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Advanced InSAR for Permafrost Related Ground Motion

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ABSTRACT

The unmatched spatial coverage of spaceborne Interferometric Synthetic Aperture Radar (InSAR) time series analysis makes it an attractive choice to provide permafrost related ground motion information for vast landmasses such as the Canadian Archipelago both for communities and climate change scientists. Monitoring permafrost with InSAR is well established; 3vGeomatics has taken part in five separate projects, monitoring over 20 communities in permafrost affected areas. At the same time, the Arctic ranks among the most challenging environments for applying InSAR, due to numerous complications such as snow cover during winter, large spatial fluctuations of soil moisture,the presence of surface water during summer diminishing InSAR quality, and the seasonal dynamics of the active layer leading to temporally non-linear motion behaviour. This study focuses on the town of Inuvik, in Canada’s Northwest Territories, which has presented the largest challenges to InSAR processing of communities monitored by 3vGeomatics. Previous attempts using traditional InSAR methods did not yield useful results here. In addition to the seasonal change problems, vegetation (which also diminishes InSAR quality) is more abundant than for the other communities, and the size of Inuvik is too small to rely solely on buildings for stable ‘targets’. However, considering Inuvik’s large dataset of 42 very high resolution RADARSAT-2 Spotlight images, this site provided a unique opportunity to develop a novel approach to Arctic InSAR monitoring of ground motion. Several new methods, such as temporary target selection, advanced atmospheric error correction, coherence sharpening, and spatio-temporal adaptive filtering combined with a parametric seasonal model of the active layer, have been incorporated into our Arctic InSAR processing. We discuss our efforts towards developing these methods, and show results demonstrating their success. The described InSAR processing innovations are generally applicable to similar sites, and offer new possibilities for measuring change in the permafrost regions.

RÉSUMÉ

La couverture spatiale offerte par l’analyse de séries temporelles réalisée par Interferometric Synthetic Aperture Radar (InSAR) est un choix judicieux, autant pour les communautés locales que pour les scientifiques, pour l’acquisition d’informations concernant les mouvements du sol du pergélisol sur de vastes territoires tels que l’Archipel Canadien. Un suivi du pergélisol via InSAR est bien implanté dans l’Arctique; 3vGeomatics a pris part à cinq projets différents dans plus de 20 communautés dans les régions pergélisolées. Toutefois, l’Arctique se classe parmi les environnements les plus difficiles pour l’application de l’InSAR, à cause de multiples complications, telles que la présence d’une couverture neigeuse pendant l’hiver et de nappes d’eau en surface durant l'été qui diminuent la qualité de l’InSAR, d’importantes variabilités spatiales de la teneur en eau du sol, en plus des dynamiques saisonnières de la couche active qui entrainent un mouvement du sol temporellement non linéaire. La présente étude se concentre sur la ville d’Inuvik, dans les Territoires du Nord-Ouest canadiens. Cette communauté présente les plus grands défis pour le suivi par InSAR de toutes les communautés étudiées par 3vGeomatics. Les méthodes traditionnelles InSAR utilisées lors de tentatives précédentes à cet endroit n’ont malheureusement pas fourni de résultats utiles. En plus des problèmes de changement saisonnier, la végétation (qui diminue aussi la qualité de l’InSAR) est plus abondante ici que dans les autres communautés et la taille d’Inuvik est trop petite pour se fier seulement aux bâtiments comme « cibles » stables. Cependant, considérant le large éventail de données disponibles composées de 42 images RADARSAT-2 Spotlight à très haute résolution, Inuvik a constitué une opportunité unique pour le développement d’une nouvelle approche de suivi des mouvements du sol en Arctique par InSAR. Plusieurs nouvelles méthodes, telles que la sélection de cibles temporaires, la correction avancée d’erreurs atmosphériques, l’amélioration de la résolution de la cohérence et le filtrage adaptatif spatio-temporel combiné avec un modèle paramétrique saisonnier de la couche active, ont été incorporées dans notre traitement des données InSAR. Nous discutons de nos efforts de développement et présentons les résultats qui démontrent le succès de la nouvelle méthodologie. Les innovations relatives au traitement de données InSAR décrites ici sont généralement applicables à des sites similaires et elles offrent de nouvelles possibilités pour mesurer les changements qui surviennent dans les régions pergélisolées.

