The importance of reference systems

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***Abstract* – The reference system is a fundamental concept in physics and geodesy. The reference system used in surveying consists not only of the coordinate system, but also of control points (geodetic network) which exist in real-world as natural material points. In addition to the coordinates, the time-factor becomes more and more important nowadays to define the reference system. In this paper I present the 3D, 2D and 1D reference systems which are used in GIS practice in Hungary. To define some problems, terms and abbreviations I bring up examples from my research work.**

About the definition of reference system

Position In physics, a frame of reference (or reference frame) may refer to a coordinate system used to represent and measure properties of objects, such as their position and orientation, at different moments of time. It may also refer to a set of axes used for such representation (en.wikipedia.org). According to Hungarian Grand Lexicon, the reference system is "... the set of material objects, to which movement of other objects is compared. In physical space specifying a location can be done in a reference system which should be completed by the possibility of measuring time. Generally a coordinate system is attached to the reference system". In Péter Biró's Satellite Geodesy notes: “The set of those material points and the connected coordinate system to which we correlate the location and the change of the location of the other points, is called a reference system…

Our coordinate system is tied to the underlying material points by the conventionally accepted coordinates of the framework. In other words the reference system (and its coordinate system) is implemented by the framework and coordinates accepted by convention” [1].

It is important to point out that the reference system is a broader concept than the coordinate system, because the latter always includes some geodetic network.

One aspect of the grouping of the reference systems is where to choose the material points (also called the frame points or control points) as a basis of comparison. If these reference points are infinitely distant stars (quasars), then it is called a celestial reference system. If the frame points cover the entire Earth, then terrestrial reference system is created. If the reference points are affecting a smaller geographical area than the whole world, it is called a local system. A local system may be continent-wide, or country-wide or may cover only a one settlement, or an industrial area, or even just a building or other object. In other context often just smaller then country-wide (national) system is called local.

Another possible classification criteria is the number of the required positioning data. According to this the reference system can be three-, two- or one dimensional (3D, 2D or 1D) in other words, spatial, planar or vertical system.

In the following paragraphs I summarize the particularities of the Hungarian geodetic and GIS applicational specifications of the reference systems, highlighting a few examples, in particular the prevalence of GNSS technology.

The spatial reference systems

The ITRFyy and the WGS84

The main important types of spatial reference systems are the terrestrial systems which are realized by control points spread across the whole Earth. Two key systems are: the ITRS and the WGS84 (International Terrestrial System, Word Geodetic System). The civil ITRS is operated by IGS and IERS (International GNSS Service, International Earth Rotation and Reference System Service). The WGS84 is originally a military system supervised by American Air Force and the military mapping service.

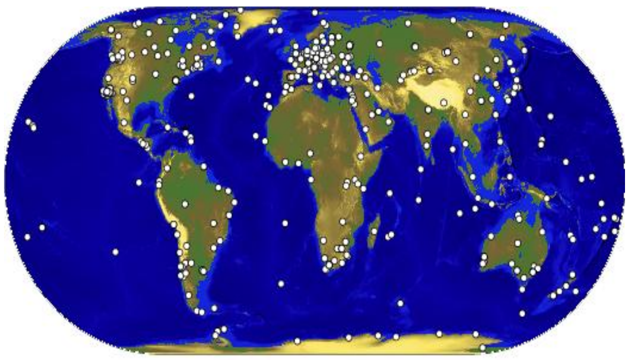

Figure 1. The IGS tracking network (http://igscb.jpl.nasa.gov/)

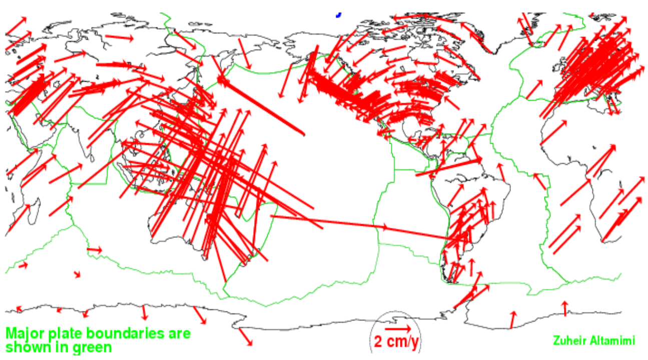

Figure 2. Velocity vectors of point-movement calculating from ITRF2008 and ITRF2005 realizations (http://itrf.ensg.ign.fr/)

