ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD) in specialty 6D071100- "Geodesy"

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IMPROVEMENT OF THE METHOD OF INTEGRATED PREPARATION AND USE OF SPACE IMAGES IN TASKS OF ASSESSMENT OF SEDIMENTATION OF INDUSTRIAL SURFACE IN THE CONDITIONS OF OPERATION OF TENGIZ OIL AND GAS FIELD

The use of space data to assess the subsidence of the industrial surface allows not only to see the current geodynamic situation in the study area, but also to look 30-40 years ago. Information extracted from archival satellite images allows us to evaluate the main trends in the displacement of the earth's surface and obtain stable deformation characteristics. At the same time, the use of satellite data does not exclude the need for planning ground-based observations, but allows them to more accurately localize and perform more sparsely in time and space. However, today, one of the classic SBAS data processing methods has many drawbacks and may not give the right result.

A potential solution is the Intermittent Small Baseline (ISBAS) method, which is a modification of the SBAS algorithm. The modification takes into account the intermittent coherence of the dynamic land cover (for example, grassland, forests, agricultural fields), significantly increasing the density of measurements in non-urban areas to provide more widespread coverage. The ISBAS method was previously used to determine surface movement due to groundwater subtraction, underground coal mining, landslides. This method has also been applied to gas fields in the Alkmaar region of the Netherlands, where it has been successfully tested using traditional leveling data. This study provided a valuable opportunity for verification, given that often there are few suitable data on land reliability for non-urban areas. However, the wider application of ISBAS for global monitoring of oil and gas operations in parts of the world with different environmental and climatic conditions remains to be demonstrated.

The Tengiz oil field, with its dynamic semi-arid landscape and the absence of settlements, is a type of terrain for which comprehensive monitoring of soil deformation can be problematic using some DInSAR methods. However, since hydrocarbon production is the only dominant factor in soil deformation and, as a rule, inadequate, dense vegetation cover, the oil field was previously explored using several DInSAR methods such as SBAS and SqueeSAR, which makes it a great example to study. Accordingly, this study aims to evaluate the effectiveness of the ISBAS method to provide a detailed, comprehensive deformation profile over the Tengiz field. First, soil motion measurements obtained using ISBAS are verified by comparison with data from the conventional SBAS technique, results from previous DInSAR studies, and level survey data. The ISBAS method is then applied to current

SAR data to present a new perspective on the recent deformation of the oil field, demonstrating its potential to support geodynamic monitoring in the region. Also, in this paper, methods for configuring critical parameters and ensuring the quality of processing at key points in the processing of radar data in the form of recommendations are presented.

All these issues are regulated by the decree of the President of the Republic of Kazakhstan dated 29.01.96 No. 2828 “On subsoil and subsoil use”, and the laws of the Republic of Kazakhstan “On oil” and “On the protection of the environment”, where oil and gas producing enterprises must to provide monitoring the state of the array of undermining facilities and utilities to ensure the normal operation of the enterprise.

The work was performed at Geomatic Ventures and at the University of Nottingham (England) under the direction of foreign scientific consultant Andrew Sowter, where a doctoral student had internship. ENVISAT ASAR satellite imagery was provided on the basis of an application for research by the European Space Agency.

The object of the study is the territory of the Tengiz oil field located in the Atyrau region.

The subject of the study is the deformation and displacement of the earth's surface, resulting from a long and intensive development of an oil field.

The purpose of the study is to improve the methodology for the integrated preparation and use of SAR data to assess the subsidence of the surface.

The idea of the work is to use ENVISAT ASAR radar data provided by the European Space Agency, Sentinel-1 SAR data of free access, leveling data of a given area, and geological data, wells.

The goal is achieved by solving the following tasks:

- perform an analysis of modern methods for observing the deformation of the earth's surfaceaA
- determine the deformation and analyze the dynamics of changes over the Tengiz field using the classical method of differential interferometry SBAS.
- to test the innovative ISBAS method for processing data to identify displacements of the Tengiz field.
- assess the accuracy of the studies.
- develop criteria for the selection of SAR data for monitoring tasks
- to improve the generalized methodology for identifying deformation for oil fields using SAR data.

Methodological base of the study

The main research and analysis methods used to complete the thesis include:

- Analysis of the available ENVISAT ASAR radar data for a given territory using the EOLISA software.
- Analysis of Sentinel-1 data available on a given territory and downloading images.
- Processing of ENVISAT ASAR and Sentinel-1radar data on Punnet software using the classic SBAS processing method and the innovative ISBAS method, including:

• Configuration of critical parameters, ensuring the quality of processing at key points.

• Phase unwrapping using Statistical-cost, Network-flow Algorithm.

• Elimination of topographic error with DTM SRTM

- Visualization and classification of results in the ArcGIS software package;
- Analysis of the dynamics of changes in the earth's surface
- Evaluation of the accuracy of the measurements.

Scientific provisions to be defended:

1. Criteria for the evaluation and selection of satellite images, allowing to obtain high-quality radar data for further processing.
2. Technique for processing satellite images with the configuration of critical parameters at key processing points, excluding interferograms with low coherence.
3. The innovative ISBAS method, allowing the use of an arbitrary reference point for calculating the displacement of the earth's surface.

Scientific novelty of the work:

The following new scientific results are obtained in the work:

1. Developed Criteria for the optimal selection of radar data for the tasks of assessing subsidence of the earth's surface under the conditions of exploitation of the Tengiz field.
2. Improved the method for processing satellite SARimages of the C band, which allows monitoring of deformation processes in technologically loaded zones.
3. Established that the use of the innovative ISBAS algorithm allows to exclude errors associated with the choice of a reference point in the monitoring of displacements.

Information about the metrological support of the dissertation.

The reliability of the results obtained is confirmed by evaluation of accuracy by using different kinds of data. The oil field was previously explored using several DInSAR methods, such as SBAS and SqueeSAR. Also, this field has data from the ground-based geodynamic monitoring method of leveling data.

