INVESTIGATING GLACIAL ISOSTATIC ADJUSTMENT IN SCOTLAND WITH INSAR AND GPS OBSERVATIONS

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ABSTRACT
Understanding the effects of glacial isostatic adjustment (GIA) is essential for the assessment of past and future sea-level trends. This study examines the applicability of Small Baseline InSAR to measure GIA-induced vertical land movement in Northern Britain. Different SAR sensors are utilized to cover a time frame of about 20 years. The aim is to establish the spatial distribution of GIA along the coast and uplift centre of Scotland in greater detail compared to results from conventional geodetic techniques, which are interpolated from point measurements. A range of possible error sources within the InSAR processing chain, that lead to orbital and atmospheric artefacts, require to be addressed in order to allow the extraction of any GIA deformation signal. Continuous GPS (CGPS) station coordinates thus need to be integrated with the InSAR data.

1. INTRODUCTION
The crustal motion of Great Britain is fundamentally influenced by the process of glacial isostatic adjustment (GIA). This is the mainly vertical response of the solid Earth to large-scale glaciation and deglaciation of its surface. Today's GIA signal in Scotland is predominantly influenced by the disappearance of the Pleistocene British-Irish ice-sheet and to a lesser extent by the Laurentide and Fennoscandian ice-sheets. The melting of the ice load resulted in uplift of the formerly depressed lithosphere in the glaciated areas of northern Britain, at long-term average rates of about 1-2 mm/yr, accompanied by subsidence in southern Britain of the same magnitude [1] (Fig. 1).

Analysing GIA in Scotland is critical for understanding the dynamics of relative sea-level (RSL) change at the coast. RSL is determined by two combined factors: (i) crustal uplift caused by GIA and other non-GIA tectonic processes, including far-field effects of, for example, Alpine crustal motion, as well as flexural effects including shelf-loading associated with eustatic sea-level fluctuations, and (ii) changes in eustatic sea-levels due to changes in ocean volume. Both contribute to significant temporal and spatial heterogeneity and variability of the RSL change in Scotland. Against a backdrop of climate change and the rise of global sea-levels caused by the ocean's thermal expansion and global melt-water influx, the modern rate and spatial distribution of GIA require to be established. This is especially important, since the process of GIA has generally slowed throughout the Holocene [2, 3]. Also, measurements over recent years of rising RSL at tide gauges around northern Britain suggest that GIA-related land uplift in Scotland may be outpaced by eustatic sea-level change, causing enhanced concerns about the impact on Scottish coasts [4].

This paper introduces investigations of the applicability of an Interferometric SAR (InSAR) time-series technique – based on the Small Baseline algorithm - for the determination of GIA-induced vertical land movement during the past 20 years in Northern Britain. Being able to measure land deformation with high accuracy and on a broader spatial scale than conventional geodetic techniques, InSAR should provide a spatially more comprehensive and detailed picture of GIA and help to locate the centre of maximum present uplift in Scotland. It thereby complements GPS estimates and recent GIA modelling of crustal uplift.

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Results of this study will eventually inform stakeholders and environmental agencies (e.g. Scottish Natural Heritage and Local Authorities) for future coastal planning purposes.

2. THE SPATIAL PATTERN OF GIA IN GREAT BRITAIN

Glacial rebound in Britain has been extensively examined, employing different research methods and observational data types.

On the one hand, geological evidence from palaeo-shorelines and undisturbed isolation basins has been used to reconstruct long-term Holocene RSL change [5, 6]. This information derived from sea-level index points has been employed to inform empirical isobase models of the uplift in Scotland using trend surface analyses [7, 8], as well as to calibrate theoretical GIA models that rely on Earth mantle rheology and ice-sheet history [2, 9-12]. The latter approach faces a common modelling problem, namely a trade-off between Earth mantle parameters that leads to non-uniqueness of the solutions [13, 14].

On the other hand, current short-term rates of GIA have been measured using different geodetic techniques in Great Britain, mainly Continuous GPS and Absolute Gravimetry (AG). AG-measurements are generally employed in Great Britain to increase the accuracy of the CGPS estimates, since the latter suffer from systematic offsets [15, 16].

These investigations commonly agree on the general spatial distribution of RSL change and GIA-induced vertical land movement in Great Britain, identifying the centre of crustal uplift and RSL fall in Scotland that corresponds to the area of maximum ice thickness at the Last Glacial Maximum. Land subsidence and a rise of RSL is shown for most parts of England. The latest processing of Continuous GPS data in Great Britain, for stations that are representative of crustal motions, shows vertical velocities roughly between 1.3 and 1.5 mm/yr in the parts of central Scotland and about -2 to -3 mm/yr in southern England. Fig. 2 illustrates the spatial distribution of those AG-aligned CGPS vertical velocity estimates produced by the British Isles continuous GNSS Facility (BIGF) from station time-series between 1997 and 2014, referenced to a global IGb08 reference frame. Data from 158 stations, which exhibit a time span greater than 4.7 years, are displayed.

