Coordinate Reference Systems Basic User Guide

On WGS 84, ITRS, ETRS89, coordinate transformations and data origination

Edition: 1.0
Edition date: 19-12-2024
Classification: Green
Reference nr: N/A

DOCUMENT CONTROL

Document Title	Coordinate Reference Systems Basic User Guide
Document Subtitle	On WGS 84, ITRS, ETRS89, coordinate transformations and data origination
Document Reference	N/A
Edition Number	1.0
Edition Validity Date	19-12-2024
Classification	Green
Status	Released
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Reviewed and endorsed by: AIRI SG and AIMG	16-12-2024	
Reviewed and endorsed by: UN-GGIM Europe Community of Interest on Geodetic Reference Frames	07-11-2024	
Approved by: N/A	N/A	

EDITION HISTORY

Edition No.	Validity Date	Author(s)	Reason
0.1	10-06-2024	Jeffrey Verbeurgt, Filip De Doncker (NGI Belgium), Aleksander Wojtowicz (EUROCONTROL)	Initial version
0.2	12-09-2024	Jeffrey Verbeurgt, Filip De Doncker (NGI Belgium), Aleksander Wojtowicz (EUROCONTROL)	After AIRI SG review
0.3	27-09-2024	Jeffrey Verbeurgt, Filip De Doncker (NGI Belgium), Aleksander Wojtowicz (EUROCONTROL)	Essential comments by Pasi Häkli (NLS Finland), updated visualizations by Elise Kazmierczak and Robson Nascimento (NGI Belgium)
0.4	07-11-2024	Jeffrey Verbeurgt, Filip De Doncker (NGI Belgium), Aleksander Wojtowicz (EUROCONTROL)	After UN-GGIM: Europe – CoI GRF review
1.0	19-12-2024	Jeffrey Verbeurgt, Filip De Doncker (NGI Belgium), Aleksander Wojtowicz (EUROCONTROL)	Released version following the AIRI SG and AIMG endorsement, integrating additional clarifications and minor editorial changes

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1 Introduction

1.1 Objective of the (informal) guide

This guide has been developed in response to various questions and discussion items raised in the EUROCONTROL Aeronautical Information working arrangements.

It aims at clarifying the aspects of geodetic datums, coordinate reference systems, transformation between the systems, traceability, metadata, and data origination aspects.

Intended primary audience of this guide are quality, regulatory and operational experts of ANSPs and AISPs.

This document is developed as an informal guide and shall be used only in the supporting role to the formal ICAO, EU and EUROCONTROL provisions.

1.2 Structure and the lifecycle of the document

The document is structured in two main chapters: Chapter 2 serving as a main part with the comprehensive theoretical explanations of coordinate systems aspects and Chapter 3 representing a quick access Q&A section for all the relevant geodesy and data origination topics.

This document is intended to be a living one and may be supplemented with additional aspects and Q&A items in the future.

1.3 Acknowledgments

This guide owes its existence to the invaluable assistance of the following organisations and individuals:

1. **EUROCONTROL Aeronautical Information Regulations Implementation Subgroup (AIRI SG)**:
    - We recognize the Subgroup's clear goal-setting and unwavering interest in addressing those interdisciplinary questions. Their constructive feedback was instrumental in shaping this guide.
2. **skeyes (AIM service - Belgium)**:
    - Their role in facilitating communication and fostering collaboration among all parties involved was pivotal.
3. **National Geographic Institute (Belgium)**:
    - Jeffrey Verbeurgt and Filip De Doncker: Major drafting force behind this guide. Their expertise significantly enriched the comprehensive description of complex geographical and geodetic concepts presented here.

2 On WGS 84, ITRS, ETRS89 and coordinate transformations

What is WGS 84? How is it related to ITRS? What is the difference between WGS 84 and ETRS89? What do I have to do to transform coordinates between these acronyms?

In this document, layman explanations are given to explain some complex geodetic concepts. Simple examples are provided to illustrate the problems. Some details are left out of this document for reasons of clarity. However, we provide references to source material in case the reader wants to learn more. After reading this document, the reader should know the answer to the questions stated in the first paragraph.

Note that this document is created to serve as background information for basic users in the European geographical region, hence the chapter about the European Terrestrial Reference System 1989 (ETRS89). Nevertheless, the chapter about WGS 84 and its relation to the International Terrestrial Reference System (ITRS) could be useful for everyone.

2.1 Terminology & Theory

To be able to understand the main concepts, it is important to know the basic terminology. Moreover, different communities use different terminology which may complicate discussion and understanding of the subject. The geodetic community has developed the concepts and the geospatial community has implemented these concepts for many practical purposes. **In geodesy**, **a terrestrial reference system (TRS)** describes the theoretical concept of a spatial reference system co-rotating with the Earth in its diurnal motion in space. This abstract concept is practically realized through a conventional **terrestrial reference frame (TRF)** with the determination of the location of an origin, the orientation of an orthogonal set of Cartesian axes (X, Y, Z), the scaling of the system, and the evolution over time. This practical realization is done by using observations of four different space-geodetic techniques gathered for specific physical locations called stations. These four space-geodetic techniques are Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Global Navigation Satellite Systems (GNSS). By combining coordinate time series of the four techniques, it is possible to determine the precise coordinates of station locations. This is why we call a TRF the practical realization of the theoretical concepts defined in the TRS. The determination of precise coordinates of physical points through the realization of a TRF is the main concept in geodesy. Over time, more observations, improved hardware, and improved processing techniques allow to create new realizations with improved accuracies for each of the components (see the following chapters on WGS 84, ITRS and ETRS89).

In the **geospatial** community, the term **geodetic datum** was often used instead of a TRF. The fundamental geospatial concept, a **coordinate reference system (CRS)** is constructed from a geodetic datum together with a **coordinate system**, which is a set of mathematical rules for specifying how coordinates are to be assigned to points on Earth. A group of multiple geodetic datums (multiple TRFs) that, for approximate spatial referencing purposes, are not significantly different, is called a **datum ensemble** in geospatial terminology. Typically, consistency of different datums within a datum ensemble, which is the accuracy of the ensemble, is at a (few) decimetre level but can reach a few meters. In geospatial terminology, the afore-mentioned ETRS89,

WGS 84 and ITRS are considered as datum ensembles. Geodetic concepts are described in more detail in the IERS conventions[1] and geospatial concepts in ISO 19111:2019 standard[2].

2.1.1 What should you remember from this chapter?

- A *terrestrial reference system* (TRS) is a theoretical concept describing an idealized spatial reference system.
- The realization of a TRS is called a t*errestrial reference frame* (TRF), which is based on geodetic observations. In ISO terminology, this is called a (geodetic) datum. In the realization of a TRS, scientists determine the precise coordinate values for station locations.
- A group of similar datums is called a *datum ensemble*. They can be used for approximate georeferencing purposes. ETRS89, WGS 84 and ITRS have many realisations giving groups of reference frames constituting datum ensembles.
- A more recent realization of a TRS is more accurately determined. For this reason, when applying accurate georeferencing, users should explicitly use one of the geodetic datums contained within the datum ensemble. In geodetic terminology this means users should explicitly use one of the realizations (TRF) of the TRS.

