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ON SOLVING THE PHASE UNWRAPPING IN REMOTE SENSING RADAR

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INTRODUCTION

The problem of interferometric phase unwrapping in radar remote sensing of Earth systems is considered. Such interferograms are widely used in the problems of creating and updating maps of the relief of the Earth's surface in geodesy, cartography, environmental monitoring, geological, hydrological and glaciological studies, and for monitoring transport communications.

Modern radar systems have ultra-high spatial resolution and a wide band, which leads to the need to unwrap large interferograms from several tens of millions of elements. The implementation of calculations by these methods takes several days.

To solve the phase unwrapping problem, the efficient inverse vortex field method was previously proposed. In this work, we implemented the inverse vortex field method as a parallel code for graphics processors using CUDA technology.

Using real radar data, numerical experiments are carried out to compare the performance of the developed code with the code previously developed for multicore CPUs. A sufficient accuracy was achieved for a set of images.

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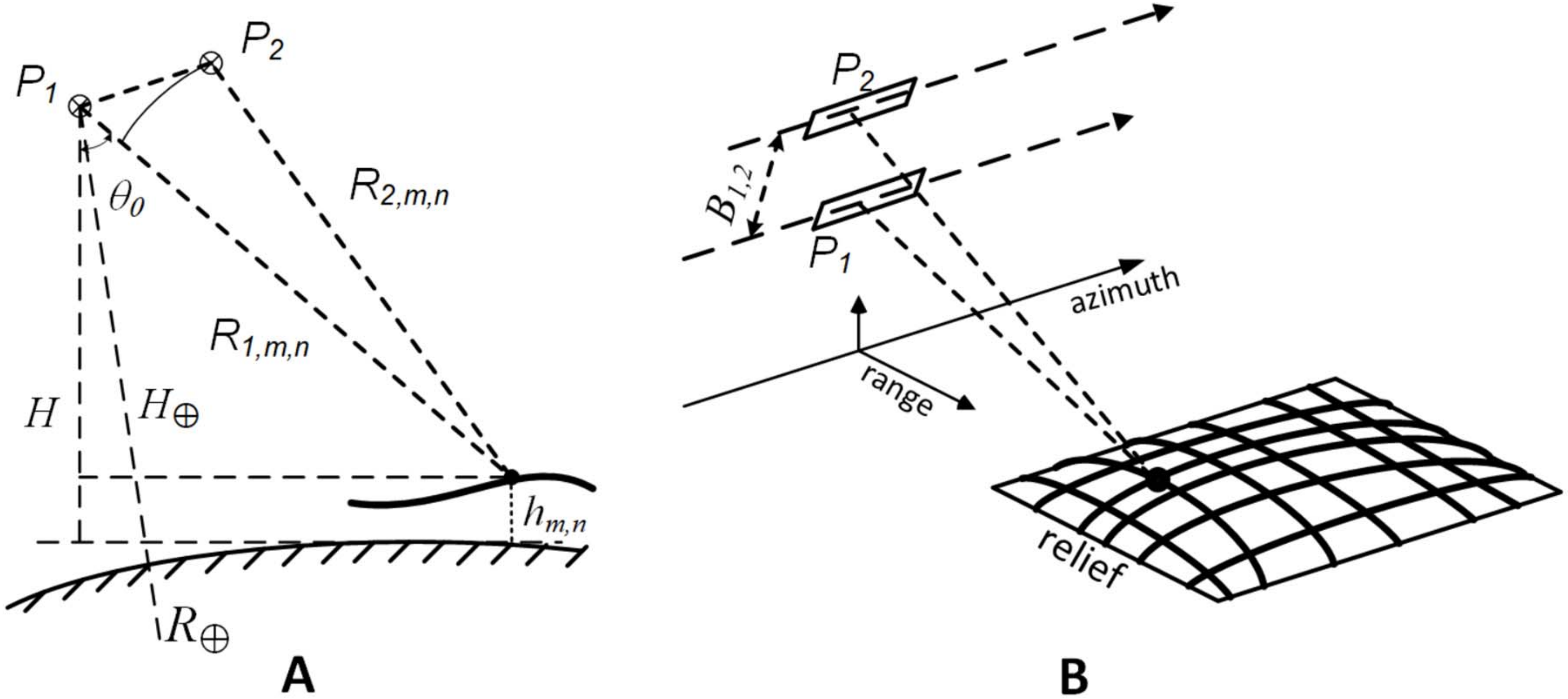
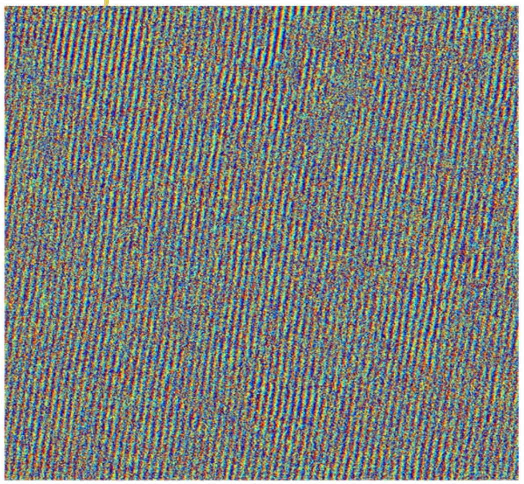
GEOMETRY OF INSAR SURVEY