The scientific significance of the work is the development of ideas about the mechanism of massif deformation during the development of oil and gas fields, including the theoretical and experimental substantiation of the methodology for the integrated preparation and use of images in the problems of assessing the subsidence of an industrial surface under operating conditions of the Tengiz field.

The practical significance of the work consists in introducing into the educational process the developed methodology for the preparation and processing of satellite images at the Tengiz oil and gas field and research organizations to perform geodynamic monitoring using Sentinel-1 and ENVISAT ASAR data, as well as the educational process during the passage of a discipline, such as Remote Sensing of the Earth.

Also, **the practical significance** of the dissertation can be justified by an article published in journals with a high impact factor cited on the web of science, Scopus, etc.

The reliability of the findings and recommendations is confirmed by a significant amount of research on the processes of interaction of natural and technogenic factors in the zone of influence of the oil and gas pipeline using elements of a system analysis, as well as the practical application of the developed methodology during the training process of the IEC.

Publications include one article on the journal with high impact-factor “International Journal of Applied Earth observation and Geoinformation” (web of science base), 4 articles in publications recommended by the Committee for Monitoring in Education and the Ministry of Education and Science of the Republic of Kazakhstan;

The structure and scope of the dissertation: the dissertation consists of an introduction, 4 chapters, conclusion, list of references from 98 titles and applications. The work is presented on 103 pages of typewritten text, contains 48 figures, 9 tables.

The introduction provides a general description of the dissertation. The relevance of the topic, the purpose and objectives of the study are formulated and considered the scientific provisions and the practical significance of the work.

The first chapter presented a description of the object of study - the Tengiz oil and gas field, which is considered as one of the giant fields in the world. The field is divided into three areas that were delimited in accordance with the structural relief throughout the field: platform, rim and flank. The majority of production wells are situated on the platform, targeting hydrocarbons in grainstone and packstone lithofacies of the Upper Visean, Serpukhovian and Bashkirian reservoirs. Fewer wells have been drilled in the predominantly microbial boundstone and breccia that compose the flank regions.

Also, in this chapter, an analysis of the use of satellite images, including radar, was carried out. The widespread use of satellite imagery data has opened up new prospects for monitoring changes in the state of the environment and processes occurring on the surface of the earth. The idea of using phase shift in the reflected signal of remote sensing data for interference was first expressed by D. Richman in 1971 (USA). However, the first practical results on the proposed method were obtained only in 1986-1989. by P.M. Goldstein and H.A. Zebker. And the first published work on the use of differential interferometry was the work of D. Massonnet in 1993, in which displacements of the earth's surface after an earthquake were estimated. Today, radar data are used in various sectors of the global economy, such as agriculture, ice cover monitoring, forestry, sea winds, etc. The use of space information in the tasks of monitoring changes in the earth's surface in the mining and oil and gas industries, as well as in monitoring the deformation of buildings and structures, has been widely distributed over the past decades in the CIS and Kazakhstan. It was also revealed that the basic method for processing space radar data in order to monitor deformations of the earth's surface in our country is the classical SBAS method.

The second chapter presents the main theoretical aspects of the SAR, including a detailed description of the classical DInSAR SBAS method. SBAS technology is a well-established DInSAR (Differential Radar Interferometry) technique that allows to determine the deformation of the earth's surface, and most importantly, analyze its development over time.

In particular, this technology is based on the use of a large amount of collected data using SAR and allows combining multi-sample interferograms using the DInSAR technique, calculated on specialized software, ultimately allowing the development of maps of the averaged displacement speed of the earth's surface.

In addition, the main problems of the use of radar interferometry, which arise from the theoretical foundations and during the use of classical algorithms for processing radar data, are considered. The main factors influencing the achievement of a qualitative result include the surface reflectivity, a large amount of vegetation, a humid climate, the choice of a reference point, in the absence of ground reference points, the “screen” of the atmospheric phase, a change in the geometry of images, the influence of DEM, etc. Many of these factors influence the production of a coherent picture, while another factor, the redundancy of images, increases the time required to create interferometric pairs, as well as during the analysis of the effect of noise. Consideration of the above sources of error is an important aspect of this research work, since the purpose of this thesis is to improve existing methods for processing SAR data.

The third chapter describes the experimental part of this dissertation. To calculate the average vertical surface deformation in the studied area over a period of time, thirty-three SAR images obtained from July 21, 2004 to February 25, 2009 were used. Images were acquired using C-band Advanced Synthetic Aperture Radar (ASAR) (wavelength 5.6 cm, frequency 5.3 GHz) on board the ENVISAT European Space Agency environmental research satellite. A complete set of ENVISAT ASAR images, which covers an area of approximately 100 km × 100 km with a spatial resolution of 25 m in range and 5 m in azimuth, was clipped to a subset of 42 x 40 km covering the study area and then processed using Differential Analysis Interferometric Synthetic Aperture Radar (DInSAR).

Prior to processing, images were co-registered with sub-pixel precision to the master scene acquired on 16th February 2005. Multilooking factors of 4 in range and 20 in azimuth were applied to reduce noise and increase coherence, producing pixels corresponding to a ground resolution of approximately 100 m × 100 m. As is common for ENVISAT small baseline surveys, interferograms were generated with a 4-year limit on the temporal baseline and 250 m on the perpendicular baseline, producing a set of 135 multi-looked differential interferograms. These restrictions minimise temporal and spatial decorrelation in the interferograms, therefore enhancing the phase quality and coherence (Gee et al., 2017), whilst reducing the impact of errors in the digital elevation model used to generate the differential interferograms. A standard coherent scatterer analysis was implemented on the multi-looked data by following the basic procedure described in Lanari et al. (2007), such that only pixels with an average coherence of ≥0.25 across every interferogram were processed. Herein, this approach will be referred to as the SBAS technique. In contrast, the ISBAS technique identifies suitable pixels for analysis by incorporating a minimum quality standard alongside the coherence (Sowter et al., 2013). Specifically, a pixel is retained if it has a coherence of ≥0.25 in a minimum number of interferograms, in doing so permitting the analysis of features that are intermittently coherent in the image stack. The minimum number of interferograms threshold allows a trade-off between the spatial coverage and accuracy of the derived deformation measurements, with a higher number of interferograms leading to a more accurate result with a sparser distribution of measurements. The optimum threshold can be identified from the empirical relationship between the standard error of the ISBAS velocity solutions and the number of interferograms (Cigna and Sowter, 2017). In this case, the minimum number of interferograms for the ISBAS technique was set as 60.