2.2 World Geodetic System 1984 (WGS 84)

The most commonly known datum ensemble is the World Geodetic System 1984 (WGS 84). It is a standard used in many applications. This coordinate system is published and maintained by the United States National Geospatial-Intelligence Agency (NGA). The reason why this is the most commonly known datum ensemble is assumed to be because the United States Global Positioning System (GPS) satellites use WGS 84 as the reference system in which they operate. However, in reality only few users have direct access to accurate coordinates in WGS 84. Most users unknowingly determine accurate coordinates in ITRS or ITRS-based solutions. This will be explained in the following chapters.

The theoretical definition of WGS 84 as a Terrestrial Reference System (TRS) is described in the standard 'NGA.STND.0036'[3]. It is a geocentric system, with the centre of mass defined for the whole Earth including oceans and atmosphere. The coordinate system is a right-handed, Earth-fixed orthogonal coordinate system. This means that a location in this system is expressed using the respective values on the X-, Y- and Z-axes. X cutting the prime meridian, Z cutting the mean pole an Y completing the right hand direction. Only by introducing an ellipsoid, with its geometric centre coinciding with the mass centre of the Earth, users can express the coordinates of a location using latitude (φ – Phi) and longitude (λ – Lambda). WGS 84 uses the WGS 84 ellipsoid. Figure 1 below shows the relation between the three axes and the WGS 84 ellipsoid.

[1] International Earth Rotation Service Conventions Centre, https://iers-conventions.obspm.fr/
[2] ISO19111:2019 – Geographic Information – Referencing by coordinates, https://www.iso.org/standard/74039.html; Open Geospatial Consortium document 18-005r8, https://docs.ogc.org/as/18-005r8/18-005r8.pdf
[3] NGA, STND.0036 1.0.0 WGS 84 (Version 1.0.0 – July 8, 2014) [formerly known as TR8350.2], DoD World Geodetic System 1984 — Its Definition and Relationships with Local Geodetic Systems, National Imagery and Mapping Agency Technical Report, July 8, 2014.

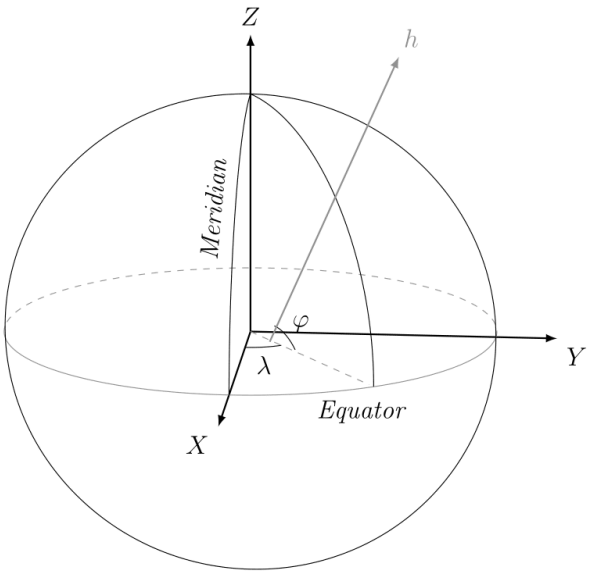


Figure1: WGS 84 reference frame and the transformation between cartesian coordinates (X, Y, Z) and ellipsoidal coordinates (φ, λ, h)

With the basic definition of WGS 84 as a TRS given, we use it as an example to explain the practical realization of a TRS through a Terrestrial Reference Frame (TRF). In the previous paragraph, the theoretical definition of the WGS 84 TRS is introduced. However, to put the definition in practice, a set of consistent station coordinates have to be determined, which is called a TRF. To be able to determine coordinates, the location of an origin, the orientation of an orthogonal set of Cartesian axes (X, Y, Z) and a scaling of the system should be practically realized by using geodetic observations. By using the observations in a consistent calculation, NGA determines the coordinates of the station locations according to the definition of WGS 84 (the TRS). Over time, more observations, improved hardware, and improved processing techniques allow to create new realizations with improved accuracies for each of the components.

Table 1 is based on information provided by NGA. It lists the geodetic datums (terrestrial reference frames; realizations) that are currently included in the WGS 84 datum ensemble. NGA uses the GPS week number in which the new geodetic datum (new realization, new TRF) is adopted to identify realizations (geodetic datums) of WGS 84 (see column 'name' in the table). The GPS-week number indicates the number of weeks passed since midnight 5-6 January 1980, which is the starting point of the 'GPS time' timescale. The table clearly indicates the improvement of the accuracy of the realizations over time. For accurate georeferencing purposes, one of the listed datums, usually the most recent one, should be selected instead of the WGS 84 datum ensemble. This way, the full potential (accuracy) of the reference frame is reached.

Table 1: WGS 84 Station Coordinate Updates (realizations)

Name/realization	Implementation date		Ref. Epoch	Absolute Accuracy
	GPS Broadcast Orbits	NGA Precise Ephemeris		
WGS 84 (Transit)	1987	1 Jan 1987		1-2 meters
WGS 84 (G730)	29 Jun 1994	2 Jan 1994	1994.0	10 cm/component RMS
WGS 84 (G873)	29 Jan 1997	29 Sep 1996	1997.0	5 cm/component RMS
WGS 84 (G1150)	20 Jan 2002	20 Jan 2002	2001.0	1 cm/component RMS
WGS 84 (G1674)	8 Feb 2012	7 May 2012	2005.0	<1 cm/component RMS
WGS 84 (G1762)	16 Oct 2013	16 Oct 2013	2005.0	<1 cm/component RMS
WGS 84 (G2139)	28 Mar 2021	3 Jan 2021	2016.0	<1 cm/component RMS
WGS 84 (G2296)	7 Jan 2024	7 Jan 2024	2024.0	<1 cm/component RMS

For more information on WGS 84 and other topics mentioned in this chapter:

- Website of the United States National Geospatial-Intelligence Agency Office of Geomatics[4]
- WGS 84 standard[5]
- More information on the four space-geodetic techniques used to determine reference frames and Earth orientation[6]

2.2.1 What should you remember from this chapter?

- WGS 84 is the reference system developed and maintained by the US NGA to support all kinds of applications, with the GPS satellites the most known application.
- Several realizations of WGS 84 (geodetic datums) exist. With each realization, the accuracy and consistency of the coordinates of the stations improves thanks to longer timeseries of data and improved mathematical techniques.
- When using EPSG codes for precise coordinates, it is important to not use the EPSG code of a datum ensemble. For example: EPSG:4326 describes the WGS 84 datum ensemble. Using this EPSG code introduces a reference frame

[4] https://earth-info.nga.mil

[5] https://earth-info.nga.mil/php/download.php?file=coord-wgs84

[6] https://ggos.org/obs/

uncertainty of about 2 meter (see Table 1). Instead, use the EPSG code for the explicit realization (see Annex B).

- The majority of users do not have accurate access to WGS 84 (sub-meter/decimetre level) because this is restricted. For most users, in practice, high-accuracy applications determine coordinates in ITRS or ITRS-related realizations, see more in following chapters.

Now that we understand what WGS 84 is -a theoretical concept- and that the practical realization is updated every few years to improve accuracy and consistency of station coordinates, it is time to introduce the International Terrestrial Reference System (ITRS) in the following chapter.

