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FINDINGS OF PERSISTENT SCATTERER INTERFEROMETRY (PSI) FOR VILNIUS AREA, LITHUANIA

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Abstract. Ground surface deformations can be related to natural and anthropogenic activities. The availability of ground movement data from regular satellite observations, combined with the knowledge of local geology and geomorphology, can help to improve our understanding of subsidence and soil geotechnical settlement phenomena, as well as to distinguish them from structural deterioration of buildings, which in urban environments represent the most common type of radar targets (PS). In Lithuania ground surface deformations are usually related to landslides, karstic, suffusion processes and anthropogenic activities (particularly in urban areas), which can trigger destruction of buildings, communication lifelines and soil consolidation. This paper is intended to illustrate considerable interpretative difficulties concerning the Persistent Scatterers Interferometry (PSI) results from synthetic aperture radar (SAR) data acquired over the Vilnius area (Lithuania) in the framework of TERRAFIRMA project. Protection of groundwater from pollution in the face of both man's intervention and geologically-driven movements is a high priority for the City Authorities. The distribution of numerous PS shows evidence of the spatial variability of the ground conditions throughout the old town and adjacent area of Vilnius. PS detected in the centre of Vilnius are characterized by velocities mainly ranging between –1.5 to +1.5 mm/year during about 8.5 years of observation. These figures are within the measurement precision error and imply a general stability of the city centre. Nevertheless, the review of the PS dataset has enabled to identify several sites within the Vilnius area characterized by spatially consistent concentrations of the downward moving PS. The localities as well as the site of the PS reference point were checked during the field reconnaissance and the implications of PS results are discussed in this paper.

Keywords: satellite remote sensing, synthetic aperture radar, interferometry, permanent scatterers, landslide, Vilnius, Lithuania.

1. Introduction

Space-borne differential synthetic aperture radar interferometry (DInSAR), and in particular new advanced processing techniques such as Permanent Scatterer Interferometry (PSInSAR or PSI, Ferretti *et al.* 2001), offer a unique possibility for wide-area, regular monitoring of ground surface displacements. Furthermore, under suitable conditions it should be possible to detect precursory deformations associated with the initiation of ground instability, a key element for early warning and hazard mitigation (Colesanti and Wasowski 2006; Ferretti *et al.* 2006). Satellite PSI data, however, have to be well ground truthed, because they reflect performance of targets, whose actual or apparent displacements may arise from a variety of causes (e.g. slope movements, fill settlement, subsurface civil engineering, mining and fluid extraction, differential movements between cut and fill parts of a building site, structure deterioration, expansion/shrinkage of soils).

Indeed, the interpretation of millimetre-centimetre ground movements detected by PSI is often difficult and some uncertainties can remain even after *in situ* controls. This work illustrates considerable interpretative difficulties concerning the PSI dataset acquired over the Vilnius area (Lithuania) in the framework of the *Terrafirma* project (www.terrafirma.eu.com).

Although the PSI results did not reveal any obvious spatial or linear deformation trends, some areas present coherent groups of PS characterised by downward displacements. These areas as well as the site of the PS reference point were checked during the field reconnaissance and the local significance of the PS motion data are discussed in this paper. The Vilnius experience suggests that more interaction between the experts in radar data processing and the PSI data users would be needed to reduce interpretative uncertainties and thus foster practical exploitation of the results.

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2. General information on PS interferometry

Satellite differential synthetic aperture radar interferometry (DInSAR) is an attractive technique for detecting and monitoring ground surface deformations arising from regional scale processes e.g. seismic, volcanic, tectonic (Gabriel *et al*. 1989; Massonnet and Feigl 1998). The technique, however, is not effective for site-specific evaluations, because of coarse resolution, coherence loss (a typical problem for vegetated areas) and atmospheric artefacts limitations (e.g. Wasowski *et al*. 2002; Colesanti and Wasowski 2006). Permanent Scatteres Interferometry (PSInSAR), developed at Politecnico di Milano (Ferretti *et al.* 2001; Colesanti *et al.* 2003), and similar innovative multi-temporal DInSAR techniques (e.g. Berardino *et al*. 2002; Werner *et al*. 2003; Bovenga *et al*. 2006) overcome in part the limitations of DInSAR and extend the applicability of radar interferometry to sub-regional and local-scale geological investigations of slope instability and soil settlement/ground subsidence. The PSI analysis allows the identification of numerous radar targets (the PS) where very precise displacement information can be obtained. Considering the regular re-visit time and wide-area coverage of satellite radar sensors, and that PS usually correspond to buildings and other man-made structures, this technique is particularly suitable for applications in urban/peri-urban environments, which often represent a harsh setting for GPS or conventional topographic surveying (Ferretti *et al*. 2006).

Basic principles of the PS interferometry were summarised by Colesanti and Wasowski (2006) as follows:

– The scattering mechanism of a certain amount of image pixels is dominated by a single point-wise element (i.e much smaller than the image pixel), whose contribution overwhelms the coherent sum of all other scattering elements present within the same sampling cell. This implies that the interferometric phase of these privileged pixels is only slightly affected by geometric decorrelation.

– The radar targets, only slightly affected by decorrelation, allow creating a set of (N) differential interferograms all referred to a unique master, regardless of temporal (even year long time spans) and normal baseline values. To this end the (N+1) available SAR images need to be re-sampled (co-registered) on the grid of the unique master image.

– The various interferometric phase contributions (residual topography due to the limited precision of the DEM used for generating the differential interferograms, orbital inaccuracies, possible ground deformation and noise) space normal baseline analysis exploiting their different spectral behaviour.

– Sampling cells that are likely to behave as Permanent Scatterers can be identified in advance by means of a pixel by pixel statistical analysis of the amplitudes of the N + 1 available SAR images.