Slight discrepancies exist regarding the location of maximum uplift within Scotland. While most CGPS solutions tend to place it in the eastern parts of Scotland [14, 17], GIA modelling results and Holocene RSL data show it positioned in the west of the country [12, 18].

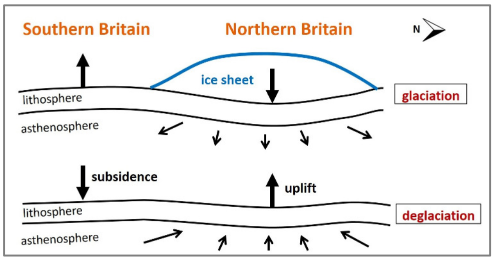

Figure 1 Concept of glacial isostatic adjustment in Great Britain during the Pleistocene (above) and Holocene (below).

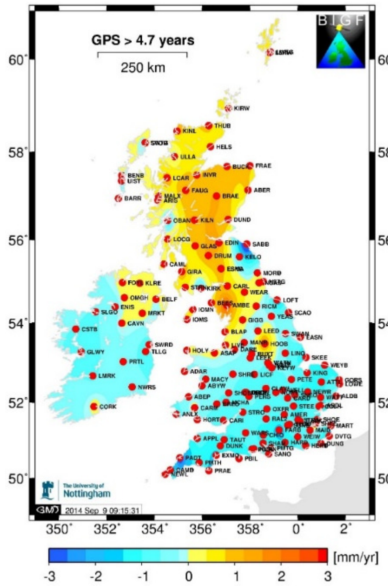

Figure 2 Vertical station velocities from Continuous GPS estimates in Great Britain for stations with a time frame of more than 4.7 years (BIGF).

3. USING INSAR TO MEASURE GIA IN SCOTLAND

SAR data sets covering the land mass of Scotland from different sensors, including ESA ERS-1/2, ESA Envisat, JAXA ALOS PALSAR, JAXA ALOS-2 PALSAR-2 and possibly DLR TerraSAR-X and ESA Sentinel-1 are being used to establish time-series of surface movements with the Small Baseline InSAR technique [19].

The aim is to use those SAR satellites to cover as long a time span as possible to ensure that the low magnitudes of vertical crustal motion due to GIA are detected. Fig. 3 gives an overview of selected SAR missions, from the early 1990s to present, giving a time frame of about 20 years for GIA analysis. The spatial coverage that can be achieved in Scotland with ALOS PALSAR images, for example, is illustrated in Fig. 4; however, the focus

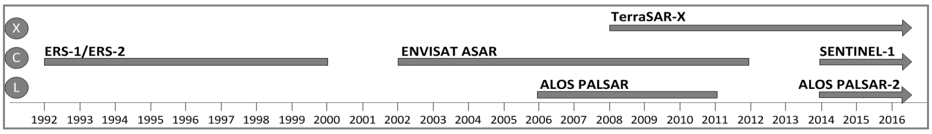

Figure 3 Temporal coverage of SAR sensors selected for analysing GIA in Scotland.

here lies on coastal areas and the suspected GIA uplift centre.

Continuous GPS measurements of the long-term 3D-displacement of the Earth's surface will be used to mitigate orbital ramps in the InSAR results in this study and as an independent data set for comparison and validation.

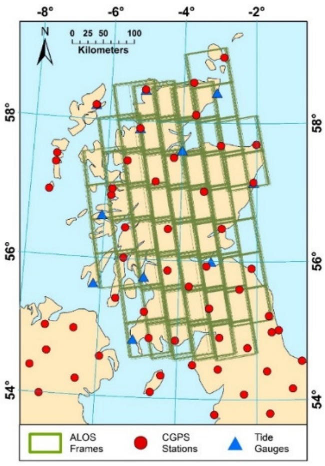

Figure 4 A selection of ALOS PALSAR tracks covering the area of Scotland, together with the location of Continuous GPS stations and tide gauges.

