Reference Systems for GNSS Users

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Present day observation techniques - VLBI and GNSS

In 2020 about 100 or slightly more GNSS satellites will be available to be utilized for ERP determination

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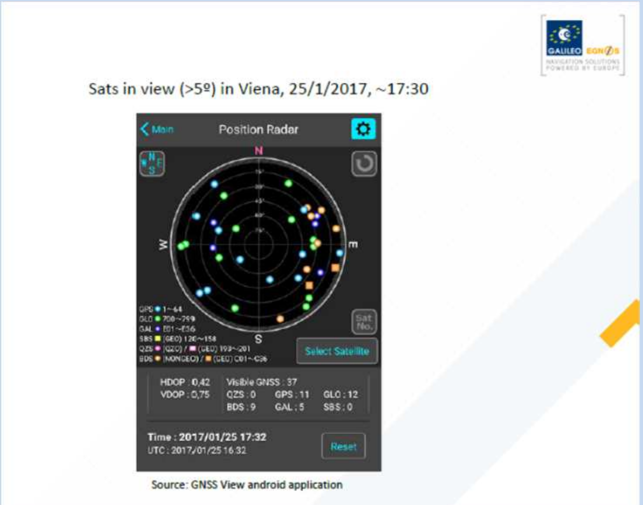
GNSS View: GNSS satellites visible for mobile phone at Vienna airport (25.1.2017)



Precise Orbit Determination +
Precise Point Positioning

request

accurate + stable Time Scales

\+

consistent Spatial Coordinate Systems

\+

adequately precise Transformation Models

Why ?

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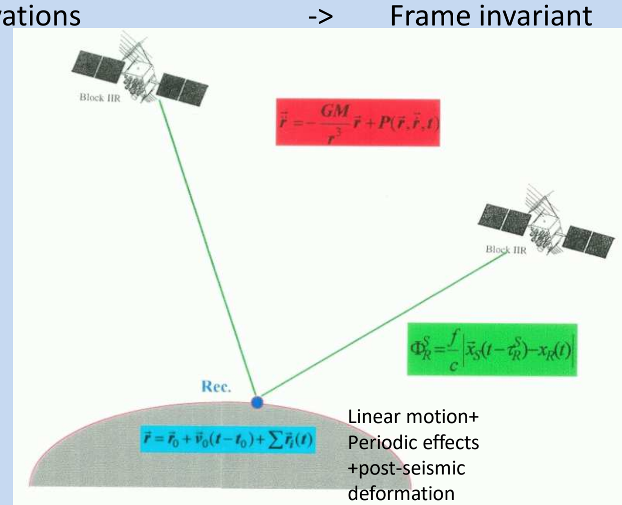
Introduction: Relevant Reference Systems

Satellite Orbit Determination	->	Quasi-Inertial Frame
Site Positions	->	Earth-Fixed Frame
Observations	->	Frame invariant



Agenda

- Introduction
- Time Scales
- Global Spatial Reference Systems
- Broadcast Frames
- Continental/ Regional Spatial Reference Systems
- Satellite specific Frame(s)
- Sun-refered Frame

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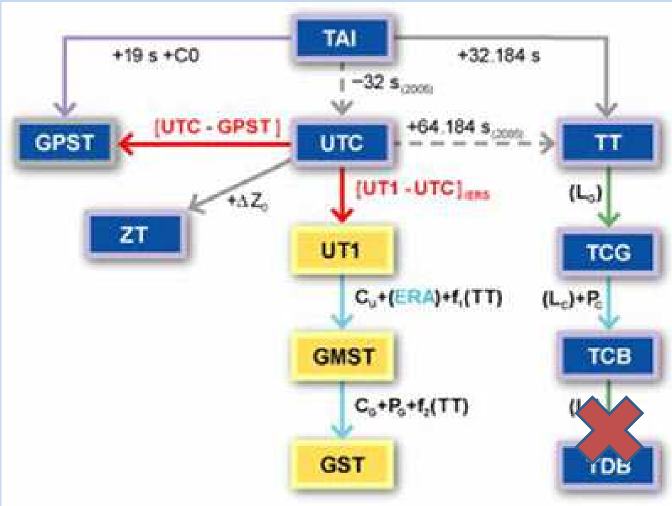
Physical Time Scales (Atomic Times/ blue) and Dynamic Time Scales (Earth Rotation/yellow)



Time Scales

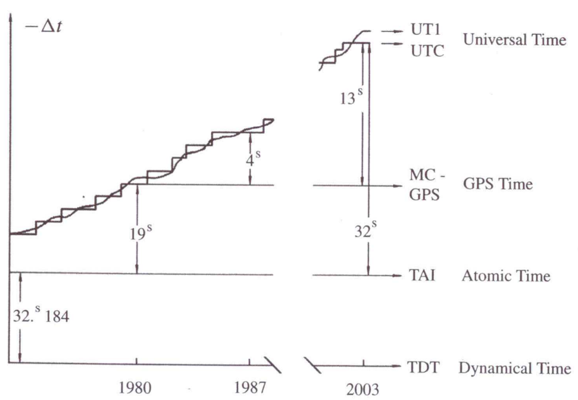


Figure 2.14. Time scales in satellite geodesy

Source: Seeber,2003

http://www.leapsecond.com/java/gpsclock.htm

GPST-UTC = 14 s (1.1.2006)

GPST-UTC = 15 s (1.1.2009)

GPST-UTC = 16 s (1.7.2012)

GPST-UTC = 17 s (1.7.2015)

GPST-UTC = 18 s (1.1.2017)

GNSS Satellite Time Systems

GPS- Time : TAI – 19 s

GLONASS Time : UTC + 3h

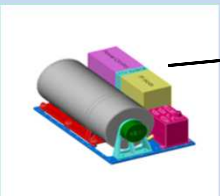
Galileo System Time : TAI – 19 s

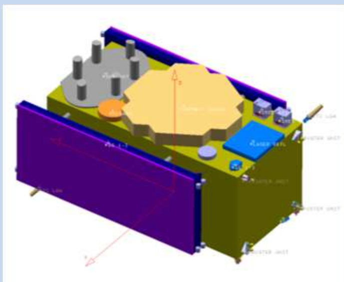
Beidou Time : TAI – 33 s

GALILEO

On-board Atomic Clocks

Passive Hydrogen Maser
18 Kg mass
70 W power





Rubidium Atomic Frequency Standard
3.3 Kg mass
30 W power

Navigation P/L:
130 Kg / 900 W

Types of Atomic Clocks

Rubidium Clock
- Cheaper and Smaller
- Better short-term stability (European RAFS s=5.0*10^{-14} at 10000 sec)
- Subject to larger frequency variation caused by environment conditions

H-Maser Clock
- outstanding short-term and long term frequency stability (10^{-15})
- frequency drift

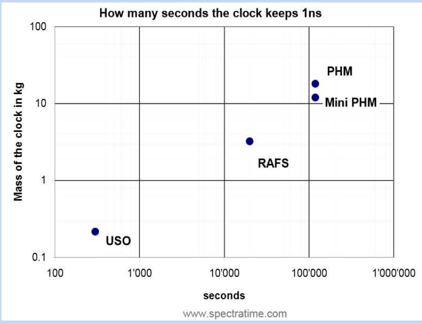
Caesium Clock
- Better long-term stability (10^{-14})
- shorter life time
- not used in Galileo

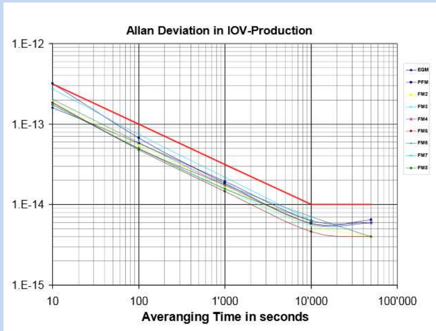
Future of clock-stability

Clock stability is related to the resonance frequency of the clock

GALILEO Hydrogen Maser

Frequency stability of Galileo –hydrogen maser better than 10 E-14
Resonance frequency 1.4 GHZ

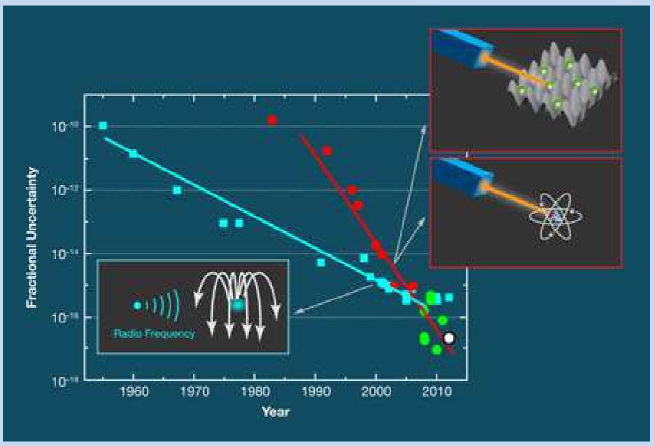




Graphics – Source : Spectra Time Company (2009)