– Permanent Scatterers form a sparse grid whose spatial density can even exceed 500 PS/km² in urban areas. It is not possible to provide a generally valid figure. For the PS density in rural or low urbanisation areas, mainly because the number of "natural" PS densities (corresponding to exposed rocks) seems to vary strongly in relation to local lithology and morphology. Recent tests showed natural PS densities varying from 0–10, 20–50 up to 200 PS/km² (the actual PS density depends also on the threshold set on phase stability to identify PS). The retrieval of empirical laws relating the expected PS density to local geological settings is of much interest as this would help to predict the success probability and the amount of output data that can be obtained by means of a PS analysis. Where PS density is high displacement sensitivities between 1 and 3 mm can be achieved.

– A sufficient number of SAR images must be available to perform a PS analysis (about 15–20 images) and the PS spatial density has to be high enough (at least 5 PS/km²). This last requirement is fundamental for isolating and removing the atmospheric phase term by exploiting jointly its spatial correlation and temporal uncorrelation.

– Permanent Scatterers (PS) can be thought of as benchmarks of a high density geodetic network. For each PS the output products of the analysis are:

- full displacement LOS (Line-of-sight) time series. The precision (in terms of standard deviation) of each single measurement ranges between 1 and 3.5 mm. As in all DInSAR applications, deformation data are relative both in time and space. In time all data are referred to the unique master image. In space data are relative to a reference PS supposed motionless. Average LOS deformation rates can be determined with millimetre precision (typical values around 1 mm/yr);
- high precision (standard deviation about 2 m) elevation estimate of PS (the phase discrimination carried out at single PS allows estimating the residual topographic term due to the limited precision of the reference DEM used for generating the differential interferograms).

The effectiveness of PSI in monitoring ground deformations was confirmed by numerous examples of practical applications in different regions (e.g. Ferretti *et al.* 2006; available from Internet: <www.terrafirma.eu.com>). PS data can assist in:

- identification and delimitation of areas affected by slow deformations;
- estimation of surface velocity and acceleration fields with millimetric precision;
- identification of the source of ground instability by analysing in situ and multi-temporal remotely sensed data.

3. Outline of the geology and geomorphology of Vilnius area

The territory of Lithuania can be regarded as one of classical regions with Quaternary cover formed during continental glaciations. The average thickness of Quaternary cover is 130 meters and varies from 10–30 m in the northern part of country – the area of prevailing glacial erosion – up to 200–300 m in marginal highlands and the buried valleys or palaeoincisions. Throughout the Quaternary period Lithuania has been covered by continental ice sheets originated in Fennoscandinavia, which corresponds to all glaciations known so far in Eastern Europe. The sediments and landforms of a least of 6 glacial stages and 8 ice free periods can be observed in the stratigraphic cross-section of the Quaternary of Lithuania (Satkūnas 1997).

The most complete Quaternary sequences and spectacular geomorphology are characteristic for the Vilnius surroundings (Fig. 1). A fragment of the Ašmena Highland unaffected by the last Glaciation, begins in the south-east from Vilnius. In Lithuania this area is named the Medininkai Highland. A network of wide flat-bottomed grooves, old marshy kettles, discernible on the undulating topography of the highland, characterizes the "mature" old relief of the Medininkai (Warthanian) Glaciation.

The typical ice margin formation of the Last Glaciation, so-called Baltija Highland, stretches to the north west of Vilnius. A 20–60 km wide, well expressed belt of hilly massifs and ridges lies at altitude of 120–250 m. The Baltija Highland surface is considered to contain a great variety of relief forms such as glaciofluvial and glaciolacustrine kames, plateau-like hills, eskers and esker-like forms, medium and large morainic and glaciofluvial hills, glacial and glaciofluvial ring-shaped ridges, endmoraine ramparts, glaciofluvial and glaciolacustrine kame terraces, as well as marginal ridges. Marginal formations of the Baltija Stage are reliably distinguishable from the "older" looking (in aerial photos) Grūda stage relief, which comprises distal slopes of the Baltija Highland (Guobytė 1996).

Extensive outwash and glaciolacustrine plains are stretched along the distal slopes of the Baltija Highland. A typical example of ice lobe depressions is the Mickūnai glaciodepression. The maximum extent of the last glacier is represented here by two parallel accurate ridges separated by a till plain.

The recent surface of glaciolacustrine and outwash plains is complicated by dunes, erosional and other post-genetic forms. The main drainage artery for the glacial melt waters was a lateral valley presently occupied by the rivers Žeimena, Neris and Vokė.

Vilnius, the capital of Lithuania is one of the country's oldest cities. It stretches along both banks of the fast flowing Neris River, and is set among hills covered by pine forests. Vilnius area is a deep valley, cut into morainic highlands by erosion. Morainic highlands have been formed during the Grūda and the Baltic advances of the last glaciation. The edge of the continental glacier was located directly NW of the present Vilnius area, and extended NE–SW. At the glacier's foreland, there was an outflow along the Žeimena, Neris, Vokė, Merkys, and Nemunas rivers valleys. The outflow was proceeding at the higher terraces level (150–155 m a.s.l.).

The city of Vilnius is located partly within a peculiar part of the Neris river valley, between the Medininkai and Baltija Highlands, and partly within a gorge cut into the Baltija Highland. Such gorges, clearly seen in the highland's hummock of the Baltic (Pomeranian) Stadial, have developed Odra, Vistula, Nemunas, and Dwina rivers, only. The section of the Neris River, located within the NW part of Vilnius, belongs to such extraordinary places of the European Lowland, characterized by a very distinct relief.

The water outflow from a huge drainage basin of the upper Nemunas, Neris, and Dwina rivers catchment proceeded through the Biebrza and Narew rivers valleys into the Vistula river valley (north of Warsaw). The further water outflow continued from the Warsaw vicinity and the Płock Depression through the Noteć and Warta valleys, and was reaching the North Sea through the Eberswald Gate and Elbe valley.

Vilnius city is, therefore, located within a very important hydrographical knot of the last glaciation Baltic (Pomeranian) time. After the continental glacier withdrawal into the NW direction, Neris and Vokė rivers have erosionally cut across the Baltic (Pomeranian) phase frontal moraines range. It resulted in the deep incision of the Neris, Vilnelė, and Vokė valleys. As a consequence, the differentiated morphology of the present Vilnius city developed. Besides the flat surfaces of the terraces, the area is characterized by escarpments, young erosional incisions, and erosional monadnocks.