The initial data for the interferometric survey of the Earth's surface are two complex radar images obtained by a synthesized aperture radar from two parallel orbits located at a short distance.



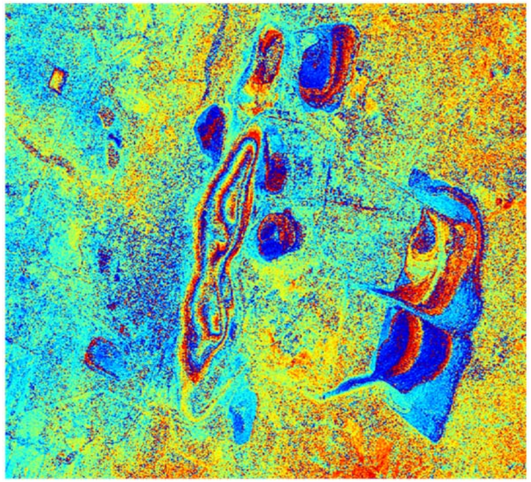
Here, P_1 and P_2 are positions of the X-ray carrier (centers of synthesized apertures) during observations of the surface element, $R_{1,m,n}$ and $R_{2,m,n}$ are the slant ranges, $R_{\oplus}$ is the Earth radius, $B_{1,2}$ is the interferometric baseline, Θ_0 is the incidence angle of the antenna beam, $H_{\oplus}$ is the height of the carrier orbit above the Earth's surface, H is the height reduced to the geometry of the "flat Earth" for the first observation: (**A**) vertical plane; (**B**) spatial disposition.