Optical clocks

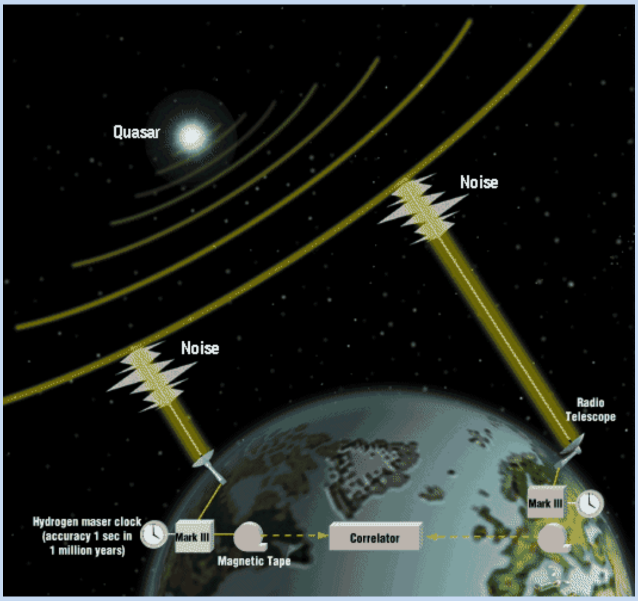
Laser clocks -> resonace frequency : 600 Tera Hz



Frequency stability beter than 10 E-17

- Introduction
- Time Scales
- **Global Spatial Reference Systems**
- Broadcast Frames
- Continental/ Regional Spatial Reference Systems
- Satellite specific Frame
- Sun-refered Frame

Celestial Inertial System (Realized by VLBI -> ICRF)



History of astrometry

130 BC	Hipparchus	precession	50 asec/yr
1718	Halley	proper motions	1 asec/yr
1729	Bradley	annual aberration	20 asec
1730	Bradley	18.6 yr nutation	9 asec
1838	Bessel	parallax	~asec
1930s	Jansky, Reber	radio astronomy	
1960s	several groups	VLBI invented	
1970s		VLBI	sub asec
1980s	"		few masec
1990s	"		< masec
2000s	"		100 μasec
2010s	Gaia	optical astrometry	70 μasec for V_{mag} 18 quasar
2010s	ICRF3	VLBI	20-70 μasec

modified from Chris Jacobs (2013)

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Why VLBI for celestial reference frames?

- Point source at infinity as a direction reference
- Advantage: sources do not move
  - billions of light years away
- But price to be paid
  - very weak sources 1 Jy = 10^{-26} Watt/m^2/Hz
  - needs lots of sq. meters 10 to 100 m antennas
  - lots of bandwidth 0.1 to 4 Gbps
  - low system temperature T_{sys} = 20 - 40 Kelvin

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How are sources and positions found?

- Single dish surveys: a (big) single radio telescope sweeps the sky to search for point-like sources
  - 10 arcsec positions
- Connected element array surveys such as the Very Large Array (VLA) or ATCA
  - positions improved to 10s of mas
- VLBI
  - mas positions

http://www.narrabri.atnf.csiro.au/public/

International Celestial Reference System

- ICRS defines barycentric coordinate system (quasi-inertial system)
  - origin in the barycentre (centre of mass of the solar system)
  - orientation defined by sources (old: axes defined by mean equinox and mean equator at J2000.0)
  - (in agreement with the optical FK5 and the corresponding error - 50 mas)
- "quasi-inertial" with practically no accelerations
  - but galactic rotation

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International Celestial Reference Frame

- ICRF is the realisation of the ICRS by positions of compact extragalactic radio sources
- IAU is the international governing body for the CRF
  - ICRF1 accepted as fundamental CRF effective 1 Jan 1998
  - ICRF2 accepted as fundamental CRF effective 1 Jan 2010
- Ongoing work towards ICRF3
  - IAU WG on ICRF3 (Chair: Chris Jacobs, JPL; Patrick Charlot)

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ICRF2

- Source positions from gsf2008a solution
- 3414 sources
- 295 defining sources
- Different number of observations
  - 1966 sources observed in 1 session
  - 2197 sources only observed in VLBI Calibrator Survey (VCS) sessions
- Noise floor of ICRF2 at 40 µas (significantly better than ICRF1)

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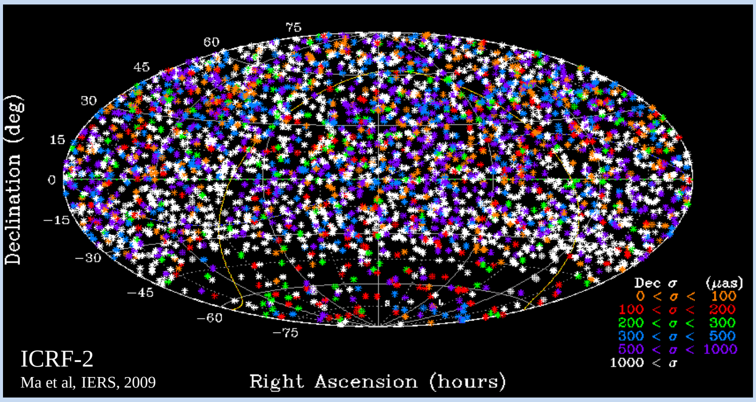
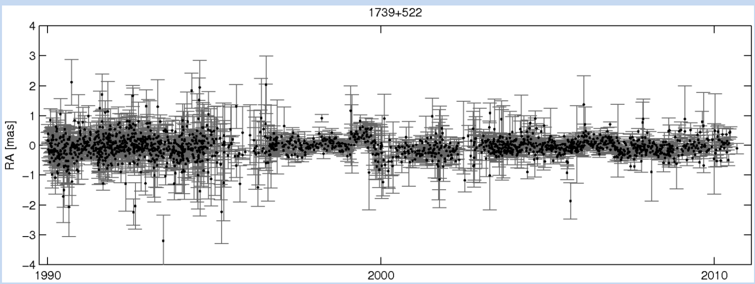
ICRF2



3414 sources in ICRF2: huge improvement compared to 608 sources in ICRF1
about 2200 single sessions survey sources (VLBA Calibrator Survey)
Deficiency: ICRF2 is sparse south of about -40 deg

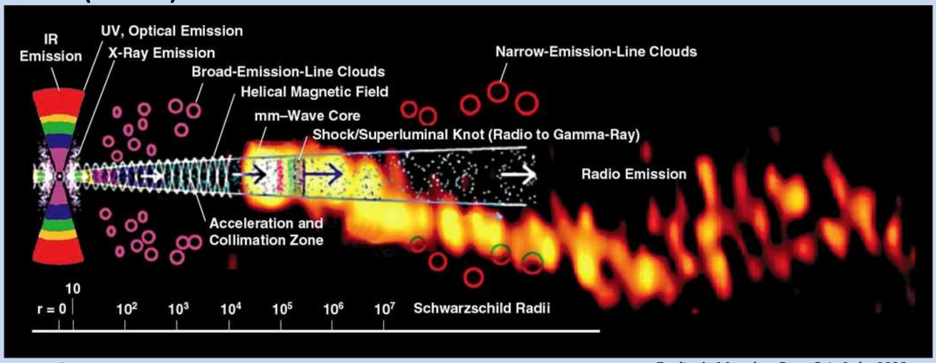
ICRF2

- 39 special handling sources in ICRF2
  - positions estimated once per session
  - treatment of special handling sources as global parameters could distort reference frames



Core shift

- Wavelength dependent shift in radio centroid (core)

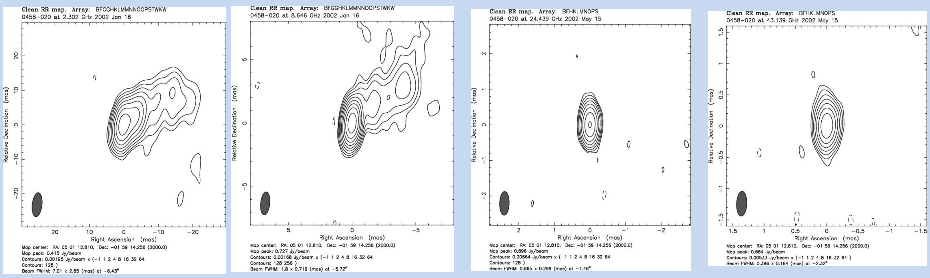


R~0.1-1 μas 1mas

Credit: A. Marscher, Proc. Sci., Italy, 2006.
Overlay image: Krichbaum, et al, IRAM, 1999.
Montage: Wehrle et al, ASTRO-2010, no. 310.