For the detection of long-term and small, long-wavelength displacements, such as GIA, a high precision and accuracy are necessary to make it a competitive tool in comparison to established geodetic techniques, such as CGPS. Under optimal conditions InSAR can be sensitive to land deformations in the low mm or even sub-mm-level [20, 21]. The accuracy of InSAR time-series techniques lies at 1 mm/yr for mean deformation velocity, but is dependent on weather conditions, the number of acquisitions available, the total time range covered by images and the distance to the reference area [22, 23].

In general, the accuracy of the height change is only as good as the accuracy of the interferometric phase. In the SBAS processing chain that is applied here (Fig. 5) the different components of the total phase signal in the differential interferograms have to be corrected for before inverting the deformation signal ϕ_{def} [24]:

$$\phi_{total} = \phi_{def} + \phi_{orbital} + \phi_{atmospheric} + \phi_{topographic} + \phi_{noise}. \quad (1)$$

In the past, Persistent Scatterer Interferometry has been successfully established on a regional scale in Great Britain to measure vertical land movements, for example in the River Thames area [25] and at selected tide gauges along the coast [26]. In the present study, Small Baseline InSAR is chosen as the time-series inversion method, since it is expected to show better applicability to measure the spatial change in glacial rebound in the rural regions of Scotland, where dominant scatterers are scarce.

4. EXTENDED NETWORK ORBIT CORRECTION

Within the processing chain, the focus lies first on the correction of orbital artefacts. Those phase ramps are especially problematic when it comes to measuring long-wavelength, wide-scale ground deformation (GIA), since both often show similar spatial patterns, which are difficult to discriminate. In this case, a simple fitting of orbital ramps to individual interferograms would also eliminate the deformation signal from the interferograms. Thus, more sophisticated methods are necessary, such as utilizing networks of interferograms.

After generating and unwrapping 69 interferograms from the ALOS PALSAR sensor for acquisitions between December 2006 and June 2010 for the greater Glasgow area in Scotland (Path 664, Frame 112), some of the interferograms exhibit strong orbital inaccuracies, identifiable by the parallel linear or non-linear (curved) residual fringes. Short- and long-wavelength atmospheric artefacts are also evident. Fig. 6 (upper row) shows a selection of this data set.

The network orbit correction method described by Biggs et al. [27] has been applied to the data in order to isolate the long-wavelength orbital (and possibly atmospheric) errors in the interferograms from the long-wavelength deformation signals. This network orbit correction technique employs the fact that the error signals behave as a linear combination of the individual components of each of the two acquisitions that form one interferogram.

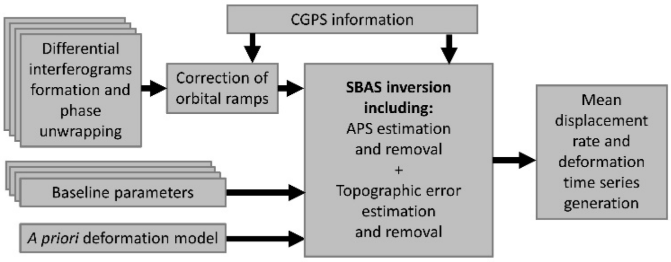

Figure 5 Processing chain of Small Baseline InSAR approach used in this study.

Using this method, it is possible to split the orbital contribution within one interferogram between its two acquisitions. Since one acquisition is usually used in the formation of several interferograms, the information that is contained in an entire network of interferograms is exploited to estimate the residual orbital errors.

A planar orbit error ϕ_{kl_p} in one interferogram is described as the difference of the orbit error contributions to acquisitions k and l:

$$\phi_{kl_p} = a_k x_p - a_l x_p + b_k y_p - b_l y_p + c_{kl} \qquad (2)$$

where $[x_p, y_p]$ are the coordinates of pixel p within the image. Each coherent pixel within each interferogram provides an observation equation for solving the system for the parameters a_k, a_l, b_k, b_l and c_{kl}. c_{kl} relates to a reference frame shift of the interferogram that appears when different seed locations are employed during interferogram unwrapping. With N number of acquisitions that create M interferograms, comprised of P pixels, there are MP observation equations with $2N + M$ unknown parameters. The system of equations is underdetermined, however, since observations or entries in the design matrix may be linearly dependent. The rank of the matrix is $2(N-1) + M$. The system can be solved with a truncated singular value decomposition (SVD). The estimated orbital planes are then subtracted from each ALOS interferogram. Fig. 6 (lower row) depicts the interferograms after orbit correction.