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1 INTRODUCTION

Ongoing climate change in the Arctic is expected to lead to widespread permafrost changes, leading to more unstable ground, from either increased active layer activity or outright permafrost decay (thermokarst) that can affect both the natural environment and the spread-out settlements within it. Surficial geology assessment can identify risk but cannot assess actual changes to permafrost stability. On the other hand, direct surveying of surface displacement using ground-based or aerial methods is expensive and can provide only inadequate coverage for monitoring the vast Arctic environments. InSAR analysis using commercial spaceborne radar sensors such as RADARSAT-2 or TerraSAR-X is able to measure large-scale surface displacement, whilst being operationally cost-effective.

2 INSAR MONITORING OF PERMFROST

Technically, the Arctic is an especially challenging environment for measuring ground motion with InSAR due to complications from persistent ice and snow cover during the winter months and widespread surface water during summer greatly affecting InSAR quality. Further seasonal ground deformation through the freeze-thaw cycle of the active layer, combined with large variations in soil moisture and atmospheric water vapour dominate the InSAR signal. These phenomena make it difficult to extract long-term trends of surface displacement needed to identify and monitor unstable ground.

2.1 Traditional Processing Chain

An interferometric data set suitable for InSAR monitoring of surface motion consists of a stack of SAR images acquired at the orbit repeat period of the SAR sensor. The repeat period varies between different sensors (24 and 11 days in the case of RADARSAT-2 and TerraSAR-X, respectively) and determines the maximum temporal resolution of the final displacement time series. Surface displacement has to be extracted from the differential radar phase measurements of all usable image pairs (interferograms). The radar phase is cyclical (wrapped) at half the sensor wavelength (2.8 cm and 1.5 cm for RADARSAT-2 and TerraSAR-X, respectively).

Besides surface displacement, errors in known topography, atmospheric water vapour fluctuations, as well as soil moisture and snow cover changes in time also contribute to the InSAR signal. Strong spatial gradients of the signal contributions, as well as outright surface disturbances and vegetation changes, all degrade the InSAR quality or coherence.

The standard approach to InSAR motion analysis is using a combination of a-priori modeling of the linear deformation trend (in time) and the other signal components (on the wrapped phase measurements) followed by solving for the unknown integer ambiguities (unwrapping) of the residual non-linear (cyclical) deformation signal. Least square inversion of the unwrapped non-linear signal and re-introduction of the linear trend gives the final deformation time series [Berardino et al, 2002]. During processing, analysis is restricted to pixels found to have sufficient signal quality throughout the period covered by the image stack. 3vGeomatics standard InSAR solution is based on the 'Dual-Scale' concept where typically dominant atmospheric water vapour fluctuations above a certaian cut-off scale are removed approximately from the wrapped phase [Rabus and Ghuman, 2009].

There are several shortcomings of the standard approach for permafrost monitoring that stem from key assumptions valid for other less challenging environments being violated for the Arctic environment.

(i) Signal from both deformation and other contributions is highly non-linear and dominates over the linear trend. This is due to the seasonal freeze-thaw dynamics of the active layer, and extensive winter snow-cover, respectively.

(ii) Areas of good signal quality are sparse, particularly for crucial interferograms that span a full year or more. This is mainly due to changing vegetation cover, and surface water.

As a consequence of (i) the standard approach thus is not able to reduce the residual signal efficiently to make it less cyclical, while (ii) results in a small ratio of permanent to temporary targets, which overwhelms the traditional MCF based unwrapping algorithm [Costantini, 1998].

The standard approach, while having been used for by 3vGeomatics operationally for a number of Arctic test sites with good results, has failed to produce useful results for others, where either active layer dynamics is larger or/and vegetation density is higher than usual. In the following paper we describe recent enhancements to the standard approach that have allowed us to extend successful processing to these particularly challenging permafrost sites.

2.2 Permafrost-specific Enhancements

To address the just described permafrost-specific issues of sparse coherence and dominating non-linear signal, the following enhancements were introduced into the InSAR processing chain.

