

Description of concepts for handling secular motions and deformation events on Iceland

*D3.1 and D3.2 of the DRF-Iceland-S1 project*

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| Delivery description: D3.1, The deformation model concept should describe the deformation in 3D at any location between any two epochs and, hereby, link objects geo-referenced at different epochs at any epoch, current epoch included. The deformations should be reliable within the uncertainties of the associated coordinates. Practically, the deformation information may be provided in a geographical grid covering the area with a sufficiently dense spacing to describe deformations in fault zones. Other representations of the deformations such as a finite-difference mesh may be considered as well. D3.2:The deformation model concept should be able to describe deformations due to continental plate motion and GIA. Those deformations are mainly linear and may be described by their respective velocity fields. The model, however, should also be able to describe deformations due to earthquakes, volcanic eruptions, and current changes in the ice sheets and glaciers. Such deformation may occur instantaneously and may have a relaxation time associated with it. Hence, discrete deformations at times of such events need to be considered, perhaps with an additional time dependent term included. |

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| Version:1.0 | Last change:2018-06-15 | Authors: Geir Arne Hjelle, Halfdan P. Kierulf and Olav Vestøl | Accepted by:DRF-Iceland team |

DRF Iceland

# D3.1 Description of concept for deformation model

The deformation model concept should describe the deformation in 3D at any location between any two epochs and, hereby, link objects geo-referenced at different epochs at any epoch, current epoch included. The deformations should be reliable within the uncertainties of the associated coordinates. Practically, the deformation information may be provided in a geographical grid covering the area with a sufficiently dense spacing to describe deformations in fault zones. Other representations of the deformations such as a finite-difference mesh may be considered as well.

## Overview of Deformation Model

The deformation model is based on observations from 175 Icelandic permanent (?) geodetic stations. North, East, and Up velocities have been calculated for each station (see the [Input Data section](#input-data)). Based on these velocities, a collocation is carried out independently for North, East and Up. The collocation picks up the trend in the station velocities, as well as a long wave (35 km) signal, while taking known fault zones in Iceland into account. The trend and the signal form the basis for the deformation model (see the [Calculating Velocity Field section](#calculating-velocity-field)).

## Input Data

The main input file is the iceland\_velo\_v.0.5.xls which contains North, East, and Up velocities for 175 Icelandic permanent (?) geodetic stations. The first 5 entries in the file looks as follows:

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Station | Lat | Lon | h | vE | vN | vh |
| ADAL | 65.247248284 | -19.448051157 | 667.955 | -0.0110 | 0.0236 | 0.0099 |
| AKAR | 64.652088161 | -22.355651926 | 78.374 | -0.0109 | 0.0204 | 0.0026 |
| AKUR | 65.685427007 | -18.122482867 | 134.2049 | -0.0100 | 0.0236 | 0.0032 |
| ALFD | 64.984151261 | -16.034184522 | 732.0026 | 0.0114 | 0.0192 | 0.0148 |
| ARHO | 66.193071173 | -17.109042279 | 123.931 | -0.0028 | 0.0204 | -0.0003 |
| ... |  |  |  |  |  |  |

In addition to the position and velocity, each line also contains some information about how the observations are done. An example of this information for the first 5 entries are shown below.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Station name | Station ID | Source | Type | period |
| ADAL | OS7378 | ISN2004-ISN2016 | BM measurments | 2004-2016 |
| AKAR | LM0310 | ISN2004-ISN2016 | BM measurments | 2004-2016 |
| AKUR | 10206M001 | NKG\_AC | Timeseries | 2001-2016 |
| ALFD | ALFD | post\_HOLU | Timeseries | 2015.2-2017.6 |
| ARHO | ARHO | ISN2004-ISN2016 | BM measurments | 2004-2016 |
| ... |  |  |  |  |

In particular, we should note that the velocities are calculated based on different sources and over different time periods. The longest time series start in 2001, while 29 of the stations have time series starting in 2015.0 or later. These late time series mainly have data until 2017.6.

**TODO:** How are velocities calculated?

## Calculating the Velocity Field

Calculation of the velocity field is done through collocation. The following procedure is carried out independently for the North, East, and Up velocities of the stations. The station coordinates are originally given as latitude, longitude and height, but are converted to UTM 27 for these calculations. We denote East and North coordinates by $x$ and $y$, respectively:

1. Coefficients (...) are calculated based on scaled $x$- and $y$-coordinates. The scaling is done for numerical stability.
2. A covariance matrix is calculated based on the distance between the stations. The covariance between two stations $i$ and $j$ is calculated as

$$c\_{i,j}=σ^{2}exp(-\frac{d\_{i,j}log2}{D}).$$

* Here $d\_{i,j}$ is the distance between the two stations in kilometers. In order to take fault zones into account, we use a modified distance as explained below in the section [Modified Distance Between Stations](#modified-distance-between-stations).
* The constant $D$ is used as a scaling factor that controls how much the signal at nearby stations affect each other. It is effectively the half distance of the covariance, as if $d\_{i,j}=D$ for some $i,j$, then $c\_{i,j}={1}/{2}σ^{2}$. In the model $D=35km$ is used.
1. Using the covariance matrix, a collocation is carried out to calculate a trend and a signal at each of the given stations. (TODO: Add equations?)
2. The residual between the given velocities and the model is calculated at each station, in order to assess the quality of the input data. The KISA station was excluded from all models, while for the North model we also excluded GFUM.
3. The final velocity field is calculated based on the above collocation. The velocity field is calculated on a grid stretching from 25°W to 13°W and from 63°N to 67°N, covering all of Iceland. Spacing between grid points is 0.050° in longitude and 0.025° in latitude.

