Modernising the Greenlandic reference system

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1. SUMMARY

The GR96 reference system, established in 1996, is experiencing increasing deformation due to accelerated ice mass loss and associated elastic and viscoelastic effects. This introduces strain within the frame, necessitating a modernized realisation. This paper details the development of a new GR96 realization leveraging the Greenland GNSS Network (GNET), a continuously operating network providing comprehensive monitoring of deformation across Greenland.

A recent GNSS campaign re-observed the fundamental stations of GR96. Data processing was performed using the Bernese software, and a transformation be-tween the current ITRF2020 coordinates of these stations and their original GR96 coordinates was established. This transformation was then applied to the GNET network, effectively assigning GR96 coordinates to the entire network.

This new realization offers significant advantages: it is continuously monitorable via GNET, eliminating the need for further costly field campaigns, and exhibits reduced internal strain compared to the original GR96. The paper also addresses practical considerations surrounding the implementation of this updated system, including communication strategies for end-users and the management of the transition within the EPSG registry where the existing GR96 CRS was updated to represent a datum ensemble encompassing both realizations.

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2. INTRODUCTION

The accurate determination of geodetic reference frames is paramount for diverse scientific and practical applications, including precise mapping, infrastructure development, resource management, and, critically, monitoring the impacts of climate change. In Greenland, the Greenland Reference 1996 (GR96) serves as the national geodetic reference system. Defined as coincident with the International Terrestrial Reference Frame 1994 (ITRF94) at the epoch of 15th August 1996, GR96 provides the foundational coordinate system for the country. The original realisation of GR96 relied on the REFGR network – 258 precisely surveyed points established between 1996 and 2006 (Klimadatastyrelsen, 2025). These points were strategically located along the coastline, primarily in settlements, and determined through repeated GPS campaigns utilising the International GNSS Service (IGS) network for global referencing.

However, Greenland is undergoing rapid and substantial geodynamic change, largely driven by accelerating ice mass loss and subsequent glacial isostatic adjustment. This loss induces both elastic and viscoelastic deformation of the Earth’s crust, resulting in significant strain within the GR96 frame. The original REFGR network, comprised of passive markers, cannot continuously monitor these dynamic processes. Periodic re-surveying is expensive, logistically challenging in the Greenlandic environment, and provides only a snapshot in time. Furthermore, the movement of GPS stations is influenced by tectonic activity, post-glacial rebound, localized instabilities such as landslides, and even minor seismic events. Consequently, the accuracy and reliability of GR96 have been diminishing, necessitating a comprehensive modernisation effort. This paper details the development and implementation of a new GR96 realisation based on the continuously operating GNET for continuous monitoring and improved long-term stability. The new realisation aims to minimize internal strain and provide a framework adaptable to ongoing geodynamic changes.

3. INITIAL REALISATION OF GR96

The initial GR96 realisation, established in the years 1996-2001 and 2006, was not a single, monolithic campaign. Rather, it comprised a series of coordinated GPS surveys designed to establish a robust and nationally consistent reference frame. The 1996 campaign served as the foundational effort, establishing four primary stations – GOH1, JUV1, JAV1, and UAK1 – observed for an extended period (13 days) to achieve the highest possible accuracy (Klimadatastyrelsen, 2025).

Subsequent campaigns (1997-2006) focused on densifying the network, connecting the primary stations to a broader distribution of points across Greenland. The 2000 campaign was