Source structure

- Sources become better ----->>>



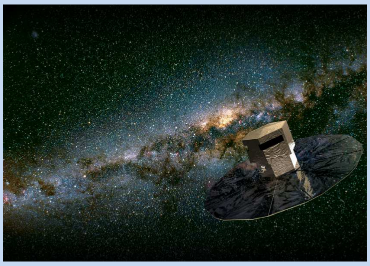
S-band	X-band	K-band	Q-band
2.3 GHz	8.6 GHz	24 GHz	43 GHz
13.6cm	3.6cm	1.2cm	0.7cm

(c) Charlot

Towards ICRF3

- ICRF3 expected for 2018 (from VLBI)
  - with contribution from TU Wien
- Then, optical realisations expected (GAIA)
- Optical catalogues will have to be linked to radio catalogues

launched fall 2013



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Relation: Celestial (Inertial) – Terrestrial System

Earth orientation parameters

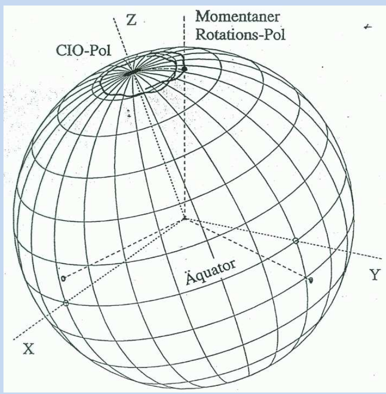
are defined as rotation angles, which connect

the Terrestrial co-rotating reference system
with the Celestial inertial system
by means of the relationship

$$r_c(t) = P\ N\ U\ X\ Y\ r_t(t).$$

P…….Precession
U……Rotation (Parameter: UT1-UTC)
X,Y…Polar motion (Parameter: Pole coordinates x,y)
N……Nutation (Parameter: Nutation offset Δδε,Δδψ)

These 5 Earth orientation parameters are linearly dependent (just 3 rotation angles theoretically independent)



Equinox-Transformation Model -> distinguishes to new CIO method (non-rotating origin) mainly by the argument of U matrix

The ITRF is defined

Origin : Center of Mass of the Earth

Scale: SI Meter / based on SI second

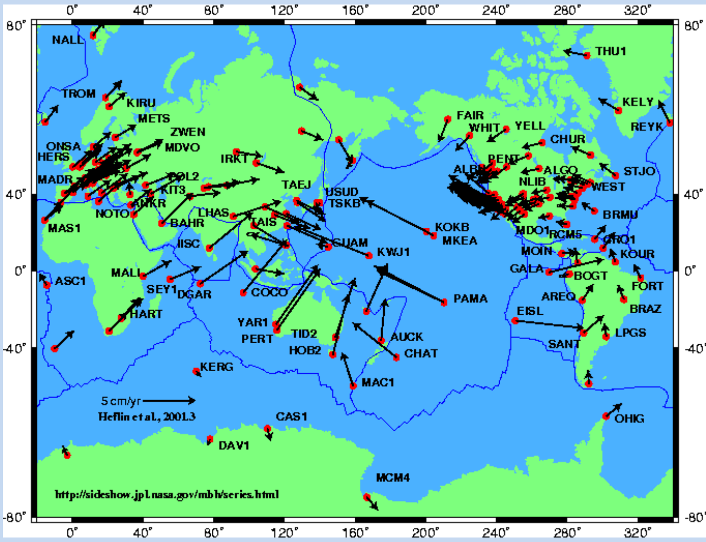
Orientation: BIH 1984; no-net rotation condition =
Orientation of the reference system has no residual global rotation

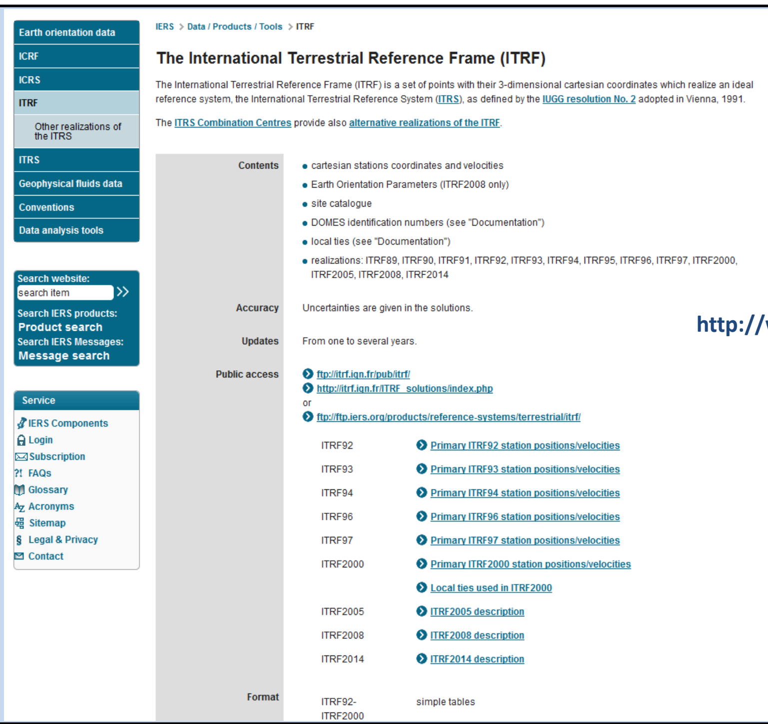
Realization of the ITRS = ITRF

ITRF (International Terrestrial Reference Frame): more than 300 global stations; Coordinate accuracy better than 5mm; plate-motion causes coordinate changes up to 8cm /year
most recent realization: ITRF2014 (T=2010.0)

ITRF 2014 models linear motion + postseismic deformations
(no periodic signals)

Plate motion





IERS > Data / Products / Tools > ITRF

Earth orientation data
ICRF
ICRS
ITRF
Other realizations of the ITRS
ITRS
Geophysical fluids data
Conventions
Data analysis tools

Search website:
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The International Terrestrial Reference Frame (ITRF)

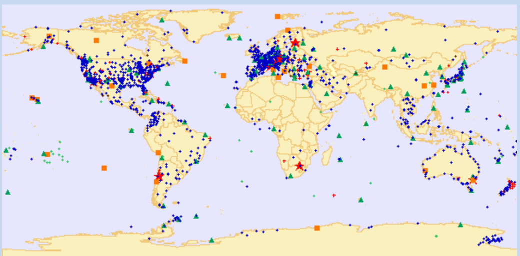
The International Terrestrial Reference Frame (ITRF) is a set of points with their 3-dimensional cartesian coordinates which realize an ideal reference system, the International Terrestrial Reference System (ITRS), as defined by the IUGG resolution No. 2 adopted in Vienna, 1991.

The ITRS Combination Centres provide also alternative realizations of the ITRF.

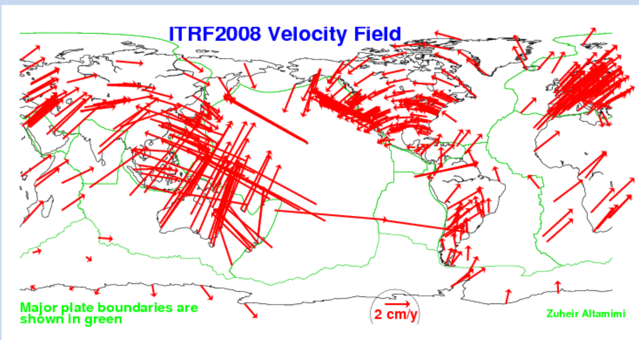
Contents	• cartesian stations coordinates and velocities • Earth Orientation Parameters (ITRF2008 only) • site catalogue • DOMES identification numbers (see "Documentation") • local ties (see "Documentation") • realizations: ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF95, ITRF96, ITRF97, ITRF2000, ITRF2005, ITRF2008, ITRF2014
Accuracy	Uncertainties are given in the solutions.
Updates	From one to several years.
Public access	ftp://itrf.ign.fr/pub/itrf/ http://itrf.ign.fr/ITRF_solutions/index.php or ftp://ftp.iers.org/products/reference-systems/terrestrial/itrf/
	ITRF92 — Primary ITRF92 station positions/velocities ITRF93 — Primary ITRF93 station positions/velocities ITRF94 — Primary ITRF94 station positions/velocities ITRF96 — Primary ITRF96 station positions/velocities ITRF97 — Primary ITRF97 station positions/velocities ITRF2000 — Primary ITRF2000 station positions/velocities Local ties used in ITRF2000 ITRF2005 — ITRF2005 description ITRF2008 — ITRF2008 description ITRF2014 — ITRF2014 description
Format	ITRF92-ITRF2000 — simple tables

http://www.iers.org/

ITRF2008 Stationen



http://itrf.ensg.ign.fr/



Transformation parameters between ITRF frames

From	To	$T_1\|\dot{T}_1$ (cm) (cm/y)	$T_2\|\dot{T}_2$ (cm) (cm/y)	$T_3\|\dot{T}_3$ (cm) (cm/y)	$R_1\|\dot{R}_1$ (0.001") (0.001"/y)	$R_2\|\dot{R}_2$ (0.001") (0.001"/y)	$R_3\|\dot{R}_3$ (0.001") (0.001"/y)	$D\|\dot{D}$ (10^{-8}) (10^{-8}/y)	t_0
ITRF92	ITRF93	- 0.2 - 0.29	- 0.7 +0.04	- 0.7 +0.08	- 0.39 - 0.11	+0.80 - 0.19	- 0.96 +0.05	+0.12 0.0	1988
ITRF93	ITRF94	- 0.6 0.29	+0.5 - 0.04	+1.5 - 0.08	+0.39 +0.11	- 0.80 +0.19	+0.96 - 0.05	- 0.04 0.0	1988
ITRF94	ITRF96	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	1997
ITRF96	ITRF97	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	1997

Table: Transformation parameters among ITRF frames for use with the **7/14-parameter Helmert model**

