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Towards a Dynamic Reference Frame in Iceland

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Abstract

There is a growing need for geodetic reference frames that on a national level support the increasing use of global positioning services. Today, the vast majority of countries have their own national reference frame. In Europe this frame is normally aligned to ETRS89. This system is co-moving with the Eurasian tectonic plate. Global Navigation Satellite Systems (GNSS) and global positioning services are normally aligned to the Earth as a whole through a global reference frame like ITRF2014. Consequently, global positioning services does not give direct access to the national reference frame without a time-dependent transformation.

A solution is to align the national reference frame directly to a global reference frame. In such a frame, the coordinates of a point fixed to the ground will change with time, - a fact leading to the expression dynamic reference frame (DRF).

To be prepared for future challenges, the Nordic Geodetic Commission (NKG) initiated a pilot-project on DRF in Iceland. Iceland has a very active and complex geodynamic situation. It is located at the boundary of two tectonic plates and affected by seismic and volcanic activity, recent ice loading changes as well as glacial isostatic adjustment (GIA). Due to this, the traditional concept of a static geodetic reference frame is difficult to maintain at the uncertainty level required by modern applications. Iceland was therefore a natural place to investigate the concept of DRF.

This paper focuses on the outcome and conclusions of the DRF project in Iceland. We give ten preconditions for a DRF. Living on an ever-changing Earth, we see that many of these preconditions have to be in place regardless of type of reference frame. Through the work in the Nordic countries and NKG, the Nordic area will be well prepared for the future challenges. However, some legal issues for instance, can be challenging. A two-frame solution combining static- and dynamic- reference frames seems like the best alternative in the foreseeable future.

Keywords: Dynamic Reference Frame, Kinematic Reference Frame, ITRF, ETRS89

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1 Introduction

There is a general growing need for geodetic reference frames that on a national level support the increasing use of global positioning services. Today most countries have established and are still maintaining their own national reference frame. In Europe most countries have a regional static reference frame (SRF) aligned to ETRS89 (European Terrestrial Reference System 1989) (*Torres et al.*, 2009). There is a growing awareness that such static reference frames are not the ideal solution for all purposes.

Globally, we see an increased number of positioning satellites belonging to Global Navigation Satellite Systems (GNSS) like GPS, Galileo, BeiDou-2 and GLONASS. In parallel, positioning services providing real-time accurate positions both for professional users and for the mass market are increasingly available and used. For example, Galileo (European GNSS) commercial service will provide a high accuracy service free-of-charge in 2020. This service will provide better than two decimetre positional accuracy worldwide in nominal conditions of use (*European Commission,* 2018). The service will be based on transmission of Precise Point Positioning (PPP) products (*GSA*, 2017). Such services will typically give positions in a global reference frame.

As ETRS89 is defined to be co-moving with the Eurasian plate, the global positioning services will not be directly compatible with national geospatial data in the national frames, without some kind of time-dependent transformation. In its simplest form, such a transformation is just a 7- or 14- parameter Helmert transformation. In areas with geophysical activity deforming the crust, more complex transformations are necessary and often deformation models are involved.

Australia is meeting this future demand with an interesting approach. They implemented a new reference frame in 2017 with epoch 2020.0 named GDA2020 (*Janssen*, 2017). In 2020 they will introduce a new national reference frame (Australian Terrestrial Reference Frame, ATRF) directly aligned to the latest International Terrestrial Reference Frame (currently ITRF2014 (*Altamimi et al.*, 2016)) and co-moving with this global frame, instead of the tectonic plate. In such a system, the coordinates of a point fixed to the ground will change with time and the frame is therefore often named a Dynamic Reference Frame (DRF).

New Zealand have to date adopted an another approach (*Donnelly et al.*, 2015). Their national reference frame is static with reference epoch 2000.0, and a deformation model is closely integrated for transformation of coordinates to the reference epoch. Updates of both the reference frame and the velocity model are allowed to happen when modeled coordinates differ from reality by a threshold. This approach is often named semi-dynamic.