There were only 13 points in the first measuring campaign in 1988 aiming for creation of ITRF89, but nowadays there are more than 500 continuously operating stations and four measuring techniques like GPS, VLBI, SLR, DORIS. Until now the following realizations have been created: ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF95, ITRF96, ITRF97, ITRF2000, ITRF2005 and ITRF2008 [2].

TABLE I. THE DIFFERENCE BETWEEN WGS84 AND THE ITRFYY REALIZATIONS

WGS84 realization	Epoch	Connected to ITRFyy realization	Accuracy (shift from ITRFyy)
WGS84 (original)	1984.0	ITRF90	Not available
WGS84 (G730)	1994.0	ITRF91	0.70 meter
WGS84 (G873)	1997.0	ITRF94	0.20 meter
WGS84 (G1150)	2001.0	ITRF2000	0.06 meter

The station coordinates calculated from different realizations make it possible to monitor the movement of continental platforms. The Fig. 2. shows the velocity field coming from 2005 and 2008 coordinates.

The difference between ITRFyy and WGS84 coordinate values are only one centimeter today, but it has been much more in the '90-ies (Table I).

The WGS84 is a reference system of American GPS and is managed by US army. In the beginning there were only five monitoring stations along the Equator on American military base camps but this number has increased. At the beginning of GPS-era (in 1990-ies) the accuracy of coordinates of these points was not up to the actual level that's why it had to improve, so the military and civil system were getting close together. This fine tuning was carried out four times, on 730, 873, 1150 and 1674 week based on GPS-calendar. As a consequence, if we want to be exact, we should add the GPS week number after WGS84.

ETRS89 and the Hungarian National GPS Network

Figure 3. The EPN stations of EUREF Permanent Tracking Network (www.epncb.oma.be)

In 1989 the establishment of spatial European network was started involving satellite-based techniques on about 30 Western European stations. This EUREF net (European Reference Network) was extended to Eastern Europe in the coming years for example to Hungary and former Czechoslovakia in 1991. Because the observatory points of this network were the same as the worldwide ITRF89 network, the first European spatial coordinates were born as ITRF89 coordinates.

Although, like we can see on Fig 2., the whole Eurasian platform is moving to north-east direction with speed 2,5 cm/year. That is why Europe needs its own reference system to avoid permanent change of coordinates. This special European system is the ETRS89 (European Terrestrial Reference System of 1989), which is based on ITRF89, epoch 1989.0 so at the beginning it was equal (coincidence) with ITRF89.