(i) A-priori Atmospheric Phase Screen (APS) modeling has been improved: instead of forming APS independently for each interferogram, per-scene APS are now inverted from a partial network of suitable coherent interferograms.

(ii) The wrapped phase is now routinely filtered before the a-priori phase component modeling using a novel adaptive filter [Reza et al, in press] developed by 3vGeomatics. Construction of this filter selects, for a suitable sub-network of interferograms, all pixels that are at least temporarily coherent and share a similar signal with sufficiently many neighboring pixels. The adaptive filter kernel is built form the identified coherent neighbor pixels weighted by their similarity and quality. Adaptive filtering significantly increases usable coherent areas of all interferograms.

(iii) Both a-priori (wrapped) and a-posteriori (after unwrapping and network inversion) signal component modeling now includes a simple active layer model that reflects the seasonal freeze-thaw dynamics [Liu et al, 2010]. The simplest form of this model uses a fixed thawing start date and length of the thawing season. An extension using temperature and precipitation records to vary temporally (for each year of the period covered by the InSAR data) the thaw start date and season length is straightforward. The additional introduction of spatial variations of thaw date and season length would require some knowledge of the spatial inhomogeneity of spring snow cover. This is difficult to measure and we did not attempt it. All winter interferograms with unknown signal contributions from variations in (again spatially inhomogenous) snow cover are excluded in the enhanced signal component modeling with the described active layer model.

(iv) With the already described enhancements, signal quality is improved through adaptive filtering and signal dynamics are reduced through better APS and a-priori signal component modeling. Nevertheless, high spatial variability and sparseness of the residual signal remained challenging to unwrap for the MCF algorithm, originally used in our standard InSAR approach. Consequently, we replaced MCF with a novel more robust unwrapping algorithm [Gara and Ghuman, 2015] that is capable of handling high spatial signal gradients and sparse coherence (temporary target case) more robustly. Optimizing this algorithm for the permafrost case is ongoing.

In the following section we show examples of the improvements achieved with our enhanced InSAR approach for the most challenging of the Arctic sites monitored by 3vGeomatics; the town site and surroundings of Inuvik, NWT.

3 INUVIK GROUND MOTION ANALYSIS

3.1 Site Background

Inuvik is located in the McKenzie Delta some 100 km from the shore of the Arctic Ocean. Despite being located above 68^{O}N, vegetation cover in Inuvik is more diverse compared to other settlements in the Canadian Arctic. This is due to a local climate that is kept unusually mild due to the possibility of advection of warmer air masses from the South along the McKenzie Valley. Denser vegetation including Jack Pine and Black Spruce is characteristic of the ground cover surrounding Inuvik (see Figure 1, middle).

Fieldwork for this site revealed clear signs of ground and infrastructure displacement from unstable permafrost (Figure 1, bottom) both inside and outside the town's footprint.

The dense vegetation, in combination with higher than average precipitation (as another result of the warmer climate) drastically reduce InSAR quality for the Inuvik area.