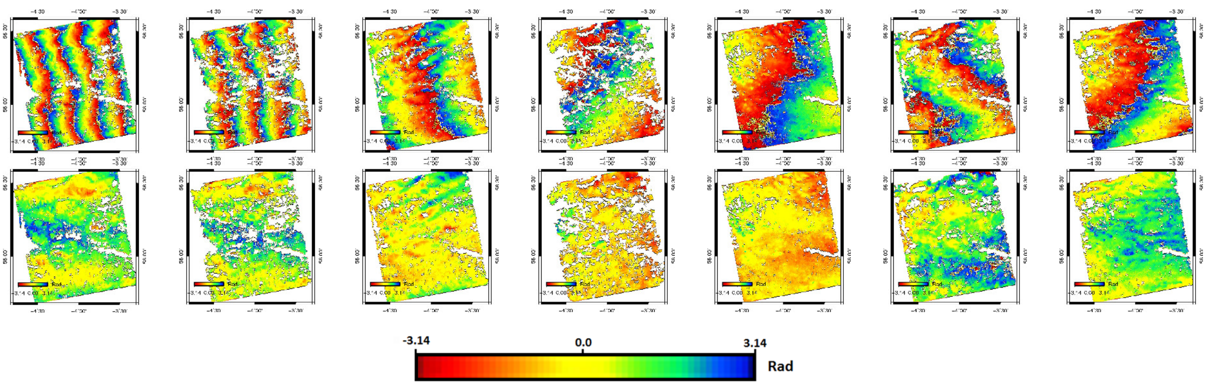

Figure 6 Selection of re-wrapped (-π to π) ALOS PALSAR interferograms between December 2006 and June 2010 (Path 664, Frame 112) before any correction of residual orbtial, atmospheric or topographic errors (above) and after correction of artefacts with network orbit correction method (below).

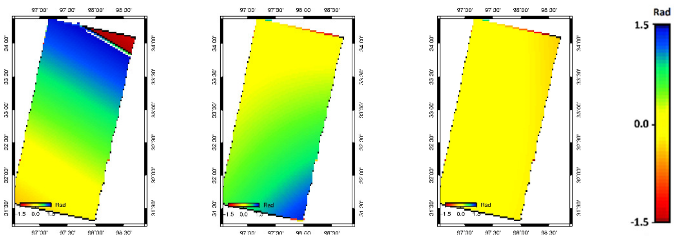

Figure 7 Left: Simulated interferogram with 2^{nd} order orbital error, middle: interferogram corrected with conventional network orbit correction method, right: interferogram corrected with extended network orbit correction approach.

In an attempt to improve results, an extended approach of the network orbit correction is tested [28]. The extended version incorporates phase loops of interferogram triplets [29]. Three acquisitions k, l, m can form the interferograms kl, km and lm. Assuming that orbital errors cancel out in a phase loop, it can be said that:

$$\phi_{kl_p} - \phi_{km_p} + \phi_{lm_p} = 0 \quad (3)$$

When inserting Eq. 2 for each of the three interferograms into Eq. 3, the following expression is obtained:

$$c_{kl_p} - c_{km_p} + c_{lm_p} = 0 \quad (4)$$

This way each interferogram triplet provides further observation equations and the design matrix of the conventional network correction approach can then be extended by placing further constraints on the phase shift parameter c.

This approach has been tested with synthetically generated interferograms containing first and second order orbital errors plus a random noise term. Fig. 7 shows a second order simulated orbital artefact, which has been removed using the extended network orbit correction. Compared to the conventional technique, the extended method is able to resolve the error almost entirely.

The application of this technique to the Scottish ALOS PALSAR data has yet to be fully examined. Also, in order to differentiate accurately between orbital artefacts and the small, long-wavelength GIA deformation signal, the information from the vertical CGPS estimates now require to be incorporated into the orbit correction.

5. CONCLUSION

In the InSAR time-series processing chain there are many challenges that have to be addressed when inverting very small signals, such as GIA in Scotland. This study investigates what can be achieved with Small Baseline InSAR time-series techniques. Orbit errors represent a dominant error source. However, other issues, like long-wavelength atmospheric disturbances, will also have to be resolved.

InSAR may be able to close existing gaps in the quantitative description of the spatial variability of vertical land movement in Northern Britain, since the observational data density of conservative methods varies between regions and spatial interpolation is necessary. With its two-dimensional monitoring capabilities, InSAR is not confined to the existing CGPS/AG station network or to the fragmentary preservation of palaeo-environmental data. This is significant when explaining spatially variable sea-level trends at the coast. Furthermore, InSAR might contribute to the validation of theoretical GIA models, where difficulties in the parameterization persist and poor fits between model and observations remain, especially in Scotland. As another independent data source, InSAR can help address biases in other GIA measurement techniques and vice versa, thus demonstrating a complementary relationship to geological and geodetic methods.

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