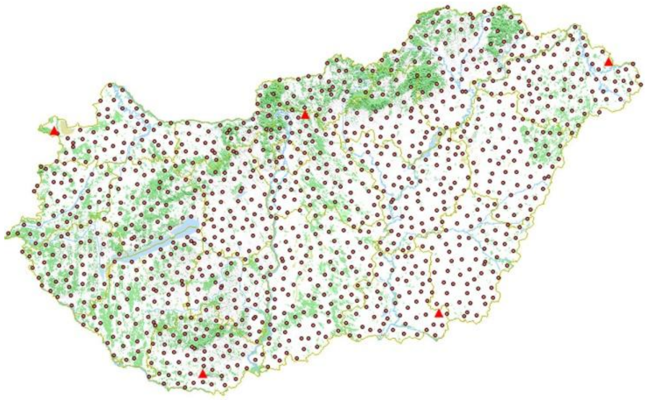

Figure 4. The National GPS Network of Hungary

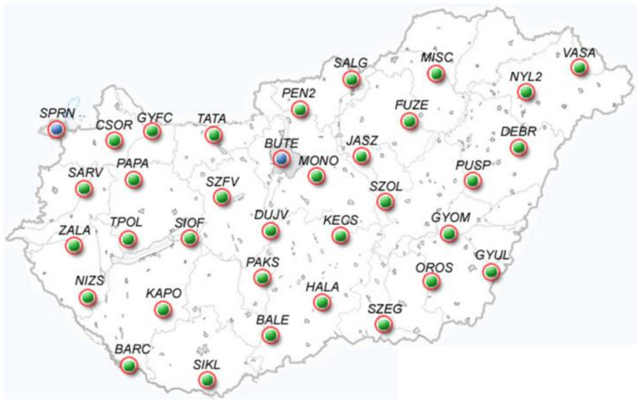

Figure 5. The National Active GNSS Network of Hungary (www.gnssnet.hu)

From global point of view the ETRS89 is not terrestrial but local system. Today the ETRS89 is not realized by observatories and by one-time measured field control points but nowadays the ETRS89 is monitored by a network of about 200 permanent GNSS tracking stations known as the EUREF Permanent Network (EPN). The IAG Sub-commission EUREF is responsible for the maintenance of the ETRS89. The ETRS89 has also more realizations because the coordinates of stations were updated some times. Until now the following realizations have been created in Europe: ETRF89, ETRF90, ETRF91, ETRF92, ETRF93, ETRF94, ETRF96, ETRF97, ETRF2000, ETRF2005, ETRF2008. Today the ETRS89/ETRF2000(R05) realization is the conventional frame of the ETRS89 system.

In Hungary the ETRS89 is the official spatial reference system also. The Hungarian National GPS Network (HNGN) and the Hungarian GNSS Permanent Network (gnssnet.hu) together realize the national spatial reference system. The HNGN consists of 1153 points and the gnssnet.hu has 35 stations inside country (and other 19 stations abroad in neighbouring countries). We have to know that the coordinates of HNGN points were updated in October 2007 [3]. The reason was the same as in the case of WGS84.

Figure 6. The WGS84 coordinates of SZFV permanent station on Google Earth

I have to underline once again that the ITRFyy and the ETRS89 is not the same, the difference between two systems is increasing by time. This linear difference is about 70 centimetres in plane today (there is no difference is height).

Let’s see an example, the geographical coordinates in both systems and its differences of the Székesfehérvár (SZFV) permanent station. The coordinates of this point in ITRF2008 system we get from Precise Point Positioning method with 24 hour long raw data and precise ephemerides; the estimated accuracy of coordinates is about 1 cm. (Remark: if we can be able measure absolute precise GPS-measurement real-time, we should get the same coordinates in WGS84 system, because the WGS84 and the ITRF2008 are mainly the same).

TABLE II.
THE COORDINATES OF SZFV PERMANENT STATION IN TWO SPATIAL EARTH-CENTERED REFERENCE SYSTEM

ITRF2008	ETRS89	diff. (arcsec)	diff. (meter)
φ= 47°11'19.57845"	φ= 47°11'19.56397"	0.01448”	0.45
λ= 18°25'07.80690"	λ= 18°25'07.78176"	0.02514”	0.53
h=173.286	h=173.287		

The well-known Google Earth shows the same coordinates if we click on the pillar in our Pirosalma-building (Fig. 6) where the Leica AT504 antenna is set up above the roof. The WGS84 coordinates are: φ=47°11'19.58", λ=18°25'07.81"; the height 129 meter above sea level.

If we want to test the accuracy of absolute positioning (single point positioning-SPP) with stand-alone receiver and the given coordinates we know in our ETRS89 system, we can take into account the difference between two reference systems.

In 19 March of 2014 we tested the accuracy of SPP using exclusively Galileo satellites [4]. It was the first opportunity to use only European Galileo satellites for positioning. The exact, precise coordinates of pillar, of course, were have known is our ETRS89 system, so we have to transform it to ITRF2008 used it by Galileo as its own system. The result was surprisingly good: the difference between the known and the measured position at the beginning was about 1 meter and at the end it was only 20 centimetres.

