Description of how to implement deformation models in GIS

D3.4 of the DRF-Iceland-S1 project

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| Delivery description: Once a suitable concept for the deformation model has been found, a viable solution for operationalizing it in GIS applications should be found. This deliverable will include a brief summary of what the state of the art is in terms of implementation of dynamic reference frames in mainstream GIS applications, with a focus on how deformation models are handled. Additionally, it will provide a prototype implementation of the Icelandic deformation model in the PROJ coordinate transformation software. PROJ is the coordinate transformation engine used by most open source GIS applications today. When the deformation model has been implemented in PROJ, it will be possible for the developers of applications like QGIS to incorporate the DRF deformation model in their application. |

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## Application of deformation models in GIS today

In general, the use of deformation models in GIS today is limited. To fully leverage a deformation model in transformations the temporal component is needed. At the time of writing no mainstream GIS application has the ability to handle spatio-temporal coordinates. There are several reasons for this including a lack of standardization and no particular widespread need for the level of accuracy that transformations with deformation models offer. So for this reason it is almost impossible to use a deformation model in coordinate transformation within a GIS today. A few workarounds are known to exists though, most notably the deformation model used by New Zealand Land Information (LINZ) for their NZGD2000 semi-dynamic datum and advanced use of recently developed features in the coordinate transformation library PROJ.

LINZ has defined their semi-dynamic datum NZGD2000 in such a way that it is updated whenever a big episodic deformation event occurs. Additionally, the datum includes a secular deformation model that absorbs the deformation of the frame as the Australasian and Pacific tectonic plates converge. In GIS applications the secular deformation is ignored because of the lacking spatiotemporal coordinates. Transformations between NZGD2000 and other reference frames is mainly done by grid translations. This requires a gridded model of the differences between NZGD2000 and the system transformed to or from. When large episodic deformation events happen, the reference frame is updated and so is the transformation grids. The coordinate movement caused by secular deformation is dealt with in these grid updates which eliminates the need for a spatiotemporal GIS. Of course this transformation strategy introduces some uncertainty but it is well below the requirements for most GIS users.

Recent development on the PROJ transformation software has introduced new functionality that enables transformations including a deformation model. This functionality was originally added in order to perform transformations in the Nordic countries which require a deformation model to adjust for the post-glacial uplift in Fennoscandia. This new functionality *can* be used in GIS applications that uses PROJ as transformation engine but not out of the box – significant custom setup is expected from the user at this point in time. This will change over time as more and more GIS developers realize the need for temporal awareness in their applications.

Apart from the two above examples there are not many cases of a deformation models being used directly in GIS software. Most often the geodetic office in a country will provide software that takes care of transformations between global frames and the national frame. While being a hassle for users it is a well-known concept that has proven its worth over a long time period. Many examples of such software exist, for example the HTPD software used in USA. This software handles both secular and episodic deformation, as well as take tectonic plate motion into account. The HTPD software can be used to create transformation grids that maps from a specific frame and epoch to another specific frame and epoch. These grids can be used in some GIS applications, for instance QGIS.

## Implementation in PROJ

In the DRF-Iceland project we strive to use PROJ as the coordinate transformation tool. PROJ is an open source software package that is used in many GIS applications spanning across all of the geospatial toolkit ranging from command line tools over desktop GIS to web mapping applications. It is likely to be the coordinate transformation tool that is in most widespread used in geospatial software. Recently the geodetic functionality of PROJ has been enhanced significantly, making it a toolkit for not only cartographic purposes but also useful for the geodesist and land surveyor who has higher accuracy requirements. This is bridging the gap between GIS and geodesy allowing much higher accuracy in coordinate operations in geospatial software.

PROJ being an open source package also means that contributions of new features in the software are generally accepted as long as they provide value to the geospatial community in general. Therefor we prototype the transformation tools needed for the Icelandic dynamic reference frame in PROJ.

For the Icelandic dynamic reference frame a deformation model is needed. It is used in coordinate transformations to bring a coordinate from one epoch to another. In the Icelandic case there are numerous geophysical phenomena the deformation model should take into account. These include plate tectonics, seismic activity and volcanism. In general, these can be divided into secular and non-secular deformation. Below are described the concepts for handling these two types of deformation in coordinate transformation. Finally, it is described how the two types of deformation are combined in coordinate transformations in the dynamic reference frame.

**Secular deformation**

The secular deformation consists of all the deformation contributions that can be predicted by a model. The main contribution to secular deformation is tectonic plate motion but various forms of intra-plate deformations can also contribute to the overall secular deformation.

In the most recent version of PROJ (5.0.1) it is possible to use a secular deformation model in transformations. This is demonstrated in the NKG ITRF transformations already. Secular deformation in the Icelandic DRF can be handled in the same way. In the NKG ITRF transformations the tectonic plate motion is not handled with the deformation model. Instead it is included in the transformation from ITRFyyyy to ETRFyyyy where the rotational velocity of the continent is included. The same is not possible for the Icelandic transformations since the North American and the Eurasian plates are diverging. This divergent velocity pattern can be reflected in the deformation model itself instead. Given such a deformation model, PROJ in its current state will be able to handle the secular deformation in the DRF transformations.

The secular deformation can be applied with a PROJ operation with the below parameters:

+proj=deformation +t\_epoch=2010.0

+xy\_grids=@iceland\_secular\_model\_xy.ct2,@null +z\_grids=@iceland\_secular\_model\_z.gtx,@null

Where it is assumed that the input coordinate is an ITRF2014 coordinate. The reference epoch for the deformation model is chosen as 2010.0, the same reference epoch that is used in ITRF2014. Effectively this allow us to propagate coordinates through time using the deformation model without introducing additional steps in the transformation.