STAGES OF IMAGE PROCESSING



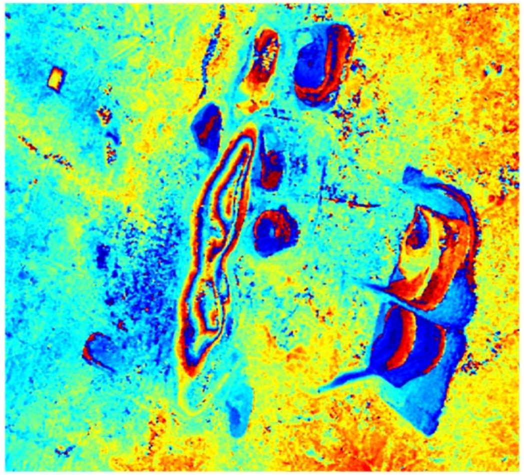
SAR Images

Interferogram calculation



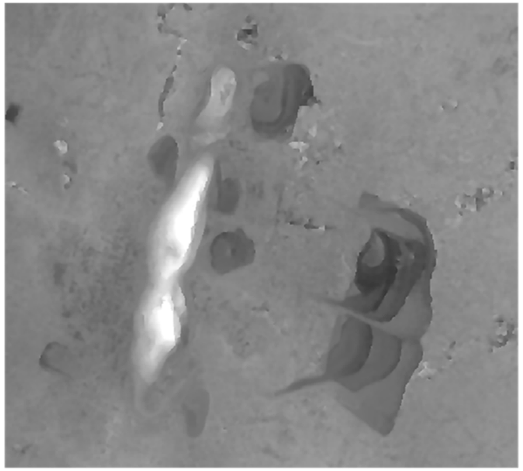
Interferogram

Phase noise filtration



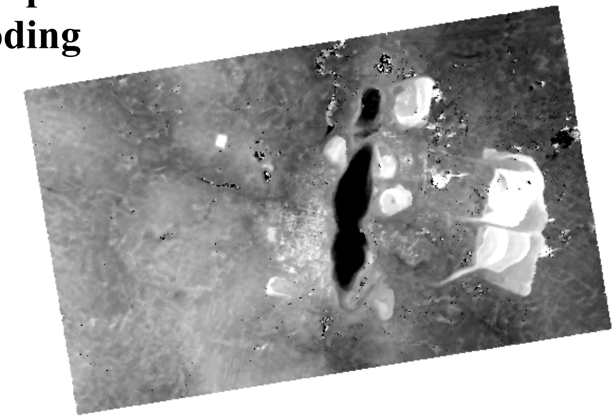
Smoothed interferogram

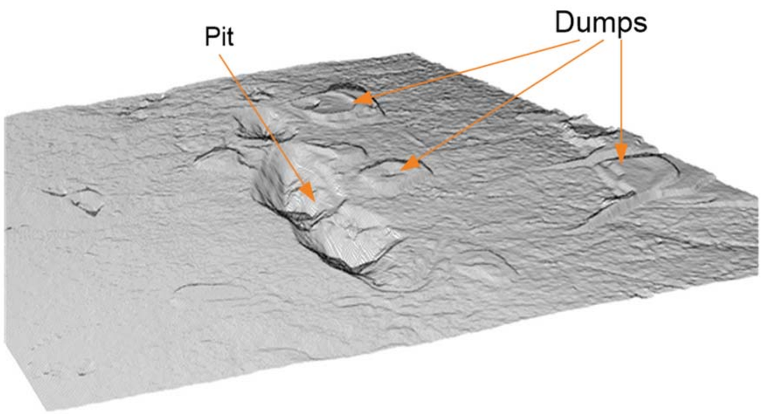
Phase unwrapping



Absolute (unwrapped) phase

Absolute phase geocoding





Georeferenced absolute phase and digital elevation model

PROBLEM STATEMENT

The main problem of interferometric radar remote sensing of the Earth from space data processing is phase unwrapping procedure. Phase unwrapping is a process of transforming a two-dimensional relative phase pattern, which takes values only in the interval $[-\pi, \pi)$, into an absolute phase.