It is important to take into account the difference between actual ITRFyy and the ETRS89. It is shown not only in arc-seconds but in ellipsoidal distances also in the Table II.

THE HORIZONTAL REFERENCE SYSTEMS

The spatial objects for visualization we transform to the plain (to the paper-based map or to the screen), so we are using map projection connecting with planar coordinate system. The horizontal reference system in this case is also much more, than coordinate system: the ellipsoid (as a base surface), the metric system and the horizontal geodetic control network is also part of it. The base surface (which is an ellipsoid in geodesy) including the horizontal network and its orientation is called geodetic datum.

In the past there was many map projection systems in Hungary due to historical events. Some names from 20. century: Budapest Stereographic Projection (ST), North Cylindrical Projection (HÉR), Central Cylindrical Projection (HKR), South Cylindrical Projection (HDR). We have to know that different triangulation networks belonged to the same projection (namely Budapest Stereographic Projection). In the other words, the coordinates of different networks were projected by the same equations to the mapping plane, so it means these are different reference systems.

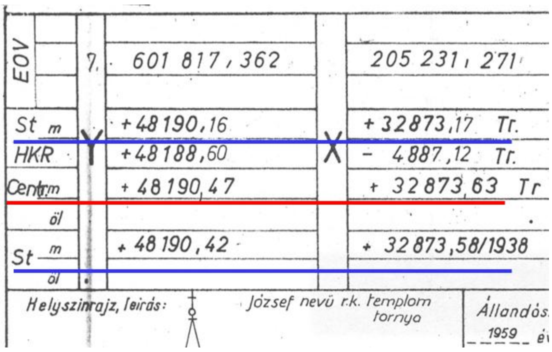

Figure 7. Different coordinates, same projection on point sheet of central point of Székesfehérvár independent network

For example: the Budapest Stereographic Projection serve not only the national triangulation network but the independent Budapest local capital network or also for independent local network of town Székesfehérvár (established in 1938). Therefore it is insufficient if we use only projection name to identify the reference system. This is how the name of Budapest capital reference system or Székesfehérvár central reference system formed. The Hungarian abbreviation is BOV (for Budapest) and "Centrális" (Székesfehérvár) for this two systems. We can see that the national and local coordinates are different browsing point protocols and other measuring documentation (Fig. 7).

The Hungarian Datum 1972 (HD72) and the Unified Hungarian Grid (EOV)

In 1970-ies the new geodetic foundations were established in Hungary: a new horizontal and vertical networks, a new base surface, a new projection, a new mapping system [5] [6]. Since there is only one official map projection system in our country (in Hungarian abbreviation called EOV - Unified Hungarian Grid). All official state base maps are made and visualized in this projection. Maybe the short abbreviation "EOV" is useful in everyday use but we have to know that horizontal reference system mean more than projection.

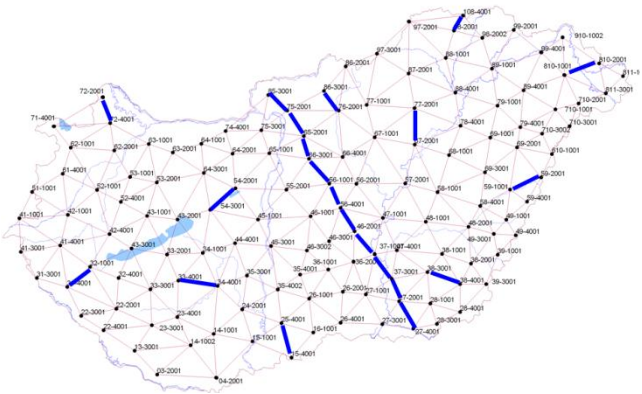

Figure 8. The first order National Horizontal Network highlighted the measured distances

The EOV is a conformal cylindrical reduced double projection applying a scale factor 0.9993. Its base surface is called GRS67 ellipsoid (the other name is IUGG67 ellipsoid). The other important part of Hungarian planar reference system is the triangulation network. This Unified National Horizontal Network (in Hungarian: EOVA – *Egységes Országos Vízszintes Alapponthálózat*) was established between 1949 and 1992.