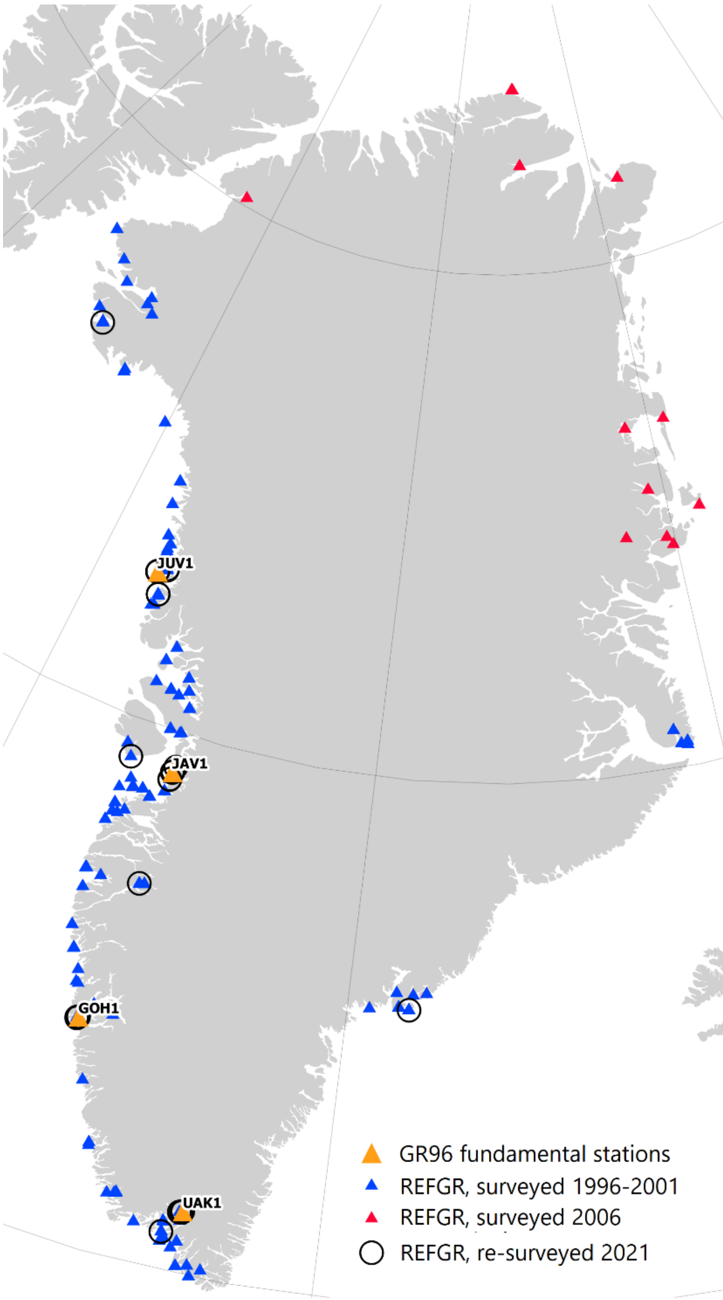

Figure 1. REFGR benchmarks established between 1996 and 2006.

particularly ambitious, aiming to reach all settlements on the west coast and those in the Scoresbysund area. This required significant logistical coordination, including reliance on helicopter transport due to the limited infrastructure in many remote communities. The campaign in 2000 was done in collaboration with the local mapping authority Asiaq. In 2006 a final densification campaign was carried out in the north eastern part of Greenland.

The methodology involved observing stations for varying durations, with main stations in towns observed for 2-7 days and shorter ties within settlements observed for 4-12 hours. The network was configured with baselines extending up to 100 km or more between the IGS stations and the main stations. This systematic approach gradually expanded the reach of the GR96 datum across the country. By 2001, REFGR consisted of 258 stations, with at least two stations established in most of the 85 settlements and towns in Greenland.

4. NEW REALISATION OF GR96

Recognizing the limitations of the initial realisation of GR96, the Danish Agency for Climate Data (Klimadatastyrelsen, KDS) initiated a project to develop a new GR96 realisation based on the continuously operating Greenland GNSS Network (GNET). At the time, GNET was comprised of 63 stations distributed across Greenland, providing a significantly enhanced geodetic monitoring capability compared to the discrete, periodically surveyed REFGR network.

