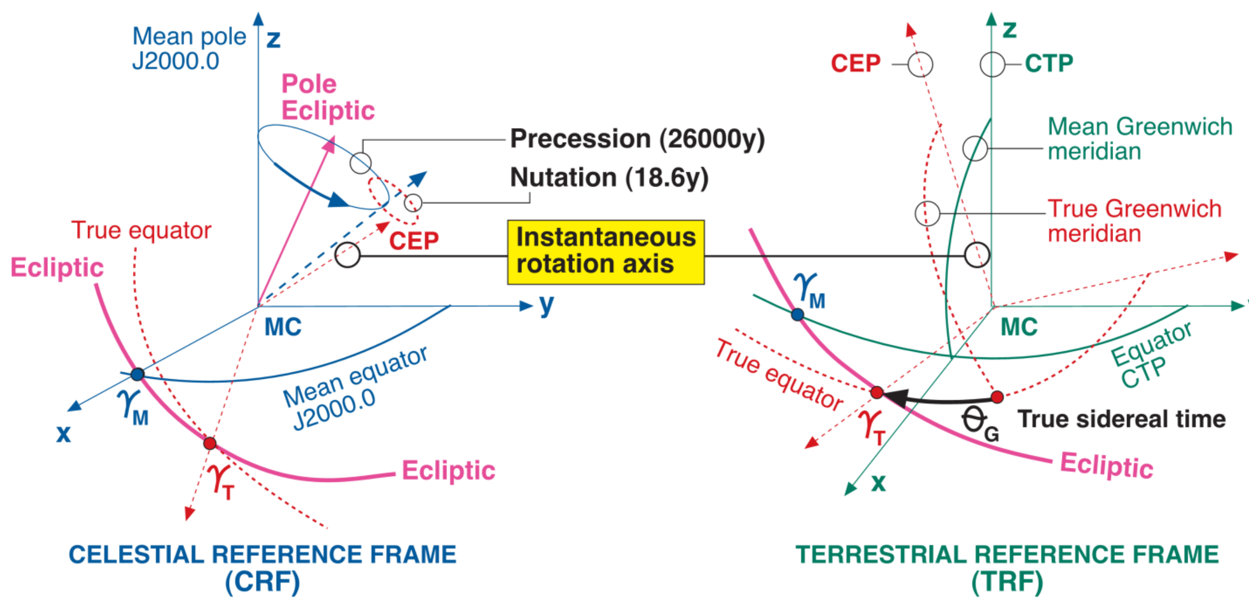
TERRESTRIAL REFERENCE FRAME (TRF)

Instantaneous Earth's Rotation Axis
[Celestial Ephemeris Pole (CEP)]

CRF ←— **Precession + Nutation** —→ **CEP** ←— **Pole movement + Earth rotation** —→ **TRF**

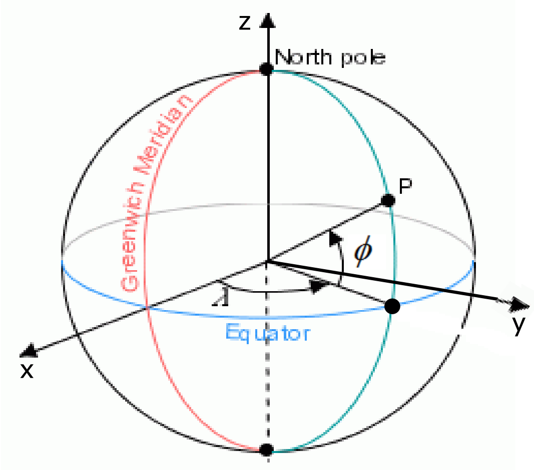
This transformation is based in **analytical expressions**, which are valid for long time intervals

But, the Earth's rotation and orientation **parameters** cannot be modelled analytically and must be periodically **updated using observations**



Contents

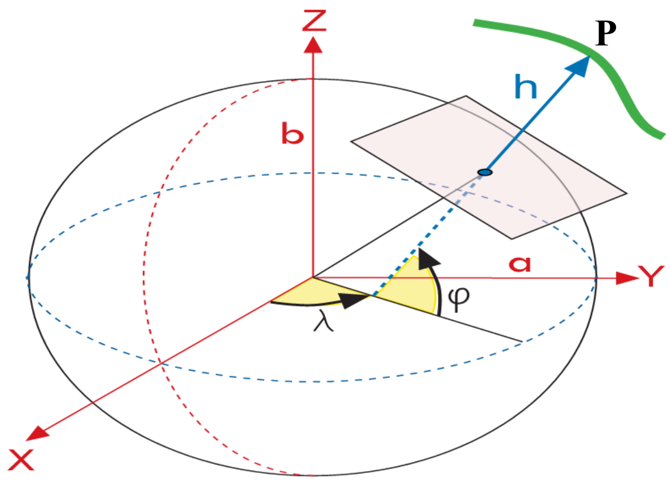
2.3.1 Spherical and Ellipsoidal coordinates



- **Geocentric latitude (ϕ)**: Angle between the normal to the sphere in the point and the equatorial plane (positive north from equator).
- **Geocentric longitude (λ)**: Angle between the Greenwich meridian and meridian of the location (positive east from Greenwich meridian).

Earth is flattened slightly at poles and bulged somewhat at equator.

- **Geodetic latitude (φ)**: Angle measured in meridian plane through P between the equatorial plane and the normal to the ellipsoid at P (positive north from equator).
- **Geodetic longitude (λ)**: The same value as the Geocentric longitude.
- **Geodetic height (h)**: measured along the normal to the ellipsoid, from the ellipsoid up to P.

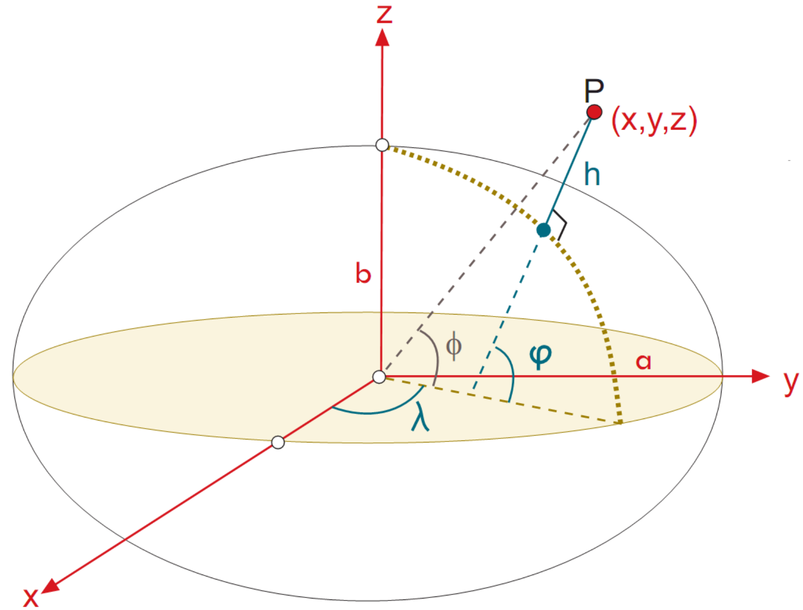


2.3.2 Coordinate conversions

From Ellipsoidal to Cartesian Coordinates

The Cartesian coordinates of a point (x, y, z) can be obtained from the ellipsoidal coordinates (φ, λ, h) by the expressions:

$$x = (N + h)\cos\varphi\ \cos\lambda$$
$$y = (N + h)\cos\varphi\ \sin\lambda$$
$$z = \big((1 - e^2)N + h\big)\sin\varphi$$



where N is the radius of curvature in the prime vertical

$$N = \frac{a}{\sqrt{1 - e^2\sin^2\varphi}}$$

and where the eccentricity e is related to the semi-major axis a, the semi-minor axis b and the flattening factor $f = 1 - b/a$

$$e^2 = \frac{a^2 - b^2}{a^2} = 2f - f^2$$

2.3.2 Coordinate conversions

From Cartesian to Ellipsoidal Coordinates

The ellipsoidal coordinates of a point (φ, λ, h) can be obtained from the Cartesian coordinates (x, y, z) by the expressions:

The longitude is given by: $\lambda = \arctan \frac{y}{x}$

The latitude is computed by an iterative procedure. The initial value is given:

$$\varphi_{(0)} = \arctan \left[\frac{z/p}{1-e^2} \right] \qquad p = \sqrt{x^2+y^2}$$

Improved values of φ, as well as the height h, are computed by iterating the equations:

$$N_{(i)} = \frac{a}{\sqrt{1-e^2 \sin^2 \varphi_{(i-1)}}}$$

$$h_{(i)} = \frac{p}{\cos \varphi_{(i-1)}} - N_{(i)}$$

$$\varphi_{(i)} = \arctan \left[\frac{z/p}{1 - \frac{N_{(i)}}{N_{(i)}+h_{(i)}} e^2} \right]$$

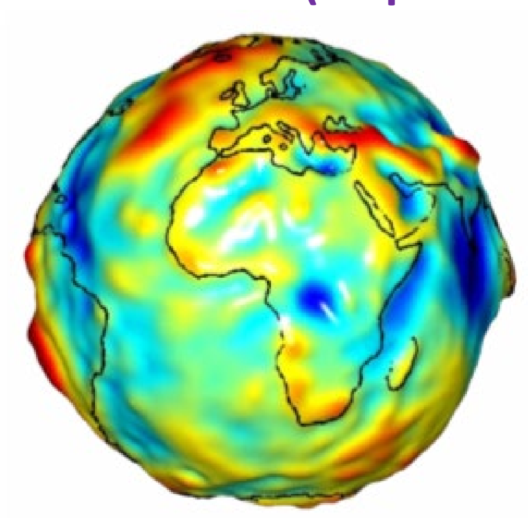
The iterations are repeated until the change between two successive values of $\varphi(i)$ is smaller than the precision required.