The final calculation and free adjustment of the first order network took place in 1972, that's why the geodetic datum (and sort abbreviation) derives from here (Hungarian Datum, HD72). The first-order network has altogether 167 points, 141 from which can be found inside country (Fig. 8), while the rest ensure the relationship with the neighbouring countries.

As Hungary was a member state of the Warsaw Pact, for confidential purposes a line had to be drawn between the military and the civil system. Originally the Krassovski ellipsoid and a Gauss-Krüger projection was designed to be the base-surface and the map grid for the military system. And also for the same horizontal network the GRS67 ellipsoid and the EOV projection was chosen to form a Hungarian civil horizontal system (HD72).

The Hungarian Datum 1972 and the ETRS89

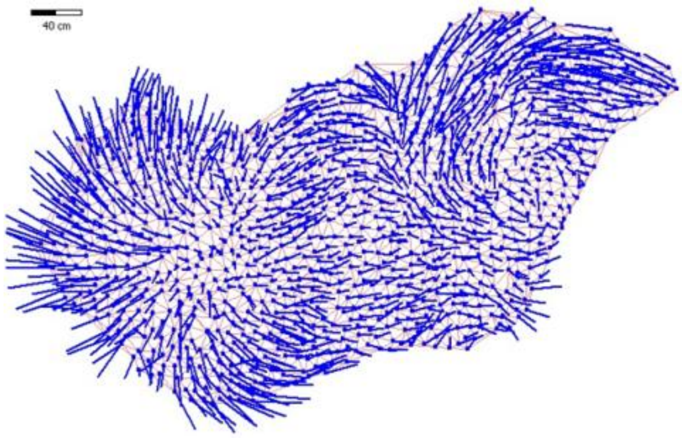

Figure 9. The linear distorsions between ETRS89 and HD72 in 1146 points after nation-wide spatial similarity transformation

After the National GPS Network was created, it became possible to define the accuracy of the EOVA coordinates. The accuracy of the National GPS Network is homogeneous over the whole area of the country and its accuracy is estimated to be 1-2 cm, but not for the EOVA. Since the National GPS Network points are given in both reference systems, they can be compared with a spatial Helmert similarity transformation. The result is known (see Figure 9), the maximal linear difference can be up to 40 cm.

That's why only a local transformation has to be used for surveying purposes covering an area of 20-30 km in diameter.

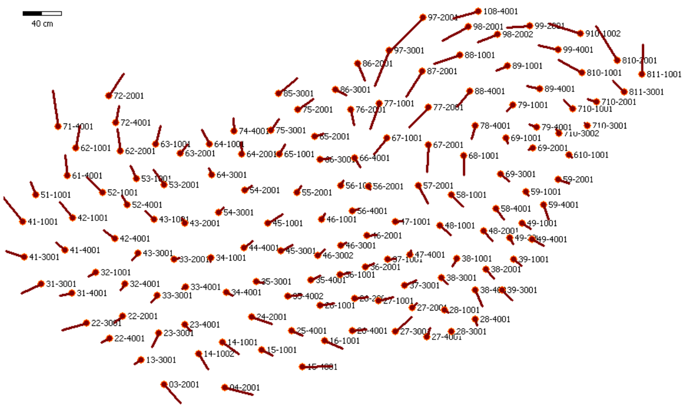

Figure 10. The linear distorsions in 141 first order points comparing two types of adjustment

I wanted to answer the question why the figure is so unique and why the lines are rotating in a special way. I would like to show the results of a previous research on the topic [7].

Electronic distance meters appeared in the 1960s, which provided the chance to measure the length of several first-order sides directly. A total of 23 distances were measured with the most modern devices (type AGA6) of that time. Two distances reached outside of the country borders. A have to point out that the adjustment of the first order network of the EOVA was prepared with a constraint relation that the measured distances can't change. These distances didn't get residuals during adjustment.