Recognizing this global development, the Nordic Geodetic Commission (NKG) initiated a pilot-project on DRF. Iceland was chosen as test area. The goal was to evaluate different aspects of DRF like; what infrastructure is needed, are the existing positioning services able to handle dynamic coordinates, and can temporal coordinates be included in Geographic Information System (GIS). Another goal was to establish GNSS analysis routines for the Icelandic reference network and compute a first draft of a deformation model for GIS applications and other transformations. In this context, it may be noted that the geodynamic situation for Australia mentioned above is much more stable compared to Iceland (and New Zealand).

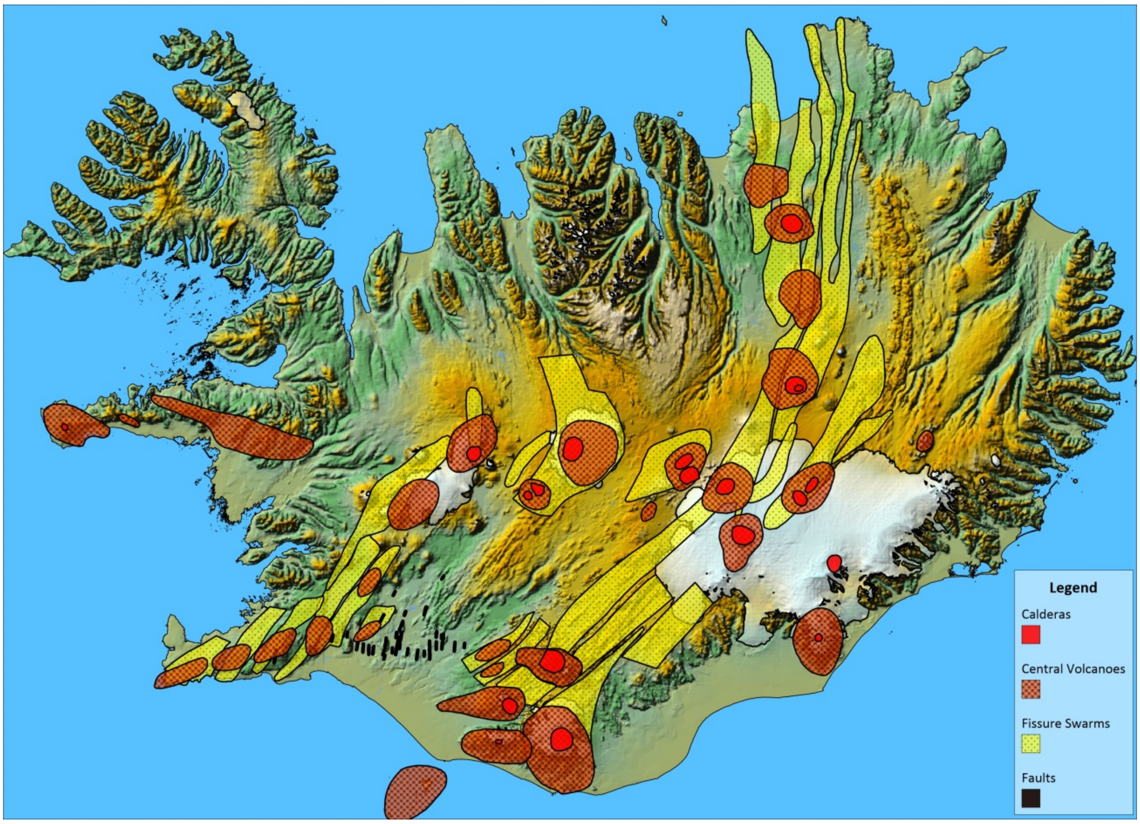

Fig. 1. Tectonics in Iceland. Red areas are calderas, orange areas are central volcanoes, yellow areas are fissure swarms and black lines faults. Data is taken from *Einarsson and Sæmundsson* (1987).