2.3.3 Geoid

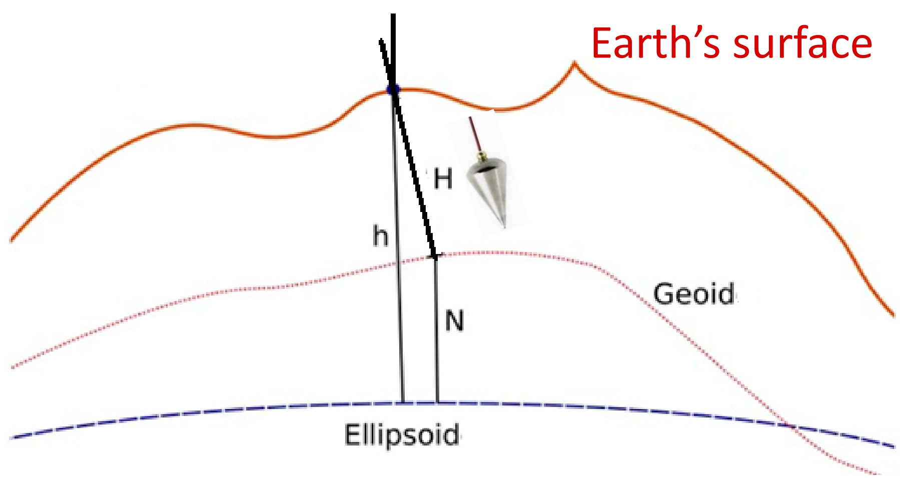
Usually height is given "over the mean see level" → Geoid

Geoid: "The *equipotential surface* of the Earth's gravity field which best fits, (global) mean sea level" (extended over land surface).

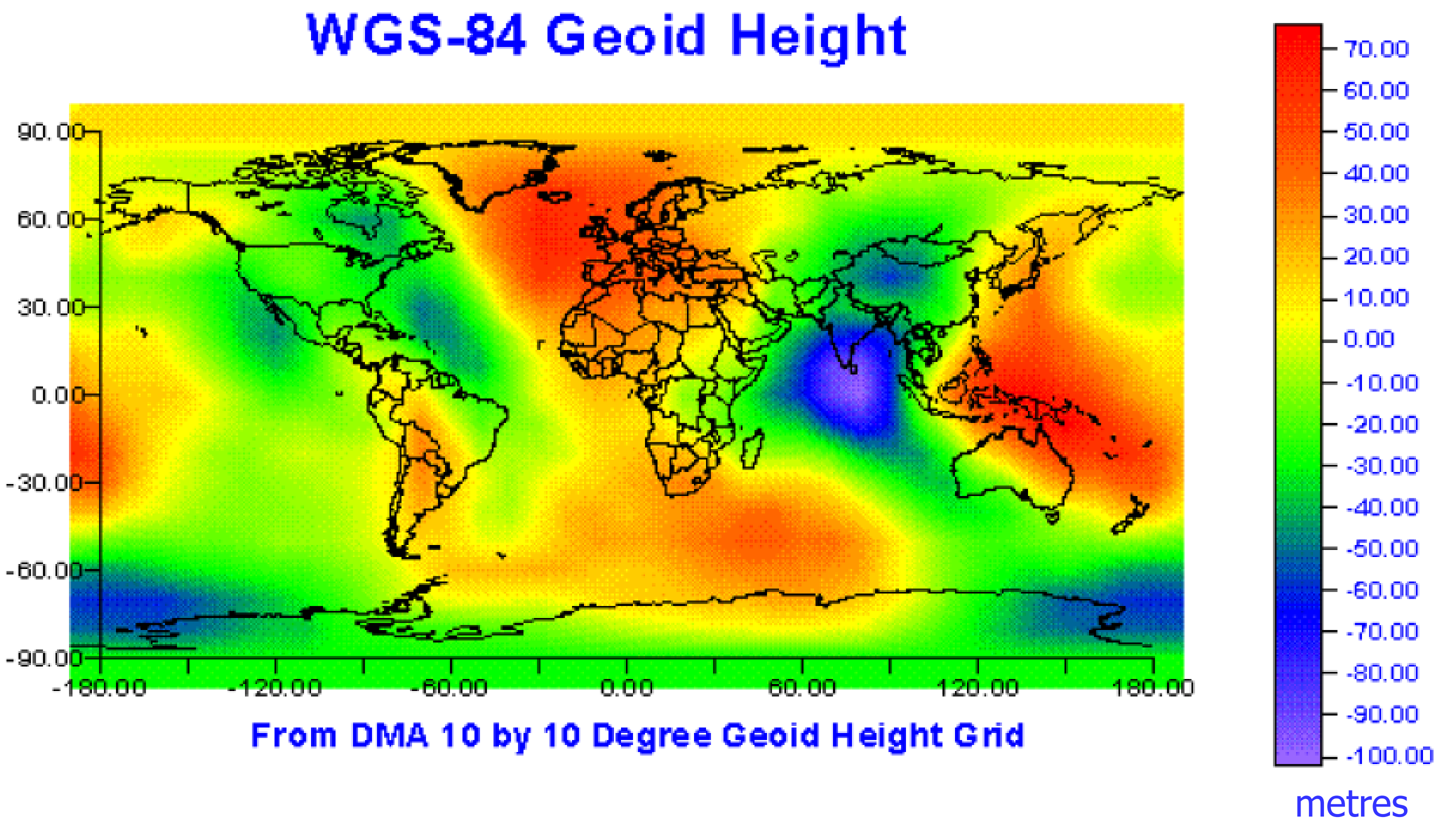
- **Geoidal height (N)** is the geoid-ellipsoid **separation**, measured along the normal to ellipsoid.
- ***Orthometric height* (H)** is the height relative to Geoid, measured along the plumb line.
- **Geodetic (ellipsoidal) Height: h= H+N.**



Source: GRACE mission (NASA)



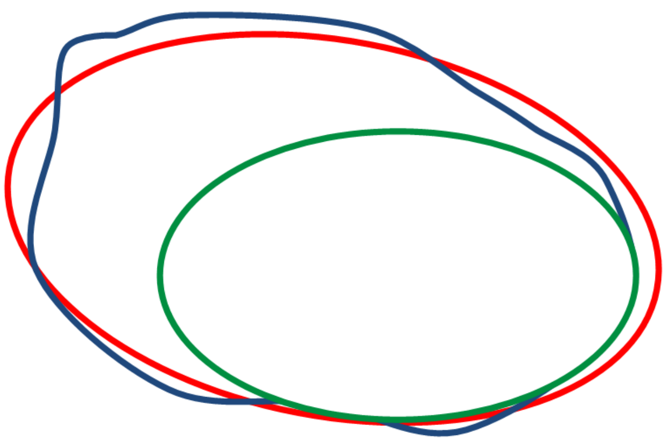
Vertical deviation less than 1-arc-minute


WGS-84 Geoid Height
90.00
60.00
30.00
0.00
-30.00
-60.00
-90.00
-180.00
-120.00
-60.00
0.00
60.00
120.00
180.00
From DMA 10 by 10 Degree Geoid Height Grid
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
-80.00
-90.00
-100.00
metres

2.3.4 Datum and Map Projections

- **A datum consist on:**
  - **An ellipsoid** relative to which the latitude and longitude points are defined, and
  - **A geoid** defining the surface of zero height**.**

- These ellipsoids are conventionally defined as fitting the geoid in the region of interest, without being necessarily geocentric or having their axes constrained to a given orientation.