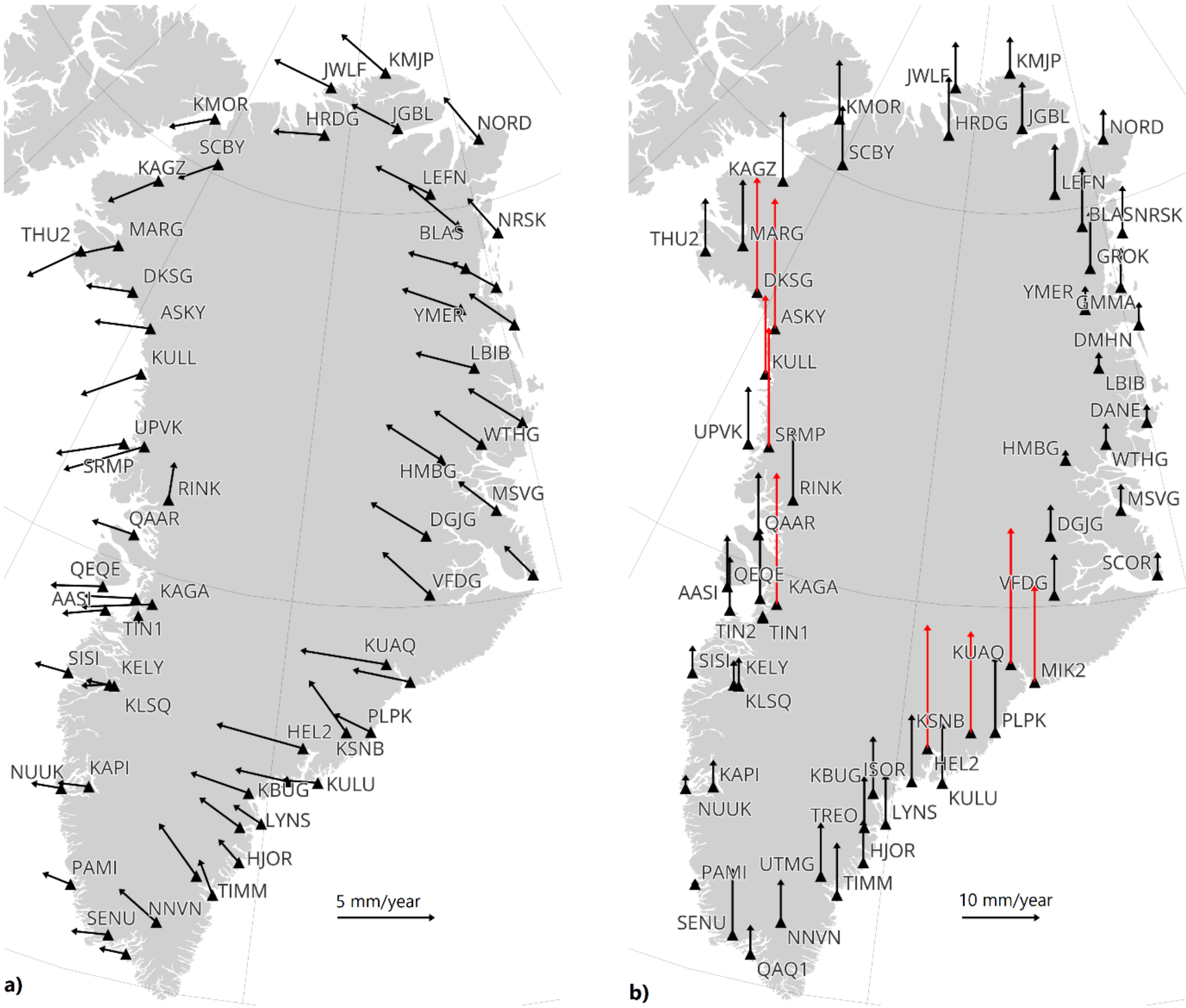

Figure 2. Velocities of GNET stations based on data from Berg et al. (2024). a) Horizontal velocity after correcting for plate motion. b) Vertical velocity. Red arrows indicate velocity higher than 10 mm/year.

In 2021, a dedicated GNSS campaign re-observed the fundamental REFGR stations (Klimadatastyrelsen, 2025), while data from the GNET stations were collected simultaneously. In addition, a number of REFGR benchmarks were re-survey during the summer of 2021 while performing maintenance at the GNET stations (see *Figure 1*). The re-surveyed benchmarks were observed for a few hours each and are used as control points for evaluating transformation accuracy.

Data processing was performed using the Bernese software package. The processing strategy adhered to established best practices for double-difference processing (Dach et al., 2015; Dach & Walser, 2013) and involved several key steps. Firstly, external data, including precise satellite orbits and clock corrections from the International GNSS Service (IGS), were incorporated to minimize systematic errors. Ionospheric and tropospheric corrections were applied using models and data from external sources, including the CODE ionosphere maps and the Vienna Mapping Functions. Ocean tide loading effects were accounted for using the FES2014b model. Antenna phase centre variations and offsets were carefully considered based on the IGS antenna calibration files. Rigorous quality control procedures were implemented throughout the processing chain, including outlier detection and cycle slip correction.