Transformation parameters between ITRF frames

From	To	$T_1\|\dot{T}_1$ (cm) (cm/y)	$T_2\|\dot{T}_2$ (cm) (cm/y)	$T_3\|\dot{T}_3$ (cm) (cm/y)	$R_1\|\dot{R}_1$ (0.001") (0.001"/y)	$R_2\|\dot{R}_2$ (0.001") (0.001"/y)	$R_3\|\dot{R}_3$ (0.001") (0.001"/y)	$D\|\dot{D}$ (10^{-8}) (10^{-8}/y)	t_0
ITRF2000	ITRF2005	- 0.01 +0.02	+0.08 - 0.01	+0.58 +0.18	0.0 0.0	0.0 0.0	0.0 0.0	- 0.040 - 0.008	2000
ITRF2005	ITRF2008	+0.05 - 0.03	+0.09 0.00	+0.47 0.00	0.0 0.0	0.0 0.0	0.0 0.0	- 0.094 0.0	2005
ITRF2008	ITRF2014	-0.16 0.00	-0,19 0.00	-0.24 +0.01	0.0 0.0	0.0 0.0	0.0 0.0	+0.020 -0.030	2010

Table: Transformation parameters among ITRF frames for use with the **7/14-parameter Helmert model**

GNSS Coordinate Broadcast Systems

GPS: WGS84 (G1674) World Geodetic System 84

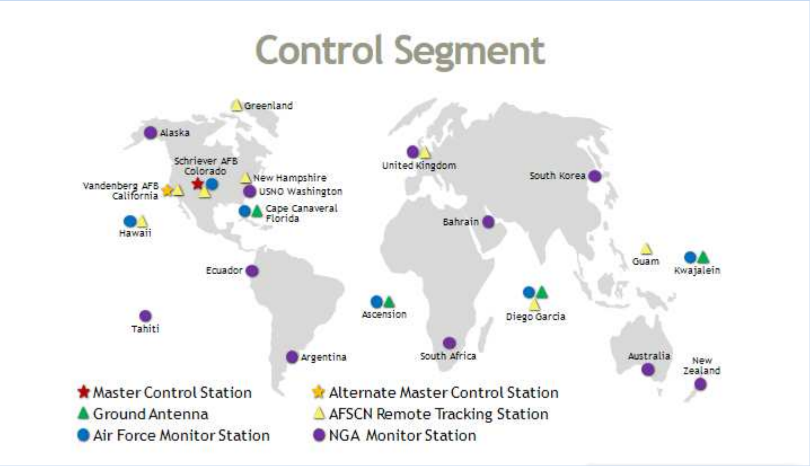
GLONASS: PZ 90.11 (Parametry Zemli 90)

Galileo: GTRF (Galileo Terrestrial Reference Frame)

Beidou: CGS2000 (China Geodetic Coordinate System 2000)

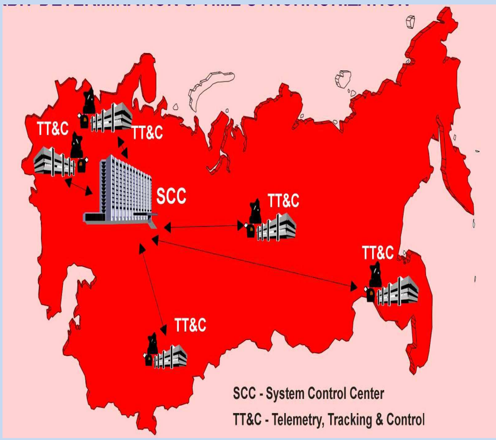
- All GNSS Broadcast Frames are realisations of the ITRS (within the current ITRF at the +/-2cm level)
- Precise Ephemeris refer to the current ITRF at the epoch of date. Therefore positions determined by GNSS in PPP-mode refer to this realisation.

GPS Control Network



Source: http://www.gps.gov/systems/gps/control

GLONASS Control Network

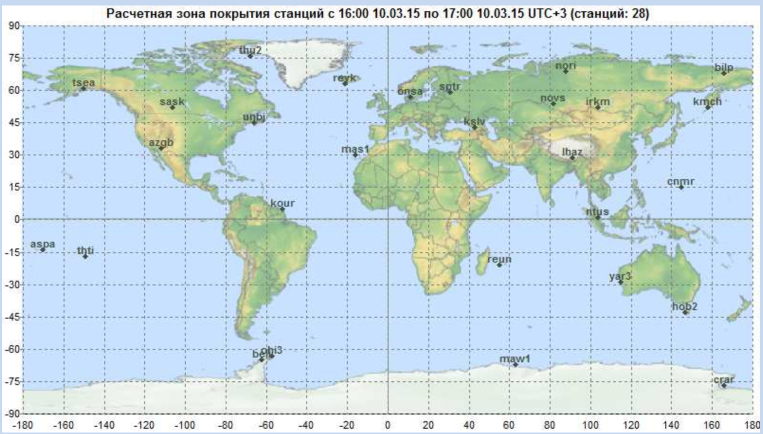


–K**GLONASS System Control Center
–KKrasnoznamensk, Moscow reg.
–SSatellite operation
–OOD&TS

•T**TT&C stations
–SSt.Petersbourg reg.
–SSchelkovo, Moscow reg
–YYenisseysk
–KKomsomolsk-Amur

•S**System clock
(Central synchronizer)
–SSchelkovo

GLONASS Post-Processing Reference Network



PZ 90.11

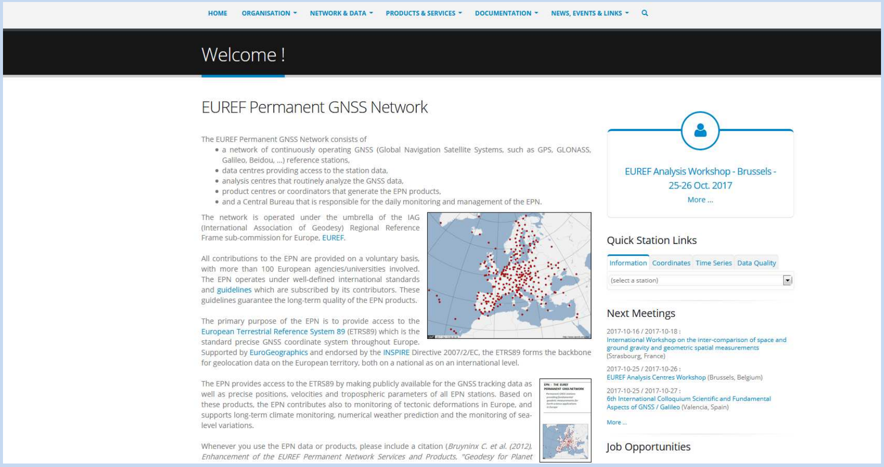
GLOBAL GEOCENTRIC COORDINATE SYSTEM

№ п/п	Из системы	В систему	ΔX, м	ΔY, м	ΔZ, м	(ω_X, угл.с) $\cdot 10^3$	(ω_Y, угл.с) $\cdot 10^3$	(ω_Z, угл.с) $\cdot 10^3$	$m \cdot 10^6$
1	ПЗ-90.02	ПЗ-90.11	–0,373 ±0,027	+0,186 ±0,056	+0,202 ±0,033	–2,30 ±2,11	+3,54 ±0,87	–4,21 ±0, 82	–0,008 ±0, 004
2	ITRF-2008	ПЗ-90.11	–0,003 ±0,002	–0,001 ±0,002	+0,000 ±0,002	+0,019 ±0,072	–0,042 ±0,073	+0,002 ±0,090	–0,000 ±0,000 3

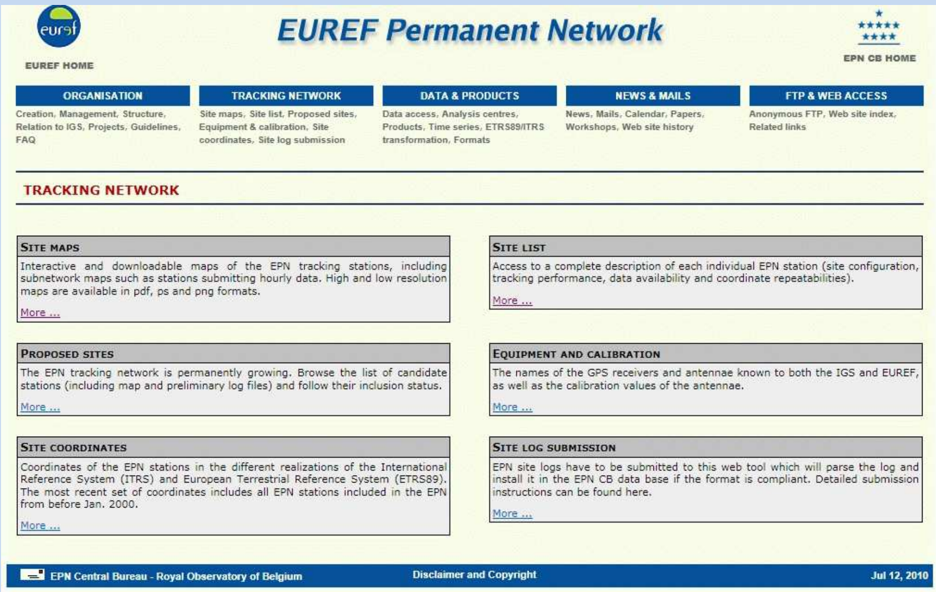
November 7, 2012
WG D – Reference Frames, Timing and Applications

- Introduction
- Time Scales
- Global Spatial Reference Systems
- Broadcast Frames
- **Continental/ Regional Spatial Reference Systems**
- Satellite specific Frame
- Sun-refered Frame

EUREF/ EPN / ETRS /ETRF



EUREF Welcome Page **http://www.epncb.oma.be/**



http://www.epncb.oma.be/

EPN Tracking Network / March 2017

Home / Network & Data / Status / Network Status

Network Status

The map below shows the actual EPN tracking status based on the availability of daily, hourly or real-time observation data. Details on how to download EPN data can be found here.