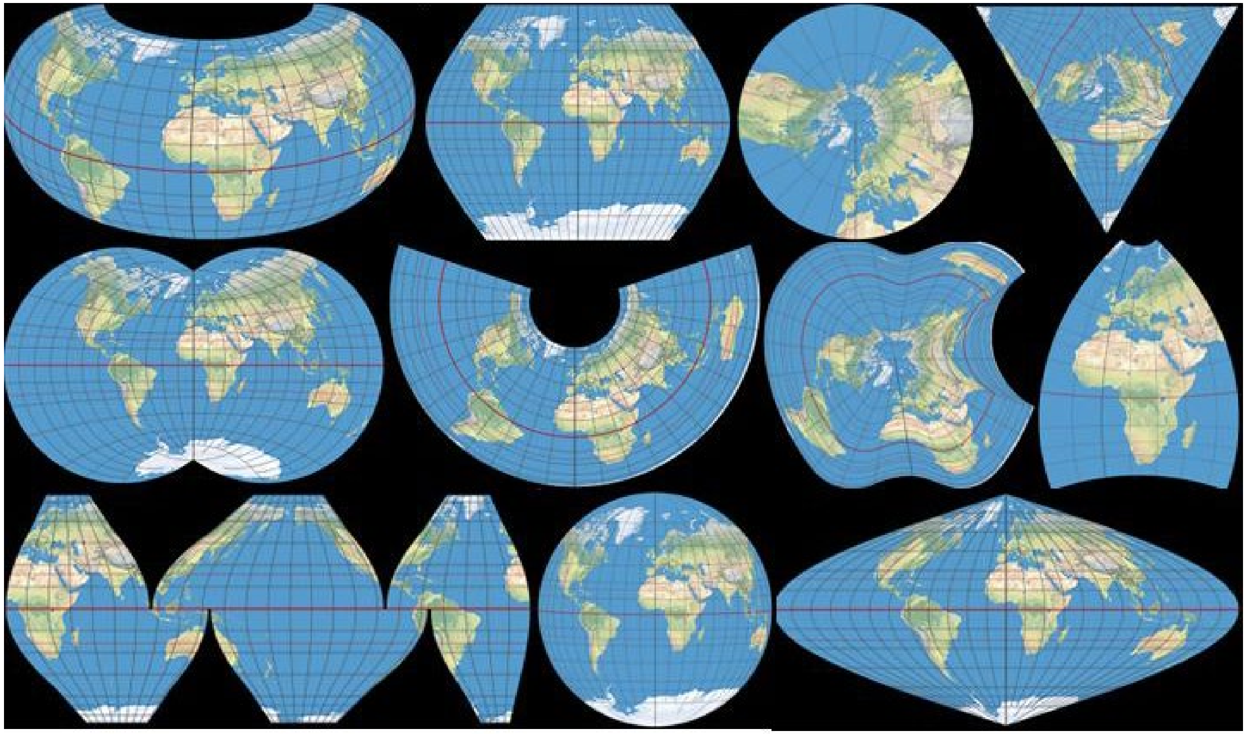


→A valuable contribution of **GPS** was to provide a **Global Reference Frame**, simplifying the mapping of Earth and unifying the diverse datums.

2.3.4 Datum and Map Projections

The ellipsoidal coordinates of the datum must then be mapped to plane coordinates using a proper projection to build a map.

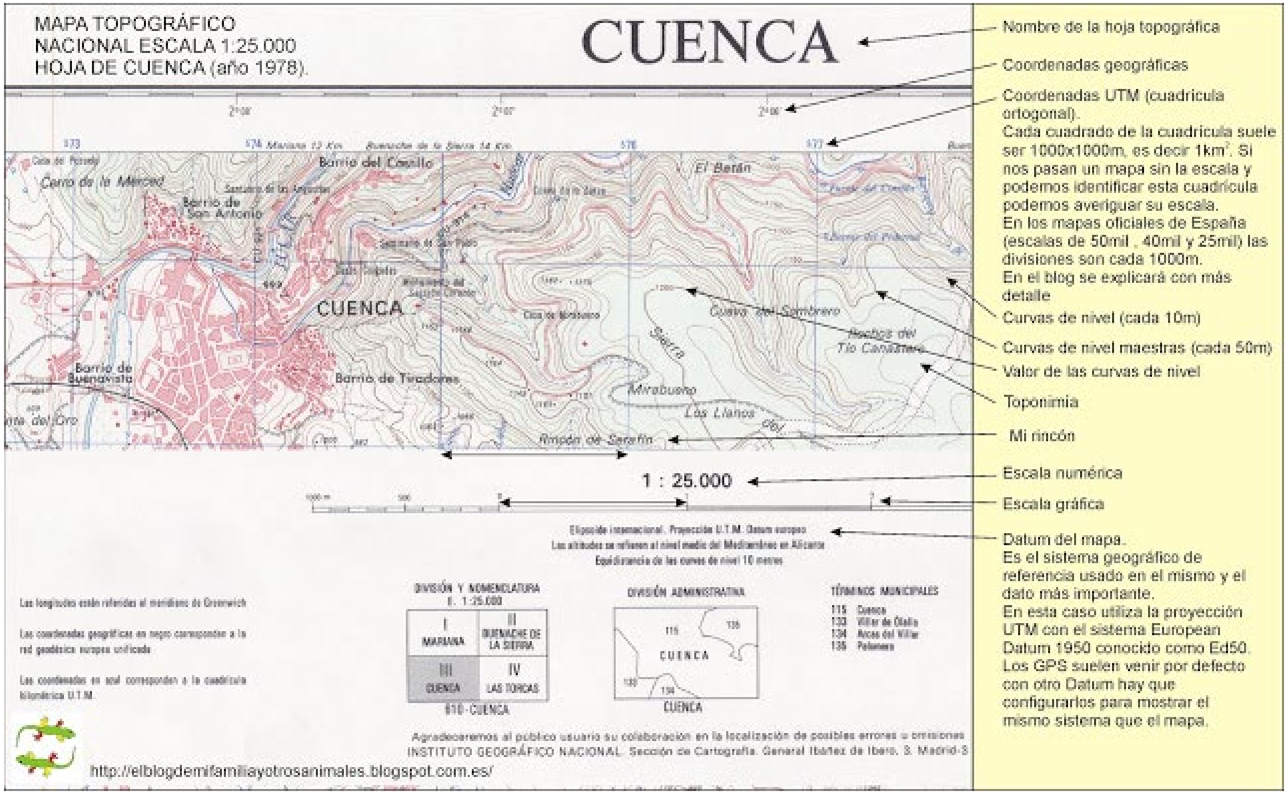
Different projections have been defined (preserving areas, angles, distances, etc.), but all of them introduce distortions due to the mapping of a curved surface to plain.



Source: http://www.mapthematics.com/ProjectionsList.php

The local maps edited by the official organisations are referenced to a given datum.

The coordinates expressed in one datum can be transformed into another with a seven-parameter transformation (i.e. a transformation in the space between two coordinate frames): $\mathbf{X}_{\mathrm{TRF2}} = \Delta\mathbf{X} + \alpha\,\mathbf{R}_1[\theta_1]\,\mathbf{R}_2[\theta_2]\,\mathbf{R}_3[\theta_3]\,\mathbf{X}_{\mathrm{TRF1}}$



➔ most of the commercial receivers incorporate the parameters for several official datums to map the WGS-84 coordinates or other GNSS systems, as well.

Contents

gAGE

2.4.1 GPS Reference Frame WGS-84

- **WGS 84** is a realization **Conventional Terrestrial Reference System CTRS** developed by the Defense Mapping Agency (DMA)
- The development of this global datum was essential to development of GPS.

  It comprises:
  - ✓ an ECEF Cartesian coordinate frame.
  - ✓ ellipsoid of revolution as a geometric model of the shape of Earth.
  - ✓ characterization of Earth's gravity field and geoid.
  - ✓ consistent set of fundamentals constants.

❖ Parameters of the WGS-84 ellipsoid (revised in 1997):

Ellipsoid		
Semi-major axis of the ellipse	a	6 378 137.0 m
Flattening factor	f	1/298.257 223 563
Earth's angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}$ rad/s
Gravitational constant	μ	$3\,986\,004.418 \cdot 10^{8}\ m^3/s^2$
Speed of light in vacuum	c	$2.997\,924\,58 \cdot 10^{8}$ m/s

2.4.1 GPS Reference Frame WGS-84

Comments:

- **The initial implementation** of WGS-84 was realised from **a set of more than a thousand terrestrial sites**, whose coordinates were derived from transit observations (with an **accuracy level of 1-2 m**, while the accuracy of the **ITRF reference stations is at the centimetre level**).

- **Successive refinements** (which also led to some adjustments of the fundamental constants), using more accurate coordinates of the Master Stations, approximate some ITRS realisations.

- For instance, realisations:
  - WGS-84(G730) and WGS-84(G873) correspond to ITRF92 and ITRF94, respectively.
  - **The refined frame WGS-84(G1150) was introduced in 2002, and agrees with ITRF2000 at the centimetre level**.

The GNSS satellites broadcast their orbits in its own (GPS, GLONASS, BeiDou, Galileo) Reference System.

2.4.1 GNSS Reference Frames

❖ Comparison of parameters of the different GNSS Reference Frames

Ellipsoid		GPS	GLO	GAL	BDS
Semi-major axis (m)	a	637813**7,000**	637813**6,000**	637813**7,000**	637813**7,000**
Semi-minor axis (m)	b	635675**2,314**	635675**1,362**	635675**2,314**	635675**2,314**
Flattening factor	f	1/298.257**223563**	1/298.257**839303**	1/298.257**222101**	1/298.257**222101**
Earth's angular velocity (rad/s)	ω_E	$7292115 \cdot 10^{-11}$	$7292115 \cdot 10^{-11}$	$7292115 \cdot 10^{-11}$	$7292115 \cdot 10^{-11}$
Gravitational constant (m^3/s^2)	μ	3986004,4**18** $\cdot 10^8$	3986004,4**00** $\cdot 10^8$	3986004,4**18** $\cdot 10^8$	3986004,4**18** $\cdot 10^8$
Speed of light in vacuum (m/s)	C	$2,99792458 \cdot 10^8$	$2,99792458 \cdot 10^8$	$2,99792458 \cdot 10^8$	$2,99792458 \cdot 10^8$

