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GIS and dynamic reference frames

# The time dimension

Dynamic reference frames are inherently spatio-temporal. This is a fundamental difference to most commonly used reference frames today. Especially in GIS, where the two-dimensional coordinate is the predominant choice. More and more geospatial software vendors are extending their software to be 3D-aware. Commonly used GIS file formats has been capable of storing 3-dimensional coordinates for a long time, and the software is now catching up as well. With the introduction of dynamic reference frames a similar switch needs to take place in the GIS world, this time by including the time in coordinates. This chapter explains the current state of GIS with regards to coordinate usage and what needs to be done before the time dimension can be applied in real world GIS applications. Below is a description of how the time dimension is handled in the three main GIS data types used today as well as a discussion about time in spatial reference system descriptions.

## Spatial reference system descriptions

Usually in GIS files the reference frame and coordinate system of the data is described in the header of the file. A common standard for this is the Well Known Text (WKT) standard by the Open Geospatial Consortium. With WKT it is possible to describe, in details, the reference frame, coordinate system and projection of a given spatial dataset. The WKT standard exists in two versions. The first version was introduced in 1999 is the most commonly used today. WKT version 2 was introduced in 2015, and still hasn’t been widely implemented in GIS applications. Unfortunately, only the latest version of WKT include ways to describe the temporal dimension of reference frames and coordinate systems. Since WKT2 is not used in most GIS applications it is not possible to create a proper description of a dynamic reference frame that can be understood by today’s GIS applications. Adaption of WKT2, or an equivalent standard, by mainstream GIS applications is an absolute necessity for implementation of dynamic reference frames.

## Vector data

Vector data consist of vertices and paths that describe different feature types, e.g. points, lines and polygons. The vertices make out the actual coordinates in the features. Most GIS applications today implement and use the Simple Features model which is a standard created by OGC and ISO (19125). The same goes for most widely used vector file formats and spatial databases.

As mentioned above, 2D coordinates are the most common in GIS today, but both 3D and 4D coordinates are also compliant with Simple Features. The first three dimensions of a coordinate are fixed as the three spatial dimensions (x, y, z), whereas it is up to the user to decide what is stored in the fourth dimension. The fourth dimension is known as the “measure”, or the m-coordinate. The intention of the m-coordinate is to enable various measurements related to the geometry to live besides the main coordinates. It could be a velocity of a tracking device or some other physical attribute related to the coordinate. With the current possibilities of the Simple Features model, the m-coordinate is the obvious choice for storing the time dimension of spatio-temporal coordinates. It is however not the ideal solution, since occupying the m-coordinate with time-tags excludes storing other measurements in that space. This will be a disadvantage in use-cases where the m-coordinate is already used for something else than time tags. The proper solution is extending the Simple Features model to include time as a dimension in itself.

Most GIS applications support 3D coordinates and a few has also extended that to include the fourth dimension, although that is not in widespread use today. Access to the fourth dimension is crucial for the implementation of dynamic reference frames in GIS applications.

Most commonly used vector file formats are already suitable for use with a dynamic reference frame if the m-coordinate is used as a placeholder for the time dimension. It is also required that WKT2 is used to describe the spatial reference system. So a practical solution is within reach with most file formats already used today but updates to the Simple Features model is necessary in order to fully implement spatio-temporal coordinates in GIS.

## Raster data

Raster data is a grid-based data type and is usually used for imagery or other area-based sensor data. The grid is comprised of evenly distributed cells organized in a number of rows and columns. Rasters consist of one or more bands of data, for instance a color aerial photo consists of three bands, one for each color channel in the image (R,G,B).

Raster data is georeferenced at one of the corner cells in the grid. The rest of the cell coordinates can be inferred from the cell-size and the row and column number in the grid. The georeference and cell size is described in the header of a raster file alongside information about the spatial reference system. Coordinates in rasters are inherently two-dimensional, since the grid only exists in two dimensions. In many cases on of the bands in a raster is used to store a height value. When extending the usage of raster data to dynamic reference frames, the same approach could also be used to store the time but since all data in a raster is usually acquired at the same time, it is more sensible to store a common time tag for the whole raster. Ideally this is placed in the header of a raster file as part of the spatial reference system description, which is possible with the WKT2 standard as mentioned above. In practice the time of data acquisition will be registered as the epoch of the dynamic reference frame.

## Point cloud data

Point cloud data sets are in many ways similar to vector data consisting of points. The main difference is that point clouds normally contain massive amounts of data with a range of sensor-based information attached to each point. Coordinates in point clouds are 3-dimensional and almost always also contain a time-tag for the acquisition time of that particular point. Since the data is spatio-temporal in nature it is fairly easy to use in a dynamic reference frame. A suitable spatial reference system description is of course still needed, which can be achieved with WKT2.

# Implementation of deformation models

Deformation models used in GIS today is primarily, if not always, gridded models that can be applied to data in a certain reference frame. This way of bringing complex deformation models into GIS is a practical solution to an otherwise complicated problem.

Gridded deformation models are inherently time invariant since they represent a deformation limited in time, e.g. non-linear changes from one datum to another. Deformation models that vary with time is not used in GIS today, and for the time being that trend seems to be continuing. Some of the reasons being that coordinate transformation will be too heavy for day-to-day use and that generic algorithms for modelling complex time-varying deformation aren’t readily available.

A deformation grid consists of regularly spaced discrete values. The grid is used to offset coordinates with the values in the grid. Bilinear interpolation is typically used to determine the exact offset between grid nodes. Normally deformation model grids consist of two bands, one for each direction in the horizontal plane. Including the vertical component is possible but is usually handled in a separate grid, that is applied either before or after the horizontal deformation model grid.