Topographic phase was removed from the differential interferograms with the aid of the 90 m Shuttle Radar Topography Mission (SRTM) digital elevation model (Farr et al., 2007), as were any orbital ramps, before a statistical-cost network-flow algorithm was used to unwrap the coherent (i.e., SBAS) and intermittently coherent (i.e., ISBAS) pixels (Chen and Zebker, 2001). An average rate of motion for each pixel was then computed relative to a reference point, which was carefully chosen to ensure that it remained coherent in all interferograms and stable throughout the period of the DInSAR analysis. The reference point is located on a built structure within the confines of the oil and gas processing plant at 53.4 °N, 46.2 °E.

Finally, in the absence of sufficient ENVISAT data from an ascending orbit for stereo analysis, the average velocities in the radar line-of-sight (LOS) were converted to effective vertical velocities by dividing by the cosine of the angle of incidence for each pixel. This conversion was performed to enable comparison with both the levelling data and more recent SAR-derived deformation. Through convention, positive effective vertical velocities represent surface uplift (or heave) whereas negative velocities indicate ground subsidence. The above ISBAS procedure was also applied to Sentinel-1 SAR data for 52 ascending images acquired between 11th November 2016 and 29th September 2017, in order to delineate recent ground deformation over the Tengiz field. Sentinel-1 is a two-satellite imaging radar mission carrying a C-Band (5.405 GHz) SAR instrument. Sentinel-1a and Sentinel-1b were launched in April 2014 and April 2016, respectively, and the two satellites currently maintain a conflict-free repeat pass of up to 6 days. A 1-year temporal baseline and 150 m perpendicular baseline resulted in 1179 multi-looked differential interferograms. The minimum number of interferograms threshold was set to 430. Again, due to insufficient Sentinel-1 descending orbit images for the same time period, the LOS measurements were converted to vertical velocities using a cosine correction, in order to normalise the different geometries between Sentinel-1 and ENVISAT for subsequent comparison.

The ISBAS average and maximum vertical rate of subsidence over the platform and rim region is −5.5 mm/year and −15.7 mm/year, respectively. As also indicated by the SBAS results, subsidence is greatest in the northern portion of the field, where the abundance of production wells and pore pressure perturbation is greatest (Dagistanova et al., 2011). Although not recognisable with SBAS, the ISBAS technique enables this deformation to be fully characterised as a subsidence bowl. This is in full agreement with the presence of a subsidence bowl previously computed through geomechanical modelling by Comola et al. (2016). Moreover, the subsidence rates are highly correlated with distinct pore pressure regions identified by Dagistanova et al. (2011). A weaker, secondary correlation with depth to the reservoir is also apparent (Collins et al., 2006), with associated changes in stresses being more readily transmitted to the surface through the thinner layers of overburden above the central and outer platform (figure 1).

A number of previous DInSAR studies have been conducted in order to reveal deformation over the Tengiz oil field. When comparing these results to those obtained here, it is important to recognise that some disparity in the velocity magnitudes and measurement coverage is inevitable, even when the same technique is used, due to differences in the processing parameters (e.g., temporal and perpendicular baselines) and time-period covered by the data. Moreover, the use of a cosine correction to convert LOS measurements to effective vertical velocities imposes the assumption that the deformation field is entirely vertical in nature. Although this conversion approach was a necessity for the comparison with levelling data and Sentinel-1 results (as outlined in Section 3.1), this assumption may be not be strictly accurate, and so it is important to appreciate that the vertical velocities derived here are a limited approximation of the true land motion.

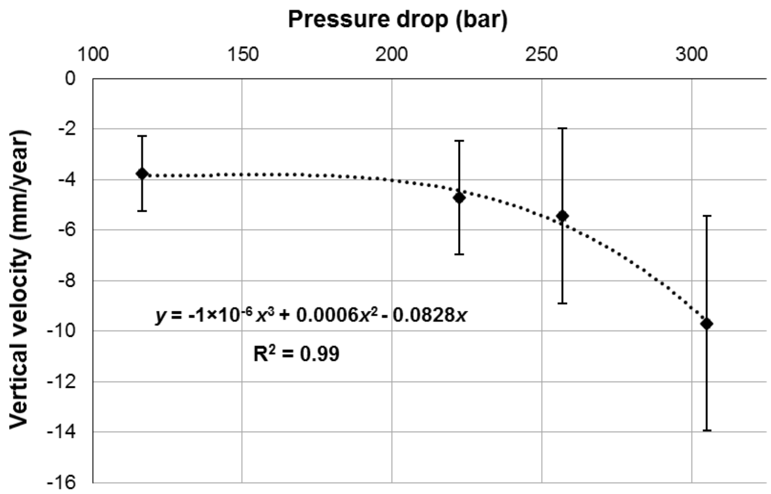

Figure 1. Correlation between pressure depletion (between 2009 and when first tapped) and mean ENVISAT ISBAS-derived subsidence rate within the pressure regions identified by Dagistanova et al. (2011).