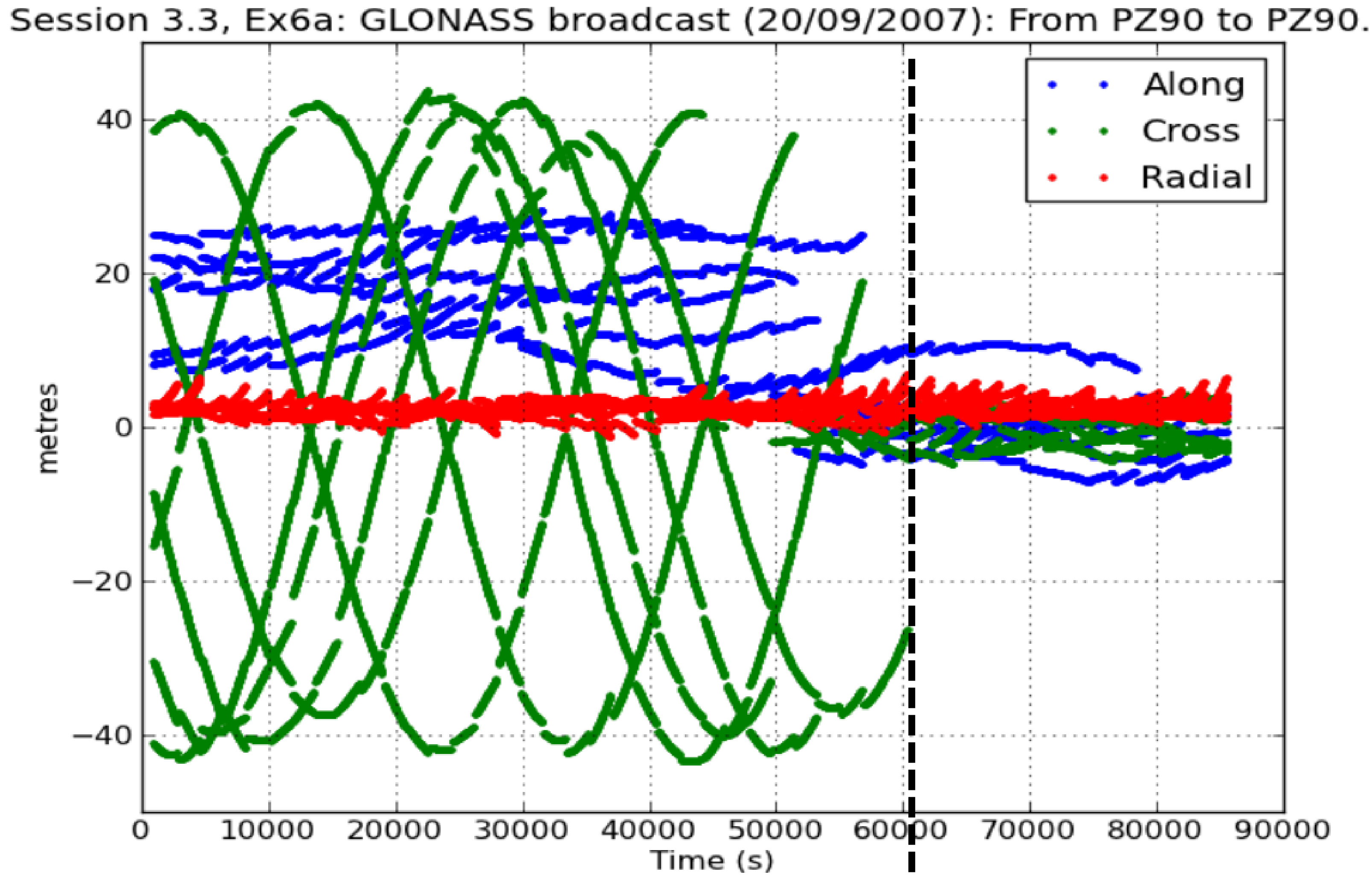
gAGE

2.4.2 GLONASS Reference Frame PZ-90 and PZ-90.02

❖ Ellipsoidal parameters of PZ.90 and PZ-90.02

Ellipsoid		
Semi-major axis of the ellipse	a	6 378 136.0 m
Flattening factor	f	1/298.257 839 303
Earth's angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}$ rad/s
Gravitational constant	μ	$3\,986\,004.4 \cdot 10^{8}$ m^3/s^2
Speed of light in a vacuum	c	$2.997\,924\,58 \cdot 10^{8}$ m/s
Second zonal harmonic coefficient	J_2^0	$1\,082\,625.75 \cdot 10^{-9}$

- According to the GLONASS modernisation plan, the ephemeris information implementing the PZ-90.02 reference system was **updated on** all operational GLONASS satellites from 12:00 to 17:00 UTC, **20 September 2007**.
- From this time on, the satellites have been broadcasting in PZ-90.02.
- The PZ90.02 reference frame is an updated version of PZ-90, the closest one to ITRF2000.



PZ-90 - ITRF2000

PZ-90.02 - ITRF2000

2.4.3 BeiDou Reference Frame CGCS2000

❖ Ellipsoidal parameters of CGCS2000

Ellipsoid		
Semi-major axis of the ellipse	a	6 378 137.0 m
Flattening factor	f	1/298.257 222 101
Earth's angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}$ rad/s
Gravitational constant	μ	$3\,986\,004.418 \cdot 10^{8}$ m^3/s^2
Speed of light in a vacuum	c	$2.997\,924\,58 \cdot 10^{8}$ m/s

CGCS2000 is referred to ITRF97 at the epoch of 2000.0.

- The reference frame of CGCS2000 currently consists of the national GPS control network 2000 and the national astro-geodetic network after combined adjustment with the GPS network.
- The GNSS Continuously Operating Reference Stations (CORS) network will be the main part of China's geodetic infrastructure and a key technique for maintaining CGCS2000.

2.4.4 Galileo Terrestrial Reference Frame GTRF

❖ Ellipsoidal parameters of GTRF

Ellipsoid		
Semi-major axis of the ellipse	a	6 378 137.0 m
Flattening factor	f	1/298.257 222 101
Earth's angular velocity	ω_E	$7\,292\,115.0 \cdot 10^{-11}$ rad/s
Gravitational constant	μ	$3\,986\,004.418 \cdot 10^{8}\ m^3/s^2$
Speed of light in a vacuum	c	$2.997\,924\,58 \cdot 10^{8}$ m/s

- The initial coordinates for the reference stations were provided using GPS observations, because the GTRF was already required by the time the first Galileo signals were emitted during the In-Orbit Validation (IOV) phase.
- Subsequent GTRF versions use both GPS and Galileo observations. Weekly solutions are performed for the long-term maintenance of the GTRF.
- **The GTRF must be compatible with the latest ITRF to within a precision level of 3 cm (2σ).**

Contents

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

3. Fundamentals of Time References

Accurate and well-defined **time references** and coordinate frames are essential in GNSSs, where **positions are computed from signal travel time measurements and** provided as a set of coordinates.

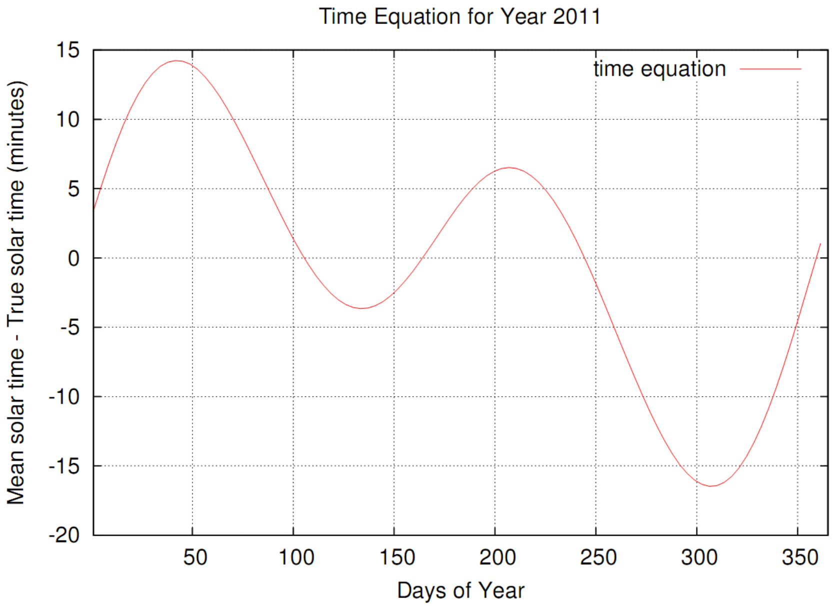
- Synchronization error of **1 μs** in a satellite clock will introduce an error of **300 m** in the pseudorange (apparent transit time of signal by the speed of light).
- Meter-level position estimates, requires clock **synchronization** among satellites maintained within a **few nanoseconds**.
- Several time references are currently in operation, based on different periodic processes associated with Earth's rotation, celestial mechanics or transitions between the energy levels in atomic oscillators.

Periodic process	Time
Earth's rotation	Universal Time (UT0, UT1, UT2) Greenwich Sidereal Time (Θ)
Earth's revolution	Terrestrial Dynamic Time (TDT) Barycentric Dynamic Time (TDB)
Atomic oscillators	International Atomic Time (TAI) Coordinated Universal Time (UTC) GNSS Reference Time

3.1. Earth's Rotation Times

Our time keeping was initially based on the **motion of the Sun**, but the way that this time flows is affected by two main causes:

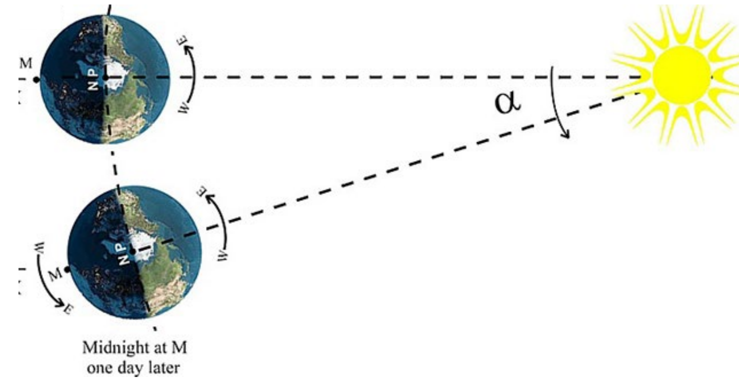
- **The orbit of Earth is elliptic**. Thus, according to Kepler's second law, the orbital speed is not constant.
- **Earth's axis of rotation is not perpendicular** to the plane of Earth's orbit around the Sun (the ecliptic), hence the angular rate is not constant. It moves fastest at the end of December and slowest in mid-September.