Iceland has a very active and complex geodynamic situation (see Fig. 1), causing large non-homogenous crustal deformations (e.g. *Àrnadòttir et al*., 2009). With its location at the Mid-Atlantic Ridge, lying on two different tectonic plates, the east and west part of the island is constantly torn apart, with a few centimeter a year (*Einarsson*, 2008). It is also affected by seismic and volcanic activities, recent ice loading changes as well as glacial isostatic adjustment (GIA). The magnitude of the divergence of an earthquake can be in the range of 1–2 meter close to the epicenter. In the 2008 Reykjavik earthquake (*Decriem et al*., 2010) co-seismic offset of more than 50 centimeter was measured with GNSS. For volcanic eruption like Holuhraun 2014 (*Sigmundsson et al*., 2015) it can be several meters close to the opening but it decays rather fast. In the area of the Vatnajökull glacier affected by both melting glacier (*Compton et al*., 2015) and active volcanoes, GNSS measure uplift of around 5 centimeter a year and approximately 20 centimeter a year horizontal deformations. Due to this situation, the traditional concept of a static geodetic reference frame is difficult to maintain at the uncertainty level required by modern applications. For instance is positioning services like network Real-Time Kinematic (RTK) delivering coordinates at centimeter level and the reference frame should be maintained at the same level. It is therefore worthwhile to investigate how a dynamic reference frame could be implemented in Iceland.

In Fennoscandia and the Baltic area, the geophysical deformations are mainly driven by plate tectonics and GIA (*Kierulf et al.*, 2014). Both processes are slow and predictable, hence the deforming aspects of the reference frames, dynamic or not, are easier to handle from a geodetic point of view. If we could solve the situation in Iceland with its complexity, we could also handle the situation in Scandinavia. However, the challenges with changing from a static to a dynamic reference frame are more difficult in Scandinavia with higher population and a more complex society, both generally and with respect to geographical data.

Transport industry and autonomous cars are an example of a sector who will benefit from a worldwide position services since consistency over national boarders are of crucial importance. Differences between national or regional reference frames and global positioning services have to be solved.

This article describes the work, results and conclusions in the DRF-Iceland project.

2 *Definitions and concept*

The terms *dynamic*, *semi-dynamic* and *static* reference frames are defined in various ways (e.g. *FIG*, 2014), which can complicate discussions on the topics. A static reference frame (SRF) is often referred to as "plate-fixed", while the terms "kinematic" or "Earth-fixed" are used for a dynamic reference frame (DRF). Usually, the term SRF refers to a reference frame co-moving with a tectonic plate while a DRF is fixed to the Earth as a whole through conventions (e.g. IERS Conventions, 2010 (*Petit and Luzum*, 2010)).

The proposed ISO-standard for geographic information (ISO19111, draft version 2018-08-28) defines a *reference frame* as "parameter or set of parameters that realize the position of the origin, the scale, and the orientation of a coordinate system" and *dynamic reference frame* as "reference frame in which the defining parameters include time evolution" (O. Kristiansen, pers. comm., November 15, 2018).

A semi-dynamic reference frame is not defined in the proposed ISO19111, but the term is in common use and normally refers to either a static reference frame with an associated crustal deformation model or a frequently updated static reference frame.

The proposed ISO19111 definition of a DRF is general. We have used the following more specific definitions: "A DRF is a reference frame aligned to a global Earth fixed reference frame, normally the latest International Terrestrial Reference Frame (now ITRF2014)." The coordinates in a DRF is by nature four-dimensional, given by its 3D-spatial coordinate and its time tag.

A global positioning technique, like GNSS, gives 4D-coordinates directly in a DRF and with the accuracy of the positioning technique being used. The time of observation makes up the fourth coordinate. No time dependent transformations are necessary to uniquely define the position in the frame. The users have direct access to the reference frame without loss of accuracy.

However, in order to compare and compile coordinates or describe the situation at a specific time, coordinates must be transformed to the same epoch using the description on how the coordinates change with time (deformation model). Coordinates of objects will normally have different time tags in a DRF.

Because the time tag is the fourth coordinate, users can always store coordinates in their databases even when the deformation model is not updated, e.g. after a large earthquake. The deformation model can be updated later and data can then be correctly transformed to the specific time reference required when needed.

3 Description

The theoretical foundation for a DRF is in most ways already present. Many of the necessary geodetic tools exists, like global positioning services, global reference frames, transformations, velocity fields and deformation models. However, improvements are needed, e.g. for deformation models in fault zones, and many practicalities have to be resolved.