21 distances I re-measured and checked with GPS-technology. After comparison the result was this: all 21 distances (the average length is 24.4 km) measured by GPS are 11 centimetres smaller then original ones. The scale factor is -4.5 ppm. Then I model the difference between the adjustment when I used the original distances and the case when I used GPS-based distances with the same angles. The two set of coordinates of first order points I transformed by planar similarity transformation. The result (Fig. 10) was mainly the same as have seen on Fig 9.

Further questions may be what should be the optimal transformation method between ETRS89 and HD72 due to the mostly used surveying technique is GNSS, but the result we want to get in local system. The best solution is the local transformation the basic of it is the 1153 points of Hungarian GPS Network as a common point database. A practical, handy software are used for this purposes like the free EHT program (from FÖMI SGO) [8] or online solutions from TU Budapest.

THE VERTICAL REFERENCE SYSTEMS

The basic (equipotential) surface of vertical measurements is the geoid which is referred to a specified mean sea surface. In Hungary two seas are used for this purpose: Adriatic sea and Baltic sea. In 1875 there was a mareograph installed in Trieste and it measured the sea level during 9 months and the average of this measures become the zero level. The height of number 1 benchmark by precise levelling is 3.3520 meter. All other benchmarks are referenced to this point, and are called Adriatic heights in Hungary. The so called main benchmarks in Nadap village (later Nadap I. point) was also defined from this network. For a long time (till 1960) the Hungarian vertical reference surface was those equipotential surface which can be found below the 173.8385 meter of Nadap I. benchmark. The Baltic sea level is mean sea surface measured by a mareograph in Kronstadt Bay.

To be able to use the chosen sea level in practice there is a need for levelling networks. In Hungary the expected density of national benchmarks is 1 point/4km2.

So far there are four levelling networks established in Hungary.

The first levelling network (1872-1914) was spread to the whole Austro-Hungarian Monarchy; the Nadap I. monument is the professional memento still existing nowadays.

The second levelling network (1925-1939) was built between two world wars.

The third levelling network was created between 1949 and 1964 by László Bendefy so sometimes it is called Bendefy-network.

The building of fourth levelling network was started in the 1970-ies and is called Unified National Vertical Network (Hungarian abbreviation: EOMA - *Egységes Országos Magassági Alapponthálózat*). The first order of this network was ready relatively quickly (1973-1978), but the densification of second and third phases became ready only by 2006 in the whole country.

In the first two networks the starting (known) point for adjustment was the Nadap I. benchmark, and the height of points was referring to Adriatic sea. In 1960 it was mandatory to change to the Baltic sea level (the reason was also the Warsaw Pact).

The starting point (the only one known point) for adjustment in EOMA is the new Nadap II. benchmark (the upper round surface) the given height is 176.23382 meter above Baltic sea level.

Figure 11. The latest National Vertical Network (EOMA)

Baltic heights or EOMA heights?

The heights of control points is changing not only because of the different basic surface. It is obvious that the heights of the same point is varying because of the technology, accuracy, adjustment method and mainly because of the movement of the surface. That is why the different networks built in different time periods mean different vertical reference systems.

But there is no appropriate expression for it. In Hungarian practice we talking about the “Baltic height” and “EOMA-height” despite the fact, the both reference systems are using the Baltic sea level and the original reference point referring to the same Nadap point.

Ellipsoidal height and mean sea level height

Today the majority of height measurement is carried out by GNSS technology therefore the question is: what is the accuracy of heights measured by GPS? It depends on two factors.

First the accuracy of GPS-measurement: this depends on technology which starts from traditional static method to network RTK, so the standard deviation is around 1-5 cm (referring to ellipsoidal height). The second factor is the transformation model, because in every case the WGS84 ellipsoidal height must be converted to the sea level height. The model of it, the method, the used geoid model and the number and quality of common transformation points all are influencing the result.

For the transformation the most commonly used software is the EHT and VITEL in our country. For both software the common base is the National GPS Network the points of which coordinates are known in both system.