The processing was not a single, linear operation but rather an iterative process. Initial adjustments revealed inconsistencies and large residuals in certain areas, particularly in north-eastern Greenland. Further investigation indicated that these residuals were likely attributable to increased ionospheric activity and potentially tropospheric disturbances in that region. Outliers were identified through residual analysis and removed from the dataset. Several adjustments were performed with refined selection of data until a stable solution was achieved, minimizing the root-mean-square residuals and ensuring consistency with independent data sources.

The key objective was establishing a precise transformation between ITRF2020 coordinates of the fundamental REFGR stations and their original GR96 coordinates. The 2021 campaign enabled a more accurate and up-to-date realisation of GR96, directly addressing the deformation observed in the original REFGR points. This is particularly important given the ongoing geodynamic processes influencing Greenland's landscape.

5. TRANSFORMATIONS

The establishment of the new GR96 realisation required the development of a robust transformation methodology to bridge the gap between the original GR96 coordinates and the current ITRF2020 coordinates obtained through the 2021 GNSS campaign. Figure 2 shows the average velocities of the GNET stations. It is evident that the level of crustal deformation varies across Greenland and as a result it is challenging to create a single Helmert transformation that minimises transformation errors at all stations. Using Bernese, a direct Helmert transformation was calculated between the ITRF2020 and the GR96 coordinates of the fundamental stations. This transformation accounts for translation, rotation, and scale differences between the two frames. However, this 7-parameter Helmert transformation is only valid at the epoch of the 2021-campaign. To remedy this, the temporal component of the transformation was addressed by incorporating the ITRF2020 plate motion model, accounting for the ongoing movement of the North American plate. This allows for better accuracy in the transformation of coordinates over time. The parameters derived from this transformation can be found in the official documentation of the reference system (Klimadatastyrelsen, 2025).

Rigorous validation procedures were implemented to assess the accuracy of the transformation. These procedures included comparing transformed coordinates with independent checkpoints in REFGR and analysing the residuals to identify systematic errors.

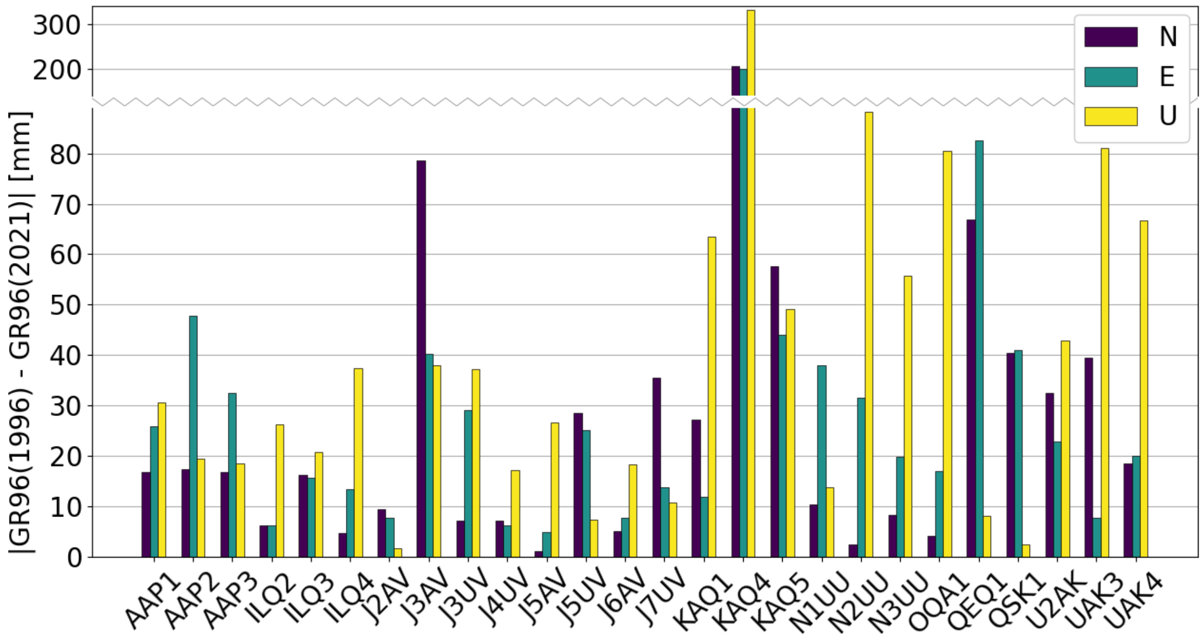

Figure 3. Validation of transformed GR96(2021) coordinates compared to GR96(1996). The figure shows the absolute differences in coordinates. Note the broken y-axis that shows the outlier at KAQA4.