The lowering of the surface towards the historical Vilnius centre, located at the Vilnelė and Neris rivers confluence (i.e. the alluvial sediments within the Cathedral and Kings Castle area), is the characteristic morphologic feature of the Vilnius area. The Gediminas Hill, Antakalnis, St. Peter and Paul, and Rasų cemeteries as well as Užupis (Zarzecze) quarter elevation are built of sands and gravels monadnocks of the Grūda (Leszno-Poznań, Brandenburg) phase highlands. Slow mass movements develop there, because of the considerable slope steepness.

An elevated train station area is a downhill part of a highland built of glacier sediments (tills, clayey sands). The vast meanders of the Neris River cut higher and lower terraces of the following Vilnius quarters: from the Verkiai quarter in the North East, through the Žirmūnai, Šnipiškės, and Lazdynai quarters, up to the Grigiškės quarter in the West. The terraces are reaching 105 m, 110 m, 120 m, 140 m, and 150 m a.s.l., there. The western Vilnius suburb is located within the Neris and Vokė rivers arms, on the terraces appearing at the 120 m, 135 m, and 150 m a.s.l. The new, northern city's quarters (Šeškinė, Fabijoniškės) are located upon a morainic highland of the Baltic phase, as high as the 170–200 m a.s.l. Similarly are located the southern quarters: on the highland of the Grūda phase, reaching the 200 m a.s.l. height.

The Vilnelė River is deeply sculpturing the highland. A river's meander in the southern part of the Vilnius city – in Pučkoriai – is undercutting the 60 m high highland's slope. There also appear mass movements, such as earth falls and landslides.

The Paneriai Hills, in the SW and S parts of the city, represent a highland of the Medininkai age modified by the Grūda phase advance, reaching the height of 200 m a.s.l. Differences in the relative heights are reaching 50–70 m within the city.

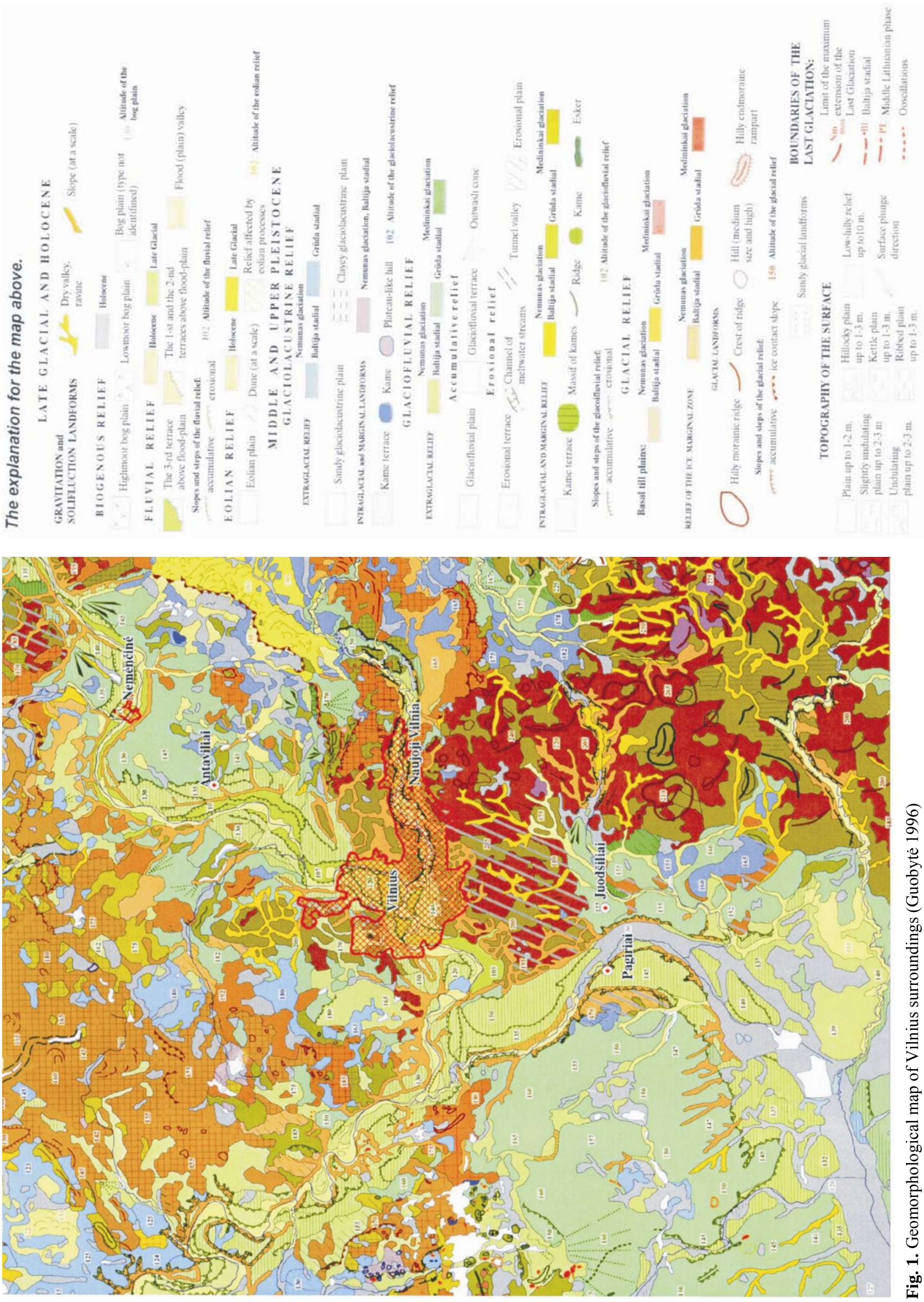

Fig. 1. Geomorphological map of Vilnius surroundings (Guobytė 1996)

The morainic forms and highlands, formed during Medininkai (Warta) glaciation are composed mainly of glaciotectonically disturbed formations (example – the Pučkoriai outcrop). However, 3–4 seams of the successive glaciations, interbedded with water-bearing, fluvioglacial sands and gravels can be identified. The Baltic Highland is composed of more evenly stratified morainic seams. The terraces' sands are partly underlayed by tills; they are also water-bearing, locally. The lowermost terrace is built of the alluvial fine grained sands with silts. The higher, fluvioglacial, terraces are built of fine and middle grained sands, while the highest terrace is built of varigrained sands with gravel. Oscillations of the groundwater tables within the terraces' depend on the atmospheric precipitation and on the water level in the streams.