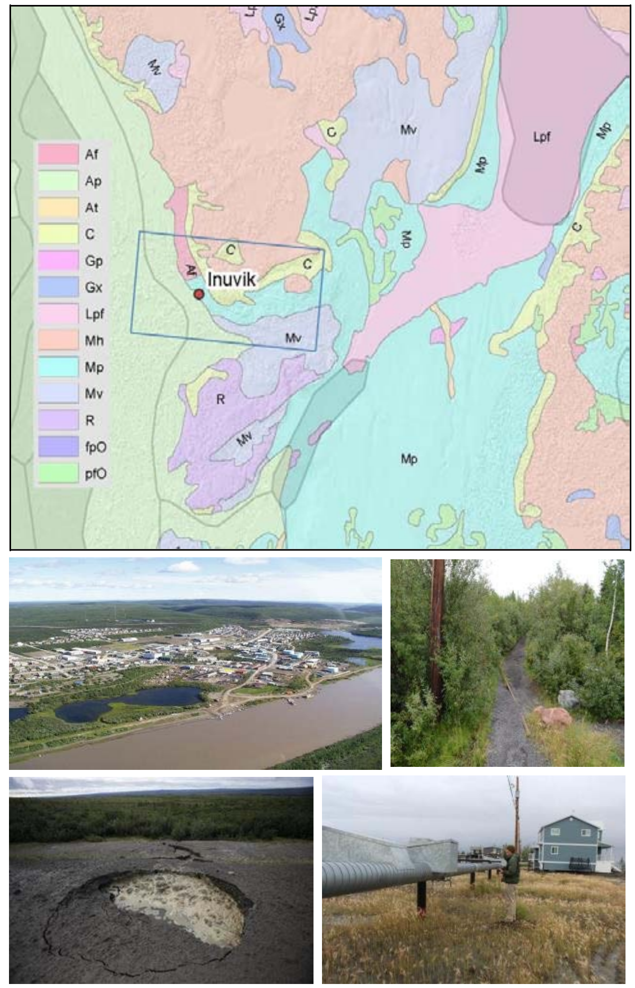

Figure 1. Inuvik site background. Top: surficial geology map (SAR footprint superimposed); Left middle: photograph of town site. Right middle: typical vegetation. Bottom: permafrost related displacement.

3.2 InSAR data set

The InSAR data set used in this study consists of an ongoing repeat pass stack of 42 RADARSAT-2 high resolution Spotlight images spanning the time period Jan 2012 to April 2015 (Figure 2).

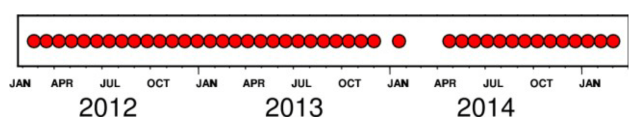

Figure 2. Schedule of Inuvik SAR acquisitions.

The sensitivity of the InSAR signal to vertical subsidence or uplift is the cosine of the signal incidence angle, 50 degrees in this case, which gives a sensitivity factor of 0.6. Image resolution on the ground is about 2.1 m and 0.5 m in satellite look and flight direction, respectively.

3.3 Traditional InSAR Result

Low and temporally fluctuating coherence, due to vegetation and snow cover changes, as well as lack of modeling of the active layer dynamics, severely limit coverage and quality of traditional InSAR analysis. The traditional InSAR processing result for the linear deformation rate is shown in Figure 3.

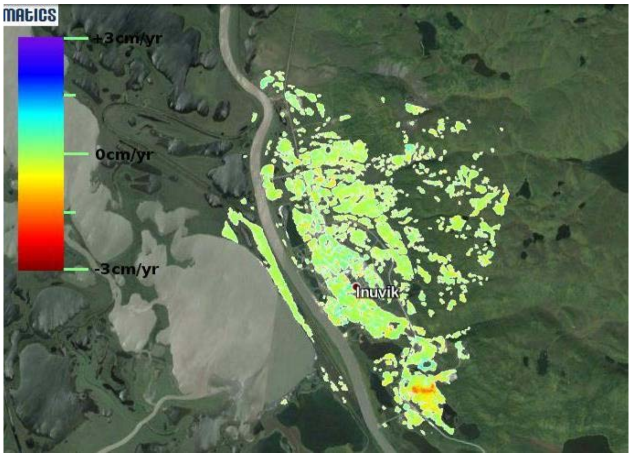

Figure 3. Linear motion trend for Inuvik, NWT. Final Result of traditional InSAR analysis (sparse coverage; restricted to actual town area)

Areas of known strong motion within the town area are not well represented in the traditional result. Further, very little of the natural permafrost areas outside the town site could be measured. Major areas of interest in terms of permafrost-related displacements such as the road to the airport and the airport runway could also not be monitored due to low InSAR quality.

3.4 Enhanced InSAR Result

The permafrost-specific enhancements described in section 2.2 are still being integrated into 3vGeomatics' operational InSAR processing solution. However, a prototype of the final enhanced solution has already been applied to a number of challenging Arctic sites, including Inuvik where the traditional solution had the most problems. In all cases we observed significant improvements in coverage and quality for the recovered long-term (linear) motion trend maps. Further, we found significant value in the additional map output from the now also modeled active layer dynamics.