The final outcome of these calculations are two grid files --- one for horizontal velocities and one for vertical velocities --- that may be used by PROJ to calculate deformations (see D3.4).

## Modified Distance Between Stations

In order to take fault zones and potentially other geophysical phenomena into account, the covariance matrix is modified. This is done indirectly by modifying the distance function used to calculate the distance between two stations. The basic idea is that two stations separated by a fault zone behave as if they are more separated from each other than indicated by their physical distance.

A few different alternatives for such modified distances have been discussed and investigated.

* One option is to give different weights to different terrain zones (typically higher weights inside fault zones), and then calculate a weighted shortest path. This concept is similar to cost calculations in GIS software (as implemented by for instance [r.cost in GRASS](https://grass.osgeo.org/grass74/manuals/r.cost.html)). In the initial prototype of the model, this option has not been implemented.
* A simpler version of the above (and the one that is currently used) is to first calculate the straight line distance (in UTM27) between two stations, $I$ and $J$. Then, if this straight line $\vec{IJ}$ passes through one or several fault zones, an extra length of

$$20×length of \vec{IJ} inside fault zones$$

* is added to the straight line distance.
* An even simpler modification was also investigated. Based on the fault zones, a ridge separating Iceland into a western and an eastern part was constructed. Based on the ridge, a modified distance was calculated by adding a big number (alternatives between 1000 km and 1000000 km were tested) to the actual straight line distance for each pair of stations on opposite sides of the ridge.

Testing indicated that the simple ridge version did not perform very well. Furthermore it was based on a artificial feature (although based on an actual fault map), so the method was harder to defend from a geophysical point of view.

In comparison, the modification based on the straight line overlap with fault zones, seems to do a good job of modelling the deformations. As noted in the [Further Work](#further-work) section, more testing will be done to tune parameters, and better quantify how well this model is doing.

So far, the r.cost-version of modified distance has not been tested, mainly due to this being more complicated to integrate with the collocation prototype. It would be advisable to at least do a feasibility study on using this algorithm, as well as try to get some sense about whether this would improve the deformation model significantly.

## Output

The actual deformation model is contained in two files, one describing horizontal velocities and one describing vertical velocities. These files can be used by PROJ as described in D3.4.

## Further Work

The current model should be considered a prototype. There is still some work to be done, including

* testing the more realistic r.cost-algorithm for taking fault zones into account,
* tuning the parameters of the straight line-fault overlap-algorithm,
* assessing the quality of the velocity field, for instance by doing cross-validation
* cleaning up the code for calculating the velocity model, making it more flexible and easier to use and adapt.

# D3.2 Description of concepts for handling secular motions and deformation events

The deformation model concept should be able to describe deformations due to continental plate motion and GIA. Those deformations are mainly linear and may be described by their respective velocity fields. The model, however, should also be able to describe deformations due to earthquakes, volcanic eruptions, and current changes in the ice sheets and glaciers. Such deformation may occur instantaneously and may have a relaxation time associated with it. Hence, discrete deformations at times of such events need to be considered, perhaps with an additional time dependent term included.

The current prototype only includes secular motions. Deformation events are planned to be handled as discrete episodic events --- at least in the first version of the deformation model --- see D3.4.

As a proof-of-concept we will model the Reykjavik earthquake in May 2008. Time-series at available stations before and after the earthquake will be used to find the horizontal and vertical shifts as well as the extent of the earthquake. Through a similar collocation technique as above (?) horizontal and vertical grids describing the deformation will be produced.

**TODO:** Will we have time to investigate this before NKG GA?

# D3.3 Determination of a preliminary deformation model

The first version of the deformation model will be developed using geodetic information about the deformations based on GNSS. Only the linear parts of the deformations will be considered, so the model will consist of grids of velocities in the three directions: North, East, and Up. In addition, information about faults (or fault zones) will have to be included. Such information may have been extracted from geological observation supplemented by earth observation from satellites.

The velocities may be estimated using an optimal estimation technique such as least squares collocation in which spatial correlations are considered and formal error estimates may be derived. It is important, however, that the information about faults can be taken into account. Hence, it is planned to derive the first version of the deformation model using a gridding technique based on a finite-differences mesh and the use of constraints to represent correlations spatially. In practice, the constraints may be adjusted to reflect the presence of faults. The velocity fields are obtained by rigorous matrix inversion and errors may be computed.