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Final qualifying work

MONITORING OF THE EARTH'S SURFACE SUBSIDENCE PHENOMENA IN MINING AREAS

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INTRODUCTION

Land subsidence monitoring is relevant in order to control the interaction of mining facilities and the environment. In recent years, remote sensing data have become important in spatial data analysis. Geographic Information Systems (GIS) and remote sensing data have the following uses: creating, data acquisition, integration, processing, visualisation, analysis and modelling information about the Earth's surface and its phenomena. The uses of GIS and remote sensing combine information at a specific space and time. This helps to analyse any scientific problems understanding the surroundings and coming up with theories that help in planning and decision-making. These tools are practically applied to create maps, predict feature environmental hazards, verifying the location of research areas, monitor environmental activities and infrastructure.

Land Subsidence is one of the common environmental problems that have led many scientists to research and study more about it. Land subsidence is the gradual settling or sudden sinking of the earth's surface owing to subsurface movement of the earth materials; it is a global problem (Galloway, 1999). Exploitation of natural resources on the earth will cause harm to the environment and result in changes such as land subsidence, soil erosion and land degradation. Scientists used to believe that subsidence of the earth's surface is a natural phenomenon that resulted from natural geographical changes, but now it has been proved that human activities also cause land subsidence on the environment. The most significant effects on the earth's surface include mining activities, deforestation and increased demand of resources.

This work helps to develop theoretical and methodological knowledge for monitoring land subsidence through the application of an advanced synthetic aperture radar (InSAR) interferometry technique, identifying the patterns and changes of land surface characteristics due to land subsidence. After analysing the data, the results will show if the study area has land subsidence and characteristics of the study area Kuznetsk coal basin (Kuzbass) Kemerovo region, over a specific period. What forces the environment to experience change is a result of practical problems experienced when mining for example inappropriate mining methods, infrastructure difficulties and lack of proper implementation of safe mining regulations.

Determining large areas with land deformation is one of the best uses of InSAR data. The use of traditional methods to monitor land subsidence of the land surface especially on large areas such as Kuznetsk coal basin (Kuzbass) Kemerovo region is very expensive. Therefore, InSAR technique is efficient and less expensive since it does not require much more time to collect data as compared to using the GPS tool, surveys, tape extensometers etc. The InSAR techniques can also detect deformations of landslides, earthquakes, volcanoes, glacier dynamics and land subsidence.

There are different factors that make the InSAR technique a useful tool for deformation monitoring (M. Crosetto, 2004).

- The technique is responsive to small land subsidence, up to a few millimetres in the best measurement conditions.
- DInSAR provides data for large areas such as 100 by 100 km using ESA satellites, with a relatively high spatial sampling density (without compression, the pixels of the ERS images have a 20 by 4 m pixel footprint).
- SAR images acquired from ESA satellites have an advantage as compared to traditional methods, of providing data images of long-term data series for example providing images that covers many decades from 1991.Thus scientist are able to study land subsidence that has occurred 15 or 10 years ago.
- Analysing data obtained from InSAR technique includes visualisation, the maps produced using the technique have high quality and displacement of the study area can be observed or measured.

However, this research is achieved through implementing advanced InSAR processing and analysis procedures. Besides its advantages, this technique involves images processing which might take more time depending on how good the processor of your computer is. The software is designed to work with plugin updates, which needs downloading new versions of modules and updating. InSAR technique involves conducting calculations and modelling using the appropriate formula to estimate displacements with high quality standards.

Extent the problem was researched:

The need to ensure continues monitoring of land subsidence and deformation of earth surface at all stages of development has motivated most scientist to carryout scientific research, observations and organisational monitoring forms. For example, the use of remote sensing to assess the impact of mining is recent and there are only a few studies on the subject including studies from Charou et al. (2010), Koruyan et al. (2012), Joao Catalao et al. 2015, and Lobo et al. (2018) and others. To control and assess the interaction between human activities such as mining and the environment requires frequent monitoring. Application of InSAR analysis and numerical modeling for the assessment of land subsidence is quite well developed in the works of Giovanni Nico, Piernicola Lollino et al., (2016),(M. Crosetto, 2004) and others. It was observed that the intensity of land subsidence depends on the capacity of activities conducted on the environment. Studies of landuse and cover change have a major role in the study of global environmental change which indicates the influence of human activities on the physical environment (Adugna Babu et al., 2015).