To get a more uniform time, a **fictitious mean Sun** is defined, which moves along the (celestial) equator of Earth with uniform speed (mean velocity of the actual Sun). Using this mean Sun, one defines **mean solar time** (as the hour angle of the centre of the mean Sun).

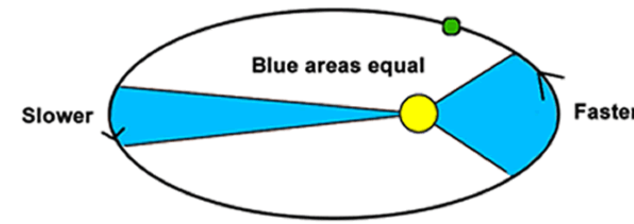
True solar day, the interval between two successive returns of the Sun to the local meridian.

Between 2 consecutive days, Earth moves over orbit by an amount α
Thence, next day the apparent sun, will appear in the meridian slightly later.

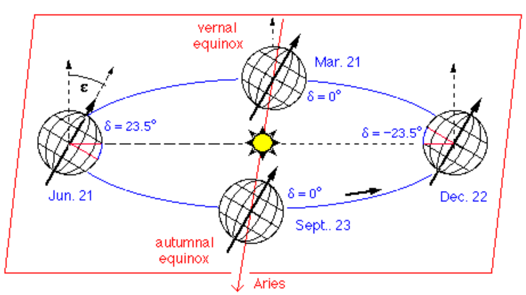


But, this amount α is not uniform because:

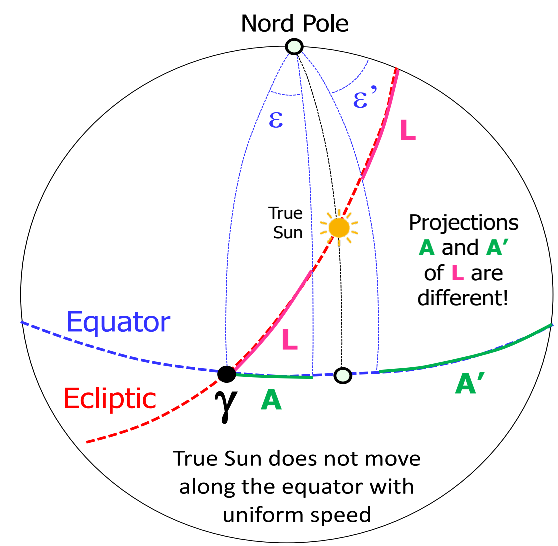
- **The orbit of Earth is elliptic**. Thus, according to Kepler's second law, the orbital speed is not constant.



- **Earth's axis of rotation is not perpendicular to the plane of Earth's orbit around the Sun (the ecliptic),** hence the apparent sun rate is not constant.



To fix ideas, let's assume that **L** is the (apparent) **ecliptic arc** travelled by Sun **in one day** (due to the orbital motion).



3.1. Earth's Rotation Times: Solar times

Mean solar time:
To get a more uniform time, a fictitious mean Sun is defined, which moves along the (celestial) equator of Earth with uniform speed (mean velocity of the actual Sun). **Using this mean Sun, one defines mean solar time** (as the hour angle of the centre of the mean Sun, i.e. begins at noon).

Civil time:
Is defined **from mean solar** time as mean solar time augmented in 12 hours, so that each day begins at midnight.
Civil time is local (i.e. associated with the local meridian).

Universal Time (UT)
In order to have a global time, i.e. not linked to the local meridian, Universal Time (UT) is defined as the **civil time at the Greenwich meridian**.

3.1. Earth’s Rotation Times: Solar times

Looking for a more stable time (UT0, UT1, UT2):
Earth's rotation rate is not uniform. It is affected by secular variations, mainly **due to tidal friction, seasonal changes and other irregular or random effects**, producing variations in Earth's distribution of mass and moment of inertia.
To deal which such effects, the following times (or refinements of UT) have been introduced:

UT0 is the **mean solar time at the Greenwich meridian** and is determined at a particular observatory by astronomical observations. As this time is **based on Earth's instantaneous rotation**, it is affected by both Earth's irregular spin rate and polar motion.

UT1 is obtained by **correcting UT0 for the effect of polar motion** on the location of the observing site (i.e. deducting the CTP pole). UT1 is the same around the world (i.e. it does not depend on the observatory's location).

UT2 is obtained **by removing periodic seasonal variations from UT1** time, but it is not uniform enough due to the other effects on Earth's rotation that still remain. Nowadays it is considered obsolete.

3.2. Atomic Times (TAI, UTC, GNSS times):

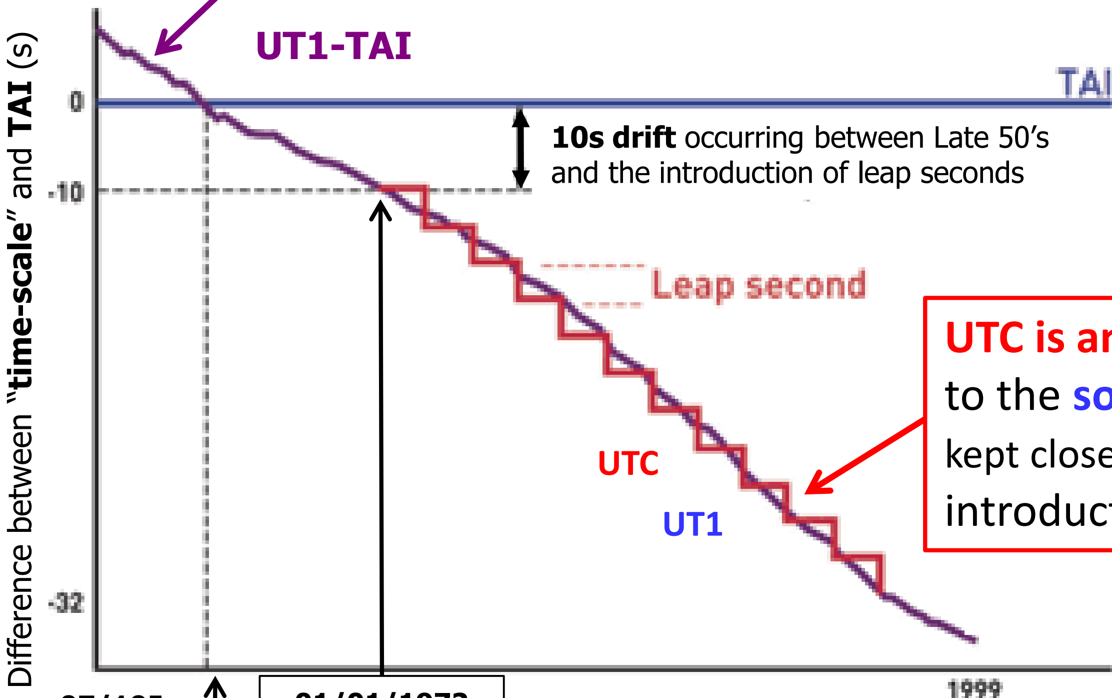
UT (UT0, UT1, UT2) is not completely uniform, so atomic time TAI was introduced to achieve a more uniform time scale.

International Atomic Time (TAI):
Was established as a reference time by the Bureau International de l'Heure. Its initial epoch was matched to the 0h0m0s of the **UT** scale of 1 January 1958, so the difference between TAI and UT2 was zero in this epoch.

The TAI second is 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.

Comments: TAI is obtained by the Bureau International des Poids et Mesures (BIPM) from about 250 Caesium clocks and hydrogen masers located in about 65 different laboratories, distributed around the world, and applying a set of algorithms to ensure a uniform time.
It is not determined in real time, but generated with a **delay of about 1/2 month**.

Earth's rotation is not uniform and **TAI and UT1 accumulate drift over time.**



UTC is an atomic time "adjusted" to the **solar time UT1** (i.e. always kept closer than 0.9s) by the introduction of "leap seconds".

07/195 Begin of the Atom Time

01/01/1972 UT1-TAI=10s Systems with Leap seconds introduced

01/01/1958 UT1=TAI

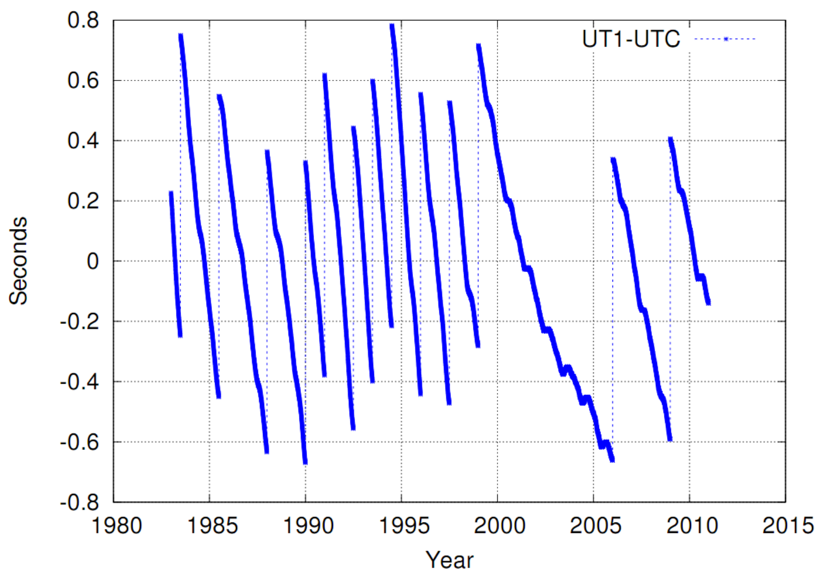
Source: http://www.cotsjournalonline.com/articles/view/100204

3.2. Atomic Times (TAI, UTC, GNSS times):

Coordinated Universal Time (UTC)

→ It is a compromise between TAI and UT1:

- **UTC is an atomic time** (and thence is as uniform as the TAI scale), but it is **always kept closer than 0.9 s with respect to UT1**, in order to follow the variations in Earth's rotation.
- This is accomplished by adding (or subtracting) a certain number of **leap seconds** to TAI: **UTC= TAI - # Leapseconds**.
- This number, which is refreshed periodically, is provided by the IERS.