The new map (seasonal motion amplitude) contains the magnitude of the seasonal dynamics of the active layer (winter frost heaving and summer thaw slumping) for all valid pixels in the image.

In the following we show some preliminary results obtained for the Inuvik site using the enhanced prototype solution. We obtained these results with the simpler active layer model, with a fixed thaw season (i.e. without meteorological time series input) from 1 June to 30 September and using only interferograms with start and end dates inside the thaw period.

Figures 4, 5, 6 show subsets of maps depicting height error, linear motion trend, and seasonal motion amplitude, respectively. These results are intermediate, in that they are not yet geocoded but still in the original SAR image geometry, which is rotated clockwise with respect to North by about 10 degrees (see image footprint in Figure 1). All measurements are with respect to a single reference point with high, persistent InSAR quality (white cross in figures).

Compared to Figure 3 the enhanced result in Figure 5 shows significantly higher coverage both inside and outside the town. Areas of identified subsidence correlate better with known problems on the ground. Likewise areas of high seasonal motion in Figure 6 correlate well with areas where ice rich permafrost can be plausibly expected, based on the surficial geology. Some of the built up areas show opposite seasonal amplitude (blue color: uplift in summer). This could be due to thermal expansion. The height error (Figure 4), also plausibly flags buildings and other topographic details that are not contained in the DEM used in our study. A peculiarity is a significant bias of the height error. This is due to a corresponding height bias of the reference point with respect to the DEM.

4 DISCUSSION AND CONCLUSIONS

We have developed several powerful permafrost-specific enhancements for 3vGeomatic's operational InSAR processing chain. The goal of the development was to mediate the temporally variable coherence loss from snow cover and surface water changes, as well as the non-linearity of the motion signal due to active layer dynamics. Implemented enhancements include improved APS removal and adaptive (wrapped) phase filtering. Further we have improved signal component modeling by using an explicit parameterization of the active layer dynamics and have introduced a more sophisticated 3D unwrapping algorithm capable of handling temporary targets.

An initial prototype of the advanced operational permafrost InSAR processing chain that is currently assembled by 3vGeomatics has been tested on the challenging Inuvik site. Preliminary results using a constant thaw season for the active layer already show drastic improvements over those obtained with our traditional InSAR analysis.

The next step towards achieving the final operational and automated permafrost-specific InSAR processing solution is a thorough test for a large number of Arctic sites with complementary environmental characteristics to optimize all tunable parameters in the prototype. This includes testing the value of driving the active layer model with the available meteorological time series, temperature, precipitation, versus using a constant thaw season parameterization. Our model allows several options of varying complexity to do this. Initially, when InSAR time series are spanning just two or three years, including meteorology drivers may make the model less robust. However, as InSAR stacks build to a greater thickness of several years using meteorology drivers reflecting temporal changes of the thaw season from year to year could lead to further significant accuracy improvements for the motion trend and seasonal motion amplitude maps.