A DRF for practical purposes requires:

1) A sufficiently dense active geodetic infrastructure, like Continuous Operating Reference Stations (CORS) with known coordinates in a global reference frame (e.g. ITRF).
2) A way to distribute the reference frame to the users, e.g. positioning services.
3) Transformations to other reference frames.
4) Deformation models with sufficient accuracy to meet the future demands for comparison and compiling coordinates from different epochs.
5) Geodetic data archives able to store and handle dynamic coordinates.
6) GIS systems that are able to handle dynamic coordinates in general and in particular the time dimension of a dynamic reference frame and the various transformations needed.
7) Legal foundation of dynamic reference frames (e.g. for cadastre).
8) Training and education of surveyors.
9) Training and education of GIS users.
10) Willingness of the users to take such a system into use.

All ten preconditions have to be in place to have a well-working DRF as the sole national reference frame in the future. Many of these points are large and demanding, and rely on the international development. E.g., Point 6) will require large development resources. However, with the announcement of the coming Australian dynamic reference frame it is expected that most GIS software vendors will be working on implementing the updated standards and improving their transformation tools.

It is also worth noting that many of these requirements have to be in place regardless of type of reference frame. Point 1) to 4) for instance, are valid also for static or semi-dynamic reference frames. We live on an ever-changing Earth and that is the basic problem we have to solve.

In this paper the points 1), 2) and 4) are dealt with in the Section “Geodetic issues”, Point 3) is a classical geodetic issue and more information can be found in e.g. *Altamimi*, 2018. Point 6) and 7) are treated in Section “GIS issues” and “Legal issues” respectively. Geodetic data is not threated explicitly, but Section “GIS issues” is relevant here as well. Points 8), 9) and 10) are about user perspective and educational issues. These last three preconditions are obvious in a well working DRF, however outside the scope of this paper.

4 Geodetic issues

4.1 GNSS infrastructure in Iceland

The National Geodetic Network of Iceland (ISNET) was measured for the third time in 2016. The network was measured for the first time in 1993 and then again in 2004. The datums ISN93 (ITRF93 epoch 1993.6) and ISN2004 (IGb00 epoch 2004.6, with absolute PCV antenna models) were both static.

The original ISNET Network consisted of 119 benchmarks and concrete pillars. In 2004, all CORS stations running at the time were also included in the new datum and the same goes for the ISN2016 campaign. Today there are more than 100 CORS stations in Iceland, most of them owned by the geophysical community. However, they are not evenly distributed. Most of them are in active areas.

The National Land Survey of Iceland (LMI) is running a network RTK service for Iceland, IceCORS. Currently there are 20 stations in the network. The stations are owned by the LMI or by the Icelandic Met Office (IMO) and their partners. The current goal is to have 31 stations in the system. Four stations from IMO are already operational but a real time data stream is missing. Then the plan is to build seven new stations. The equipment on the stations is very heterogeneous, ranging from modern GNSS receivers down to old GPS-only receivers. The service is operated with GNSMART software and the correction data is free of charge. The network is running on a best effort basis: if something breaks down LMI or IMO tries to fix it as soon as possible.

Several benchmarks other than ISNET points have been measured repeatedly with long (24h+) GNSS observations. Those observations can be used to densify the velocity field for Iceland, especially in deforming zones of Iceland.

The planned 31-station CORS network for the IceCORS is sufficient for the RTK-service at Iceland. However, an upgrade of the equipment will improve the robustness and stability of the service. More stations are also needed in deformation areas to update deformation models and patches after large earthquakes and volcanic eruptions.

4.2 Analyzing GNSS data

NKG has a service on GNSS processing and analysis called NKG GNSS analysis centre (NKG AC). The NKG AC follows the guidelines of the EUREF Permanent

GNSS Network (EPN) (*Bruninx et al.*, 2012) and is therefore consistent with the Pan-European EPN solutions (*Lahtinen et al.*, 2018). An idea of the NKG AC is to spread the GNSS processing and analysis to different institutions. Consequently, it has eight local analysis centers (one from each Nordic/Baltic country) and two combination centers. Iceland is one of the local analysis centers and therefore the existing NKG AC service will be utilized for realizing and maintaining the Icelandic DRF.

The EPN, and also the NKG AC network, are aligned to ITRF through a regional alignment. There are arguments and indicative plans for extending the EPN to also include globally distributed stations and perform a global alignment to ITRF. This has been done in the DRF-Iceland project where seven global ITRF stations were added to the NKG_AC_ISS network (see Fig. 2). Then data from 24 CORS stations in Iceland was processed for the period from 2001 and through 2017.

