MAPPING OF VOLCANIC TOPOGRAPHY DYNAMICS ON THE BASIS OF INSAR (TOLBACHINSKY DOL, KAMCHATKA, RUSSIA)

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Abstract

The paper presents results of assessing radar interferometry as an independent method for mapping changes in lava flow topography. The study region is Tolbachinsky Dol (Kamchatka), where a fissure eruption occurred in 2012-2013. This research is based on two-pass differential interferometry for processing a series of Radarsat-2 radar images acquired both from the ascending and descending orbits. During interferometric processing the coherence maps were calculated, which can be used as an additional data source for mapping of the properties of active lava flows. We also calculated the values of lava surface displacements, which highlighted the processes of thermal subsidence. As a result, we have defined a list of mapping parameters that can be extracted from interferometric materials, and have created maps of the dynamics of the lava fields topography.

Keywords: interferometric processing, mapping of topography dynamics, TTI-50 eruption

INTRODUCTION

The advantages of remote sensing data in comparison with the other sources of mapping are their large spatial coverage, simultaneous availability of information for the whole area and high periodicity. However, SAR images are used very little as an independent method of mapping due to processing complexity, specific distortions and difficulties in image interpretation. Radar interferometry (InSAR) is a relatively new method of obtaining information about Earth covers. At the moment, there is still a lack of developed mapping methods based on InSAR.

The method of radar interferometry started to develop from the mid-1970s in studies of extraterrestrial objects, and has been actively used in geographic research since relatively recently, the early 1990s (Briole et al., 1997, Lanari et al., 1998, Masson et al., 1995). As a result of multistage interferometric processing, in which at least two radar images are needed, the absolute terrain heights or surface displacements values are extracted. The method imposes strict requirements on the source images and is rather sensitive to the acquisition conditions (Zakharov et al., 2012).

The result of interferometric processing is a raster image whose pixels contain information about the absolute altitude of surface or its displacement. These values, in international research practice, are used directly for further analysis of the selected area, without creating a map. At the same time, the creation of thematic maps based on the results of interferometric processing would make it possible to obtain a new, holistic information on the state of objects and on the processes occurring within the study area.

To study the potential for mapping using results of interferometric processing, we have selected a locality of Tolbachinsky Dol in Kamchatka, where a large fissure eruption occurred in 2012-2013. It was named by Kamchatkan volcanologists the Tolbachik fissure eruption of 2012-2013, abbreviated in Russian as TTI-50. The eruption was effusive. As a result, three lava fields were created: in the first months, Vodopadnoe and Leningradskoe fields were formed, and then the Toludskoe lava field appeared in the last months of eruption (Dvigalo et al., 2014, Skripko et al., 2014).
DATA AND METHODS

Radarsat-2 radar images acquired during the last months of the eruption, as well as a set of optical remote sensing data (for those months in which radar images are missing) were used to reconstruct the dynamics of lava fields. We also used digital elevation models (DEM) and results of field geodetic measurements in the Tolbachinsky Dol in August 2013.

The analysis of the radar images identified only 4 image pairs suitable for calculation of the displacements values - two from the ascending orbit (26.06.2013-19.07.2013, 12.08.2013 - 05.09.2013) and two pairs from the descending orbit (29.06.2013-23.07.2013, 16.08.2013-09.09.2013). The processing was performed with the method of two-pass differential interferometry; its main steps are shown in Fig. 1.

As a result, we calculated vertical displacements of the lava fields surface (Fig. 2). The negative displacement values enable us to conclude that, in this period of eruption, the dominating process of lava flow field formation was the thermal subsidence with the maximum values about 6 cm.