The highlands are built of tills and of englacial and marginal glaciofluvial sands and gravel. The deluvial and solifluction sands and silts appear within the valleys of small streams, flowing out of the highlands, within the dry valleys and on the slopes. The total thickness of the Pleistocene sediments is reaching 100–150 m.

Springs appear typically on the highlands slopes, at the outcrops of the water-bearing beds. In the past these springs were very often taken in for the water supply, for instance, at the Subačiaus Street (the Misionierių Spring). Within the city, there are several groundwater intakes from beds and sediments filling Neris, Vilnelė, Vokė River valleys water. The groundwater reserves recharge is facilitated by high permeability of sediments and hydraulic connections between intertill aquifers in the paleoincisions, inherited by present river valleys.

The morphology of the Vilnius city area has mainly resulted from the accumulation and erosion processes of the last 15 000 years. Since XIII century, an influence of human activities is also visible.

The ground surface level changes tentatively could be caused by:

- changes of the groundwater levels influenced by the atmospheric precipitation;
- groundwater extraction from the water intakes for the centralized water supply;
- mass movements (locally);
- excavations (ground unloading), embankment construction (loading);
- embankments subsidence;
- compaction of compressible grounds (especially anthropogenic soils);
- neotectonic movements.

The investigations of the recent vertical Earth crust's movements and the recent geodynamic processes in the territory of Lithuania were studied by Zakarevičius (Zakarevičius 1994, 2003).

In Vilnius area landslide phenomena were inventoried by Bucevičiūtė S. and Mikulėnas V. under the project "Inventory of karst and landslide phenomena in Lithuania" (2004). Studies on the intensity of erosion processes in the Vilnius area were performed by Česnulevičius *et al.* (2006). These results could also be taken into the consideration during the evaluation of ground motion registered by the PSI.

Vilnius is situated in an area whose ground surface was formed by glacial, cryogenic, periglacial limnic, fluvioglacial, fluvial and other processes during the glaciations of the Middle and Late Pleistocene. These varying geomorphological processes created a complex relief in Vilnius marked by a high vertical and horizontal structural variety. This kind of relief requires special consideration while planning development of urban territories and structure.

The evaluation of the relief dynamics in the Vilnius city was based on instrumental measurements and data from topographic maps. Recent investigations of the state and dynamics of the Vilnius relief were carried out in morpho-lithogenetic areas of the city territory. The areas were selected based on the relief genesis, its morphographic elements, morphometric indices and composition of deposits (Česnulevičius *et al.* 2006).

The erosion potential and relief energy indices were quantified in the morpho-lithogenetic areas. Detailed changes of relief were recorded in the reference areas by repeated precise levelling. Six levelling profiles were made in: Ribiškės, Guriai, Kairėnai, Pylimėliai, Visoriai and Dobrovolė. Comparison of relief profiles from different periods allowed determining the thickness of the eroded layer and evaluating the intensity of dynamic processes in selected points.

Precipitation is one of the major factors determining relief dynamics (erosion). Its distribution was evaluated in two aspects: amount and intensity. The quantitative dependence between the amount of precipitation and erosion intensity was determined. Climatic conditions are responsible for the kind, intensity of precipitation, thickness and duration of snow cover, the depth and duration of frozen ground, and surface and groundwater regime. These climatic elements are among the major factors determining the slope stability. The slope stability is especially dependent on the intensity of rainfall.

The strongest rainfalls of 2005 were recorded on May 5 and 6 (51.1 mm), May 12 and 13 (38.0 mm), August 6–10 (180.9 mm) and September 16 (19.7 mm). The rainfall of August 9 (85.1 mm), especially strongly affected the ground surface.

The intensity of the potential erosion processes was evaluated according to the potential thickness of the eroded layer. The index of potential erosion indicating the potential thickness of the eroded layer was determined in eleven areas of morphometric types of relief.

On its basis, the territory of Vilnius was divided into energy potential classes of erosion. The potential annual amount of eroded material reaches 1 000 000 m³ (Česnulevičius *et al.* 2006).

Finally, the four geodynamic types of the Vilnius relief were determined:

- *Preserved relief*: green zones of the city, water bodies and water protective belts. They are territories where urban activity does not take place. The intensity of erosion and deflation processes does not exceed 0.1 mm/year. Only sedimentation processes can take place in water bodies (up to 10 mm/year). Such zones occur in the Vingis Park, Giruliai Forest, Burbiškės Park and Aukštagiriai Forest.

– *Regenerating relief*: intensively urbanized areas in flat and undulating plains where transformation is negligible (up to 1 mm/year). Relief transformation is limited to cut and fill practices ground levelling of building sites. These areas occupy most of the Vilnius territory.
– *Urbodynamic relief:* urbanized areas in dissected ground with a high level of surface transformation for building purposes (1–3 mm/year). Conditions for processes intensively transforming the surface (planar and stream erosion) are present in such areas. They are located between Rasos, Paupys, Užupis and Antakalnis and on the northern side of the Neris River between Šnipiškės, Baltupiai and Santariškės (north – south elongated area).
– *Geodynamic relief:* natural terrains where erosion processes are intensive (more than 3 mm/year) and complementary protective measures are necessary in case of urbanization. Such areas were determined along the section of the Vilnelė River between Belmontas and Kučkuriškės.