<u>Real-time **estimates** of UTC (or TAI)</u> are computed and provided by different centres, such as UTC(USNO), from the United States Naval Observatory (USNO); UTC(NIST), from the National Institute of Standards and Technology (NIST); and UTC(SU) from Russia.

Official time is the one **used by all nations in the world**. It usually differs by an **<u>integer number of hours</u> with regard to UTC**. This difference is given by **time zones** and the proper <u>adjustments in summer and winter</u>.

3.2. Atomic Times (TAI, UTC, GNSS times):

GPS Time (GPST):

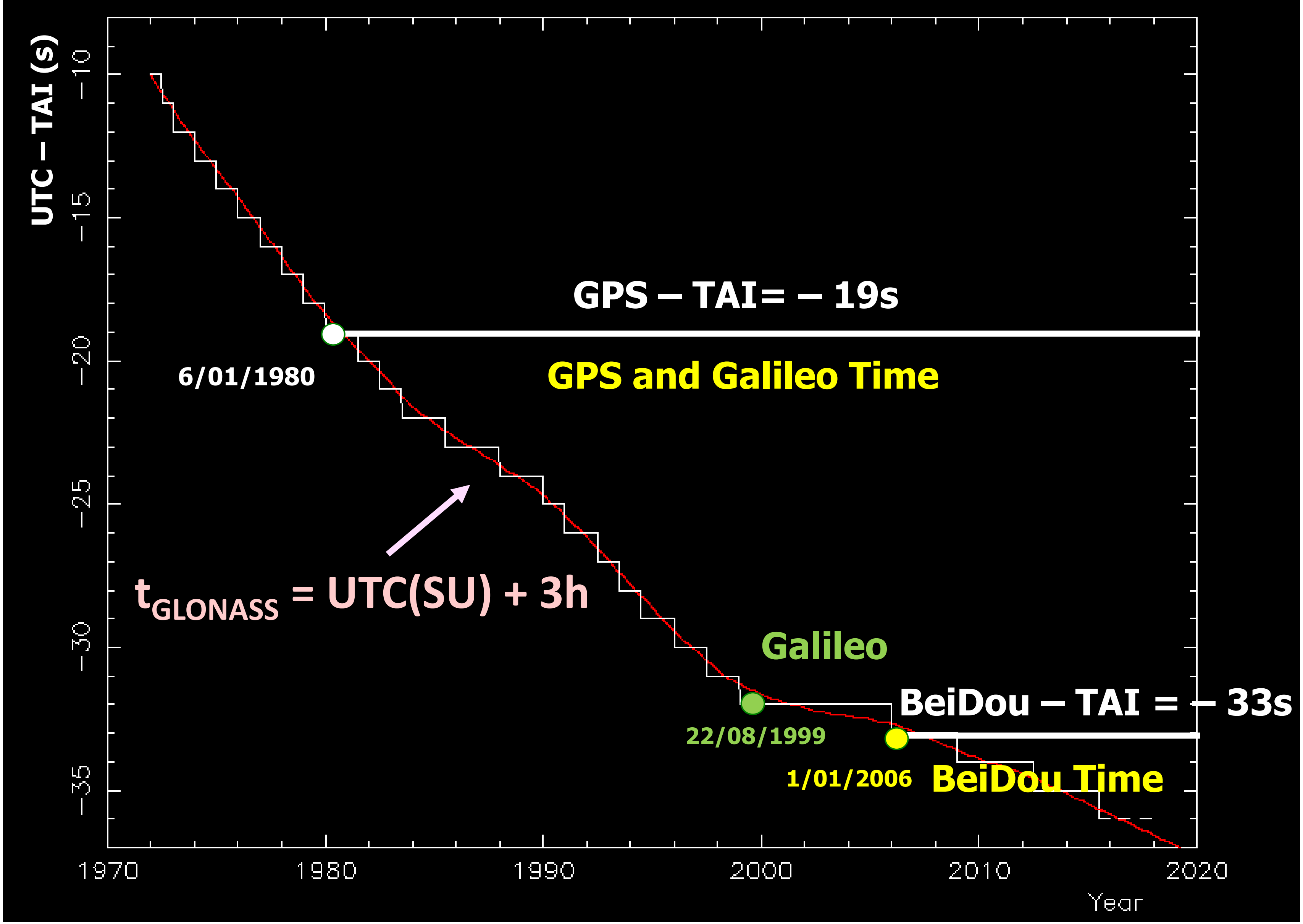
It is a continuous time scale (*no leap seconds*) defined by the GPS control segment on the basis of a set of atomic clocks at the Master Control Station and onboard the satellites.

- It starts at **0h UTC 6 January 1980**. At that epoch, the difference TAI-UTC was 19 s, i.e. **GPS-TAI= 19s**.
- GPST is synchronised with UTC(USNO) at the 1 ms level, module 1 second (actually kept within 25 ns).

Comments: GNSS satellites broadcast in their navigation messages the necessary parameters to compute real-time estimates of UTC.

For instance, these parameters allow a GPS receiver to calculate accurate estimates of UTC(USNO) at the level of 25 ns RMS, and remote clocks can be compared with an accuracy of 5 ns.

UT1 – TAI (Red line) and UTC – TAI (white line)



3.2. Atomic Times (TAI, UTC, GNSS times):

GLONASS Time (GLNT):

It is generated by the Glonass Central Synchroniser.

- The difference between UTC(SU) and GLNT should not exceed 1ms plus 3 h (i.e. $\mathbf{t_{GLONASS} = UTC(SU) + 3h - \tau}$, where $|\tau| < 1$ ms),
  ➔but is <u>typically better than 1 μs</u>.
- Note that, unlike GPS, Galileo or Beidou, the GLONASS time scale <u>*implements leap seconds, like UTC*</u>.

Galileo System Time (GST)

It is a continuous time scale maintained by the Galileo central segment and <u>synchronised to TAI with a nominal offset below 50 ns</u>.
The GST **start epoch is 0h UTC on Sunday, 22 August 1999**,
(but for "practical reasons" it uses the same reference epoch as GPS)

BeiDou Time (BDT)

It is a continuous time scale **starting at 0h UTC on 1 January 2006**, and is <u>synchronised to TAI within 100 ns</u>.

References

[RD-1] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 1: Fundamentals and Algorithms. ESA TM-23/1. ESA Communications, May 2013.

[RD-2] J. Sanz Subirana, J.M. Juan Zornoza, M. Hernández-Pajares, GNSS Data processing. Volume 2: Laboratory Exercises. ESA TM-23/2. ESA Communications, May 2013.

[RD-3] Pratap Misra, Per Enge. Global Positioning System. Signals, Measurements, and Performance. Ganga –Jamuna Press, 2004.