For the final implementation of the DRF the possibility to exclude the plate motion from the deformation model should be investigated. This will require development of an operation in PROJ that can distinguish coordinates from either side of the plate boundary and apply different velocities depending on the position of the coordinate.

**Non-secular deformation**

Non-secular deformation consists of deformation events that can’t be predicted and can only modelled after they have occurred. In the Icelandic case non-secular deformation is primarily caused by earthquakes. Earthquakes usually result in two types of deformation. Coseismic deformation, that happen more or less instantaneously, and post-seismic deformation that takes places in the time immediately after the earthquake to several decades after the seismic event. The biggest contribution comes from the coseismic deformation but the post-seismic signal is in many cases so big that it can’t be ignored. In this study we only focus on the coseismic contribution to the non-secular deformation. It is possible to also handle post-seismic deformation in the transformations but that is out of scope for this project. However, it should be mentioned that it is indeed possible to implement post-seismic deformation models in PROJ. This subject will be studied further in the future.

Coseismic deformation can be handled as a series of grid shift transformations that, when applied sequentially, model the deformation evolution of a certain area. That is, a gridded model will be created for each major deformation event that happens in the lifespan of the reference frame. 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 epoch of the deformation event the grid models, it will be affected by grids *G3* and *G4*, but not *G0* and *G1*.

This method of transformation is available in PROJ from version 5.1 an onwards. It is implemented by extending the *hgridshift[[1]](#footnote-1)* and *vgridshift[[2]](#footnote-2)* operations with the option of only being applied when a coordinate is transformed from an epoch before the deformation event of the grid to a later epoch. An example of a transformation based on a stack of grids modelling episodic events could look something like:

+proj=pipeline +t\_final=2025.0

+step +proj=hgridshift +grids=@event1\_xy.ct2 +t\_epoch=2019.23

+step +proj=hgridshift +grids=@event2\_xy.ct2 +t\_epoch=2020.82

+step +proj=hgridshift +grids=@event3\_xy.ct2 +t\_epoch=2022.64

For the sake of simplicity, the example only covers the horizontal parts but the concept can easily be extended to the vertical as well. This would add an additional step for each modelled event. In the example +t\_final=2025.0 is a global parameter that is applied to all subsequent steps in the chain of operations in the transformation. It denotes the final epoch of the coordinate after transformation, that is a coordinate (xt\_in, yt\_in, zt\_in, tin) becomes (xt\_final, yt\_final, zt\_final, tfinal) after the transformation. If the tepoch of a grid is between tin and tfinal the gridshit is applied, otherwise the step is skipped.

For day-to-day use it would be practical to have the option of setting +t\_final to “now”, so that coordinates automatically are transformed to the epoch of the day.

**Combining secular and episodic deformation in coordinate transformation**

Both the secular and episodic deformations need to be combined in the transformation before the dynamic reference frame can be used in practice. For the sake of simplicity, we essentially handle the combination as a two-step process. First the correction for secular deformation is applied to the coordinate which is then followed by a potential correction for episodic deformation. On figure 1 below the concept is explained schematically. Here we consider a time period of ten years in which two earthquakes happen. The secular velocity is 2.5 mm/yr. In fig. 1a the displacements due to both secular and episodic deformation is displayed in the order they occur. That is, first we have 3.4 years of secular deformation, then deformation due to an earthquake, then 5.3 years of secular deformation followed by yet another earthquake and finishing off the remaining time period with secular deformation. The displacement of each deformation contribution is written under the figure. This is how deformation happen in nature. For coordinate propagation from one epoch to another within the DRF we adopt a simpler approach and separate the secular and episodic deformation contributions from each other. This is seen in the schematic in fig. 1b where the secular deformation for the whole time period is first applied and then the episodic deformations. This is merely a matter of changing the order of operations and the transformations will still be accurate while also as simple as possible.

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Figure 1. Example of displacements due to secular and episodic deformation over a ten-year period. Arrows denote secular deformation and stars denote episodic deformation from e.g. an earthquake. The secular deformation is chosen as 2.5 mm/year. **a)** Deformation contributions in the order they occur in nature. **b)** Deformation contributions as they are handled in the proposed coordinate transformation.

An example of the chosen coordinate transformation approach is shown below in the form of a PROJ transformation setup:

+proj=pipeline +t\_final=2025.0

+step +proj=deformation +t\_epoch=2010.0

+xy\_grids=@iceland\_secular\_model\_xy.ct2,@null +z\_grids=@iceland\_secular\_model\_z.gtx,@null

+step +proj=hgridshift +grids=@event1\_xy.ct2 +t\_epoch=2019.23

+step +proj=hgridshift +grids=@event2\_xy.ct2 +t\_epoch=2020.82

+step +proj=hgridshift +grids=@event3\_xy.ct2 +t\_epoch=2022.64

The above transformation is only an approximation since in principle the secular velocity will be slightly different for each of the periods between the earthquakes. The reason for this is that the velocity varies across the secular deformation model and when a coordinate is moved within the model a slight change in velocity is to be expected. The magnitude of the change in secular velocity is for most practical purposes negligible and will not be dealt with in the initial prototype.

1. https://proj4.org/operations/transformations/hgridshift.html [↑](#footnote-ref-1)
2. https://proj4.org/operations/transformations/vgridshift.html [↑](#footnote-ref-2)