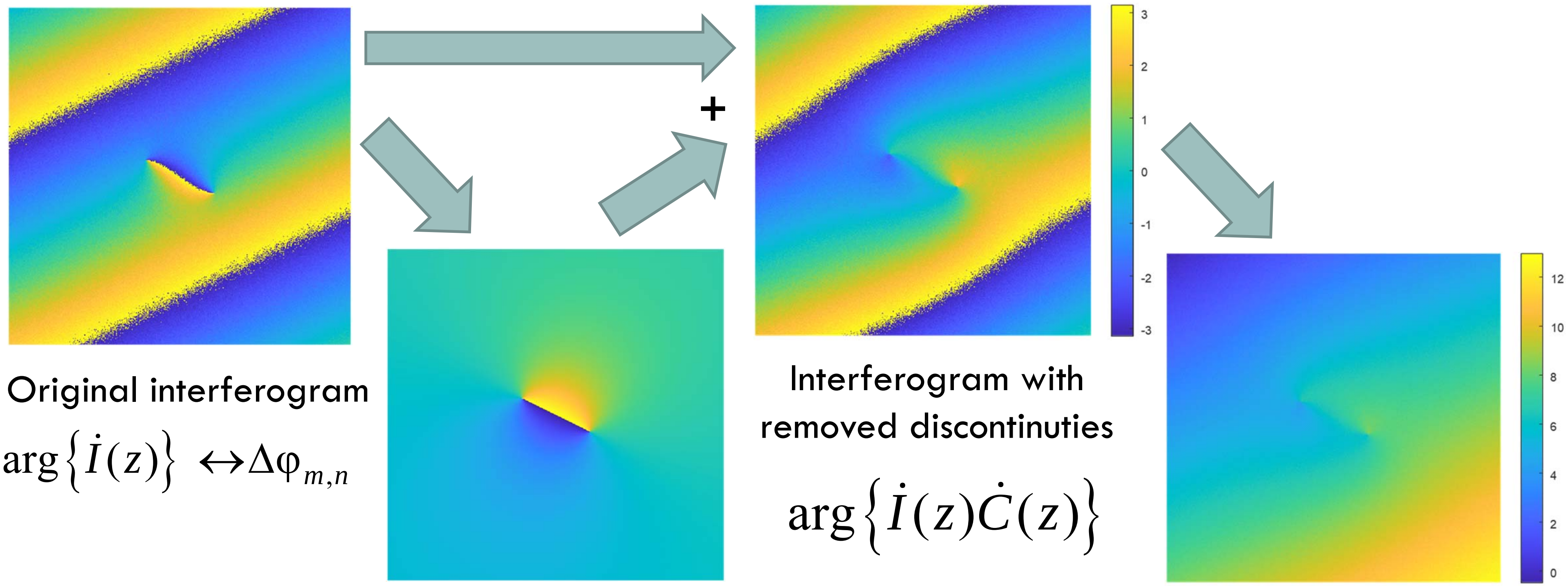
Phase unwrapping is still the most problematic stage of interferometric processing, since such a problem does not have an analytical solution and is solved approximately.

Processing of interferograms takes a long time and can reach several days, which makes it difficult to use the data for the operative solution of monitoring tasks. To unwrap the phase, algorithms have been developed, many of which have high computational complexity and require the use of approximations and simplifications that lead to a decrease in accuracy.

The main problem of phase unwrapping is the presence of phase discontinuities on interferograms.

INVERSE VORTEX FIELD METHOD FOR PHASE UNWRAPPING

The algorithm, which resolves the phase discontinuities, uses the model of unit vortex (slide 8) with the opposite sign. After summing the interferogram and inversed unit vortices for all points, the continuous interferogram is obtained. Such interferogram can be transformed to the absolute phase without errors and artifacts.



Original interferogram

$$\arg\{\dot{I}(z)\} \leftrightarrow \Delta\varphi_{m,n}$$

Inverse vortex field

$$\arg\{\dot{C}(z)\}$$

Interferogram with removed discontinuties

$$\arg\{\dot{I}(z)\dot{C}(z)\}$$

Absolute phase

$$\tilde{\Psi}_{m,n}$$

PARALLEL IMPLEMENTATION

This algorithm can be easily parallelized, unlike the most other unwrapping algorithms. It is realized on multicore processor and the GPU.