2.3 International Terrestrial Reference System (ITRS)

The International Terrestrial Reference System (ITRS) is, just like WGS 84, a theoretical definition of an idealized terrestrial reference system. The ITRS is numerically realized by the International Terrestrial Reference Frames (ITRF). The International Earth Rotation and Reference Systems Service (IERS), a service of the International Association of Geodesy (IAG), is responsible for the definition and maintenance of the ITRS. The ITRS and its realizations are adopted by a large number of organizations and serves as the de facto standard reference system. This is described in ISO-standard ISO19161-1. Similar to WGS 84, the ITRS has already been realized with several ITRFs. With each consecutive realization using more data and improved processing techniques, the quality of the ITRF-solutions improves over time. Following Table 2 gives an overview of the different realizations, similar to Table 1.

Table 2: Realizations of the ITRS

Name/realization	Ref. epoch	Absolute Accuracy
ITRF91	1988.0	N/A
ITRF92	1988.0	N/A
ITRF93	1993.0	N/A
ITRF94	1993.0	N/A
ITRF96	1997.0	N/A
ITRF97	1997.0	N/A
ITRF2000	1997.0	N/A
ITRF2005	2000.0	N/A
ITRF2008	2005.0	When compared to ITRF2005, better than 0.01 m
ITRF2014	2010.0	When compared to ITRF2008 and ITRF2005, better than 0.01 m
ITRF2020	2015.0	When compared to ITRF2014, ITRF2008 and ITRF2005, better than 0.005 m

Because of the ITRS being accepted as the standard reference system, most modern three-dimensional reference systems are aligned to one of the ITRF solutions, including WGS 84 (since 1994). The question now is: how close are realizations of ITRS and WGS 84 to each other? Table 3 indicates which WGS 84 realization and which ITRS realization were in use at approximately the same time. Since the WGS 84 (G1762) realization, WGS 84 is consistent with ITRF2008 and ITRF2014 at the level of 1 cm RMS. Since WGS 84 (G2139), standard users may assume that the coordinates expressed in WGS 84 are similar to the coordinates expressed in the corresponding ITRS realization.

Table 3: Approximate corresponding WGS 84 and ITRS realizations

WGS 84 realization	ITRS realization
WGS1984 (Transit)	Has been connected to ITRF90 using a 7-parameter Helmert transformation
WGS 84 (G730)	ITRF92[7]
WGS 84 (G873)	ITRF94[8]
WGS 84 (G1150)	ITRF2000 (centimetre level)
WGS 84 (G1674)	ITRF2008
WGS 84 (G1762)	ITRF2008/2014 (within 1 cm RMS)
WGS 84 (G2139)	ITRF2014 (practically coinciding)
WGS 84 (G2296)	ITRF2020 (practically coinciding)

2.3.1 What should you remember from this chapter?

- Just like WGS 84, ITRS is a terrestrial reference system (geodetic terminology) with many realizations that combined make up a datum ensemble (ISO terminology).
- ITRS is adopted as the standard reference system for many (scientific) applications. It is maintained by contributions of the global scientific community and can be used by everyone. This is one of the main differences compared to WGS 84, which is maintained by the US authorities.
- WGS 84 realizations are aligned to ITRS realizations, just like many other terrestrial reference frames, as ITRS is the de facto standard global reference system.
- For practical applications nowadays, users can assume that a coordinate expressed in a WGS 84 terrestrial reference frame (geodetic datum) has the same values as a coordinate expressed in the corresponding ITRF.

[7] Some sources provide ITRF91 instead of ITRF92.
[8] Some sources provide ITRF96 instead of ITRF94.

2.4 Reference epoch and station velocities

The reference frame epoch of a realization gives us the exact date on which the coordinates of a reference frame solution are valid. The main reason for this can be explained simply: Earth is dynamic. Assume a permanent GNSS antenna installed somewhere in Europe. While one might assume that the coordinates of this antenna are fixed, this is not the case since the Eurasian continental plate is influenced by plate tectonics. On a more local scale, ground deformation stemming from all kinds of sources influences the stability of our GNSS antenna as well. It is for this reason that, when a new realization of WGS 84 or ITRS is determined, the solution consists of both coordinates of the stations and their respective velocities (the rate at which the stations move). This explains why a coordinate solution should be supplemented with an epoch (timestamp), as the coordinate is only valid at that moment in time. Using the velocities, users can extrapolate the coordinate solution to another epoch. Appendix A contains figures to indicate the velocities of different locations in realizations of ITRS and ETRS.



Figure 2 : Physical BRUX Antenna representing an ITRF (and ETRF) point [EUREF Permanent GNSS Network]

Following Table 4 gives an indication of the concept of epoch and station velocities. The GNSS antenna BRUX (Figure 2), located in Brussels (Belgium), was used in the determination of the most recent realization of the ITRS, ITRF2020. The first row in the table contains the published values for this station. The following rows indicate the extrapolation of the coordinate over time. We see the coordinate changing at a rate of about 18 mm in the eastern direction and 16 mm in the northern direction. Combined, this entails a movement of about 2.4 cm per year in the northeastern direction. We refer to '2.7 On transforming coordinates' for the formulas and tools used to perform this simulation.

Table 4: Example of coordinate evolution over time in ITRF2020

Epoch	Geocentric Coordinates [m]	Velocities [m/year]	Geographic Coordinates [°λ, ° φ, m h]	Delta North, East, Up [mm] with previous
2015.00	4027881.4464 (X) 306998.6631 (Y) 4919498.9696 (Z)	-0.0135 (vX) 0.0169 (vY) 0.0104 (vZ)	50.798063937 4.358565457 158.1406	
2016.00	4027881.4330 (X) 306998.6801 (Y) 4919498.9800 (Z)	-0.0135 (vX) 0.0169 (vY) 0.0104 (vZ)	50.798064081 4.358565711 158.1410	16 (Δ North) 18 (Δ East) 0 (Δ Up)
2017.00	4027881.4195 (X) 306998.6970 (Y) 4919498.9904 (Z)	-0.0135 (vX) 0.0169 (vY) 0.0104 (vZ)	50.798064224 4.358565965 158.1414	16 (Δ North) 18 (Δ East) 0 (Δ Up)

The above example illustrates the movement of BRUX station expressed in the ITRF2020 realization of the ITRS. A visualization of the movement of other ITRF2020 stations is given in Figure 3 below. The northeastern movement of the European continental plate on the spheroid is clearly visible in this figure. Because of these movements, it is essential to communicate a coordinate set at all times with an accompanied epoch of those coordinates.



Figure 3: Horizontal velocities of stations in ITRF2020

2.4.1 What should you remember from this chapter?

- Reference frames (such as ITRF2020) are realized by actual, physical locations for which both the position and the movement over time ("shifts" or "velocities") are determined.
- In global reference systems like WGS 84 and ITRS, coordinates of a location change over time because of plate tectonics. To be unambiguous, coordinates in a dynamic CRS should be accompanied by their coordinate epoch.
- The stable part of the European continental plate moves each year about 2.4 cm in a northeastern direction when observed in the WGS 84 and ITRS realizations.

Now that we know what a global terrestrial reference system is, that a realization results in the determination of the coordinates and velocities of stations, and that due to the velocities the coordinates of a station change over time, it is time to introduce the European Terrestrial Reference System 1989 (ETRS89).