4. PSI Dataset of Vilnius and its interpretation

The PSI dataset of Vilnius was acquired on the basis of the agreement between the Lithuanian Geological Survey and the Terrafirma Consortium and were processed by NPA SAR Interferometry (United Kingdom) using GAMMA IPTA software. Overall 32 ERS-1 and ERS-2 scenes were used for analysis, covering the time period between 8 May 1992 and 13 August 2001.

The NPA Company made also several remarks regarding the site conditions and quality of the data:
– Complex processing site;
– Small dataset of ERS scenes;
– Highly variable seasonal weather conditions;
– Poor data from 2002 onwards;
– Lack of prerequisite knowledge of ground motion;
– Low density of PS points detected.

The above presented facts indicate that the PSI analysis of the Vilnius dataset could be a very complicated task.

Totally, 7662 PS were identified. The average PS density was low, amounting to 9 points/km². The following statistics of ground motion in five selected velocity classes is revealed in the Table 1 (according to NPA). The minimum and maximum velocity values do not appear credible (from the geological point of view) and probably indicate processing errors. In particular, the presence of upward movements exceeding 1 cm/year appears very unlikely. The distribution of PS shows evidence of the spatial variability of the ground conditions throughout the old town and adjacent area of Vilnius city. PS detected in the centre of Vilnius are characterized by velocities mainly ranging between –1.5 to +1.5 mm/year (77.5% of observed 7662 points) during about 8.5 year period of observation. Average annual motion rate is –0.4 mm/year and Vilnius city and hence the area could be considered as generally stable.

Table 1. Statistics of ground motion in five selected velocity classes according to NPA

Point motion statistics (mm/year classes)	Points in each mm/year class	Percentage
Range	Count	%
–68.4 to –3.5	464	6.1
–3.5 to –1.5	784	10.2
–1.5 to 1.5	5936	77.5
1.5 to 3.5	171	2.2
3.5 to 56.2	307	4.0

For the interpretation purposes the PSI dataset was combined with a digital ortophoto based on colour aerial photos. This enables to locate precisely negative and positive velocity PS, respectively indicative of downward and upward displacements. The PSI dataset was divided in three categories: PS with velocities greater than +2 mm/year, PS between +2 mm/year and –2 mm/year and PS with velocities lower than –2 mm/year. This facilitated comparison and interpretation with other cartographic materials.

The Vilnius PSI dataset has been analysed with the aid of different geological data, among them: "Quaternary geological map of vicinities of Vilnius city at a scale of 1: 50 000" (Guobytė 1996) and geodynamic maps of the Vilnius relief (Česnulevičius *et al.* 2006). The field reconnaissance in the selected parts of the city was also performed.

The PSI dataset of Vilnius is characterised by the irregular distribution of moving and stable PS. There are no clearly visible general spatial or linear trends that could provide some evidence of a possible relation between ground motion and tectonic or neotectonic activity, which is postulated for the Vilnius area.

Nevertheless, the review of the PS dataset has enabled to identify several sites within the Vilnius area characterized by spatially consistent concentrations of the negative PS. These localities as well as the site of the PS reference point were checked during the field reconnaissance and are discussed below.

Site No. 1: PS – reference point, located in the Lazdynai area near the bank of the Neris River, close to the large transportation route – Oslo Street (Fig. 2). The reference point is surrounded by a group of stable PS, situated on the alluvial terrace (Fig. 3). This concentration of PS is related to radar signals coming from the roofs of small sheet metal garages, which, however, are not necessarily stable constructions and can be subjected to thermal dilation changes. Furthermore, in the close vicinity of the reference point, several negative velocities PS could be also found (radar targets coming from the "Hyundai" car saloon). On the other side of the Oslo Street landsliding takes place, which is also confirmed by the presence of negative velocity PS. Taking under consideration all the above presented facts, there are some doubts whether the PS reference point was selected properly.

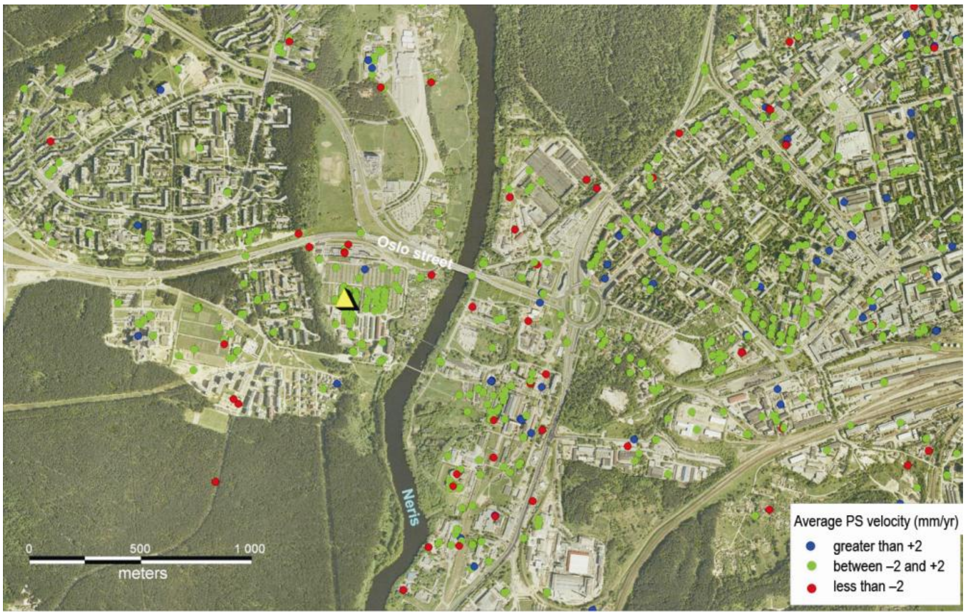

Fig. 2. PS – reference point (shown by yellow triangle), located in the Lazdynai area near the northern bank of the Neris River, close to the important transportation route – Oslo Street, PS with negative velocities below –2 mm/yr are represented by red dots, PS with velocities exceeding +2 mm/yr are in blue colour, stable points between –2 mm/yr and +2 mm/yr are in green. Background image is a high resolution orthophoto

Fig. 3. PS with negative velocities below –2 mm/yr (red dots), PS with velocities exceeding +2 mm/yr (blue), stable points between –2 mm/yr and +2 mm/yr (green) and reference point (yellow triangle) superimposed on the background of geological map at the scale 1: 50000 (Guobytė 1996). Numbers I, II and III indicate alluvial terraces of Neris River, brown colour shows delluvial deposits

Site No. 2: The negative velocity PS located on the steep slope of the Gediminas Castle hill in the heart of the Vilnius old town (Fig. 4 – point 1). The hill slope shows indications of a landslide, which was stabilised in the past. Some parts of the slope appear subjected to creeping as revealed by the characteristic shape of the trees trunks – "slope hooks". The PS in this place most probably correspond the stone stairs, which can give strong radar reflection.