Figure 1. Steps of interferometric processing for radar images

Figure 2. Vertical displacements calculated on the basis of SAR image pairs, 12.08.2013 – 05.09.2013 and 15.08.2013 – 09.09.2013
The very close dates for image pairs from the ascending and descending orbits allowed us to estimate the accuracy of the displacements values, based on their difference. A direct comparison of the displacement values showed that for the June-July pairs the differences reach about 9 cm, and for August-September pairs it changes from 1-2 cm (Leningradskoe lava field) to more than 5 cm (Vodopadnoe and Toludskoye lava fields with greater height gradients). The analysis of stable objects of the Tolbachinsky Dol such as lavas of previous eruptions revealed a systematic error in the displacement values. After its subtraction and the introduction of correction coefficients based on the regression analysis (eliminating errors associated with different acquisition geometry), the accuracy of the displacements determination for the Leningradskoe and most of the Vodopadnoe lava fields reached 2 cm, but for areas of lava fields that are located at large absolute heights, the accuracy remained at 5-6 cm (due to the atmospheric influence). It caused the exclusion of such areas from mapping and further thematic analysis.

Other valuable information which is extracted during the interferometric processing is an image of coherence values. The coherence values characterize the consistency of two differently reflected signals and the stability of the object surface in time. The higher the coherence values, the more accurately we can extract the surface displacement values.

Thus, it is possible to delineate three results of interferometric processing, which can be used as sources for mapping - coherence values, displacement values and absolute altitude values (digital elevation models).

Interpretation of coherence values implies an initial knowledge of the possible processes that occur with the object. The mature lava field is the object of the volcanic region that most strongly reflects the radar signal and therefore it stands out against the background of the surrounding terrain. Vodopadnoe and Leningradskoe lava fields serve as an example in Figure 3. If the lava is liquid and continues to flow, it is impossible to calculate the coherence values for such areas due to a strong decorrelation between two multitemporal reflected signals. For example, the Toludskoe lava field in Figure 3.

The lava topography is actively formed during the eruption and after it ends. For example, the surface of the Toludskoe lava field was actively formed in June-July 2013. It was cracked, so it is impossible to calculate the coherence values for such areas. By August 2013, in the last month of the eruption, the proportion of cracking lava decreased significantly, the surface of the greater part of the lava field has formed and demonstrated high coherence values, enabling the detection of the surface subsidence due to thermodynamic processes.

In addition to information on the motion of the surface, the displacement values themselves can indirectly indicate the presence of other volcanological processes or phenomena. Figure 4 shows the principle of lava channels interpretation based on the displacement map. The comparison of lava channel locations which were detected using the displacement map and the image in the middle infrared band of OLI/Landsat-8 showed the good agreement between the two. The application of infrared and visible bands is possible only when the movement of liquid lava in active channels continues, increasing the lava surface temperature relative to the surrounding areas. The detection of the lava channels system from the surface displacements maps is possible even for several years after the eruption is ended, while the thermodynamic processes are active.
The other results of interferometric processing are digital elevation models. This method was used to calculate the SRTM DEM, which in our study characterizes the Tolbachinsky Dol topography before the TTI-50. The optical SPOT-6 stereopairs after the end of TTI-50, allowed us to create a DEM, characterizing the topography after TTI-50. The difference between the two DEMs showed that the maximum thickness of the new lava fields exceed 80 m. The average lava thickness is 13 m.

Since the eruption occurred during the snow-covered period, the contrast of the hot lava flow and cold snow allowed us to reconstruct the dynamics of lava fields from the optical satellite imagery for the first months of the eruption. We also noted that it is possible to identify periods and areas of lava thickness increase from the optical imagery.

Radar interferometry as an independent method of mapping

The analysis of the interferometric processing results demonstrated that it is possible to identify parameters of topography dynamics, some of which indicate the formation of mesorelief and others characterize the lava fields microrelief. The large amount of remote sensing data made it possible to compare the capabilities of SAR and optical imagery to obtain characteristics the topography dynamics (Table 1).

We have defined the list of mapping parameters (Table 1) which characterizes the volcanic topography dynamics from two points of view. On the one hand, this is the growth of lava fields during the eruption (the formation of mesorelief in the volcanic region), and on the other hand it is the change in their surface after the eruption (the formation of the lava fields microrelief). It determines the two types of maps, a map of the lava fields growth and a map of the surface lava formation.