2.5 European Terrestrial Reference System 1989 (ETRS89)

As mentioned in the previous chapter, due to plate tectonics the coordinates of a specific location change over time when expressed in global reference systems like WGS 84 or ITRS. This makes these reference systems difficult to use for national matters like land registry, official documentation of possession of land, databases containing geographic features, etc. because using these coordinates would mean that they should constantly be updated. For this reason, in 1989, the European Terrestrial Reference System 1989 (ETRS89) was proposed. ETRS89 is, just like ITRS, a theoretical framework describing an idealized terrestrial reference system. However, one element of the resolution to establish ETRS89 makes it different from WGS 84 or ITRS. "*The IAG Subcommision for the European Reference Frame recommends that the system to be adopted by EUREF will be coincident with the ITRS at the epoch 1989.00 and fixed to the stable part of the Eurasian Plate and will be known as European Terrestrial Reference System 89 (ETRS89)*". The adopted approach to define ETRS89 positions from coordinates expressed in an ITRS realization consists of moving coordinates back to epoch 1989.00 with respect to the rigid motion of the Eurasian tectonic plate (continental drift). Consequently, the tectonic motions expressed in the ETRS89 realizations are significantly reduced and the ETRS89 coordinates can be considered stable (unchanged) over time for large part of Europe. Note that even in ETRS89 there are still residual velocities present due to other ground movements. These can be minor for some regions, but can be significant for other regions like Italy and Greece (planimetric) or Scandinavian countries (altimetric).

Compiling the information of the previous paragraph means that the difference between the coordinates of a location expressed ITRS and ETRS89 is growing constantly since 1989. As mentioned in the previous chapter: for the GNSS antenna BRUX, a northeastern movement of 2.4 cm per year is observed in ITRF2020. This means that in the period 1989-2024 the BRUX antenna has moved 2.4 cm * 35 years = 84 cm in ITRF2020. This is a value that cannot be ignored for many applications! At the same time, the following Table 5 shows the evolution of the coordinates of the BRUX-antenna when expressed in ETRF2000, which is one of the ETRS89 realizations.

We clearly see that the values of the coordinates remain almost the same, which is significant for practical users.

Table 5: Example of coordinate evolution over time in ETRF2014

Epoch	Geocentric Coordinates (m)	Velocities (m/year)	Geographic Coordinates (°λ, °ϕ, m h)	Delta East, North, Up (mm) with previous
2015.0	4027881.8406 (X) 306998.2646 (Y) 4919498.6442 (Z)	-0.0003 (VX) -0.0004 (VY) -0.0002 (VZ)	4.358559396 50.798059562 158.1177	
2016.0	4027881.8403 (X) 306998.2642 (Y) 4919498.6440 (Z)	-0.0003 (VX) -0.0004 (VY) -0.0002 (VZ)	4.358559390 50.798059563 158.1173	0 (Δ East) 0 (Δ North) 0 (Δ Up)
2017.0	4027881.8400 (X) 306998.2637 (Y) 4919498.6438 (Z)	-0.0003 (VX) -0.0004 (VY) -0.0002 (VZ)	4.358559385 50.798059564 158.1170	0 (Δ East) 0 (Δ North) 0 (Δ Up)

2.5.1 What should you remember from this chapter?

- ETRS89 is defined in such a way that the influence of plate tectonics is minimized, resulting in relatively stable coordinates over time.
- The difference between coordinates of a location expressed in WGS 84 or ITRS, compared to coordinates of the same location expressed in ETRS89, will grow constantly. In our example, we showed that for Belgium the difference is about 84 cm over 35 years.
- For some regions in Europe (e.g., Scandinavia, Apennine Peninsula, Peloponnese), other ground movements are still present in ETRS89. This results in coordinates that still have velocities, but not due to the average (rigid) motion of the Eurasian continental plate. It is recommended that AISP (Aeronautical Information Service Provider) are aware of their local conditions and engage with their respective experts (see Appendix C for more details).
- Most European countries have a national reference frame defined in one of the realizations of ETRS89. Measurements performed by surveyors usually result in ETRS89 coordinates. This means specific coordinate transformation procedures should be applied to the results to obtain precise coordinates in a specific realization of ITRS (or WGS 84).

2.6 On the influence of the ellipsoid parameters

WGS 84, ITRS, and ETRS89 realizations use different reference ellipsoids (spheroids) to transform geocentric cartesian (X, Y, Z) coordinates to geographic (φ, λ) coordinates. WGS 84 uses WGS 84 ellipsoid whereas ITRS and ETRS89 use GRS80 ellipsoid. There are small differences in the definition of the parameters of the WGS 84 and the GRS80 ellipsoids. The (inverse) flattening differs due being defined using slightly different values for gravity. For the WGS 84 ellipsoid, 1/f = 298.25722**3563**. For the GRS80 ellipsoid, 1/f = 298.25722**2101.** This results in a 0.105 mm difference in the semi-minor axis of the ellipsoid. However, while this minor difference exists in the definition of axes, this difference is practically negligible. Following example will prove this.

Suppose geocentric XYZ-coordinates [4027859.6309; 307006.6277; 4919508.6380], which are coordinates expressed relative to the axes as shown in Figure 1. These values can be transformed to the commonly used (latitude, longitude, height) representation using the ellipsoidal parameters of WGS 84 or GRS80. Working this out:

Assume geocentric coordinates [4027859.6309; 307006.6277; 4919508.6380]:

1) Use WGS 84 ellipsoidal parameters
    a. [DD] 50.7982661744°; 4.35870161354°; 152.267 m
    b. [DMS] 50°47'53.75823"; 4°21'31.32581"; 152.267 m
2) Use GRS80 ellipsoidal parameters
    a. [DD] 50.7982661754°; 4.35870161354°; 152.267 m
    b. [DMS] 50°47'53.75823"; 4°21'31.32581"; 152.267 m

The absolute difference between the two geographic coordinates, expressed in metric units in a local topocentric system is:

- For the north component: 0.2 mm
- For the east component: 0.2 mm
- For the upward component: 0.0 mm

We can conclude **no difference between the ellipsoidal coordinates is observed on millimetric level**. Therefore, the small difference in the ellipsoids does not play a role compared to other differences in reference frame realizations.

2.6.1 What should you remember from this chapter?

- The difference in the inverse flattening parameter of the WGS 84- and GRS80 ellipsoid is negligible for practical purposes.

2.7 On transforming coordinates

Knowing that nowadays we can assume WGS 84 to be equal to ITRS, this final chapter is about transforming coordinates between WGS 84/ITRS and ETRS89. By now, we know that this is a time-dependent transformation. The relation between realizations of ITRS and ETRS89 is published on the official website of ETRS89, the mathematical description is given in the EUREF Technical Note 1 'Relationship and Transformation between the International and the European Terrestrial Reference Systems', which is a technical note that is updated regularly (together with the publication of a new realization of the ITRS and/or the ETRS89).

A transformation tool is maintained by EUREF, the IAG Reference Frame Sub-Commission for Europe, and can be used online. Note that only geocentric XYZ-coordinates can be transformed. Users should convert between geocentric (X, Y, Z) and geographic (φ, λ, h) coordinates themselves.

PROJ, the OSGeo project that allows for coordinate transformations and is used in many (nearly all) of the open-source geo-software, has included time-dependent transformations (also called *spatiotemporal transformations*, see the transformation pipelines documentation).