Site No. 3: The negative velocity PS in the vicinity of the former Sluškai (Słuszków) Palace at the bank of Neris River, within the alluvial deposits area (according to Geological Map of Vilnius by Guobytė (1996)) – Fig. 4 – point 2. Several broad cracks on the walls of the palace and neighbouring buildings were observed. It is interesting that the palace built in 1690 has an erection table with Latin text, which translated provides the following information: "the mountains were removed, Neris waters were pulled out from its courses, the nature elements were defeated". This shows that the palace was built on an artificial mound and the course of the Neris River was slightly changed. This legacy is probably the reason of the presence subsidence in this area, as indicated by the PSI dataset.

Site No. 4: The negative velocity PS at the Sport stadium located near the hills of Antakalnis (Fig. 4 – point 3). The radar signal is coming from the stadium tower covered by sheet metal. The explanation for occurrence of the negative PS could gather by examining the external side of the stadium. This part of the stadium including the tower was built very close to an escarpment, within the area of deluvial deposits (Fig. 5). The cracked and partly ruined concrete stairs indicate the presence of ground instability possibly linked to slow landsliding phenomena.

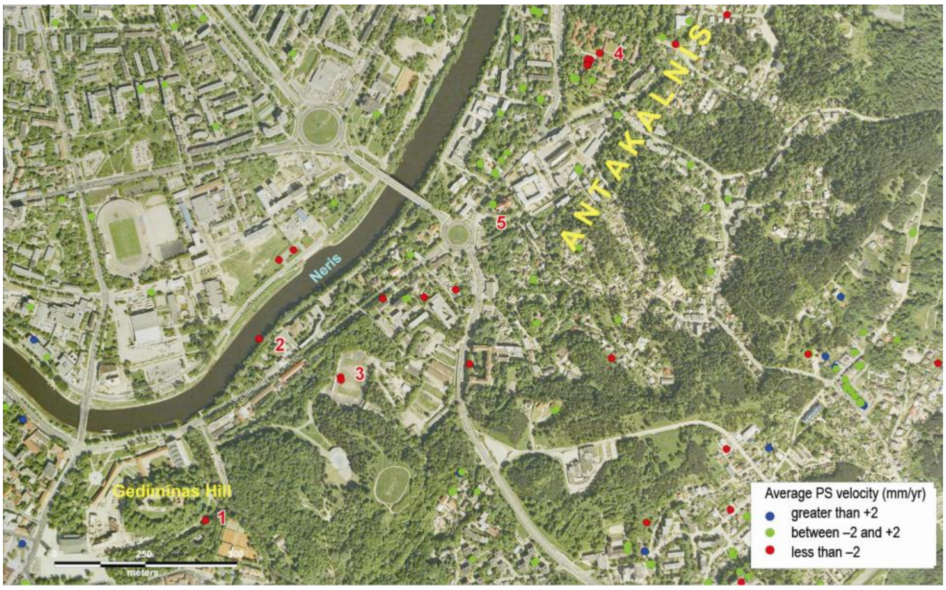

Fig. 4. Location of PS with negative velocities below –2 mm/yr (red dots), PS with velocities exceeding +2 mm/yr (blue), stable points between –2 mm/yr and +2 mm/yr (green) in the downtown of Vilnius and the Antakalnis area. Gediminas Hill is in the lower left corner of the image (red dot with number 1). Others PS points with negative values are: point 2 (vicinity of the former Słuszków Palace, at the bank of Neris River and within the alluvial deposits area), point 3 (sport stadium, located near the hills of Antakalnis), point 4 (former Sapieha Palace, built in 1691) and point 5 (the St. Peter and St. Paul's Church)

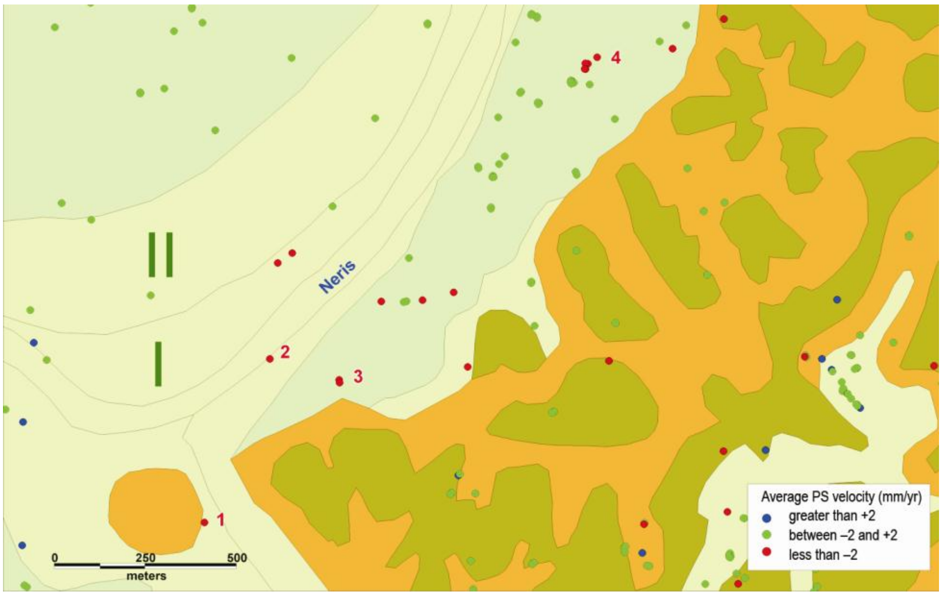

Fig. 5. PS with negative velocities below –2 mm/yr (red dots), PS with velocities exceeding +2 mm/yr (blue), stable points between –2 mm/yr and +2 mm/yr (green) in the downtown of Vilnius and the Antakalnis area superimposed on the background geological map at the scale 1 : 50 000 (Guobytė 1996). Negative instability points (1–4) are the same like in Fig. 4