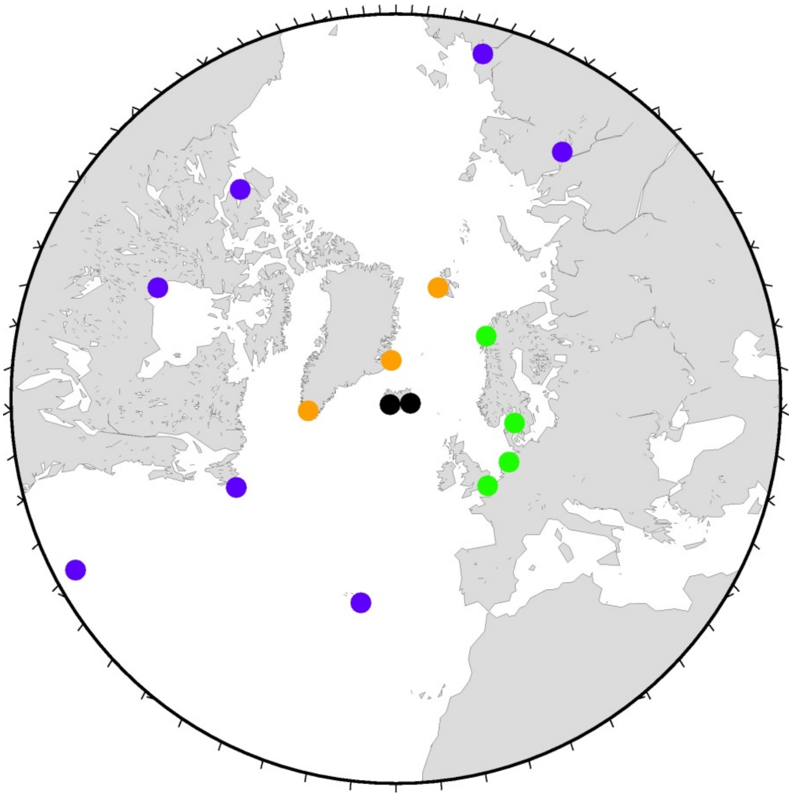

Fig. 2. Global network used in the DRF-Iceland project. The blue circles represent global IGS (International GNSS Service) stations located in tectonically stable areas (or otherwise “stable” IGS stations) surrounding Iceland to ensure good global realization of the reference frame. Green circles are stable European stations included in NKG and EPN analysis. Orange circles are IGS stations west and north of Iceland, that might be unstable due to changes in local glaciers. The two black circles are the IGS stations in Iceland.

4.3 *Time-series*

A fundamental part in constructing and using a DRF is good knowledge of crustal deformation processes. Analysis of time-series of daily GNSS coordinates is the cornerstone to establish the velocity field and deformation model. In the DRF-Iceland project, the time-series analysis software Hector (*Bos et al.*, 2008) was used. It is well known that geodetic observations are temporally correlated. We have therefore opted to use a combination of white noise and flicker noise (see e.g. *Williams et al.*, 2004, for details). In the time-series analysis, we solved for offsets, trends, annual- and semiannual- signals as well as an offset for stations affected by earthquakes or other abrupt changes of station coordinates. The GNSS time-series of Icelandic stations reflect the very complicated mixture of geophysical processes going on in Iceland. In Figure 3 the time-series for the north, east and height components are included for three stations located in areas with very different geophysical conditions.