The transformation pipeline can only be used when users know which epoch and realization of WGS 84/ITRS and ETRS89 should be used both for input and output.

Due to afore-mentioned residual velocities in ETRS89 in some regions, the accuracy of the official pan-European transformation may not meet the requirements and consequently national approaches to improve the transformation accuracy may exist. For such needs, users should consult the national mapping authorities. We refer to an example in the Nordic and Baltic countries here[9].

2.8 Conclusions

For high-accuracy applications, it is important that coordinates of geographic data are expressed in an appropriate terrestrial reference frame (geodetic datum). Users should be aware that a terrestrial reference system is a theoretical definition of an idealized reference system. Using long timeseries of geodetic observations and scientific methods, coordinates and velocities of stations are determined in practical realizations of the theoretical terrestrial reference system. This is commonly called 'a terrestrial reference frame' or a 'geodetic datum'.

A commonly known terrestrial reference system is WGS 84, maintained by the US NGA. The most recent realization is WGS 84 (G2296). As a result of worldwide cooperation between geodetic scientists, ITRS constitutes the de facto standard for terrestrial reference systems, and is currently realized by ITRF2020. Users can assume recent WGS 84 realizations to be coincident with the recent realizations of ITRS. The practical problem with these global reference systems is that coordinates expressed in these reference systems change over time, due to plate tectonics. For this reason, ETRS89 was defined for the continent of Europe. A mathematical operation is used to eliminate the plate tectonics in this reference system. This results in coordinates that remain relatively stable over time, which is favoured in many applications. **The difference between the coordinates of a location expressed in WGS 84/ITRS and ETRS89 grows**

[9] NKG2020 transformation: An updated transformation between dynamic and static reference frames in the Nordic and Baltic countries. Journal of Geodetic Science. https://doi.org/10.1515/jogs-2022-0155.

over time with on average a few cm/year. For this reason, users should always be aware of the exact coordinate system and timestamp of data acquisition (epoch).

2.9 Recommendations

- National mapping agencies are usually responsible for the definition of the national terrestrial reference frame (geodetic datum). In Europe, the national reference frames are usually defined in a specific realization of ETRS89. We recommend users to contact their national mapping agency (or the organisation responsible for the national reference frame) to inform how they can transform coordinates in the national reference frame to ITRS/WGS 84. See Appendix C for an overview of European organizations responsible for the national coordinate reference system.
- When data is shared in WGS 84/ITRS, it is important to always mention the date of measurement (epoch) and the specific realization of the used reference system as well.
- When using EPSG codes, it is advised to use the coordinate reference system codes that are linked to an exact datum (reference frame) instead of datum ensemble. As mentioned before: most coordinate reference systems have a general EPSG code to describe a group of reference frames (datum ensemble), but often each realization (datum) has a specific EPSG code as well. See Appendix B for an overview of the EPSG codes for the different realizations mentioned in this document.

3 Common questions and answers

Q1. What is WGS 84?

The World Geodetic System 1984 is a terrestrial reference system defined and maintained by the United States National Geospatial-Intelligence Agency (NGA). Mathematically speaking, it is an orthogonal coordinate system consisting of an X-, Y- and Z-axis in which coordinates of a location can be described. It is best known as the reference system used by the GPS system.

We refer to the first two paragraphs of the chapter 'World Geodetic System 1984 (WGS 84)' of the basic user guide for more information.

Q2. What is ITRS?

The International Terrestrial Reference System (ITRS) is - just like WGS 84 - a global terrestrial reference system. However, the ITRS is defined and maintained by the global scientific community. The ITRS is adopted as the standard reference system. For this reason, WGS 84 is aligned to the ITRS. This means nowadays that the coordinates of a location expressed in the WGS 84 system can be assumed to have the same values as the coordinates of the same location expressed in the ITRS.

We refer to the first two paragraphs of the chapter 'International Terrestrial Reference System (ITRS)' of the basic user guide for more information.

Q3. What is ETRS89?

The European Terrestrial Reference System 1989 (ETRS89) differs from WGS 84 and ITRS. It is also a terrestrial reference system, but only useful for locations in the European geographical region. WGS 84 and ITRS are global reference systems and their coordinates include motions of the dynamic Earth. Due to the northeastern movement (plate tectonics) of the Eurasian continental plate, coordinates of a location expressed in WGS 84 or ITRS change over time. For ETRS89, the influence of the plate tectonics of the Eurasian plate is reduced to a minimum. This results in more stable coordinates, which has many practical advantages. For this reason, nearly all countries in the geographical region of Europe adopted a national reference frame based on ETRS89.

Note however that some European countries still experience regional ground movements. This still results in coordinates that change over time, even when expressed in ETRS89. But in general, using ETRS89 remains opportune for these countries. It is recommended that AISP are aware of their local conditions and engage with their respective experts.

We refer to the chapter 'Reference epoch and station velocities' and the chapter 'European Terrestrial Reference System 1989 (ETRS89)' of the basic user guide for more information.

Stemming from the Infrastructure for Spatial Information in Europe (INSPIRE) directive some countries could have adopted a formal requirement that ETRS89 shall be the datum used for spatial data sets. Within the geographical scope of ETRS89, the use of

ETRS89 as the datum for the aviation domain should be considered for data storage if applicable and transformed to ITRS for data provision.

Q4. Why is it important to understand the difference between the systems?

In the WGS 84 or ITRS realizations, Europe moves about 2.4 cm in a northeastern direction each year. This is not practical for many users. For this reason, most European countries have adopted ETRS89 as basis for the national reference frame (geodetic datum).

When a surveyor performs measurements, the observations are usually done in the national reference frame (geodetic datum) (either through passive benchmarks with known coordinates or through positioning services based on active benchmarks, such as RTK-GNSS). While the coordinates in the national reference frame usually remain relatively stable over time, this is not the case when the coordinates are transformed to ITRS/WGS 84.

This is important to know for many critical applications such as aviation infrastructure. As it means that in one coordinate system (ETRS89 or the national realization of ETRS89) the values of a coordinate will remain valid and within accuracy requirements; while in the other coordinate system (ITRS or WGS 84) the values of the coordinates will have to be updated regularly (depending on accuracy requirements e.g. each year) to remain valid by taking into account the station velocities on the location of the coordinates.

We refer to the chapter 'Reference epoch and station velocities' of the basic user guide for more information.

Q5. What is a coordinate reference system baseline for aeronautical information?

ICAO and EU regulatory provisions dictate that the only coordinate reference system baseline to be used in order to exchange aeronautical information is WGS 84. Although WGS 84 shall be used for the aeronautical information data chain downstream flow, other aspects mentioned in this Q&A should be considered for data origination, as in e.g., EUROCONTROL Specification for the Origination of Aeronautical Data (EUROCONTROL-SPEC-154) [1] .

Q6. What is a realization of a terrestrial reference system?

A terrestrial reference frame is a realization of a terrestrial reference system through a consistent set of three-dimensional station coordinates and velocities (movement over time), taking into account all kinds of factors such as the continental drifts. Examples are ITRF2000, ITRF2005, ITRF2008, ITRF2014, ITRF2020. The coordinates of the same location might differ slightly between different realizations, as in each realization improved data and techniques are used to practically determine ("realize") the best possible solution of the theoretical description that is contained in a coordinate reference system's definition.

Q7. How to transform between these reference frames?