The one problem is that the big parts of these points is not originally levelled but converted values from ellipsoidal heights. Another problem is that the levelled points are erected partly from Bendefy-network and partly from EOMA. Due to this even the transformation itself could cause several centimetres or one decimetre error. The latest versions of these transformation software give better transformation results as the basic data and the transformation model was updated and fine-tuned.

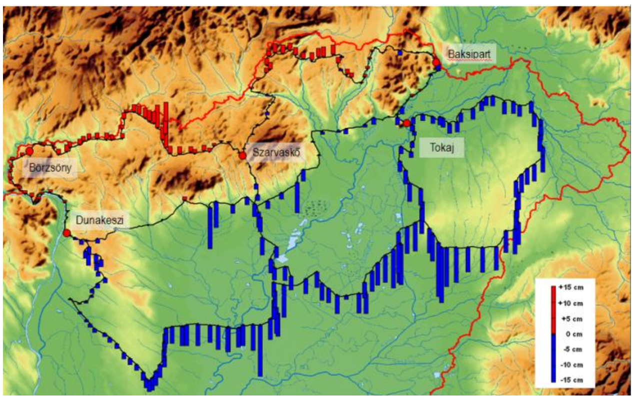

Figure 12. The surface movement at North-east part of Hungary between 1977 and 2009 determined from re-measured levelling benchmarks in three EOMA polygons

Finally I have to mention the problem of recent vertical crustal and surface movement. No matter how accurately we measure the levelling network if meanwhile the physical position of benchmarks are changing due to surface movement. In 2007-2009 three first order levelling polygons was re-measured in the North-east part of Hungary. The results (Fig. 12) have shown the height differences reaching 10 centimetres during 32 years.

To fully answer the question the whole EOMA network should be re-levelled in Hungary but it has financial obstacle.

THE TIME FACTOR IN THE VISUALIZATION

In so far, in my paper I wanted to show that geodetic networks established at different times are mean different reference systems. While in the past it took very long time (typically some decades) to create a national network, nowadays it is possible in hours or days and the network can be continuously refined. So the coordinates from different dates must be fitted with year or more accurate date.

The development of modern software also allows you to visualize time-varying processes and phenomena on a computer screen to illustrate the movement itself, creating dynamic maps (in the same reference system).

Well known example is representing meteorological phenomena (wind speed and direction, wind zone, rainfall intensity etc) versus time, creating an animated drawing. Hungarian websites (like www.met.hu or www.idokep.hu) are such services greatly helping both experts and lay people's work and raise awareness of a possible impending adverse event.

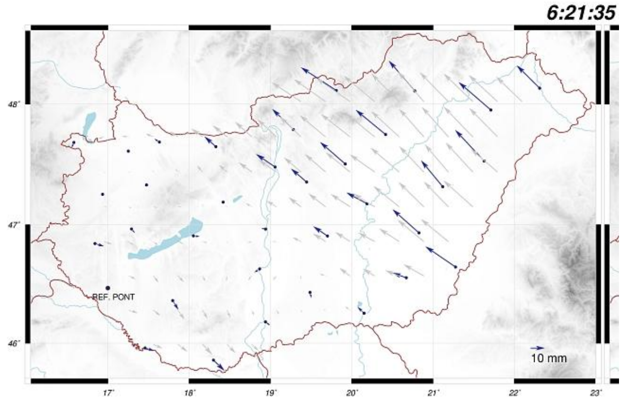

Figure 13. Snapshot of deformation in Hungarian active points caused by Rayleigh-wave during Japan earthquake on 11 March 2011 UTC 6:21:35 (www.urvilag.hu)

Colleagues of FÖMI SGO studied the big Japanese earthquake in 11 March 2011, using the Hungarian active GNSS network's second rate measures (raw data, Rinex files) relative to a reference point Nagykanizsa (NIZS). The result was presented with speeded up animation on urvilag.hu (Fig. 13) [9].

Satellite orbiting, geoid-image change, building or structure displacement, deformation or any dynamic phenomenon can be virtualized by computer, accelerating or slowing down the process in time as required.

There is no doubt that in the future there will be even more demand of cartographic presentation of changing processes in time, and hopefully the technical possibilities will be available also.

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