When implementing dynamic reference frames in GIS, the need for time varying deformation models is evident. Since classical time varying deformation models are not suited for GIS, a grid-based solution can be implemented instead. A grid based approach requires a series of grids that, when applied sequentially, model the deformation evolution of a certain area. The grids need to be supplied with time tags that delineate the time span a certain grid is applicable within. This makes it possible to derive the proper deformation when transforming coordinates from one epoch to another. For instance, if coordinate *C* is transformed from epoch 2 to epoch 5 in a setting with grids *Gt*, where *t* is the starting epoch of the grid and *t+1* is the end epoch of the grid, it will be affected by grids *G3* and *G4*, but not *G0* and *G1*.

The maintainers of a reference frame will regularly have to issue new grids when significant deformation events happen. For the users of the reference frame this can be a problem, since they need to be aware of any updates to the deformation model.

# Challenges

Before a practical implementation of dynamic reference frames can be realised in a modern GIS application, there is a series of challenges that need to be overcome. This section will describe the most important ones.

## Implementation of new standards

Today spatial reference systems in GIS datasets are described with the initial version of the Well-Known Text standard[[1]](#footnote-1). This version unfortunately does not have temporal awareness. This has been introduced in version 2 of the format, but that is still not in widespread use. The main reason for that is that version 2 of WKT omits the “towgs84” parameter, which describes a 7-parameter Helmert transformation to WGS84 (realization and epoch unspecified). The towgs84-parameter ensures that software can transform coordinates in any coordinate reference system to any other coordinate reference system with WGS84 as a pivot datum. Without the “towgs84”-parameter, transformation software will have to approach the problem in a fundamentally different way.

## The EPSG geodetic parameter dataset does not include epochs of reference frames

The EPSG geodetic parameter dataset[[2]](#footnote-2) is the de facto standard for indexing coordinate reference systems and transformation between them. More or less every GIS uses the EPSG database to describe coordinate reference systems and determine how to transform between them. Unfortunately, the EPSG database does not include information about which realization and epoch reference frames are given in. This poses a problem since a dynamic reference frame can’t be fully described within the current model of the EPSG dataset. Generally, the time dimension is ignored within the EPSG dataset.

## Transforming coordinates to current epoch of data from its original “time tag” epoch

This challenge is tied to the two sections above that discusses the missing awareness of the time dimension of GIS data. We want to use data that relates to a static reference frame in a dynamic reference frame context. In theory it is possible to mix data between static and dynamic reference frames. For this to work, the realisation and epoch of the static reference frame needs to be known. In current reference frame metadata in GIS files and databases this information is not readily available. As mentioned above, in most cases it will be possible to derive an approximate epoch for a given reference frame. For instance, a dataset marked as ETRS89 can be referenced to more than ten different realizations. This is a problem if you need high-precision coordinate interoperability.

## Management of databases

As long as the issues regarding the time dimension outlined above is taken care of, most problems with management of geospatial databases are solved. There are some finer details which need to be taken care of still.

Some datasets are so big that on-the-fly coordinate transformation is not feasible. An example of this is national scale raster data. These types of datasets are typically served through the internet via WM(T)S and are available in a few different coordinate reference systems. These data are pre-compiled in different coordinate systems because re-projecting images tends to obscure the data. This can be problematic when mixed with data in a dynamic reference frame. A practical solution to this could be to update the raster datasets at fixed intervals and transform them to the epoch of the update time. As long as the update intervals are not too long agreement between the database coordinates and the local coordinates will be sufficient for most use cases. The update intervals are dependent on the accuracy that is needed for a specific purpose. For this you have to take plate movement into account and update the coordinates whenever the reference frame has moved far enough away from the coordinate at the specified epoch. In general, this will be governed by the velocity model, but special attention is needed when big deformation events occur. A sudden deformation event like an earthquake most likely requires the release of a new deformation grid, in which case the coordinates should be update immediately after the grid has been released to the public.

Another issue to be aware of with regards to managing spatial databases is that the INSPIRE directive requires all datasets within the context of INSPIRE to be referenced to ETRS89. If a dynamic reference frame is adopted as a country’s main reference frame, a large amount of data will have to be managed in a different system. Many datasets will very likely be kept in two different versions.

## Implement DRF in geospatial software

Two ways of implementing dynamic reference frames in geospatial software exists. Either existing software is extended to be able to handle time-varying coordinates, or stand-alone software that can translate between DRF data and data that exist within a static reference frame.

The first option has been discussed thoroughly above. It relies on the geospatial community adopting newer standards like the WKT2 for spatial reference system descriptions. It also relies on the willingness of software vendors to implement the needed changes. This is the optimal solution for a practical implementation of dynamic reference frames, but it is also likely to be solution that will take many years to implement and be fully adopted by the geospatial community as a whole.

The second solution is to supply a stand-alone application that can handle time-varying coordinate transformations. The stand-alone application will convert data to and from formats that are usable by existing geospatial software. This approach is also used today by e.g. professional surveyors. that need to carry out high-precision coordinate transformations. Datasets can be transformed to the same coordinate system by the payload application and then opened in a GIS where the data can be analysed. analysed.

1. <http://docs.opengeospatial.org/is/12-063r5/12-063r5.html> - OGC: Geographic information - Well-known text representation of coordinate reference systems. [↑](#footnote-ref-1)
2. [http://www.iogp.org/pubs/373-07-1.pdf](%20http%3A//www.iogp.org/pubs/373-07-1.pdf) EPSG Guidance Note 7.1: Using the EPSG Geodetic Parameter Dataset [↑](#footnote-ref-2)