As explained in the basic user guide, users can assume WGS 84 to be coincident with ITRS. The question is thus reduced to 'how to transform between ITRS and ETRS89'. This time-dependent transformation is described in the EUREF Technical Note 1 'Relationship and Transformation between the International and the European Terrestrial Reference Systems'. It consists of a 14-parameter transformation where users need to know the realization of the coordinates and the epoch of the coordinates in the input reference frame (geodetic datum / realization). Using the correct parameters, the 14-parameter transformation can be used to determine coordinates in the output reference frame.

We refer to the chapter 'On transforming coordinates' of the basic user guide for more information.

Q8. In which coordinate reference system should I originate?

There is no straightforward answer to this question, also due to the fact the coordinates' transformation provides data originators with certain flexibility.

Data origination may take different forms when it comes to obtaining geographic coordinates e.g., surveying through terrestrial methods to capture details of the aerodrome, using close-range photogrammetry (from UAS platforms) or satellite imagery.

Despite the theoretical and practical possibilities to originate coordinates directly in WGS 84/ITRS/, due to specific prerequisites, data origination may be required in local or national reference frames.

Q9. In which coordinate reference system should the data be submitted?

For EUROCONTROL, Specification for the Origination of Aeronautical Data [1] describes that data is preferably submitted in ITRF2008. This is due to the alignment with ICAO and EU regulatory provisions (assumed equality of WGS 84 and ITRF2008).

As the process to update the ICAO and EU documents is iterative and does not always reflect the pace of development of new terrestrial reference systems it represents certain "snapshot" of these developments. A practical approach would be to originate and submit coordinates in ITRF2008 **or a more recent ITRF**.

In practical terms, ITRF2008, 2014 and 2020 will result in very similar coordinates. The epoch will have more influence on the coordinate values.

For the provision of geographical data to aeronautical data management systems, the approach is usually to assign the coordinates the EPSG:4326 code, as it also supports multiple applications downstream the data chain. However, as EPSG:4326 refers to a two-dimensional datum ensemble, more specific EPSG codes are advised to be used (see: Appendix B). Whatever conversion should be implicated, it should always be done in a traceable manner.

The data can be additionally checked by business rules ensuring accuracy, completeness, traceability, and integrity. As a matter of interoperability, other EPSG codes are sometimes also accepted and there are initiatives to open-up the

Aeronautical Information eXchange Model (AIXM) GML profile to accept ITRF-related EPSG codes directly.

Q10. How to set metadata for correctly providing coordinates?

Given the time-dependent nature of coordinates expressed in global terrestrial reference systems such as WGS 84, it is of major importance that data providers take the differences between reference frames into account. Ideally, data providers report on the specific realization of the coordinate system ("reference frame") used during the measurements, the coordinate transformations that have been applied, and the coordinate frame in which the data is submitted. As time-dependency is the main factor, data providers should always report the epoch ("date of validity") of the data.

Additionally, an important aspect of providing metadata for the geographic coordinates is to always provide them with the corresponding EPSG code. Appendix B contains the EPSG codes for different realisations of WGS 84, ITRS and ETRS89.

Q11. How to tackle this problem practically?

A. If you don't know in which reference frame you are performing your measurements, contact the agency responsible for your national coordinate system. In case of using correction data from e.g. an RTK correction stream, also consider the epoch of the network coordinates used by the RTK-provider.
B. Transform the coordinates to ITRF2008 (which is assumed to be the same as WGS 84 in EUROCONTROL-SPEC-154).
C. Apply the EGM2008 geoid model on the WGS 84 coordinates to deliver correct heights.

Q12. Are there any Aeronautical Data Quality (Management) implications?

There are several aspects that should be considered when it comes to the Aeronautical Data Quality and Data Quality Requirements linked to handling geographic coordinates.

Data origination (surveying) and data processing (e.g., coordinate transformation) have direct effect on data accuracy (e.g., achieving Aeronautical Data Quality-prescribed accuracy levels) and data integrity related risks:

- E.g., failing to fulfil accuracy requirements for an item classified as "routine" has different risks allocated to it, when compared to an item classified as "critical".

Establishing transparent terms of data origination is required to properly handle aeronautical data quality management. Putting in place unambiguous formal arrangements with your data originators (surveyors) and executing them is key.

EUROCONTROL offers a general template for formal arrangements [2] that can be useful to prescribe the rules for the data origination and data provision.

Q13. What to consider when dealing with a data originator/surveyor/geo(matics) consultant?

A first thing to remember is that the area of Aeronautical Information Management and geodesy/geomatics can have very little interface with each other. This may cause potential misunderstanding, dissatisfaction, and data quality problems.

In order to avoid potential issues, specifying clear data quality requirements and explaining the intended use of the gathered data might prove useful.

The structure of knowledge and experience with handling geographic coordinates may differ from State to State: e.g., regular land surveyors may not know much about coordinate transformations as this knowledge may be reserved for geodesy competent authorities (Head Offices, Institutes, universities etc.) or (higher-level) licensed land surveyors etc.

Local surveyors may also be bound by law to gather geographic coordinates in local/national system that would trigger a need for coordinate system transformation.

Establishing data origination contracts with foreign parties that are not familiar with respective local conditions may bring additional challenges: e.g., not considering local horizontal and vertical reference systems, not being aware of national data repositories (official source geoportals, usually publicly available), inclination to using publicly available tools not exactly meeting data quality requirements (e.g., using Google Earth rather than procuring dedicated quality-assured imagery). This can be mitigated accordingly through formal arrangements and/or raising awareness.

Q14. How often a resurvey should be performed?

There is no official, internationally recognized interval at which a resurvey should be performed. EUROCONTROL DO Spec [1] [requirement DO-SVY-220] mentions that intervals should be considered at a national level.

While a straightforward, universal interval cannot be prescribed, there are few cases in which specific action may be needed on a national level, to be enabled through regular monitoring or based on reports/events:

- resurvey items/data elements of critical integrity every X years (dependent on the local/regional drift velocity), or
- resurvey items/data elements of critical integrity if half of the "accuracy allowance" has already been consumed, or

Note: E.g., for an item of critical integrity – "Runway end-position" if drift velocity progresses over time, there exist additional regional ground movements etc. this may lead to "consuming" 0.5 m out of 1 m Aeronautical Data Catalogue-prescribed accuracy allowance. In such cases a resurvey is recommended.

- resurvey items/data elements of critical integrity in case of local/regional natural disasters e.g., major earthquakes.

All those strategies should be consulted among various stakeholders and experts representing AISP/ANSP data quality, geodesy, regulatory fields.