Zhantaev et al. (2012) applied an SBAS analysis to ENVISAT ASAR and ALOS Phased Array L-band Synthetic Aperture Radar (PALSAR) data acquired for the periods 2004–2009 and 2007–2010, respectively. Both results show a deformation pattern consistent with the ISBAS result, dominated by the subsidence bowl over the northern portion of the field with a maximum rate of ground motion of up to −20 mm/year in the radar LOS. In terms of coverage, the ALOS SBAS result of Zhantaev et al. (2012) provides more ground motion measurements than the ENVISAT SBAS result present here, which is likely because more coherent pixels were identified given that the longer wavelength ALOS signal (L-band, 23.6 cm) is less sensitive to temporal changes in surface conditions. However, notably, the ALOS SBAS result of Zhantaev et al. (2012) visually appears to provide significantly fewer measurements across the study area. Correlation between pressure depletion (between 2009 and when first tapped) and mean ENVISAT ISBAS-derived subsidence rate within the pressure regions identified by Dagistanova et al. (2011). Error bars represent standard deviation of vertical velocities within the regions. Although in vegetated areas L-band data permits coherent phase recovery over longer temporal baselines compared to C-band, coherence can still decrease to < 0.25 for time intervals of less than one year.. Therefore, without applying a minimum temporal baseline to ALOS SBAS analysis, it is conceivable that some temporal decorrelation will inevitably occur over vegetated parts of the oil field. Consequently, pixels exhibiting any degree of temporal decorrelation will be immediately discarded in the ALOS SBAS analysis, whereas intermittently coherent pixels are retained in the ISBAS analysis, accounting for the additional ground motion measurements observed here despite utilising C-band data. Comola et al. (2016) also processed ENVISAT data for 2004–2007 to ascertain parameters for optimising their geomechnical modelling. The data were processed using the SqueeSAR technique (Ferretti et al., 2011), which utilises both persistent and distributed scatterers in order to enhance the density of ground motion measurements in non-urban areas. The SqueeSAR outcome further verifies the ISBAS result by revealing a well-defined subsidence bowl over the reservoir with radar LOS displacement rates of up to −20 mm/year, which is assumed to be almost entirely vertical given the small angle of incidence. Comola et al. (2016) also report strong west-east components (8–10 mm/year) in the ground displacement field, however, it is not possible to verify this in the present study owing to the lack of sufficient data from an ascending orbit for 2004–2009. Visually, the SqueeSAR technique provides comparable coverage of the reservoir to that of ISBAS, while the reported average densities for persistent and distributed scatterers are 33 measurements/ km2 and 50 measurements/km2, respectively, resulting in 150,000 measurements (Comola et al., 2016). Although the density of measurements might appear lower than obtained using ISBAS, a comparison is inappropriate because of inherent differences between the two techniques (i.e., data type – points vs. pixels) and the ENVISAT scene extent and time period. The enhanced coverage provided by ISBAS resolves other interesting deformation features not previously referenced. A notable example lies to the southwest of the field, where an area of stability interlaced with localised patches of subtle uplift (< 3.5 mm/year) is observed. This area overlies the flank of the reservoir, which, unlike the platform and rim regions, was observed to have undergone an unsystematic decline in pressure during the latter half of the time period covered by the DInSAR analysis (Collins et al., 2013). In fact, wells in this region were reported to have experienced either no change or a small increase in pore pressure during this time (Dagistanova et al., 2011), which would likely account for the observed deformation.