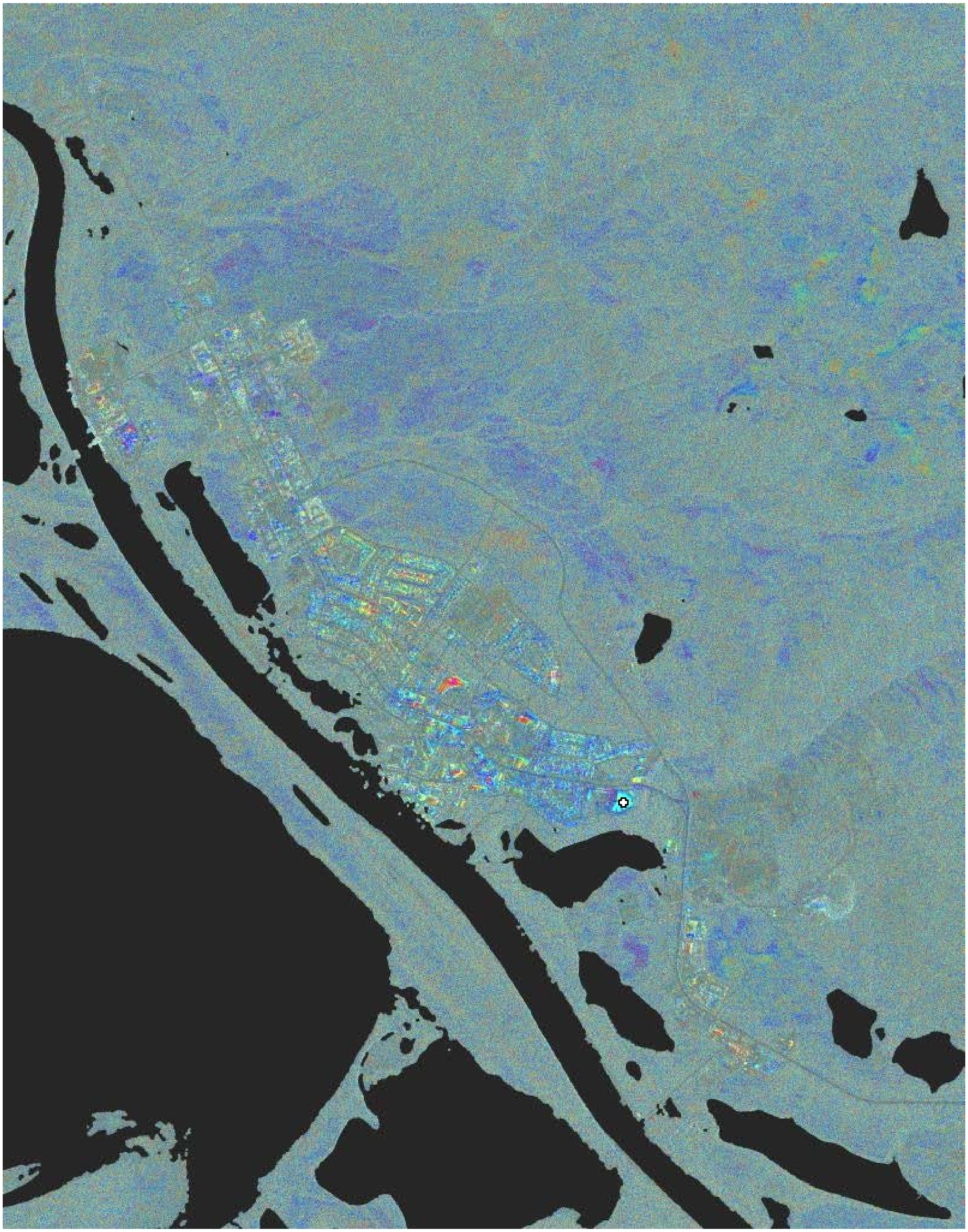

Figure 4. Height error map for Inuvik, NWT. Intermediate Result (SAR image geometry) of enhanced InSAR analysis. Blue to red color scale ranges from -25 to +25 metres (reference point indicated by white cross)