- Overall data availability (how is it computed?)
  - Data available
  - Data not available
- Availability of daily data
  - Data available
  - At least last day missing
  - At least last 3 days missing
- Availability of hourly data
  - Data available
  - At least last hour missing
  - At least last 3 hours missing
- Availability of real-time data
  - Data available
  - At least last 15 minutes missing
  - At least last hour missing

Update map

Stations responding to the criteria

- Select a station -

Get in Touch with the EPN Central Bureau

Definition ETRS / ETRF

EUROPEAN TERRESTRIAL REFERENCE SYSTEM 89 (ETRS89)

Definition

The IAG Subcommision for the European Reference Frame (EUREF) , following its Resolution 1 adopted in Firenze meeting in 1990, recommends that the terrestrial reference system to be adopted by EUREF will be coincident with ITRS at the epoch 1989.0 and fixed to the stable part of the Eurasian Plate. It will be named European Terrestrial Reference System 89 (ETRS89).

Realization

Following its definition, ETRS89 could be realized through several ways, and specifically:

- using ITRS realizations: for each frame labelled $ITRF_{yy}$ a corresponding frame in ETRS89 can be computed and labelled $ETRF_{yy}$. The following ETRF solutions are presently available:
  - ETRF89
  - ETRF90
  - ETRF91
  - ETRF92
  - ETRF93
  - ETRF94
  - ETRF96
  - ETRF97
  - ETRF2000

  The EUREF Technical Working Group (TWG) recommends not to use the ETRF2005 and rather to adopt the ETRF2000 as a conventional frame of the ETRS89 system, see the memo for more details. However, in order to benefit from the quality of ITRF2005 solution, the TWG has also recommended that all European stations coordinates (GNSS, VLBI, SLR and DORIS) which are available in the ITRF2005 to be expressed in the ETRF2000 frame and to call the resulting set of coordinates (positions and velocities) ETRF2000(R05):

  - ETRF2000(R05)
  - ETRF2000(R05) (SINEX file)

  Similarly, the European station coordinates available in ITRF2008 solution were also expressed in ETRF2000 and the corresponding list is called ETRF2000(R08):

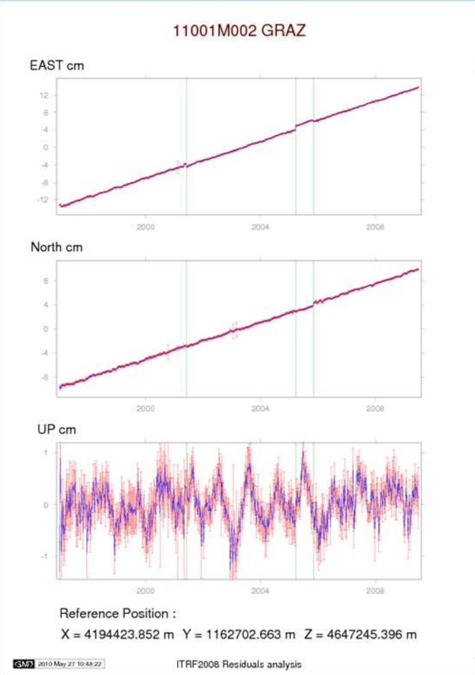
  - ETRF2000(R08) (Warning, the file format has changed)
  - ETRF2000(R08) (SINEX file)

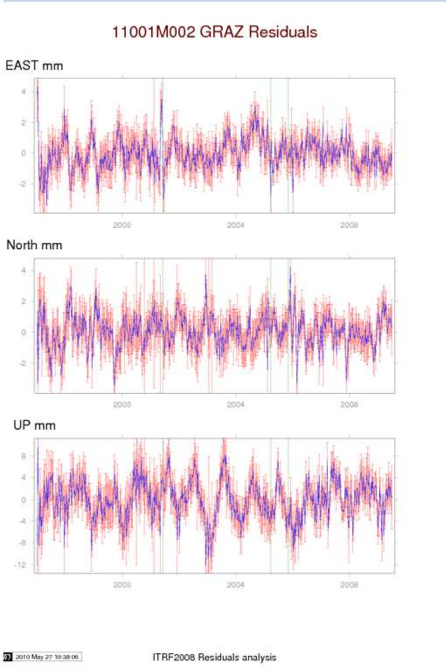
  Similarly, the European station coordinates available in ITRF2014 solution were also expressed in ETRF2000 and the corresponding list is called ETRF2000(R14):

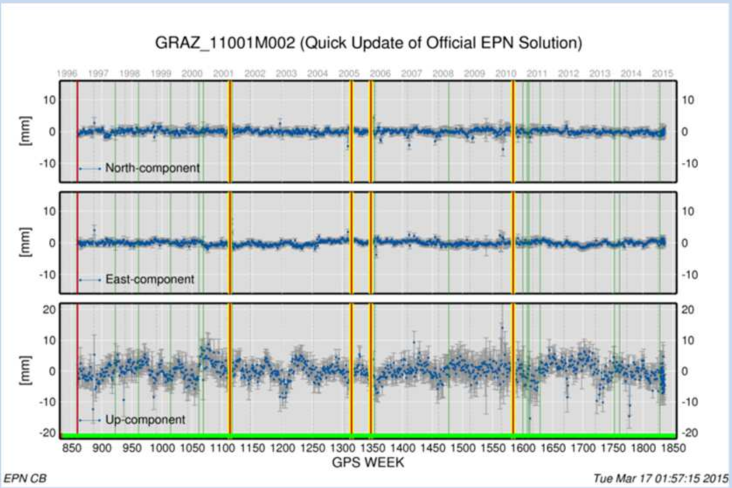
  - ETRF2000(R14) (Warning, the file format has changed)
  - ETRF2000(R14) (SINEX file)

- positioning with GNSS measurements of a campaign or permanent stations: using recent $ITRF_{yy}$ station coordinates and IGS precise ephemerides following the procedure described in (Boucher and Altamimi, 2011): Postscript version, PDF version

Links


11001M002 GRAZ
EAST cm
North cm
UP cm
Reference Position :
X = 4194423.852 m Y = 1162702.663 m Z = 4647245.396 m
ITRF2008 Residuals analysis


11001M002 GRAZ Residuals
EAST mm
North mm
UP mm
ITRF2008 Residuals analysis


GRAZ_11001M002 (Quick Update of Official EPN Solution)
North-component
East-component
Up-component
[mm]
GPS WEEK
EPN CB
Tue Mar 17 01:57:15 2015

- Introduction
- Time Scales
- Global Spatial Reference Systems
- Broadcast Frames
- Continental/ **Regional Spatial Reference Systems**
- Satellite specific Frame
- Sun-refered Frame

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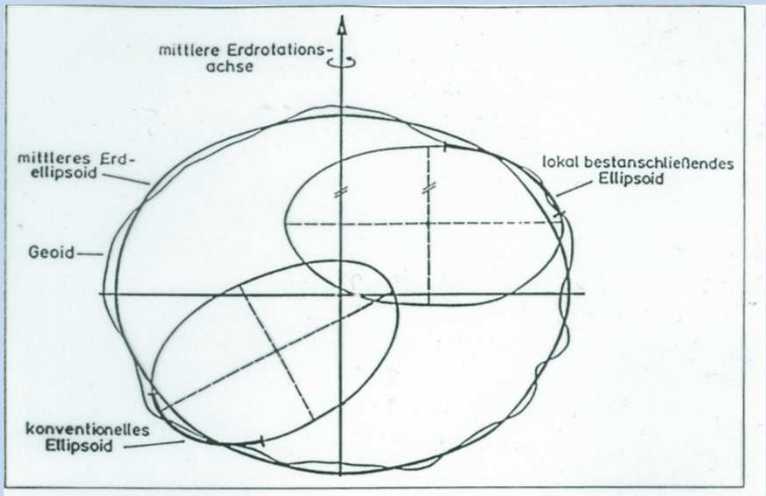
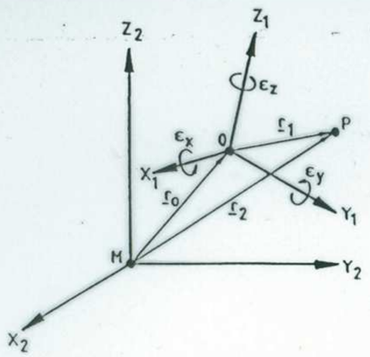
Regional Reference Ellipsoid (e.g.. Bessel 1841)



Datum Transformation (3P-, or 5P, or 7Parameter Transformation)
Captured by the EPSG Parameter Sets for GIS applications
-> **coordinate rotation** versus **axis rotation** mode !!!