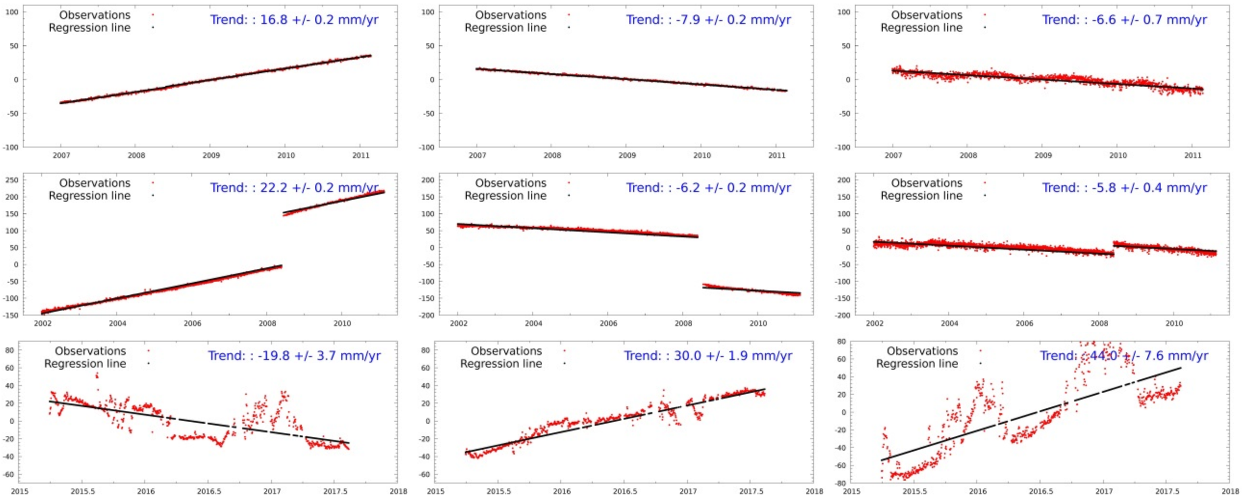

Fig. 3. Time-series of three Icelandic GNSS stations. The stations are from top: NYLA, HVER and GFUM. The components are from left: north, east and height respectively, and given in millimeter. The NYLA station is dominated by the movement of the North-American tectonic plate with a small linear movement in northern and western direction. The station is also subsiding. The HVER station is also located at the North-American plate with a long-term drift similar to NYLA (*Einarsson*, 2008). The station has a large co-seismic displacement due to its location close to the epicenter of the 2008 Reykjavik earthquake. The lowermost station, GFUM, shows large irregular fluctuations in all components due to the volcanic activity (*Sigmundsson et al*., 2015) in the area and also partly the crust response on the ongoing melting of the Vatnajökull glacier (*Compton et al*., 2015).

The main parameters for the prototype velocity field and deformation model developed in the DRF-project are the long-term linear (secular) velocities and the offset due to the co-seismic deformation in the 2008 Reykjavik earthquake. The post-seismic deformation, as seen for station HVER in Figure 3, is not taken into account in this project, but has to be included for maximal accuracy in the deformation models. Local effects from volcanic eruption are very difficult to include and is a topic for future investigations.

4.4 Secular velocities and deformation models

As part of the project, a prototype for a secular velocity field and deformation model has been constructed. The prototype is based on observations from 173 Icelandic geodetic stations. North, east, and up velocities have been calculated for each station, see Figure 4 (left). Based on these velocities, we have carried out a least-squares collocation independently for North, East and Up components with a method described in

Vestøl (2006). The covariance matrix is $C = C_{ij}$, where $C_{ij} = \sigma^2 exp\left(\frac{-log2}{D} d_{ij}\right)$, d_{ij} is the distance between the GNSS station i and station j, D=35 km is the correlation length and σ^2 is the variance. By having log 2 in the exponential decay function, the correlation length means the distance where the correlation reach one-half. The collocation picks up the trend in the station velocities, as well as a possible long-wave (35 km) signal. The sum of the trend and the signal makes up the deformation model.