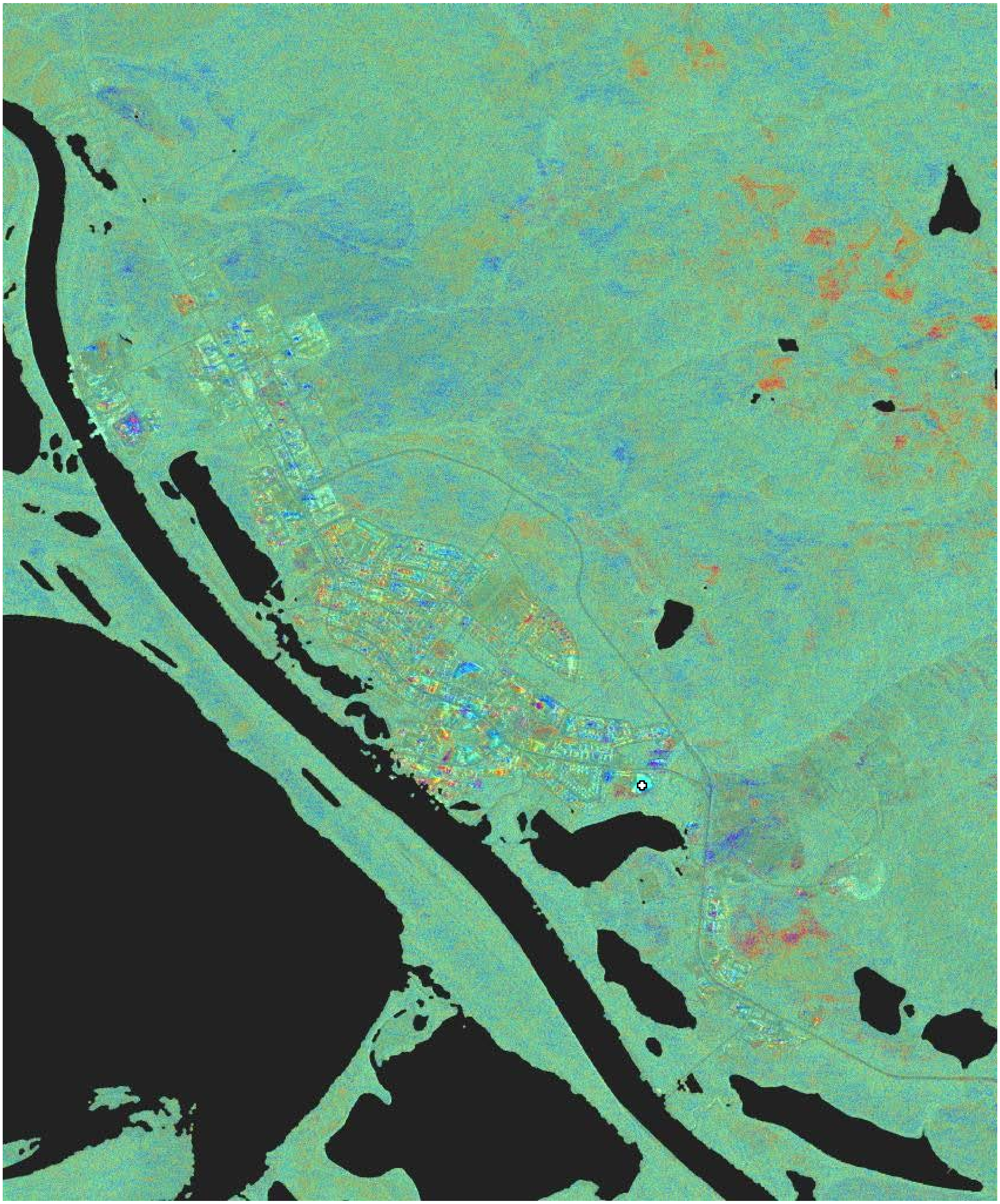

Figure 5. Linear motion trend for Inuvik, NWT. Intermediate Result (SAR image geometry) of enhanced InSAR analysis. Blue to red color scale ranges from -0.5 to +0.5 cm per year (reference point indicated by white cross)