$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_2 = \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}_{1,2} + (1+m) \begin{pmatrix} 1 & \varepsilon_z & -\varepsilon_y \\ -\varepsilon_z & 1 & \varepsilon_x \\ \varepsilon_y & -\varepsilon_x & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_1$$

Geodetic Datum Austria (rough values)

Austria (ITRF-> MGI):

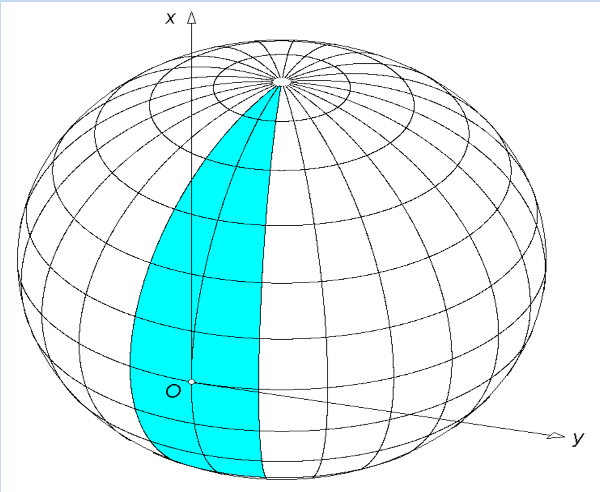
Shift: dx=-575m Rotations: ex=5.1”

dy= -93m ey=1.6”

dz= -466m ez=5.2“

Scale = -2.5 E-6 (ppm)

National Map Projections (e.g. UTM, GK, …..)



Austrian National Map Projection (Gauss-Krüger)

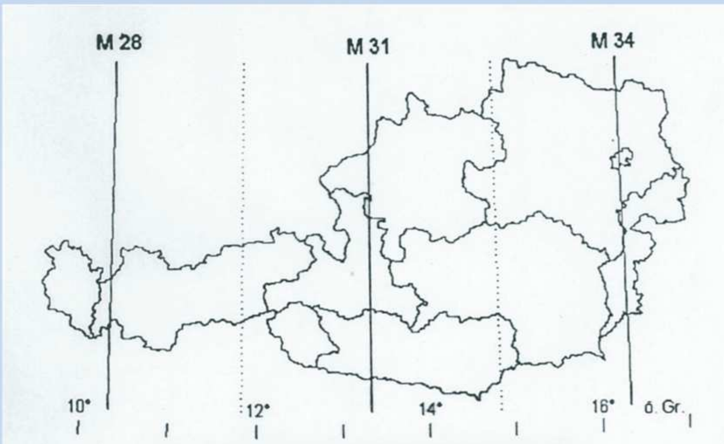
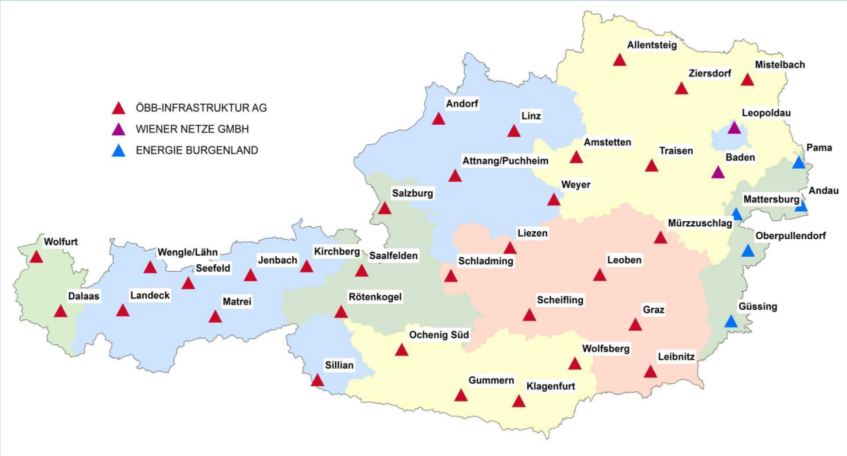


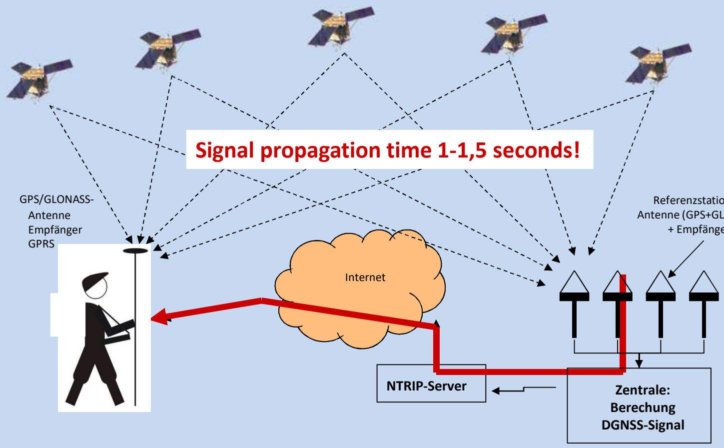
Abb. 9: Das österreichische Meridianstreifensystem

Positioning with RTK -> Reference Frame?
EPOSA – GNSS Service Provider - Network



EPOSA Reference Frame – ITRF2014, Ep. 2010.0

GNSS- RealTime Positioning Services



NTRIP = Networked Transport of RTCM via Internet Protocol

Datum / Net Distortions

In Austria operating active Reference networks refer to

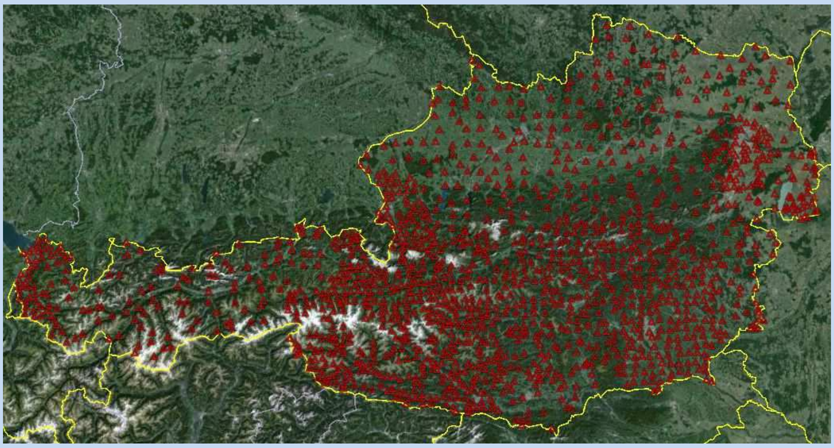
- ITRF2000/ Ep. 1997.0 (expiring)
- ITRF2014 / Ep. 2010.0 (EPOSA)
- ETRS89 / (Ep. 1989.0) (APOS)

- The transformation to the local datum MGI is realized by a ‚mean' 7-Parameter Transformation z.B. for EPOSA ->

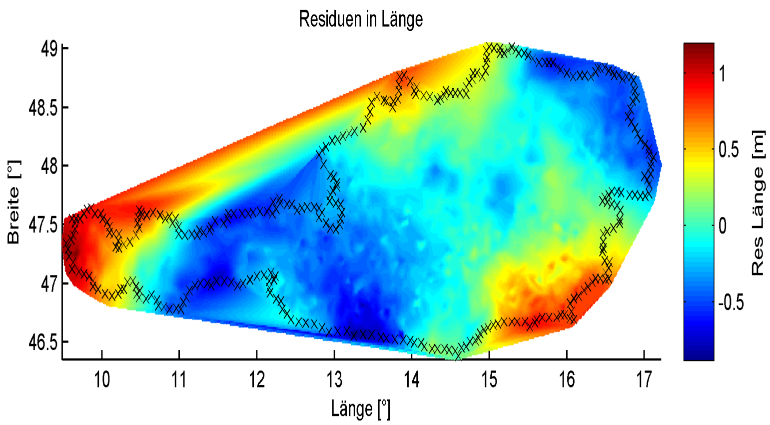
ΔX	-577.326 m
ΔY	-90.129 m
ΔZ	-463.919 m
α(X)	5.137"
α(Y)	1.474"
α(Z)	5.297"
dm	-0.0000024232

Net distortions remain – these distortions can be minimized by
a) locally or regionally fitted Helmert parameter sets
b) by 2D- or 3D- grid corrections forwarded via RTCM 3.x

Control points for calculation of ‚distortion grid'

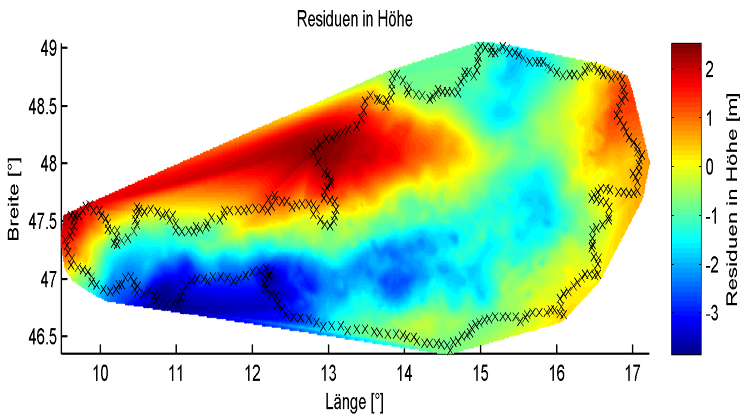


EPOSA – Grid - Longitude



Residuals refer to mean transformation parameter set

EPOSA – Grid - Height



Corresponds approximately to negative Geoid Undulations
Residuals refer to mean transformation parameter set