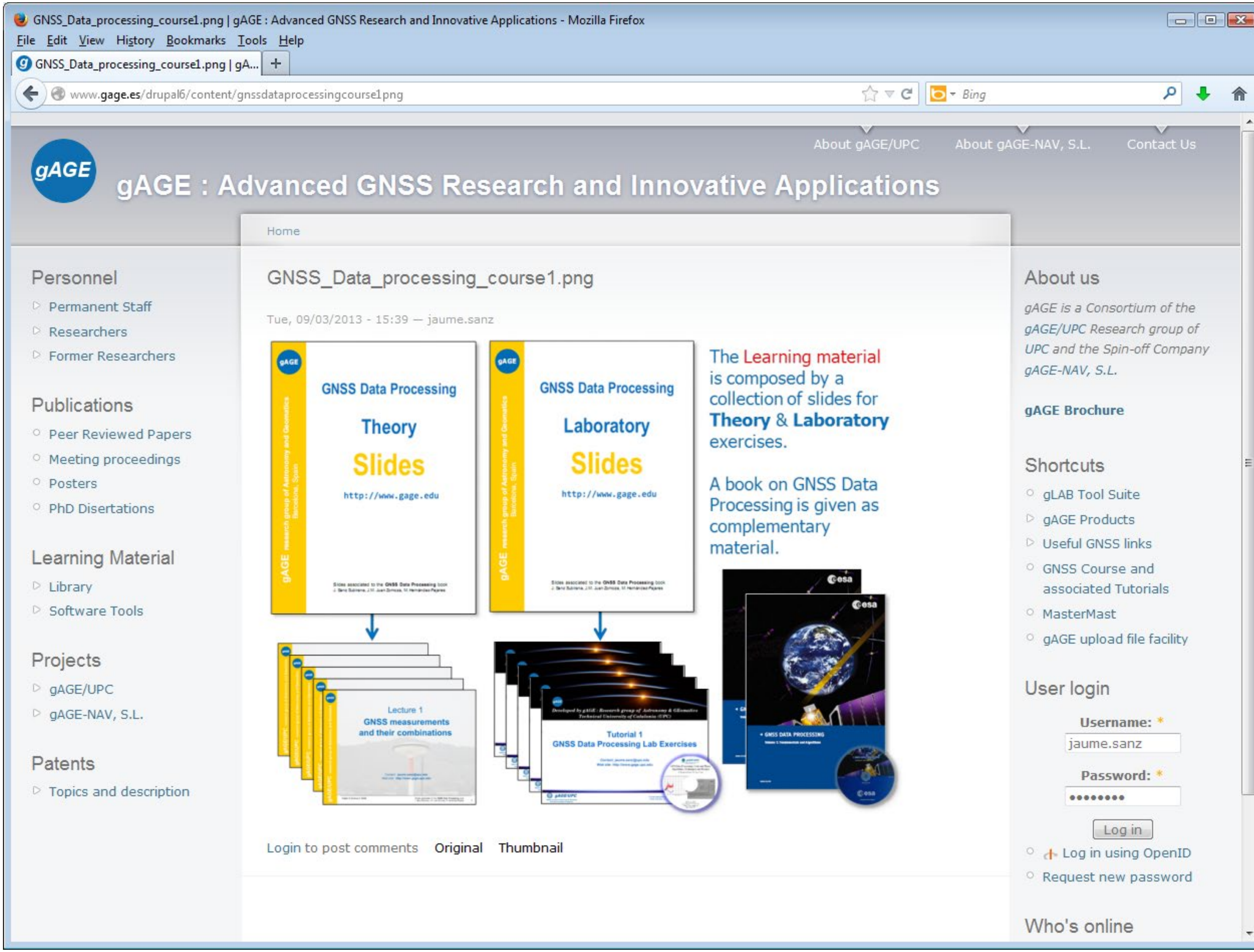
[RD-4] B. Hofmann-Wellenhof et al. GPS, Theory and Practice. Springer-Verlag. Wien, New York, 1994.

[RD-5] B. W. Parkinson and J.J. Spilker. Global Positioning System: Theory and Applications, Vol1 and Vol2. Progress in Astronautics and Aeronautics, Volume 164, Cambridge, Massachusetts, US.

[RD-6] ESA/JRC International Summer School on GNSS 2015. Presentations Booklet. Barcelona, Spain. August 31st to September 10th 2015.

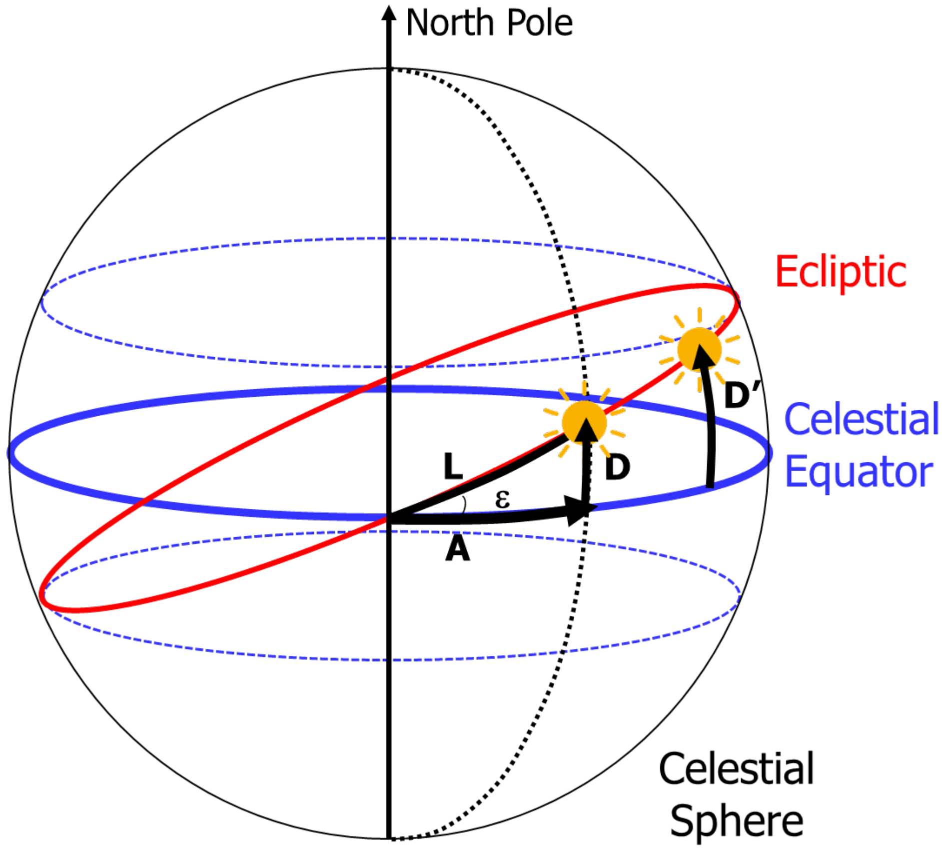
Thank you

gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

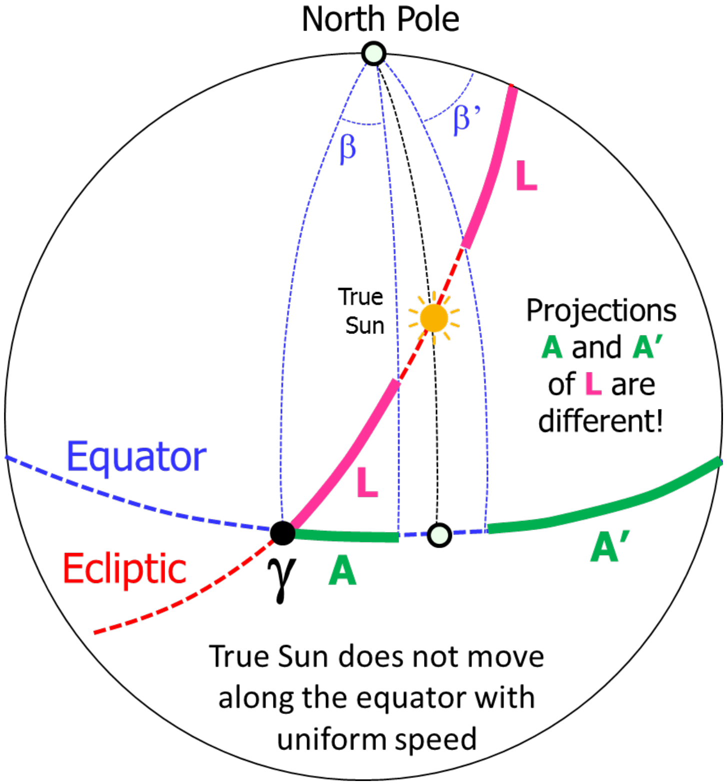


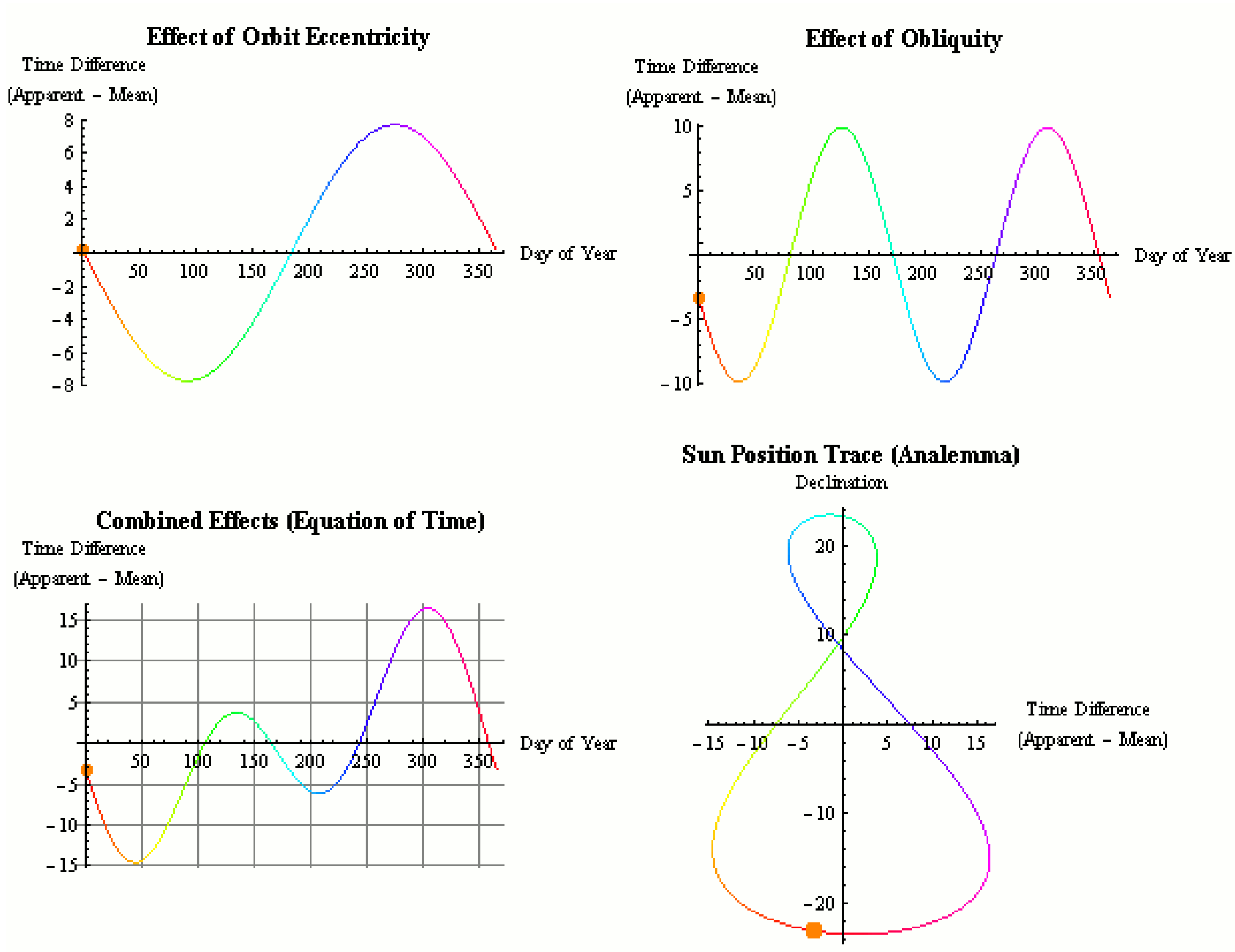
GNSS Data Processing, Vol. 1: Fundamentals and Algorithms.
GNSS Data Processing, Vol. 2: Laboratory exercises.