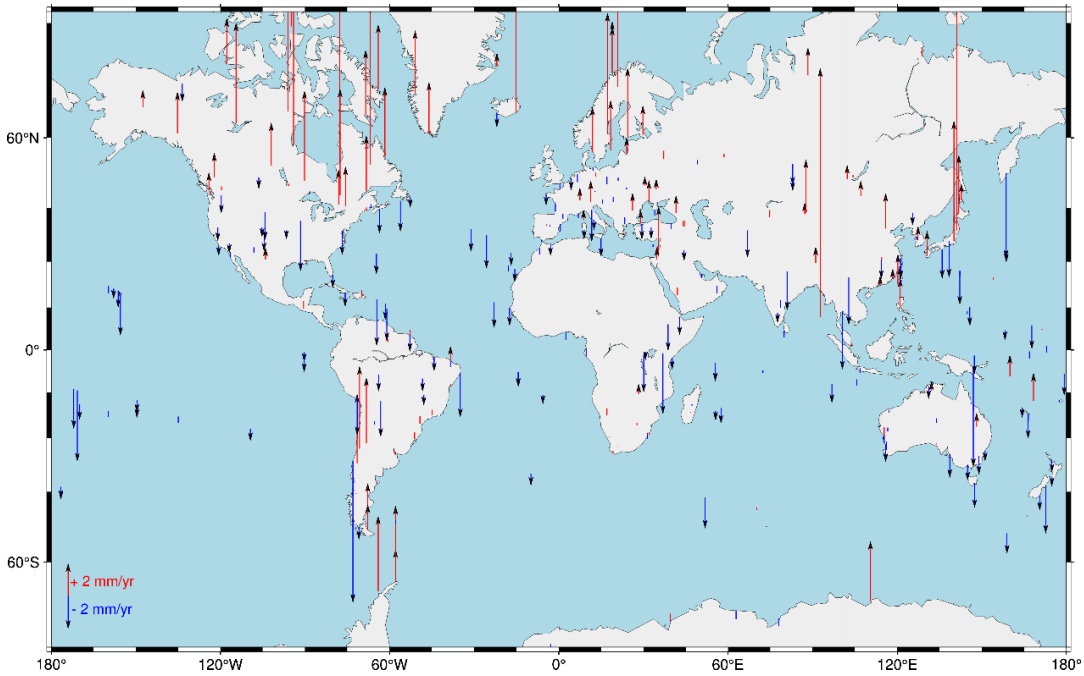
Appendix

A. Visualization of velocities in reference frames

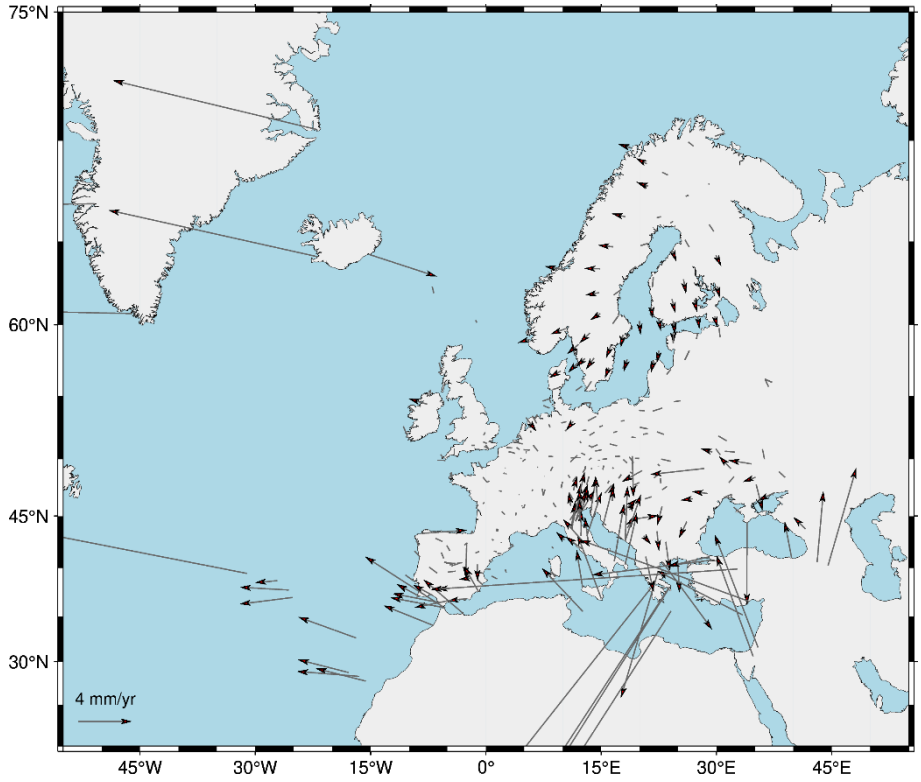
The Figure A1 below shows the horizontal velocities of stations in ITRF2020 on epoch 2015.00. The velocities in realizations of WGS 84 will be of the same magnitude.



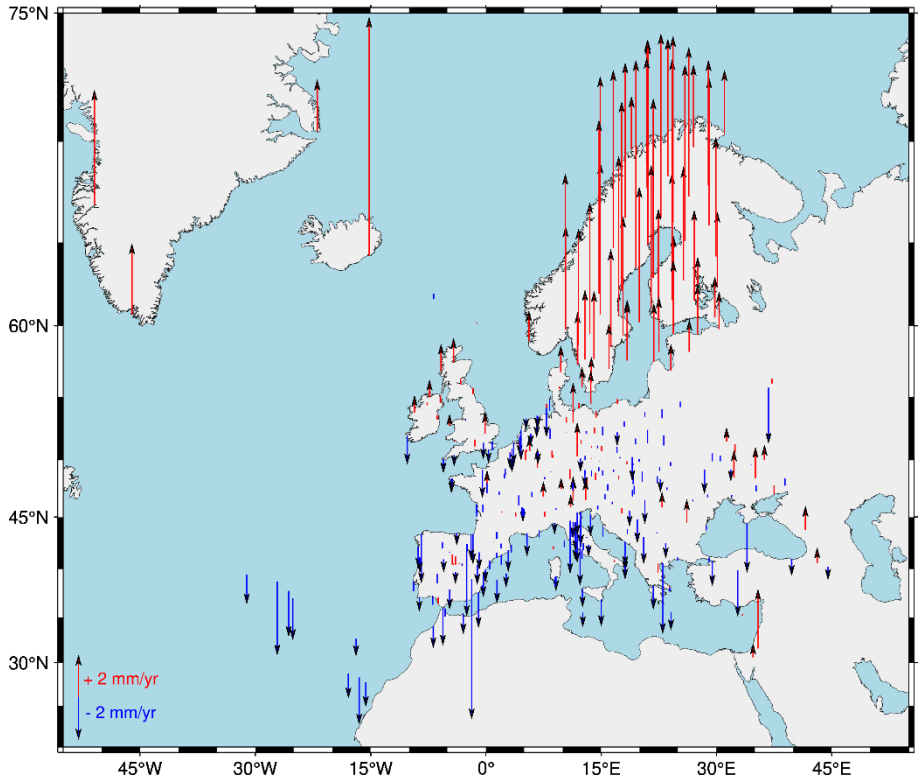
The Figure A2 below shows the vertical velocities of stations in ITRF2020 on epoch 2015.00. The velocities in realizations of WGS 84 will be of the same magnitude.



The Figure A3 below shows the horizontal velocities of stations in ETRF2000 on epoch 2010.00. Compared to Figure A1 (note the scale difference in the legend), the effect of plate tectonics is less present.



The Figure A4 below shows the vertical velocities of stations in ETRF2000 on epoch 2010.00. We clearly see important values in Northern Europe due to Glacial Isostatic Adjustment.