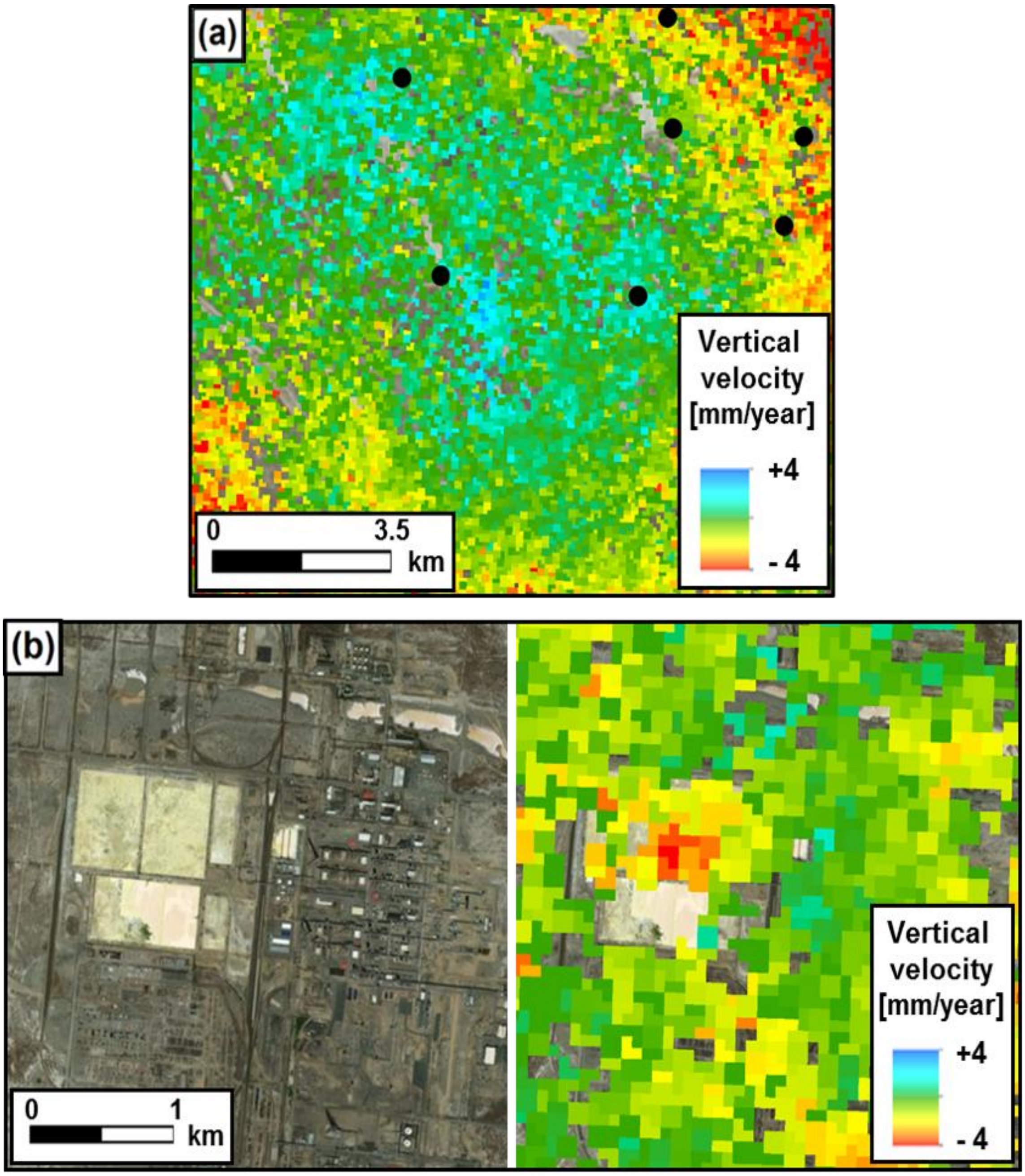

Figure 2. Localised deformation revealed by the ISBAS technique applied to ENVISAT. (a) Area of stability and uplift observed of the southeastern flank of the Tengiz oil field and (b) subsidence over the sulphur pads. Black circles represent well locations.

Additionally, a small area of subsidence is observed over the sulphur pads at the oil and gas processing plant (Fig. 2b). Sulphur is produced as a by-product of the refining process, and the motion is indicative of steady reduction in the height of the stockpile either through settlement or as a result of action to remove all reserves from the site during 2007–2015. The lack of velocity measurements over the pad directly south of the subsidence arises because of prolonged loss of coherence due to rapid changes in the scattering characteristics of the pad over time – most probably due to rapid removal of significant amounts of stockpiled material.

A direct comparison reveals a reasonable level of agreement between the high-precision levelling and ENVISAT ISBAS measurements, with a root-mean-square error (RMSE) of 3.18 mm/year and mean absolute error of 2.71 mm/year (Table 1).

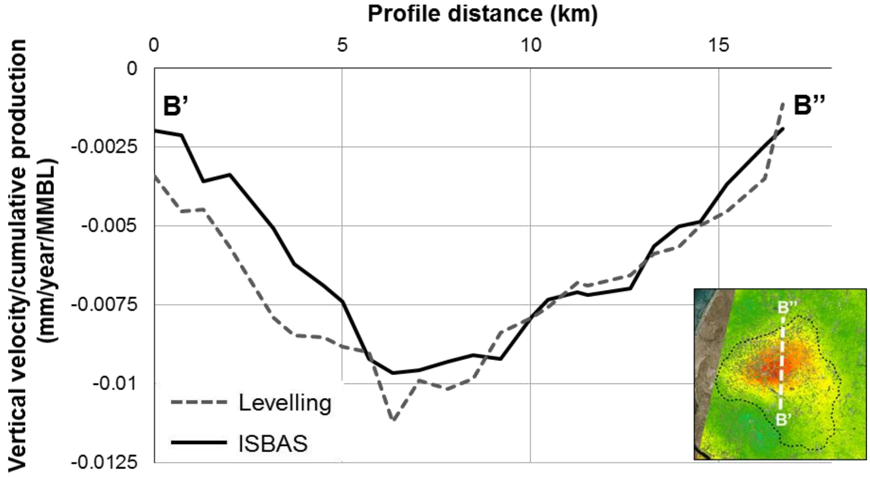

Figure 3. Comparison of productivity-normalized strain rates of the Tengiz reservoir, measured using leveling (for the period 2001–2005) and ISBAS (2004–2009).

Measurements on the periphery of the reservoir show greater correspondence through an RMSE of 0.64 mm/year. Differences in the subsidence rate are largest towards to the centre of the reservoir, where the maximum rates are −13.7 mm/ year and −9.9 mm/year for the ISBAS technique and levelling, respectively (figure 3). This discrepancy is anticipated to be due primarily to the temporal offset between the two sets of measurements, meaning that they do not reflect the exact same field operating conditions. For instance, the levelling measurements cover the period 2001–2005 when oil production was relatively low and steady, while the DInSAR analysis captures the substantial post-2007 rise in oil production that likely led to increased reservoir compaction and ground deformation. To account for this discrepancy, the two sets of ground motion measurements were normalised to cumulative production between 1993 and the end of each measurement period (i.e., cumulative production for 1993–2005 and 1993–2009 for the levelling and DInSAR data, respectively). This produces a higher level of correspondence between the deformation trends, clearly confirming the presence of a subsidence bowl over the reservoir. Moreover, it confirms that production rate is a primary control on the rate of deformation observed over the oil field. Any minor residual discrepancy between the two datasets will arise from the contribution of other factors, including the comparison between point-based and areal measurements, use of different reference points for measuring rates of surface displacement, LOS cosine correction, and other variations in the field operating conditions. 4.2. Recent ground deformation The ISBAS technique applied to Sentinel-1 data (2016–2017) provides a novel insight into recent ground deformation over the Tengiz field (Fig. 4a).