RTCM SC -104

Differential GNSS Standards

- ursprünglich 1983 entwickelter Standard für die DGPS-Positionierung (Genauigkeitsziel 5m)
- Version 2.0 , 1990, im Kern GPS-Codekorrekturen
- Version 2.1 , 1994, beinhaltet erstmals RTK - Phasenbeobachtungen (nur GPS – proprietäre Message erlaubt FKPs)
- Version 2.2 , 1998, inkludiert GLONASS
- Version 2.3 , 2001, viele neue Messages, (z.B kombinierte Nutzung GNSS und of Loran-C) und Reduktion der Menge der Übertragungsdaten
- Versionen 3.0, 3.1 (2004,2006) zielen in erster Linie auf verbessertes RTK, und definieren ‚Network RTK'- Messages
- Version 3.1, Anhänge 1-6 (2008-2012): beinhalten u.a. Koordinatentransformation in nationales Datum, Korrekturraster f. Netzspannungen, SSR –für PPP

Version 3.2 (2013): Multi Signal Messages für Galileo, Beidou, QZSS

Version 3.3 (2016): neue Navigationsmessages, SBAS

ITRS / ETRS /Reference Frames

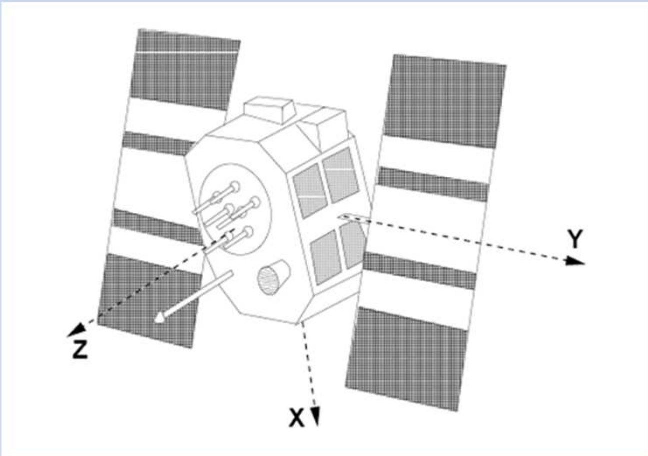
- Any ITRS Realization (=ITRF) can be converted to any ETRS89 realization (ETRFxxxx) at the +/-1-2mm accury level.
- Rover positions determined by means of RTK-services in difference mode refer to the reference frame of the service provider.
- Current coordinate difference between

  ITRF2000 (Ep. 1997.0) and ETRS89 (Ep. 1989.0) : about 20cm

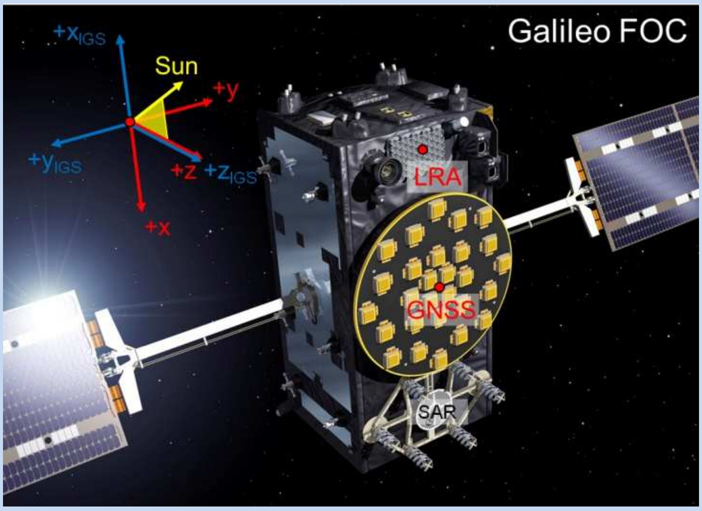
  ITRF2014 (Ep.2010.0) and ETRS89 (Ep. 1989.0) : about 52 cm

Satellite Specific Frame(s)

Useful to specify location of sensors of the satellite with respect to Geometric Origin or CoM



Z-direction : main antenna - in direction to Earth
Y-direction: along the solar panel axes



Galileo Antenna and LRA Positions

FOC

			Coordinates (w.r.t. origin)			Coordinates (w.r.t. CoM)			Reference
			x_{IGS}	y_{IGS}	z_{IGS}	x_{IGS}	y_{IGS}	z_{IGS}	
GNSS Antenna (since week 1915)	FOC-1,2	E1				+160.0 mm	-10.0 mm	+1050.0 mm	[4]
		E5a/b/ab				+160.0 mm	-10.0 mm	+1050.0 mm	[4]
		E6				+160.0 mm	-10.0 mm	+1050.0 mm	[4]
	others	E1				+120.0 mm	-10.0 mm	+1100.0 mm	[4]
		E5a/b/ab				+120.0 mm	-10.0 mm	+1100.0 mm	[4]
		E6				+120.0 mm	-10.0 mm	+1100.0 mm	[4]
GNSS Antenna (before week 1915)	FOC-1,2	E1				+150.0 mm	0.0 mm	+1000.0 mm	
		E5a/b/ab				+150.0 mm	0.0 mm	+1000.0 mm	
		E6				+150.0 mm	0.0 mm	+1000.0 mm	
	others	E1				+150.0 mm	0.0 mm	+1000.0 mm	
		E5a/b/ab				+150.0 mm	0.0 mm	+1000.0 mm	
		E6				+150.0 mm	0.0 mm	+1000.0 mm	
LRA	FOC-1		+703.0 mm	+27.5 mm	+1120.5 mm	+1034.7 mm	+14.0 mm	+558.6 mm	[1],[2]
	FOC-2		+703.0 mm	+27.5 mm	+1120.5 mm	+1017.0 mm	+14.9 mm	+558.1 mm	[1],[2]
	FOC-3		+703.0 mm	+27.5 mm	+1120.5 mm	+962.1 mm	+18.3 mm	+559.3 mm	[1],[2]
	FOC-4		+703.0 mm	+27.5 mm	+1120.5 mm	+963.6 mm	+18.2 mm	+559.3 mm	[1],[2]
CoM (Feb 2016)	FOC-1		-316.9 mm	+13.5 mm	+561.9 mm				[2]
	FOC-2		-311.6 mm	+12.6 mm	+562.3 mm				[2]
	FOC-3		-259.5 mm	+9.2 mm	+561.1 mm				[2]
	FOC-4		-261.1 mm	+9.2 mm	+561.1 mm				[2]
	FOC-5		-258.6 mm	+9.9 mm	+565.5 mm				[2]
	FOC-6		-259.2 mm	+9.5 mm	+565.3 mm				[3]
	FOC-8		-261.1 mm	+10.4 mm	+565.3 mm				[2]
	FOC-9		-261.5 mm	+9.6 mm	+565.0 mm				[2]

Due to an initial lack of publicly available measured antenna phase center offsets conventional values of $(x,y,z)_{IGS}$=(-0.2 m, 0.0 m, +0.6 m) and $(x,y,z)_{IGS}$=(+0.15 m, 0.0 m, +1.0 m) were recommended for orbit and clock determination of the Galileo-IOV and -FOC satellites, respectively, until GPS week 1914. These values provided a first estimate of the actual phase center relative to the center of mass based on the images and models or coarse phase center estimates.

Source: IGS MGEX Website : http://mgex.igs.org/IGS_MGEX_Status_GAL.html

Beidou Konstellation I

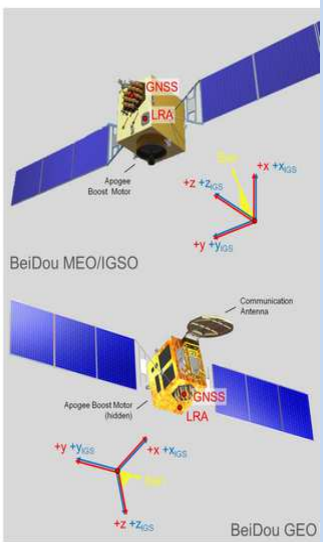
Spacecraft Characteristics

A comprehensive collection of technical information with associated references for the BeiDou satellites can be obtained at the CNSS page of ESA's eoPortal .

BeiDou-2			
Parameter	GEO	IGSO	MEO
Launch mass	4600 kg	4200 kg	
Dry mass	1550 kg	1900 kg	
Body size	~1.8 m x ~2.2 m x ~2.5 m	~1.8 m x ~2.2 m x ~2.5 m	~1.8 m x ~2.2 m x ~2.5 m
Solar array size	2 x 3 x 2.2 m x 1.7 m	2 x 3 x 2.2 m x 1.7 m	2 x 3 x 2.2 m x 1.7 m
Span width	~17.7 m	~17.7 m	~17.7 m
Cross section	~27 m^2	~27 m^2	~27 m^2
SRP acceleration	102 nm/s^2	122 nm/s^2	

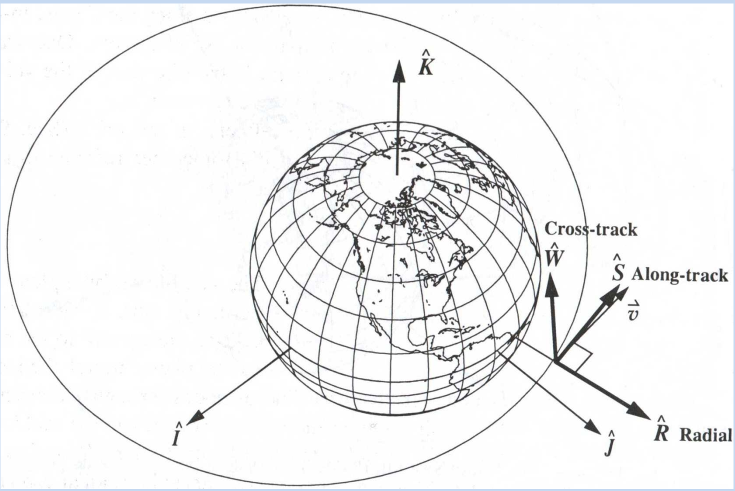
The BeiDou-2 spacecraft are equipped with broadband GNSS antennas for the B1, B2, and B3 frequency bands as well as a laser retroreflector array (LRA) for satellite laser ranging.