Table 1. List of mapping parameters of volcanic topography dynamics based on interferometric processing

<table>
<thead>
<tr>
<th>The process of lava field formation</th>
<th>Mapping parameter</th>
<th>Step of interferometric processing of SAR images</th>
<th>The possibility of obtaining information from optical imagery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics of the lava fields area</td>
<td>Boundaries of lava fields for different dates</td>
<td>Calculation of coherence values</td>
<td>Possible with limitations</td>
</tr>
<tr>
<td>Movement of lava material</td>
<td>Direction of movement for lava flows; lava channels location</td>
<td>Calculation of vertical displacements</td>
<td>Possible, directly in the eruption period</td>
</tr>
<tr>
<td>Lava thickness increasing</td>
<td>Lava thickness</td>
<td>DEMs before and after the eruption</td>
<td>Possible by using DEMs built before and after the eruption</td>
</tr>
<tr>
<td>Active formation of the lava fields surface</td>
<td>Lava surface cracking</td>
<td>Coherence calculation</td>
<td>Impossible</td>
</tr>
<tr>
<td>Thermodynamic subsidence of lava material</td>
<td>Surface subsidence</td>
<td>Calculation of vertical displacements</td>
<td>Impossible</td>
</tr>
</tbody>
</table>
The baseline part of such thematic volcanological maps should contain information about the geological and geomorphological conditions of the eruption. In our case, this includes the hillshade maps of Tolbachik volcanic massifs (using the SPOT-6/NAOMI DEM), location of magmatic structures, and age of the past lava fields and cones. The scale of the maps is 1:70,000, the projection of UTM (WGS-84), zone 57.

For the map of the lava field growth, the following content was defined: the boundaries of the lavas for different dates, areas of increasing lava field thickness, direction of lava flows during the periods of thickness increase, the active cones of TTI-50. Such a set of parameters allows us to illustrate the eruption dynamics. Maps of lava surface formation should contain the following information: areas of cracking and subsidence of the lava field surface, lava thickness, and lava channels location. Such mapping content demonstrates the processes of lava surface formation (Fig. 5).

![Volcanic products of TTI-50](image)

**Figure 5. Example of a map lava surface formation for the period 29.06.2013-23.07.2013**
DISCUSSION OF THE RESULTS

Thematic mapping and further analysis of the maps enables us to explore the method of radar interferometry as an independent mapping method. Thus, results of interferometric processing are DEMs and the surface displacements values. If in the first case the DEM can be calculated for global, regional and local levels of mapping, then in the second case it is almost always detailed mapping at the local level. It should also be noted that geographical features of the territory (for example, vegetation or large heights) and the state of the atmosphere during the acquisition can limit the calculation of surface displacements.

It should be taken into account that the spatial resolution of the satellite image defines the scale of the designed maps. From this point of view, SAR imaged have its own peculiarity - any thematic processing, including interferometric, leads to a deterioration of spatial resolution by several times. Accordingly, the scale of mapping becomes smaller.

The dependence of the results of InSAR on a number of factors that are variable in time (for example, cloud cover at the time of acquisition etc.) necessitates the analysis of the accuracy and reliability of the displacement values before they can be used in the mapping and geographic analysis.

This study demonstrated the possibilities of obtaining both qualitative and quantitative characteristics of the volcanic topography dynamics. Maps of the lava fields growth clearly demonstrate the mesorelief dynamics of the volcanic regions. Maps of lava surface formation illustrate formation of the lavas microrelief. The two types of maps give us a complete picture of the volcanic topography dynamics and new information about the current processes of the topography formation of volcanic regions.

ACKNOWLEDGMENTS

Authors acknowledge financial support of Russian Foundation for Basic Research (project N18-07-00816).

REFERENCES


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