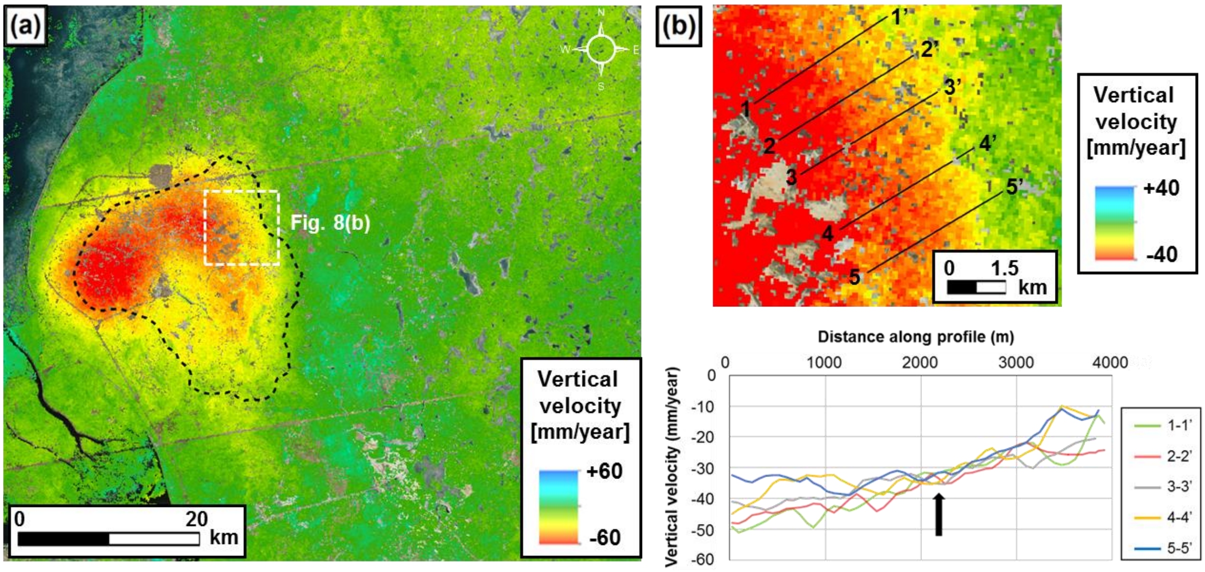

Figure 4. (a) A recent soil deformation map of the study area, showing the vertical velocities calculated from Sentinel-1 (2016–2017) using the ISBAS method. (b) A scaled subset of the strain map and cross-sectional profiles on the eastern edge of the oil field. A black arrow indicates a potential subtle bias.

The deformation map – which extends beyond the ENVISAT analysis and covers 79% of the study area – illustrates that the previously recognised subsidence bowl has evolved into a broader region of subsidence that now spans the entirety of the reservoir. In fact, the subsidence has extended by up to 3 km beyond the denoted confines of the platform and rim region and into the flanks on all but the eastern side, which is seemingly bound by northwest-southeast trending faults at this margin (Anissimov et al., 2000). A potential, albeit subtle, northwest-southeast lineament formed by a break-of-slope in the rate of subsidence across strike is somewhat apparent in this area (Fig. 4b). The average and maximum rates of subsidence observed over the platform and rim region are −36.1 mm/year and −79.3 mm/year, respectively. This represents substantial 6.6-fold and 5-fold increases in subsidence compared to the 2004–2009 period (figure 5). The greatest increases in subsidence rate are at the northern, eastern and western margins of the field, coinciding with zones of superpermeability (Anissimov et al., 2000). Such areas have been subject to recent field development due to their high fracture densities, making them the highest producing areas in recent years (Collins et al., 2014). Deformation in the north and west has accelerated most, with subsidence typically increasing by 50–60 mm/year with respect to the 2004–2009 rates. Subsidence rate over the central and southern portions has increased by approximately 50% of that over the north and west of the field (i.e., 20–30 mm/year). The centre of the platform is less fractured than the margins, although sour gas injection technology was utilised for enhanced oil recovery in this particular region in 2008. Based on the Sentinel-1 ISBAS result, the net volume loss over the main platform and rim region for the period 2016–2017 alone is estimated at 5.61 × 106 m3 /year. Such volume loss and subsidence rates are expected to be associated with significant pressure depletion and compaction over the field – this is presumably one of the key drivers behind the recent Future Growth

Project-Wellhead Pressure Management Project that is designed to boost production across the field.

Recent soil deformation The ISBAS method applied to Sentinel-1 data (2016–2017) provides a new understanding of recent soil deformation over the Tengiz field. The deformation map, which is beyond the scope of ENVISAT analysis, shows that the previously recognized sedimentation bowl has evolved into a wider subsidence area covering the entire formation. In fact, subsidence extended up to 3 km outside the platform and rim area and on the flanks from all sides except the eastern side, which, apparently, is associated with the northwest-southeast shear faults along this edge (Anisimov et al., 2000). A potential, albeit thin, north-west-south-east lineament formed by a gap in the subsidence velocity across the strike can be detected in this area (Figure 4b).

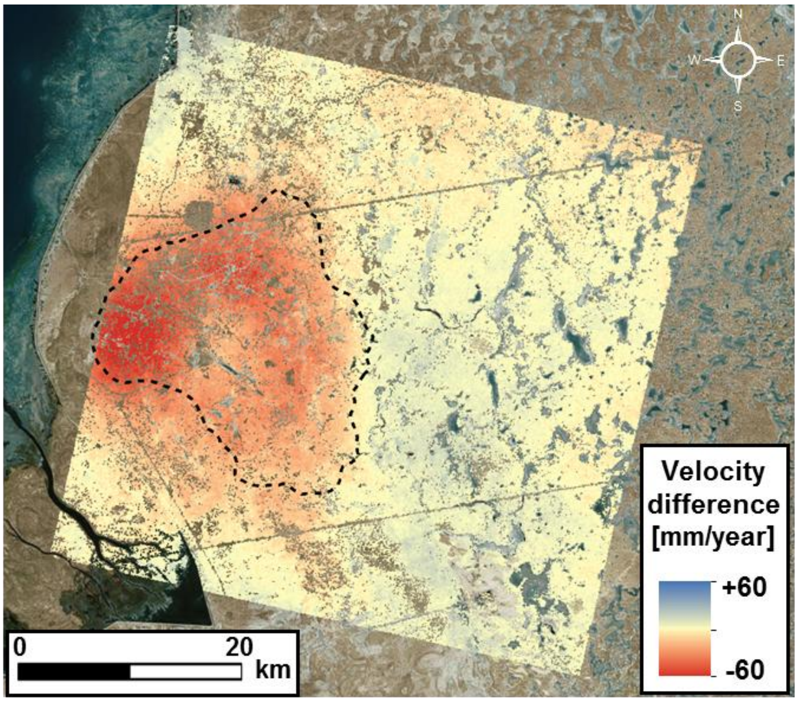

Figure 5. The difference in the rate of vertical soil deformation between the periods 2016–2017. (Sentinel-1) and 2004-2009. (ENVISAT). Negative differences in speed represent an increase in settling rate from 2004 to 2009.