Backup slides



$$\cos(A) = \frac{\cos(L)}{\cos(D)}$$

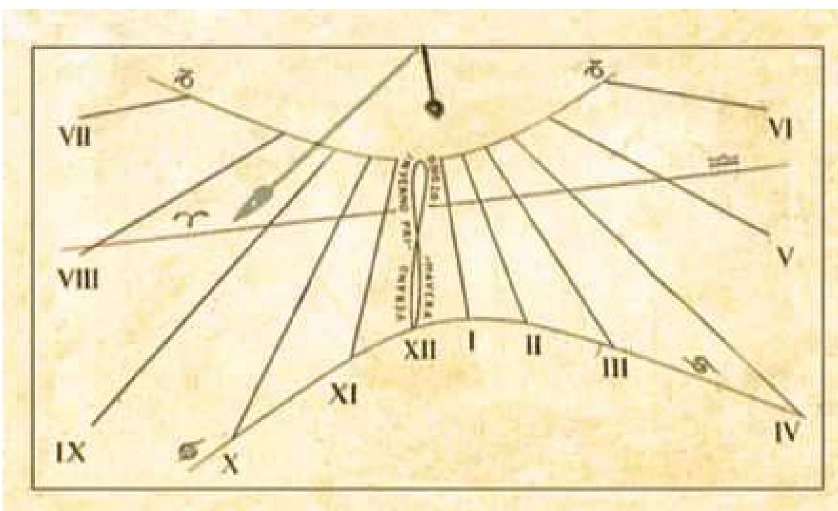


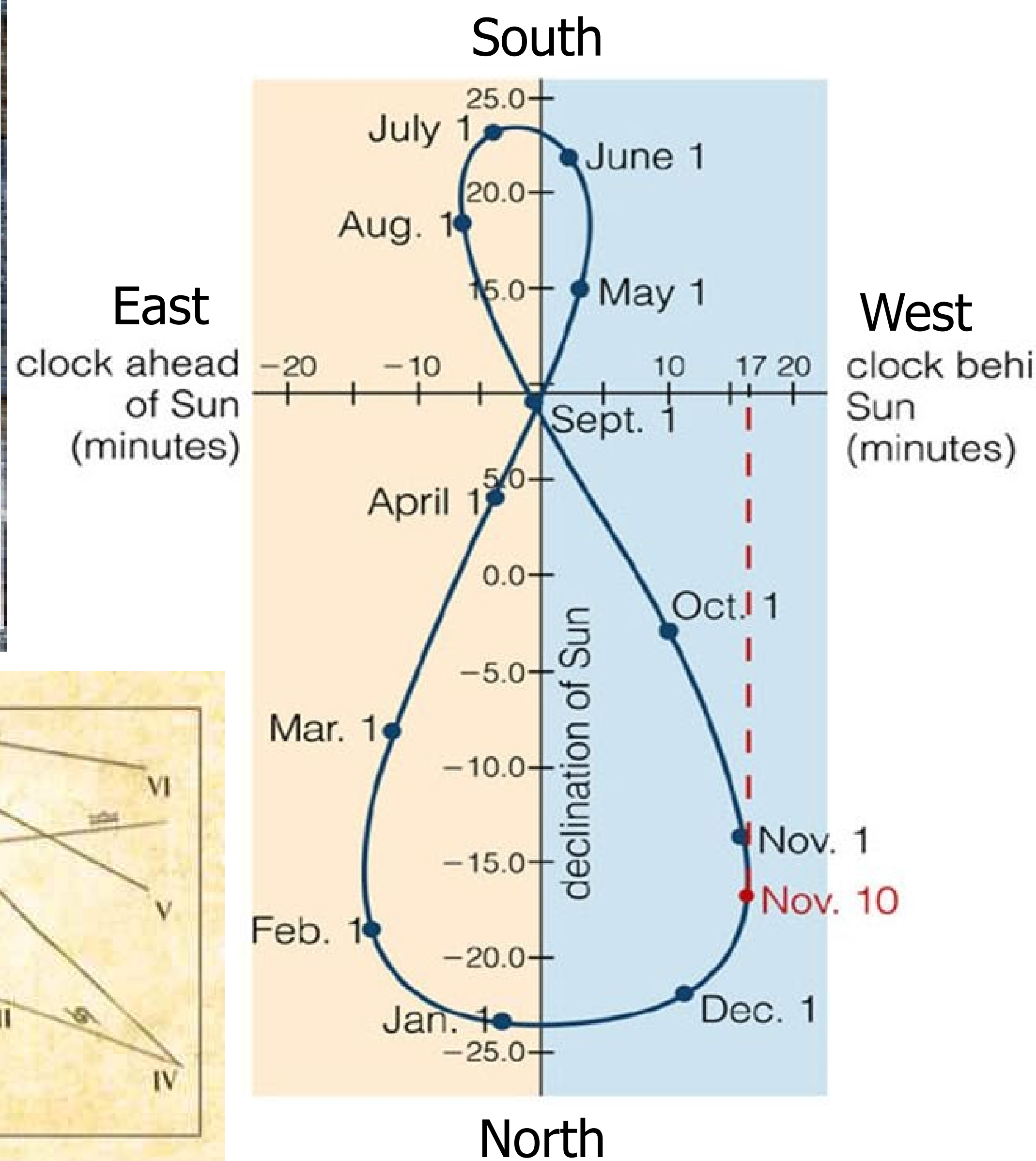


Source https://en.wikipedia.org/wiki/Equation_of_time

gAGE
gAGE/UPC research group of Astronomy and Geomatics
BarcelonaTECH, Spain

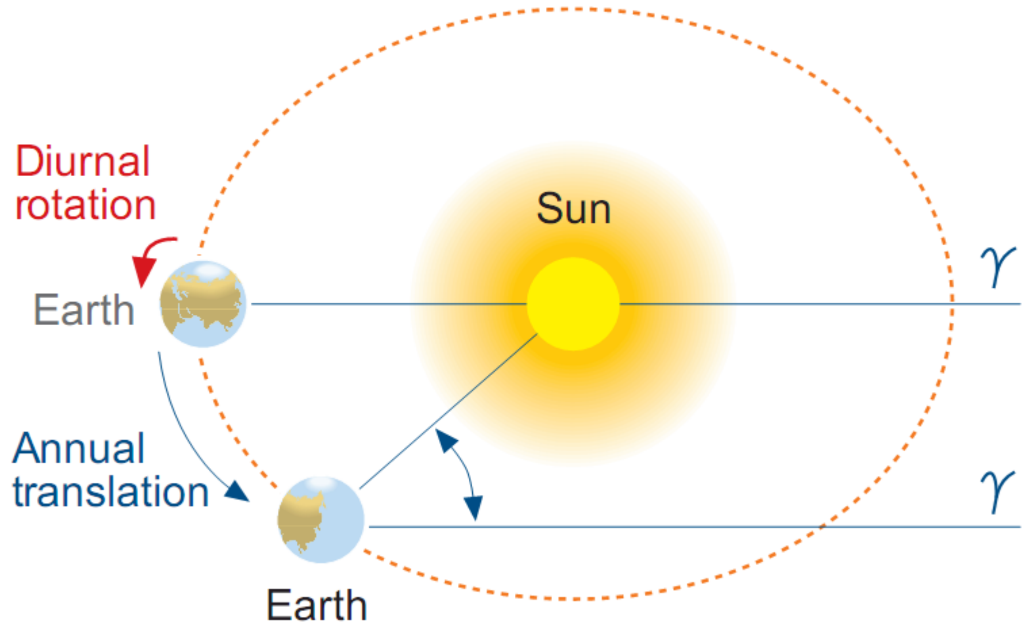
Stylet shadow at 12h mean time





3.3. Annex: Earth's Rotation Times: Sidereal time

Sidereal time uses the Vernal Equinox (the Aries point) as a reference.



After one year, the directions of the Sun and Aries coincide again, but the number of laps relative to the Sun (solar days) is one less than those relative to Aries (sidereal days).

$$\frac{24\text{h}}{365.2422} = 3^{\text{m}}56^{\text{s}}$$

Thus, a sidereal day is shorter than a solar day for about $3^{\text{m}}\,56^{\text{s}}$.