Figure 3 illustrates the distribution of residuals after applying the transformation to the re-surveyed REFGR-benchmarks. The benchmarks were observed for about an hour, simulating a somewhat realistic surveying scenario at a building site or similar. The RMS of the transformation was found to be 60.14 mm across all three dimensions, although after removing the significant outlier at KAQA4 the RMS residual is 34.83 mm. We found that the majority of stations exhibited residuals within acceptable limits, indicating a high degree of accuracy in the transformation process. However, a small number of stations displayed significantly larger residuals, potentially indicative of local deformation effects or inaccuracies in the original REFGR coordinates.

6. IMPLEMENTATION

Following the successful development and validation of the new GR96 realisation and the associated transformation methodology, a comprehensive implementation strategy was enacted to ensure seamless integration into the wider geodetic and geospatial community.

This implementation was not simply a technical update, but also required careful communication and coordination with stakeholders to facilitate a smooth transition.

The first critical step was the formal publication of comprehensive documentation detailing the new GR96 realisation. This documentation, released by Klimadatastyrelsen (2025), outlined the underlying principles of the new datum, the transformation parameters, the processing methodologies employed, and clear guidance on utilising the new system in various applications. This documentation served as a central resource for users seeking to understand and implement the updated reference frame.

A key aspect of the implementation was updating the EPSG registry, the widely recognised and utilized database of coordinate reference systems. GR96 was transitioned to a *datum ensemble* encompassing both the original 1996 realisation and the new GNET-based realisation. This approach ensures backwards compatibility while allowing users to explicitly select the appropriate realisation based on their specific accuracy requirements and application context. The two realisations of GR96 are known as GR96(1996) and GR96(2021) where the number in the parentheses is the year of the campaign that supports the realisation.

The practical accessibility of the new transformation was significantly enhanced by their inclusion in the PROJ 9.7.0 release, dated September 15th, 2025 (PROJ Contributors, 2025). PROJ is an open-source library widely used in Geographic Information Systems (GIS) and mapping software, meaning its adoption instantly broadened the reach of the new GR96 realisation. This integration allows developers to readily incorporate the new transformations into their software, making them available to a vast user base. Consequently, users of downstream software in releases following PROJ 9.7.0 will benefit from the improved accuracy and reliability of the new datum without requiring manual intervention.

Recognising the importance of stakeholder engagement, KDS undertook a proactive outreach effort. This involved organizing workshops and providing direct support to key stakeholders. These engagement activities were designed to communicate the changes, address concerns, and provide practical guidance on migrating existing datasets and workflows to the new GR96 realisation. The emphasis was on minimizing disruption and maximizing the benefits of the improved reference frame for all users.

7. FURTHER WORK

While the implementation of the new GR96 realisation represents a significant advancement, ongoing research and development efforts are crucial to maintain and improve its accuracy, reliability, and adaptability to the dynamically changing environment of Greenland. Several key areas are currently under investigation, with the aim of pushing the boundaries of geodetic accuracy and providing a more robust framework for scientific and practical applications.

One priority is the implementation of an improved plate motion model. The current model, based on ITRF2020, provides a good measure for the overall long-term movement of the North American plate. However, no GNSS-stations in Greenland were included in the development of the model due to the complexities of the Greenlandic geodynamic environment, which is influenced by localised deformation patterns associated with ice mass loss and glacial isostatic adjustment (Altamimi, 2023). A consequence of this is that the ITRF2020 plate motion model does not fully capture the tectonic plate movement, which in the end results in a transformation with reduced accuracy. Berg et al. (2025) has presented a new plate motion model based mainly on data from the GNET stations which may provide an improvement in the GR96 transformations.

Another crucial area of focus is the development of a deformation model that explicitly accounts for the elastic and viscoelastic effects of ice mass loss in coordinate transformations. A commonly used technique is to incorporate a velocity model that predicts the change in coordinates over time e.g., Häkli et al (2023). However, in the case of Greenland that approach is likely to not be sufficient as the elastic deformation is strongly correlated with the mass loss of the ice, which changes from year to year.

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