The fourth chapter contains developed criteria for the selection of images and improved recommendations for processing radar data.

1. To obtain a high-quality interferogram, it is recommended to apply a 4-year limit on a temporary baseline and 250 m on a perpendicular baseline. These constraints minimize the temporal and spatial decorrelation in interferograms, thereby improving phase quality and coherence (Gee et al., 2017), while reducing the effect of errors in the digital elevation model used to generate differential interferograms.

2. To reduce noise and increase coherence for ENVISAT and ERS data, it is better to use multi-looking coefficients of 4 in range and 20 in azimuth to obtain pixels corresponding to a ground resolution of approximately 100 m × 100 m.

3. At that time, for spatial averaging of pixels of interferograms created from Sentinel-1 data, coefficients 6 and 30 are set in the directions of azimuth and range,

respectively. This can be justified by the fact that the SLC Sentinel-1 format is very different from the ERS and ENVISAT formats: Sentinel-1 is generated using the TOPS processor, while ERS and ENVISAT are generated using the Stripmap processing.

4. By manipulating the subparameter files, you can reduce the region of interest, which would increase the speed of creating interferograms. This manipulation can be performed if any errors appear during processing (for example, after 18 hours of processing) and after detecting the error and eliminating it.

5. Application of the ISBAS method, since this method determines the appropriate pixels for analysis by including a minimum quality standard along with coherence (Sowter et al., 2013). In particular, a pixel is preserved if it has a coherence of ≥0.25 in the minimum number of interferograms, which allows to analyze elements that are periodically coherent in the image stack (Figure 9).

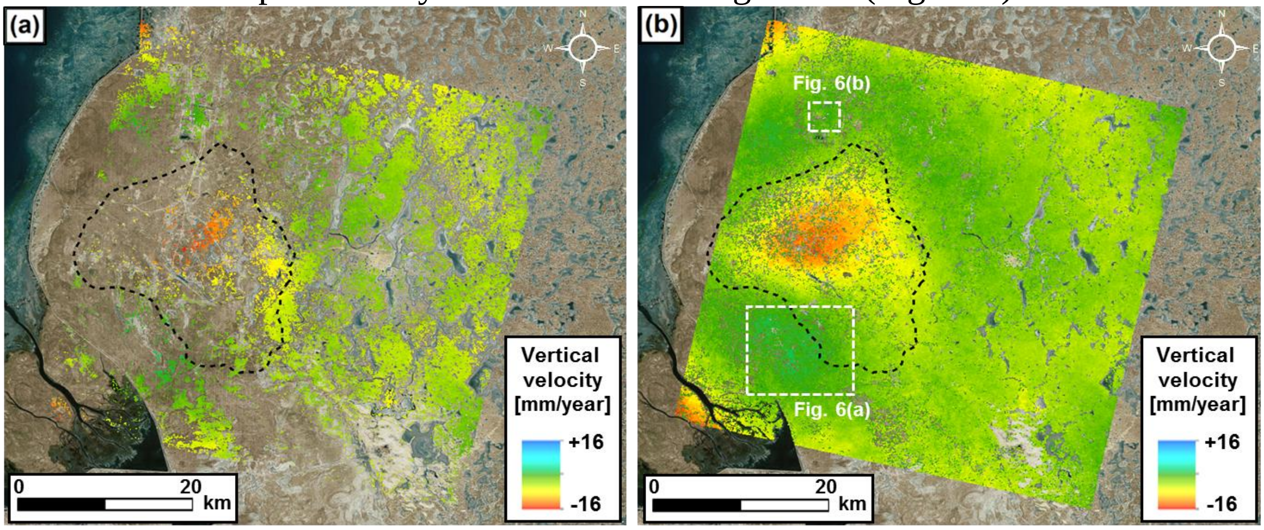

Figure 6. Soil strain maps showing vertical velocities calculated according to ENVISAT data (2004–2009) using (a) SBAS and (b) ISBAS methods. Positive speeds indicate a rise, and negative speeds indicate a subsidence. The dashed black line shows the length of the platform and the rim area of the Tengiz oil field. The location of figures 6 (a) and (b) is shown.

Average vertical velocity ground measurements computed from ENVISAT data (2004–2009) using the SBAS and ISBAS techniques are shown in Fig. 4. A total of 102,398 coherent pixels were identified using the SBAS technique, equating to an average of 60 measurements/km2. Coherent pixels tend to cluster around areas dominated by stable scatterers, such as the Tengiz Oil and Gas Complex just north of the platform boundary, and over blocks of less dissected ground in the centre and east of the study area (Fig. 6a). Including pixels that exhibit intermittent coherence in the analysis markedly increases the spatial coverage and density of ground motion measurements (Fig. 6b). At 366,842 pixels, the number of ISBAS ground motion measurements is 3.6-times greater than for SBAS, equating to an average of 215 measurements/km2. Overall, the ISBAS results cover 77% of the study area (in terms of total number of pixels) compared to just 22% coverage provided by SBAS. The additional measurements are situated across land cover types that are typically unfavourable for conventional DInSAR analysis; notably locations with dense scrubby vegetation cover. Such areas are often dynamic between observations due to physiological changes in the vegetation, and so will appear coherent in some interferograms but not in others (Sowter et al., 2013). The SBAS results reveal predominantly stable ground, with the exception of a small area of subsidence near the centre of the field. The maximum subsidence rate is found to be −14 mm/year over the northern portion of the platform. However, the enhanced coverage provided by the ISBAS technique better characterises the spatial pattern of deformation, revealing a more extensive area of subsidence that demarcates the extent of the reservoir

6. The choice of the optimal minimum number of threshold values of interferograms. The right choice allows to find a compromise between spatial coverage and the accuracy of the obtained strain measurements, with a large number of interferograms, which leads to a more accurate result with a rarer distribution of measurements. The optimal threshold can be determined from the empirical relationship between the standard error of the ISBAS speed decisions and the number of interferograms (Cigna and Sowter, 2017).