B. Overview of EPSG-codes

Realization	EPSG code geocentric (XYZ)	EPSG code geographic 2D (φ, λ)	EPSG code geographic 3D (φ, λ, h)
ITRF88	EPSG:4910	EPSG:8988	EPSG:7900
ITRF89	EPSG:4911	EPSG:8989	EPSG:7901
ITRF90	EPSG:4912	EPSG:8990	EPSG:7902
ITRF91	EPSG:4913	EPSG:8991	EPSG:7903
ITRF92	EPSG:4914	EPSG:8992	EPSG:7904
ITRF93	EPSG:4915	EPSG:8993	EPSG:7905
ITRF94	EPSG:4916	EPSG:8994	EPSG:7906
ITRF96	EPSG:4917	EPSG:8995	EPSG:7907
ITRF97	EPSG:4918	EPSG:8996	EPSG:7908
ITRF2000	EPSG:4919	EPSG:8997	EPSG:7909
ITRF2005	EPSG:4896	EPSG:8998	EPSG:7910
ITRF2008	EPSG:5332	EPSG:8999	EPSG:7911
ITRF2014	EPSG:7789	EPSG:9000	EPSG:7912
ITRF2020	EPSG:9988	EPSG:9990	EPSG:9989
WGS 84 (datum ensemble)	EPSG:4978	EPSG:4326	EPSG:4979
WGS 84 (Transit)	EPSG:7815	EPSG:8888	EPSG:7816
WGS 84 (G730)	EPSG:7656	EPSG:9053	EPSG:7657
WGS 84 (G873)	EPSG:7658	EPSG:9054	EPSG:7659
WGS 84 (G1150)	EPSG:7660	EPSG:9055	EPSG:7661
WGS 84 (G1674)	EPSG:7662	EPSG:9056	EPSG:7663
WGS 84 (G1762)	EPSG:7664	EPSG:9057	EPSG:7665
WGS 84 (G2139)	EPSG:9753	EPSG:9755	EPSG:9754
WGS 84 (G2296)	EPSG:10604	EPSG:10606	EPSG:10605
ETRS89 (datum ensemble)	EPSG:4936	EPSG:4258	EPSG:4937
ETRF89	EPSG:7914	EPSG:9059	EPSG:7915
ETRF90	EPSG:7916	EPSG:9060	EPSG:7917
ETRF91	EPSG:7918	EPSG:9061	EPSG:7919
ETRF92	EPSG:7920	EPSG:9062	EPSG:7921
ETRF93	EPSG:7922	EPSG:9063	EPSG:7923
ETRF94	EPSG:7924	EPSG:9064	EPSG:7925

Realization	EPSG code geocentric (XYZ)	EPSG code geographic 2D (φ, λ)	EPSG code geographic 3D (φ, λ, h)
ETRF96	EPSG:7926	EPSG:9065	EPSG:7927
ETRF97	EPSG:7928	EPSG:9066	EPSG:7929
ETRF2000	EPSG:7930	EPSG:9067	EPSG:7931
ETRF2005	EPSG:8397	EPSG:9068	EPSG:8399
ETRF2014	EPSG:8401	EPSG:9069	EPSG:8403
ETRF2020	EPSG:10569	EPSG:10571	EPSG:10570

C. Responsible agencies

Agencies responsible for the definition and maintenance of the national geodetic frame.

Country	Responsible Agency
Albania	State Authority for Geospatial Information (ASIG) Rr. "Pope John Paul II", Nd. 2, H. 3, 1010 Tirana Oltjon.Balliu@asig.gov.al - Head of Geodetic Reference Frame Sector info@asig.gov.al - State Authority for Geospatial Information (ASIG) in Albania.
Austria	Federal Office of Metrology and Surveying (Bundesamt für Eich- und Vermessungswesen) Dept. Geodetic Reference System (G1) Schiffamtsgasse 1-3, 1020 Wien referenzsysteme@bev.gv.at
Belgium	Nationaal Geografisch Instituut / Institut géographique national Kortenberglaan 115, 1000 Brussel, België info@ngi.be
Finland	National Land Survey of Finland (Maanmittauslaitos) Opastinsilta 12 C, 00520 Helsinki customerservice@nls.fi
Germany	Federal Agency for Cartography and Geodesy (BKG) Service Centre dlz@bkg.bund.de
Latvia	Latvian Geospatial information agency (Latvijas Ģeotelpiskās informācija aģentūra) O.Vācieša iela 43, Rīga pasts@lgia.gov.lv

Country	Responsible Agency
Luxembourg	Administration du Cadastre et de la Topographie 1 rue Charles Darwin, 1433 Luxembourg spslux@act.etat.lu
Netherlands (The)	Nederlandse Samenwerking Geodetische Infrastructuur Hofstraat 110, 7311 KZ Apeldoorn, Nederland rd@kadaster.nl
North Macedonia	Agency for Real Estate Cadastre Trifun Hadzi Janev 4, 1000 Skopje North Macedonia info@katastar.gov.mk
Poland	Head Office of Geodesy and Cartography Żurawia 6/12, 00-926 Warsaw, Poland gugik@gugik.gov.pl
Portugal	Directorate-General for Territory (Direção-Geral do Território – DGT) Rua de Artilharia 1, nº 107 1099-052 Lisboa Portugal
Republic of Serbia	Republic Geodetic Authority Vojvode Mišića Boulevard No. 39 11040 Belgrade, Serbia office@rgz.gov.rs; gs@rgz.gov.rs
Slovakia	Geodetický a kartografický ústav Bratislava Chlumeckého 4; 827 45 Bratislava gku@skgeodesy.sk
Switzerland	Federal Office of Topography swisstopo Seftigenstrasse 264, 3084 Wabern info@swisstopo.ch www.swisstopo.ch
United Kingdom (Great Britain)	Ordnance Survey Adanac Park, Southampton, SO16 0AS CustomerServices@os.uk

D. References

[1] EUROCONTROL Specification for the Origination of Aeronautical Data (EUROCONTROL-SPEC-154), Edition 2.0, 16 December 2021

[2] EUROCONTROL Formal Arrangement template (revised), Edition 2.0, 28 June 2023

E. Abbreviations

Abbreviation	Meaning
AIRI	Aeronautical Information Regulations Implementation subgroup of EUROCONTROL
AISP	Aeronautical Information Service Provider
ANSP	Air Navigation Service Provider
DD	Decimal degrees
DMS	Degrees, Minutes, Seconds
DO	Data Origination
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EGM2008	Earth Gravitational Model 2008
EPSG	European Petroleum Survey Group (registry)
ETRF	European Terrestrial Reference Frame
ETRS	European Terrestrial Reference System
EUREF	Regional Reference Frame Sub-Commission for Europe
EUROCONTROL	European Organization for the Safety of Air Navigation.
GNSS	Global Navigation Satellite System
GRS80	Geodetic Reference System 1980
IAG	International Association of Geodesy.
ICAO	International Civil Aviation Organization
IERS	International Earth Rotation and Reference Systems Service
INSPIRE	Infrastructure for Spatial Information in the European Community
ISO	International Organization for Standardization
ITRF	International Terrestrial Reference Frame -
ITRS	International Terrestrial Reference System -
NGA	National Geospatial-Intelligence Agency of USA
RTK-GNSS	Real-Time Kinematic Global Navigation Satellite System
SLR	Satellite Laser Ranging
TRF	Terrestrial Reference Frame
TRS	Terrestrial Reference System
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management
VLBI	Very Long Baseline Interferometry
WGS 84	World Geodetic System 1984

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