Multithreaded CPU code:

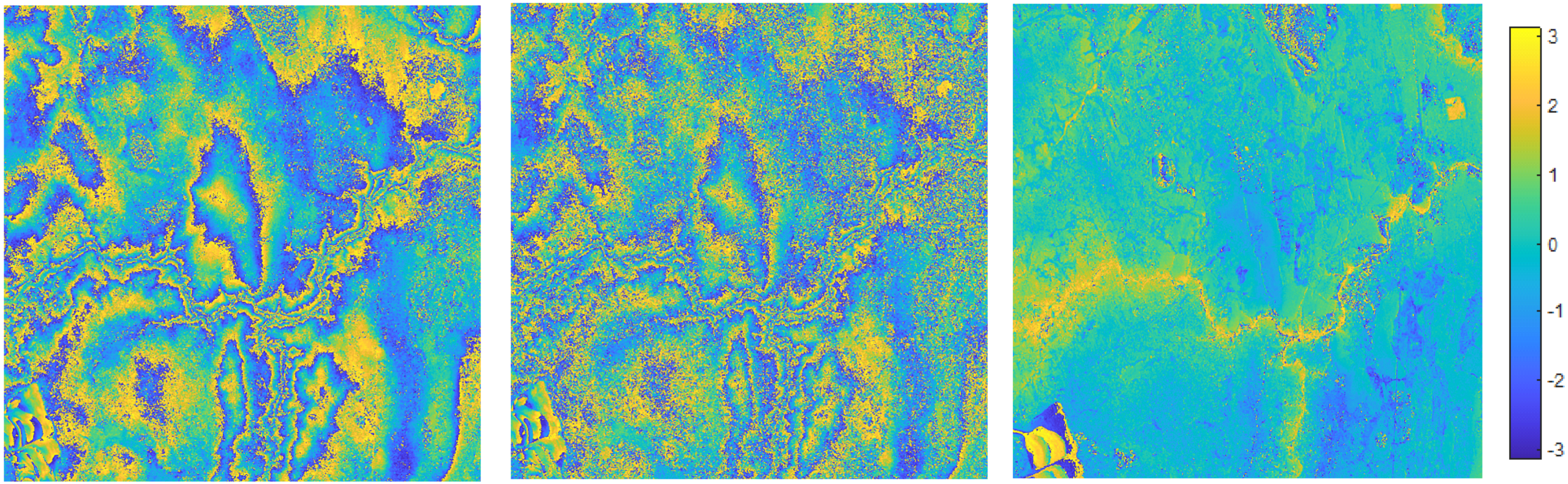
- The elemental vortex field twice the size of the interferogram is precalculated and fragments (centered at singular points) are obtained by computing the relative pointers;
- The outer loop iterated over rows of images and is distributed to OpenMP threads;
- The middle loop iterates over the list of singular points;
- The inner loop iterates by columns and is vectorized and tiled to blocks to utilize the cache and vector instructions.

GPU code:

- Each CUDA thread processes a single image element;
- Inverse vortex field and interferogram fragments are preloaded into the local memory.

NUMERICAL EXPERIMENTS

Interferograms by the ALOS PALSAR radar, area of Asbest city, Sverdlovsk Region, Russia



A Scene 1: HH-polarization, $B_{\perp} = 3500$ m

B Scene 2: HV-polarization, $B_{\perp} = 3500$ m

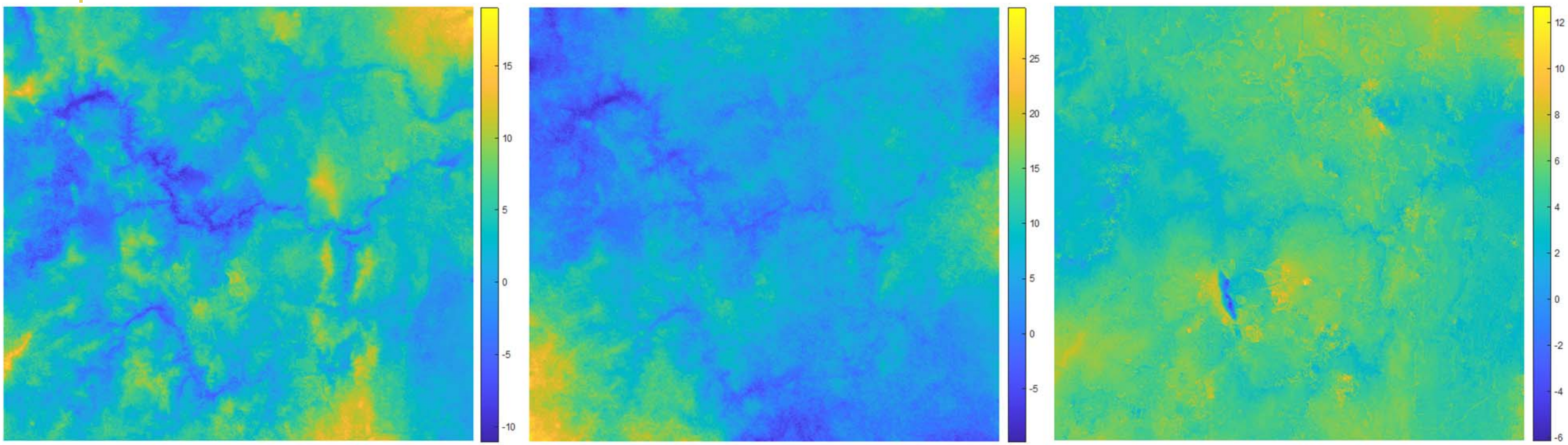
C Scene 3: HH-polarization, $B_{\perp} = 500$ m