7. The choice of the optimal reference point. A stable correctly selected reference point determines the final result, including the presence of deformation of the earth's surface in the oil industries. However, the use of the ISBAS method does not require the deployment of angular reflectors and the use of an arbitrary control point, which does not require absolute ground-based positioning data, which increases the practicality of monitoring.

8. Independence of the pixel value from neighboring pixels.

Brief conclusions on the results of dissertation research

The dissertation describes scientifically based technical developments to improve the methodology for the comprehensive preparation and use of satellite imagery to assess the subsidence of the earth's surface, providing a solution to the applied problems of the oil and gas industry - safe and effective field development, using the example of the Tengiz oil and gas field.

The main results of the research are as follows:

1. The ISBAS DInSAR technology was used to monitor soil deformation over the Tengiz oil field in Kazakhstan.

2. A clearly defined bowl was identified with a maximum settling rate of -15.7 mm / year as a result of the analysis of ENVISAT SAR data for the period 2004-2009, which is confirmed by data from other DInSAR studies and is confirmed by leveling data.

3. A clear pattern of soil deformation with a maximum speed of -79.3 mm/ year was obtained based on the extended coverage and density of accurate measurements by the ISBAS method, which is achieved without the need for deploying angular reflectors and using an arbitrary reference point and does not require absolute ground-based positioning data, which increases practicality of monitoring.

4. It is established that the use of ISBAS can offer more cost-effective operational tools for regional, long-term deformation monitoring than a conventional ground-based sensor network. Paraphrase itself in a general way, pliz.

5. It was revealed that more detailed and comprehensive measurements of the movement of the soil can allow a better characterization and control of the formation, as well as a better understanding of the risk associated with this, represented by subsidence of the soil and reactivation of the tectonic disturbance.

6. Developed guidelines for the preparation and processing of space data, based on experimental research.

Assessment of the completeness of the solution of tasks:

In the dissertation, a comprehensive analysis of domestic and foreign experience on the use of space data to assess the deformation of undermined territories was made, which allowed to improve the methodology of the integrated preparation and use of satellite images in the tasks of assessing the subsidence of the earth's surface under conditions of exploitation of hydrocarbon deposits.

The proposed methodology allows ensuring the promptness and accuracy of the results of assessing the geodynamic situation in the study area, ensuring the efficiency and safety of hydrocarbon field development.

Thus, the task is completed in full, in particular:

1) The analysis of modern methods for observing the deformation of the earth's surface.

2) The deformation is determined and the dynamics of change over the Tengiz field is analyzed using the classical SBAS differential interferometry method.

3) The innovative ISBAS method was tested for processing C-band data while monitoring the displacements of the Tengiz field.

4) The accuracy of the studies was evaluated.

5) Elaborated criteria for the selection of SAR data for monitoring tasks

6) The generalized methodology for calculating the settlement trough for oil fields using SAR data has been improved.

Recommendations and baseline data on the specific use of the results. It is possible to apply the methods and sequence of work when performing similar works for other oil fields of Kazakhstan.

The results obtained in the thesis and written in the form of an article in a journal with a high impact factor were used in research in Albania, which is confirmed by citation.

Assessment of the cost-effectiveness of technology. When applying the proposed methods for monitoring the deformation of the earth's surface, the safety and economic efficiency of development in other oil and gas fields will increase.

Assessment of the scientific level of the work performed in comparison with the best achievements in this field.

The performed analysis of literary sources, the developed recommendations and the improved methods presented in this work allow us to conclude that the dissertation work corresponds to the modern scientific and technical level.

The above results are reliable and of scientific value due to the use of an innovative method of processing, analysis of displacements of the earth’s surface, which was confirmed by publications of the author’s relevant scientific papers in conferences near and far abroad, as well as in a journal with impact factor 4.8 included in the web of science database.

PUBLICATIONS ON THE THEME OF THE DISSERTATION

Articles in peer-reviewed international journals

1. Stephen Grebby, Elmira Orynbassarova, Andrew Sowter, David Gee, Ahmed Athab. Delineating ground deformation over the Tengiz oil field, Kazakhstan, using the Intermittent SBAS (ISBAS) DInSAR algorithm. International Journal of Applied Earth Observation and Geoinformation, Issue 81, pp. 37-49, 2019

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2. Orynbassarova E. The history of the development of the use of satellite images for monitoring the deformation of the Earth's surface. Bulletin of KazGASA, ISSN 1680-080X. No. 2 (64), 2017, p. 219-224

3. Orynbassarova E, Kenesbaeva A. Possibilities of using data from the new Sentinel-1 satellite. Bulletin of KazGASA, ISSN 1680-080X. No.2 (68), 2018, p.168-173

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5. Orynbassarova E. Features of the formation of full-scale experimental data from satellite images of the Tengiz field. International Forum of Surveyors "Innovative Technologies in Surveying and Surveying", ISBN 978-601-228-810-0. Almaty 2015. - ss. 194-197.

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7. Orynbassarova E., Kakimzhanov Y., Kamza A., Yerzhankyzy A., Levin E. Comparison of digital elevation models generated with open Source software from various satellite imagery. International Multidisciplinary scientific geoconference& EXPO SGEM, ISSN 1314-2704. Issue 2.3, 2018, Bulgaria 2018, pp. 73-80

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11. Schultz R., Levin E., Yerzhankyzy A., Orynbassarova E.O. Using aerial photographs for ground laser scanning. Interexpo GEO-Siberia. XIV Int. scientific Congr. ISSN 2618-981X, 2018, Novosibirsk: Plenary Session: Sat materials. - Novosibirsk: SGGiT, 2018 .-- ss. 69-74

12. Kurmankozhaev A., Orynbassarova E., Yerzhankyzy A. Digital model in the problems of the development of modern cartography. Scientific discussion, ISSN 3041-4245. Vol 1, No 22, Prague, 2018, pp. 36-40