Site No. 5: The negative velocity PS located in the area of the Former Sapiega Palace, built in 1691, now surrounded by a large park of the Antakalnis zone (Fig. 4 – point 4). Presently the buildings are occupied as a hospital. This zone was classified as area of the urban dynamic relief, characterized by ground movements of 1–3 mm/year. Deep cracks of some segments of the palace walls could perhaps be related to the presence of such movements (Fig. 5).

Instead, the famous tourist place the Church of Saints Paul's and Peter's, located in the close vicinity (Fig. 4 – point 5), in the centre of Antakalnis is stable, as indicated by the PS spatial distribution.

Site No. 6: The negative velocity PS concentrated in the complex of the Jočionys (Gariūnai) heat and power plant. The complex is located on the higher terraces of the Neris River. The negative PS points correspond to the following different objects:

- round store of crude oil (with one moving PS and three others stable);
- sheet metal warehouse standing on the concrete foundation, propriety of "Volkswagen". The concrete foundation is cracked in several places;
- tracks and rail siding, belonging to the railway fuel delivery system of the heat power plant. The curved tracks and its cracked backing suggest ground movements.

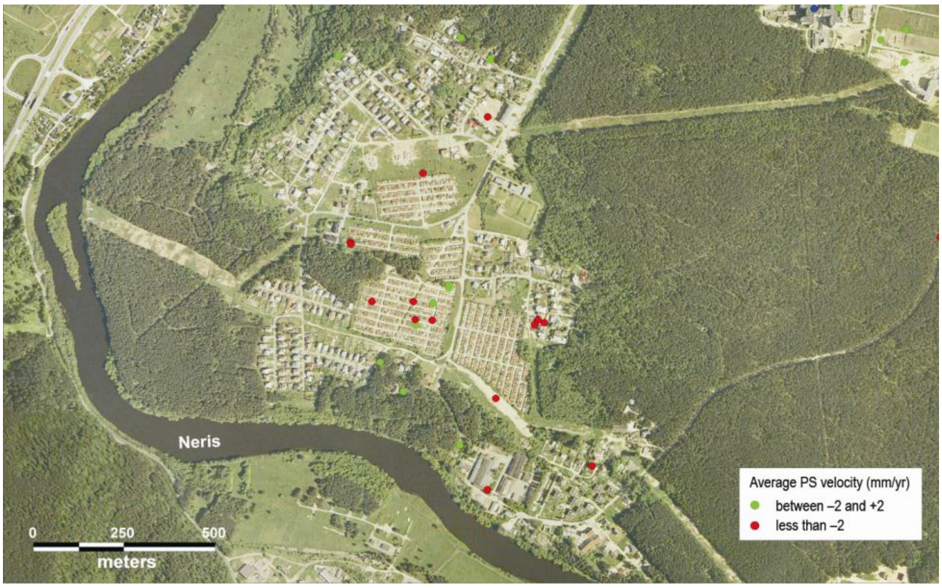

Fig. 6. Location of PS with negative velocities below –2 mm/year (red dots) and stable points between –2 mm/year and +2 mm/year (green dots) in Lazdynėliai area

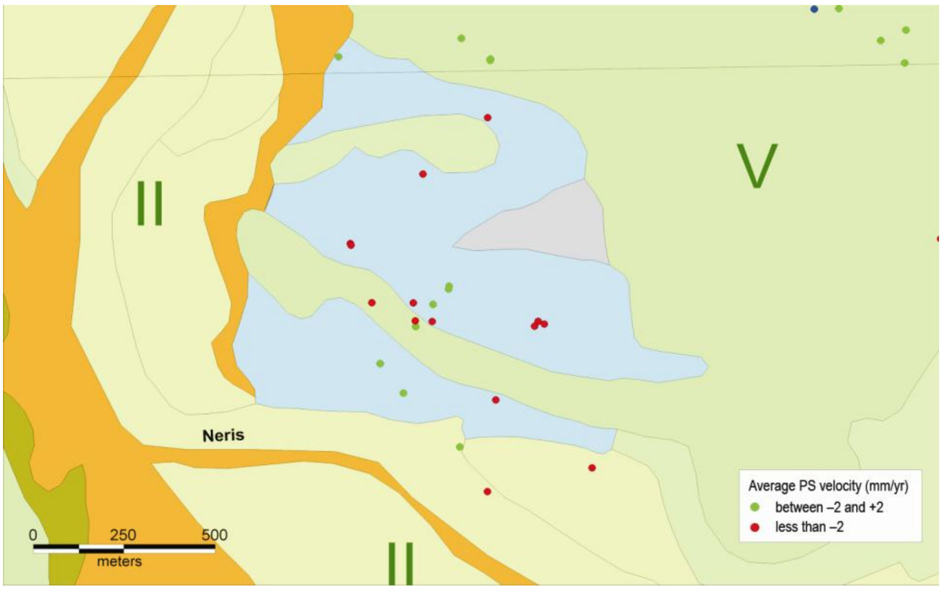

Fig. 7. PS with negative velocities below –2 mm/yr (red) and stable points between –2 mm/yr and +2 mm/yr (green) in the Lazdynėliai area, superimposed on the background of geological map at the scale 1: 50 000 (Guobytė 1996). Note that most PS in the area of lacustrine deposits (blue colour) show negative velocities

There is no obvious explanation for the ground motions detected in that area. Most probably the indicated subsidence could be related to the layers of the soft compressible deposits present within the alluvial terraces and ground water extraction in the closed Bukčiai well field.