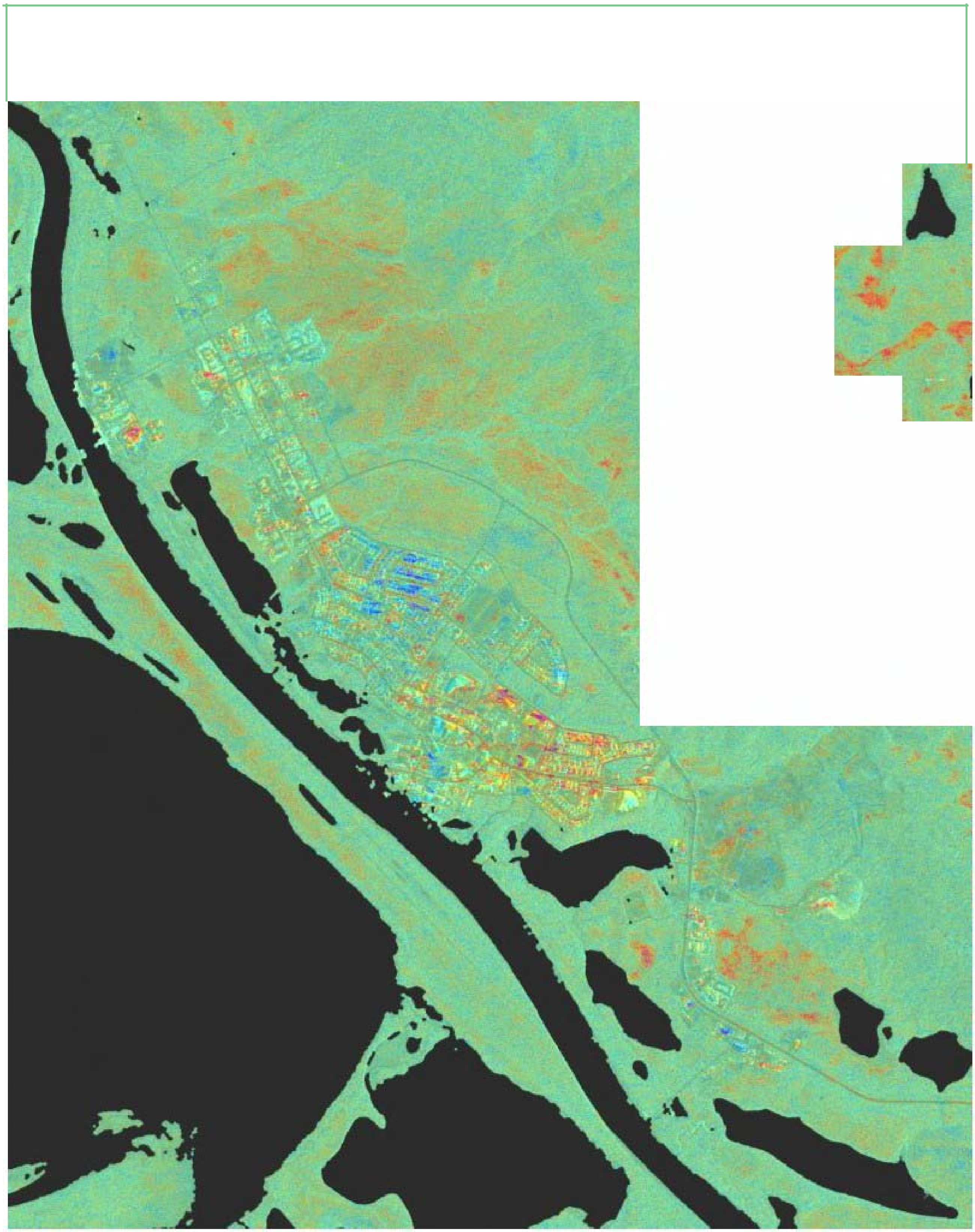

Figure 6. Seasonal motion amplitude for Inuvik, NWT. Intermediate Result (SAR image geometry) of enhanced InSAR analysis. Blue to red color scale ranges from -2 to +2 cm per year (reference point indicated by white cross)

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REFERENCES

Rabus B, P. Ghuman, 2009. A Simple Robust Two Scale Phase Component Inversion Scheme for Persistent Scatterer Interferometry (dual-scale-PSI), Canadian Journal of Remote Sensing, 35(4): 399-410

Costantini M, 1998, “A novel phase unwrapping method based on network programming”, IEEE Trans. Geosci. Remote Sens. 36(3), 813-821 (1998)

Berardino P, G. Fornaro, R. Lanari, and E. Sansosti. 2002 “A new algorithm for surface deformation monitoring based on small baseline differential interferograms,” IEEE Transactions on Geoscience and Remote Sensing, Vol. 40, No. 11, 2375~2383.

Gara M, P. Ghuman, 2015. Phase unwrapping with reformulated MCF using Anchor Points. Proceedings of the FRINGE 2015 meeting in Frascati, Italy

Liu L, T. Zhang, and J. Wahr, 2010. InSAR Measurements of Surface Deformation Over Permafrost on the North Slope of Alaska, J. Geophys. Res., 115, F03023, doi:10.1029/2009JF001547

Reza, T., Zimmer, A., Ghuman, P., and Ripeanu, M., in press. Accelerating Persistent Scatterer Pixel Selection for InSAR Processing. In Proceedings of the 26th IEEE International Conference on Application-specific Systems, Architectures and Processors (ASAP’15), Toronto, Ontario, 27 - 29 July, 2015