Initial scene size was 18000×4500 samples for Scenes 1 and 2, and 18000×9000 for Scene 3. The interferograms were resized to 1024×1024.

The reference terrain heights are represented as a set $\{H_{0i}\}, \quad i = 1, \dots, N$ of at least $N = 1500$ points from a topographic map with a vertical accuracy of 0.5 m.

The reference heights were recalculated to the reference absolute phases $\{\Psi_{0i}\}$.

NUMERICAL EXPERIMENTS: UNWRAPPED SCENES



A
Scene 1
$\widetilde{\sigma_\Psi}$=5.8%

B
Scene 2
$\widetilde{\sigma_\Psi}$=11.1%

C
Scene 3
$\widetilde{\sigma_\Psi}$=14.0%

Absolute phase error

$$\sigma_\Psi = \sqrt{\sum_{i=1}^{N} \frac{(\Psi_i - \Psi_{0i})^2}{N-1}},$$

Relative phase error

$$\widetilde{\sigma_\Psi} = \sigma_\Psi / \sigma_{\Psi 0}.$$

Here, σ_Ψ is the absolute phase error, $\widetilde{\sigma_\Psi}$ is the relative phase error, N is the number of reference points, Ψ_i are the absolute phases, Ψ_{0i} are the reference absolute phases, $\sigma_{\Psi 0}$ is the reference absolute phase standard deviation.

NUMERICAL EXPERIMENTS: COMPUTING TIME

Table contains the computing times of the CPU and GPU code for the scene 2. It contains the time for the CPU code for various numbers of OpenMP threads and time for the GPU code. The speedup coefficients $\boldsymbol{S_n = T_1/T_n}$, where T_n is the computing time for n OpenMP threads, and T_1 is the time for serial (single-threaded) code. For the GPU, the speedup coefficient is $\boldsymbol{S_{\mathrm{GPU}} = T_1/T_{\mathrm{GPU}}}$, where T_{GPU} is the time obtained on the GPU.

Device and number n of threads	Computing time T_n, seconds	Speedup S_n	Efficiency $E_n = S_n/n$
AMD Ryzen 7500H 1 thread	24.4	—	—
2 threads	12.2	2.0	1.0
4 threads	6.3	3.9	0.97
8 threads	4.3	5.7	0.7
NVIDIA GeForce RTX 3070 Mobile	2.4	10.1	—

CONCLUSIONS

- A parallel code for graphics processors based on CUDA technology has been developed for solving the interferometric phase unwrapping problem in radar systems for remote sensing of the Earth.

- Using real SAR images, numerical experiments were carried out to compare the performance of the developed GPU code with the code previously developed for multicore CPUs.

- **Two-fold speedup** was achieved for the GPU code in comparison with the multithreaded CPU code (8 threads).

- The **relative error** for the best case is about **10%**, which is sufficient for various topographic applications.