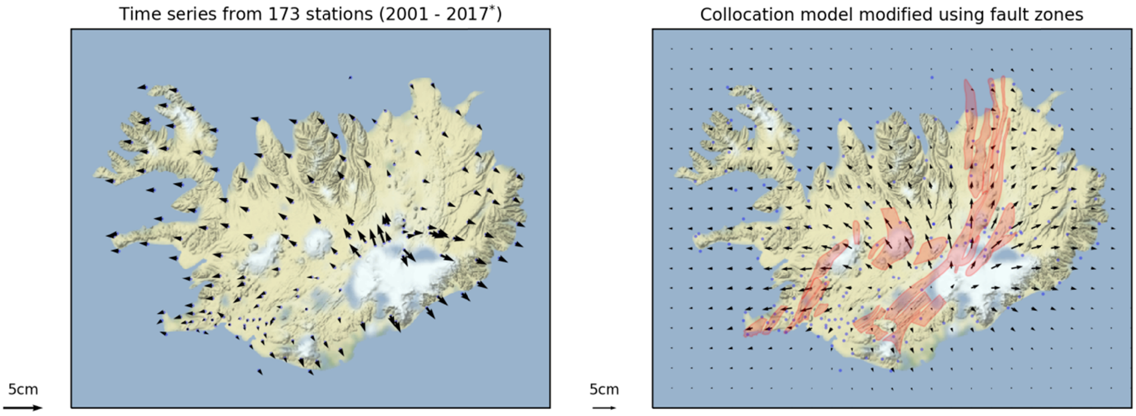

Fig. 4. Horizontal velocities at the 173 stations used in the model (left) and example of a gridded deformation model showing horizontal velocities (right). The model is based on collocation where the covariance matrix has been modified to take the geophysical fault zones into account. For clarity, the north component has been reduced by 2 cm/yr in the figures.

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 d_{ij} used to calculate the covariance 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 their real physical distance.

At this prototype stage, we have tried a few different ways of modifying the distance. Figure 4 (right) shows an example of this. When the straight line between two stations crosses a fault zone, the distance between the stations is increased. However, more testing is needed to investigate other modifications and give recommendations. For a more rigorous examination of non-stationary covariance modelling, see e.g. *Darbeheshti and Featherstone* (2008).

Currently, the model is based on the full length of all 173 time-series. However, the time-series are not homogeneous. They cover different time spans, come from stations of different quality, include both permanent stations and campaign measurements, and – as noted above – exhibit quite different dynamic properties. For a final deformation model, strategies on exclusion of time-series, weighting, and handling of seasonality and jumps are needed.

As an example of a jump in the time-series, consider the 2008 Reykjavik earthquake (see station HVER in Figure 3). Our proposed way of handling jumps is through so-called patches. The background deformation model will be calculated based on time series where jumps are removed. Then, whenever a major event like an earthquake occurs, a patch is calculated. Such a patch is a grid that spatially describe the displacement for a smaller area caused by the event, and can be added to the base model when needed. How the patch should be calculated is still an open question, but it seems natural to look towards proper geophysical models.

5 GIS issues

Before a practical implementation of dynamic reference frames is possible in a modern GIS application, there is a series of challenges to solve. Principally, there are two major challenges with implementing dynamic reference frames in GIS applications. One is the lack of suitable standardization, the other is missing functionality in existing GIS applications.

5.1 Standardization

There are three standards that are relevant when considering the implementation of dynamic reference frames in GIS applications: (1) the Simple Features model, (2) the Well-Known Text coordinate reference system description format and (3) the geodetic parameter registry (EPSG).

The Simple Features model (1) is basically a description of how to organize coordinates in geospatial data files. The model defines different types of coordinates, such as 2D and 3D coordinates. Unfortunately, a 4D spatiotemporal coordinate is not defined in the Simple Features model. This will have to change before real world use of dynamic reference frames is viable at scale.

Today spatial reference systems in GIS datasets are described with the initial version of the Well-Known Text standard (*OGC*, 2015) (2). This version unfortunately does not have temporal awareness. This has been introduced in version 2 of the format but is still not in widespread use.

The EPSG geodetic parameter dataset (*IOGP*, 2012) (3) is the de facto standard for indexing coordinate reference systems and transformation between them. More or less every GIS application uses the EPSG database to describe coordinate reference systems and how to transform between them. Unfortunately, the EPSG database does not include information about realization and epoch of the coordinate reference system. This poses a problem since a dynamic reference frame cannot be fully described within the current model of the EPSG dataset. Generally, the time dimension is ignored within the EPSG dataset. Within the confines of ISO/TC211 the international geodetic community is currently in the process of developing a standardized Geodetic Registry which is meant to be the ISO counterpart of the EPSG registry.

Fixing the discrepancies in the various standards is not an easy task. It is a slow process that requires international collaboration. At this time, the Well-Known Text 2 standard (2) is under revision and is more or less up to par with current needs for dynamic reference frames. Updates of both the Simple Features model (1) and the EPSG registry (3) can be expected as dynamic reference frames come into more wide-spread use.