The BeiDou-3 will transmit legacy B1 signals similar to the BeiDou-2 satellites as well as modernized signals in the L1, E5, and B3 band.



Quelle: http://mgex.igs.org/IGS_MGEX_Status_BDS.html

Frame to express external forces acting on satellite



Perturbation Equations by Gauß

$$\dot a = \sqrt{\frac{p}{\mu}}\frac{2a}{1-e^2}\left(e\cdot\sin(\nu)\cdot R + \frac{p}{r}S\right) \qquad (6.18a)$$

$$\dot e = \sqrt{\frac{p}{\mu}}\left[\sin(\nu)\cdot R + (\cos(\nu)+\cos(E))\cdot S\right] \qquad (6.18b)$$

$$\dot i = \frac{r\cdot\cos(u)}{na^2\sqrt{1-e^2}}W \qquad (6.18c)$$

$$\dot\Omega = \frac{r\cdot\sin(u)}{na^2\sqrt{1-e^2}\cdot\sin(i)}W \qquad (6.18d)$$

$$\dot\omega = \frac{1}{e}\sqrt{\frac{p}{\mu}}\left[-\cos(\nu)\cdot R + \left(1+\frac{r}{p}\right)\cdot\sin(\nu)\cdot S\right] - \cos(i)\cdot\dot\Omega \qquad (6.18e)$$

$$\dot t_p = -\frac{1-e^2}{n^2 ae}\left[\left(\cos(\nu)-2e\frac{r}{p}\right)\cdot R - \left(1+\frac{r}{p}\right)\sin(\nu)\cdot S\right] - \frac{3}{2a}\left(t-t_p\right)\cdot\dot a \qquad (6.18f)$$

R .. Radial
S .. Along Track
W.. Out of Plane

Galileo – Satellite Characteristis

Spacecraft Characteristics

A comprehensive collection of technical information with associated references for the GIOVE-A and GIOVE-B spacecraft can be obtained at ESA's eoPortal as well as the ESA report on GIOVE Experimentation Results (ESA SP-1320). Information on the IOV satellites is presently limited to the ESA Galileo IOV Fact Sheet.

Parameter	GIOVE-A	GIOVE-B	IOV	FOC
Launch mass	602 kg	530 kg	700 kg	733 kg
Dry mass	550 kg	502 kg	n/a	n/a
Body size	1.3 m x 1.8 m x 1.65 m (stowed envelope)	0.95 m x 0.95 m x 2.4 m	2.74 m x 1.58 m x 1.59 m	2.5 m x 1.2 m x 1.1 m
Solar array size	2 x 2 x 1.74 m x 0.98 m	2 x 4 x 1.5 m x 0.8 m	2 x 2 x ~3 m x ~1 m	2 x 2 x 2.5 m x 1.1 m
Span width	~10 m	~10 m	14.5 m	14.7 m
Cross section	9 m^2	12 m^2	n/a	n/a
SRP acceleration	99 nm/s^2	151 nm/s^2	113 nm/s^2	n/a

The GIOVE-A/B and Galileo-IOV spacecraft are equipped with broadband GNSS antennas for the E1, E5ab and E6 frequency bands and with a laser retroreflector array (LRA) for satellite laser ranging.

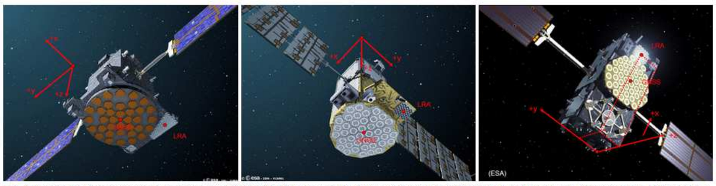


Fig. 1 Spacecraft reference system and sensor location for the GIOVE-A (left), GIOVE-B (center) and Galileo-IOV (right) satellites (images: ESA). Note that the Sun incidence direction in the artist's drawings of GIOVE-A and GIOVE-B does not comply with the true attitude control of the two spacecraft, which always keeps the Sun in the -x-hemisphere.

Quelle – IGS-MGEX Webpage: http://igs.org/mgex/Status_GAL.htm

Frame for Parametrization of Solar Radiation Pressure

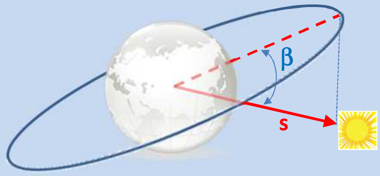
- D(u) =D0 + D1C cos u +D1S sin u
- Y(u) =Y0 + Y1C cos u + Y1S sin u
- B(u) =B0 + B1C cos u + B1S sin u

D corresponds to direction satellite-sun
Y points along solar panel axis
X completes a right-handed system

The 9 parameters can be expressed as functions of the argument of latitude and the angle β (= sun elevation above orbital frame)

The Beta Angle

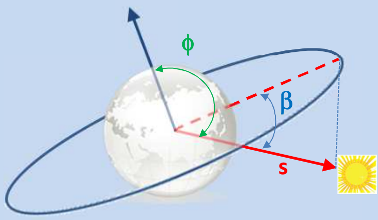
The beta angle, β is the angle between the solar vector, **s**, and its projection onto the orbit plane;



Calculating the Beta Angle

To most easily calculate the angle between a vector and a plane, it is necessary to determine the angle between the vector and a vector normal to the plane, denoted here by ϕ;

We note that $\beta = \phi - (\pi/2)$ radians.



Calculating the Beta Angle

We see that β is limited by:

$$\beta = \pm(\varepsilon + |i|)$$

Beta angles where the sun is north of the orbit plane are considered positive -- beta angles where the sun is south of the orbit are considered negative.

For GLONASS i= 63 !!

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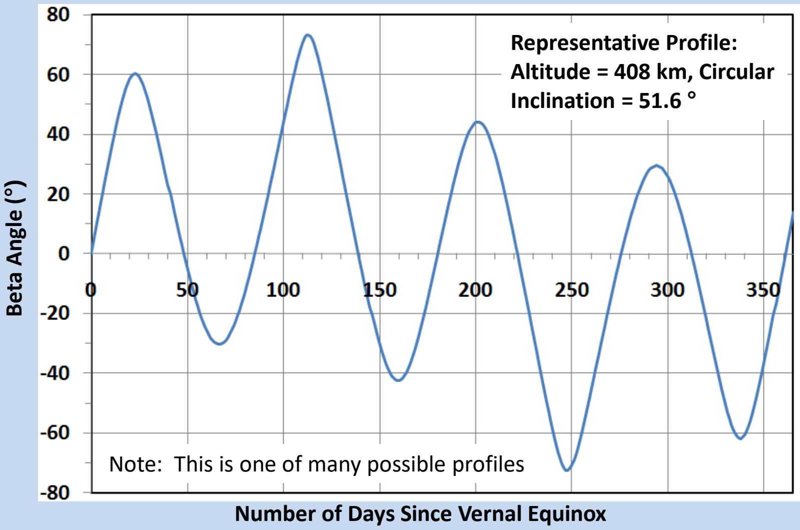
Variation of the Beta Angle Due to Seasonal Variation and Orbit Precession



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Galileo –(IOV) Orbit Determination

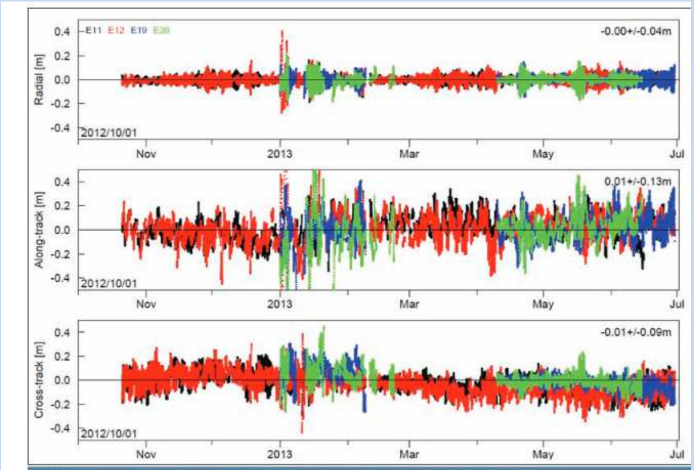

FIGURE 5 Difference (TUM-minus-CODE) of MGEX precise orbit products for the Galileo IOV

Thank you for your attention