Site No. 7: The negative velocity PS concentrated in the Grigiškės area, within the alluvial deposits of the Neris and Vokė rivers. In this terrain, the settlement of the small houses and hats occurs at present. In the 1950s the small artificial dam was constructed on the Vokė River. The negative PS could perhaps be related to changes of the groundwater regime. Further studies are necessary to confirm this hypothesis.

Site No. 8: The analysis of the PS spatial distribution within the context of the lithologic boundaries of the Vilnius geological map indicated some interesting interrelations. One example comes from the Lazdynėliai area, where the coincidence between the lacustrine deposits and negative velocity PS is observed (Figs. 6 and 7). The other example is the coincidence between the peat deposits and negative velocity PS in the Šnipiškės area.

5. Conclusions

1. The PSI dataset of Vilnius is characterised by irregular spatial distribution of moving and stable PS; nevertheless, the latter represent about 80% of the total population of PS.

2. The interpretation of the Vilnius PSI dataset has enabled to show some relations between the negative velocity PS and the local geological conditions and geodynamic phenomena in selected areas of the city and its neighbourhood. However, the general pattern of the PS distribution shows no obvious linkage to the geological setting as depicted in the map of a scale 1:50 000. Probably having more detailed maps the results would be more comparable with lithological modifications. Negative and positive velocity PS occur both in the areas covered by alluvial deposits and on the morainic uplands.

3. The examples of movements detected by PSI examined on site included subsidence linked to the presence of compressible deposits (organic, lacustrine) mass movements, changes of groundwater level, and location of large engineering constructions.

4. The range of the registered ground motions is close to the values obtained from the analysis of the intensity of erosion processes in Vilnius.

5. There is no clearly visible spatial or linear trend of PS, which could provide some evidence of a possible relation between ground motions and tectonic or neotectonic activity, which is postulated for the Vilnius area.

6. There is no obvious explanation for or relation between the detected positive velocity PS and any geodynamic or other geophysical phenomena. Their occurrence could perhaps be connected with the behaviour of the reference point. In some places the positive ground deformation could be related to the recovery of groundwater level and need to be further investigated.

7. The PSI dataset of the Vilnius should be further verified by using precise geodetic measurements (levelling and GPS) as well as data on groundwater extraction.

8. The results of the PSI dataset interpretation should be presented and discussed with the spatial planners and decision makers responsible for planning and management of large and important constructions (for example power plants).

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VILNIAUS IR JO APYLINKIŲ INTERFEROMETRINIŲ MATAVIMŲ DUOMENŲ ANALIZĖS REZULTATAI

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Santrauka

Žemės paviršiaus pokyčius sukelia nuošliaužos, žemės drebėjimai, potvyniai, kranto erozija, gruntų sėdimas, kurį lemia požeminio vandens išsiurbimas ir požeminis naudingųjų iškasenų eksploatavimas, požeminės karstinių tuštumų įgriuvos ir kitos priežastys. Duomenys apie žemės paviršiaus pokyčius tam tikroje vietoje, gauti atlikus palydovinius stebėjimus, kartu su geologiniais ir geomorfologiniais duomenimis apie tiriamąją vietovę gali padėti nustatyti žemės paviršiaus grimzdimo reiškinius. Lietuvoje žemės paviršiaus pokyčius daugiausiai sukelia nuošliaužos ir karstinės įgriuvos, dėl kurių dažnai sugriūva pastatai ir komunikacijos. Analizuojami Vilniaus ir jo apylinkių palydovinės interferometrijos (SAR) duomenys ir aptariamos problemos, su kuriomis teko susidurti juos interpretuojant. Preliminari duomenų analizė rodo, kad Vilniaus ir jo apylinkių žemės paviršius gana stabilus, kasmetinis žemės paviršiaus judesių greitis svyruoja nuo –1,5 iki +1,5 mm/metus. Pavienėse Vilniaus teritorijose užfiksuotos ir anomalios neigiamos grimzdimo reikšmės. Šių reikšmių atitiktis vietovėje buvo tikslinama lauko darbų metu. Išsamiai aprašomi tyrimo rezultatai.

Reikšminiai žodžiai: nuotoliniai palydoviniai tyrimai, radaro sintetinė apertūra, interferometrija, nuolatinės sklaidos taškai, nuošliaužos, Vilnius, Lietuva.

АНАЛИЗ И РЕЗУЛЬТАТЫ ИНТЕРФЕРОМЕТРИЧЕСКИХ ИЗМЕРЕНИЙ НА ТЕРРИТОРИИ ГОРОДА ВИЛЬНЮСА И ЕГО ОКРЕСТНОСТЕЙ

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Резюме

Оползни, землетрясения, наводнения, береговая эрозия, оседания грунта из-за откачивания подземных вод и эксплуатации подземных полезных ископаемых, а также обвалы подземных карстовых пустот и другие причины изменяют земную поверхность. Данные об изменениях земной поверхности в различных местностях, полученные по результатам сателлитных наблюдений, совместно с геологическими и геоморфологическими исследованиями изучаемой местности могут помочь установить явления погружения земной поверхности. Изменения земной поверхности в Литве в основном связаны с оползнями и карстовыми обвалами, часто разрушающими здания и коммуникации. В статье обсуждается проведенный анализ данных сателлитной интерферометрии (SAR) на территории города Вильнюса и его окрестностей, а также проблемы, с которыми пришлось столкнуться при интерпретации этих данных. Предварительный анализ данных показывает, что земная поверхность территории города Вильнюса и его окрестностей достаточно стабильна, ежегодная скорость движения земной поверхности колеблется от −1,5 до +1,5 мм/год. Однако на некоторых участках города Вильнюса наблюдаются и аномальные отрицательные значения. Точки с такими значениями проверялись на местности во время проведения полевых работ, а результаты исследования детально описаны в настоящей статье.

Ключевые слова: дистанционные спутниковые исследования, синтетическая апертура радара, интерферометрия, точки постоянного рассеяния, оползни, Вильнюс, Литва.

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