5.2 Functionality in GIS applications

Today most GIS applications have only basic support for the wide range of various geodetic transformations that are possible. The most commonly used transformation methods are usually included though. The 7-parameter Helmert transformation and grid adjustments are normally the only two methods available for transformations between reference frames. Both of these techniques are not available in the time-domain.

The DRF developed in this project requires the use of a 14-parameter Helmert transformation for transformations within ITRF2014 and a temporally enabled grid adjustment procedure allowing for the use of a background deformation model. Additionally, a grid adjustment procedure that allows patches to be applied at specific epochs is needed. In this project, these methods have been introduced to the commonly used transformation library PROJ (*PROJ contributors*, 2018). PROJ is used as the transformation engine in several popular GIS applications, e.g. QGIS. The PROJ library is distributed on a permissive open source license that allows software manufacturers to freely use the library or parts of it in their own software. By adding and documenting the operations required for the DRF to PROJ, we expect that over time manufacturers of GIS software will include these in their software which eventually will make adoption of dynamic reference frames simpler. Adopting the spatiotemporal features of PROJ in GIS software is going to be a long process since it requires intrusive changes to foundational parts of the underlying code. So while spatiotemporal transformations are possible they are only still available in a few specialized GIS tools.

6 Legal issues

For European Union member states, the exchange of geospatial information are regulated through the INSPIRE (Infrastructure for Spatial Information in Europe) directive (*INSPIRE*, 2007, Point 7). The geodetic reference systems to be used are the ETRS89 for 3D and 2D representation, and the EVRS (European Vertical Reference System) for gravity-related heights (*INSPIRE*, 2009). The INSPIRE directive only regulates the reference systems for exchange of geospatial information between public authorities, but give freedom for compatible geodetic reference frames used within each organization or at the national level. Within the Nordic and Baltic countries, national realizations of ETRS89 have been adopted as national geodetic reference frames, according to the guidelines of EUREF.

Especially for the cadastre, implementation of DRF is challenging, and to what extent there is also a difficult legal aspect will depend on whether the cadastre is coordinated or not. In Australia, the MERCURY project (*MercuryPS*, 2018) postulates, "... that if these issues can be resolved for the cadastre, the findings and outputs can be translated to the management of other layers of spatial information." Because of practical and legacy issues, the DRF will be supplemented by a static frame in foreseeable future (so called two-frame approach).

7 Conclusions

A modern society depends on accurate handling of geospatial data and therefore on an appropriate reference frame. Areas like construction work, geographic information systems, cadastre and science all depend on the reference frame. The transport sector with development of autonomous vehicles and a mass market with access to positioning on decimeter and centimeter level challenge existing national reference frames. The difference between traditional static reference frames and global reference frames exceeds the uncertainty of the coming positioning techniques. The geodetic community in the public sector has to handle this to avoid a variety of different solutions and services from a variety of different commercial companies using their own reference frames.

Several solutions are suggested. One is keeping the old static reference frame and develop deformation models. Another is to introduce a dynamical reference frame allowing time dependent changes of coordinates due to all kinds of large-scale geophysical processes.

The first alternative solves, to some extent, the problem with discrepancies between national and global frames. However, the fundamental problem with geospatial databases in a national reference frame and global positioning services running in global frames remains. The second alternative mostly eliminates the problem with national frames, but time dependent coordinates might introduce legal issues e.g. for cadastre.

A principal difference is the question of where the time dimension and transformation should be managed. The first solution implies that providers of global positioning services must implement deformation models and transformations in their service. The second solution implies that GIS and geospatial databases must handle the time dimension and transformations e.g. through PROJ.

Australia, with an upgraded static reference frame GDA2020 and the dynamic reference frame ATRF to be implemented in 2020, go for a two-frame approach (see e.g. *Donnelly et al.*, 2015). The two frames are meant to live together as long as there is a need for both. A two-frame approach seems like a realistic solution in foreseeable future, also for Iceland and the Nordic area.

Independent of the solution for the reference frame, the basic geodetic concepts like CORS network, positioning services, geodetic analysis, velocity fields and deformation models have to be in place anyway. Through the DRF-Iceland project, many of these basic concepts were examined and tested and we have a good understanding of the geodetic tool that have to be in place for a well working dynamic reference frame for the Nordic area. However, several issues remain, for instance legal issues and the practical implementation in GIS.

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