Aim

- To develop methodological system for monitoring land subsidence of the surface, through implementing the advanced synthetic aperture radar (SAR) interferometry technique

Objectives

- To monitor land subsidence in mining areas using through the application of advanced synthetic aperture radar (InSAR) interferometry techniques.
- Identifying the patterns and development of land subsidence in Kuznetsk coal basin (Kuzbass), Kemerovo region).
- Address the effects of mining activities to the land surface;
- Familiarize with the causes of land subsidence and the existing methods of monitoring subsidence;
- Map land subsidence in Kuznetsk coal basin (Kuzbass), Kemerovo region using advanced InSAR methods;
- Identification of changes and development of land subsidence due to mining activities at Kuznetsk coal basin (Kuzbass), Kemerovo region;

- Process and analyse remotely sensed data through the application of an advanced synthetic aperture radar (InSAR) interferometry technique;

Theoretical and practical significance of the work

The results of this research provides methods for monitoring land subsidence for large areas, Kemerovo region which is about 95 725 km^2 where there is Kuznetsk coal basin that has an area of around 10,000 square miles (26,000 km^2).The research also provide information for research that can be useful for government agencies, scientific and educational institutions. The results help making development plans for Kuznetsk coal basin (Kuzbass), Kemerovo region for example to solve the following practical problems: monitoring engineering, geological conditions of the territory and making environmental friendly decisions of mining. The work provides comprehensive assessment of land subsidence caused by coal mining activities and estimate the changes of the characteristics of the study area over a certain period. Application of the satellite data improves the methodology used to monitor land subsidence in relation to the mining activity.

CHAPTER 1: ANALYSIS OF THE STUDY OF LAND SUBSIDENCE PROCESSES

Monitoring land subsidence

The extent or development of land subsidence depends on the capacity of activities conducted at the mining area. Studies of land cover changes, land degradation and land subsidence have become key components for managing natural resources and monitoring environmental changes, it plays a major role in the study of global environmental change which indicates the influence of human activities on the physical environment (Adugna Babu et al., 2015). As indicated before, using remote sensing to assess impacts of mining activities on the environment is recent. There are only a few studies on the subject including studies from Charou et al. (2010), Koruyan et al. (2012), Joao Catalao et al. 2015, and Lobo et al. (2018).Therefore there is need for scientists to carry out more research on land subsidence using the application of remote sensing to ensure continuous monitoring of deformations.

Research on land subsidence processes controls the interaction between mining activities and the environment. Environmental monitoring is known as a system of repeated observations of the quality of the natural environment in space and time with certain goals to control the risks of environmental degradation. Environmental monitoring was introduced in 1972. In 1974, Yu. a. Israel clarified this concept and designated it as a system not only of observations, but also of assessment and forecast, which allows us to identify those changes in the environment that occur as a result of human activity, i.e. anthropogenic changes (G. Schweitzer, A.Phillips1986). Monitoring of the land subsidence includes complex and specific types of monitoring, aimed respectively at observing characteristics of the environment such as vegetation cover, river channels and elevation of the study area.

Current methods for monitoring the Earth's surface

Different monitoring systems are used to control the potential risks on the environment and update dynamic changes that occur on the earth's surface. Geodynamic monitoring is one example of a particular type of environmental monitoring; its aim is to study exogenous and endogenous geological processes. As indicated on *diagram 1*, geodynamic-monitoring is under monitoring of the geological environment. However, there are other types of monitoring such as geographical monitoring, biological monitoring and social monitoring indicated below.

According to the Developments in Earth and Environmental Sciences, O.G. Sorokhtin et al. (2004) geodynamics is the science of processes occurring in the Earth's crust and its superficial zone.

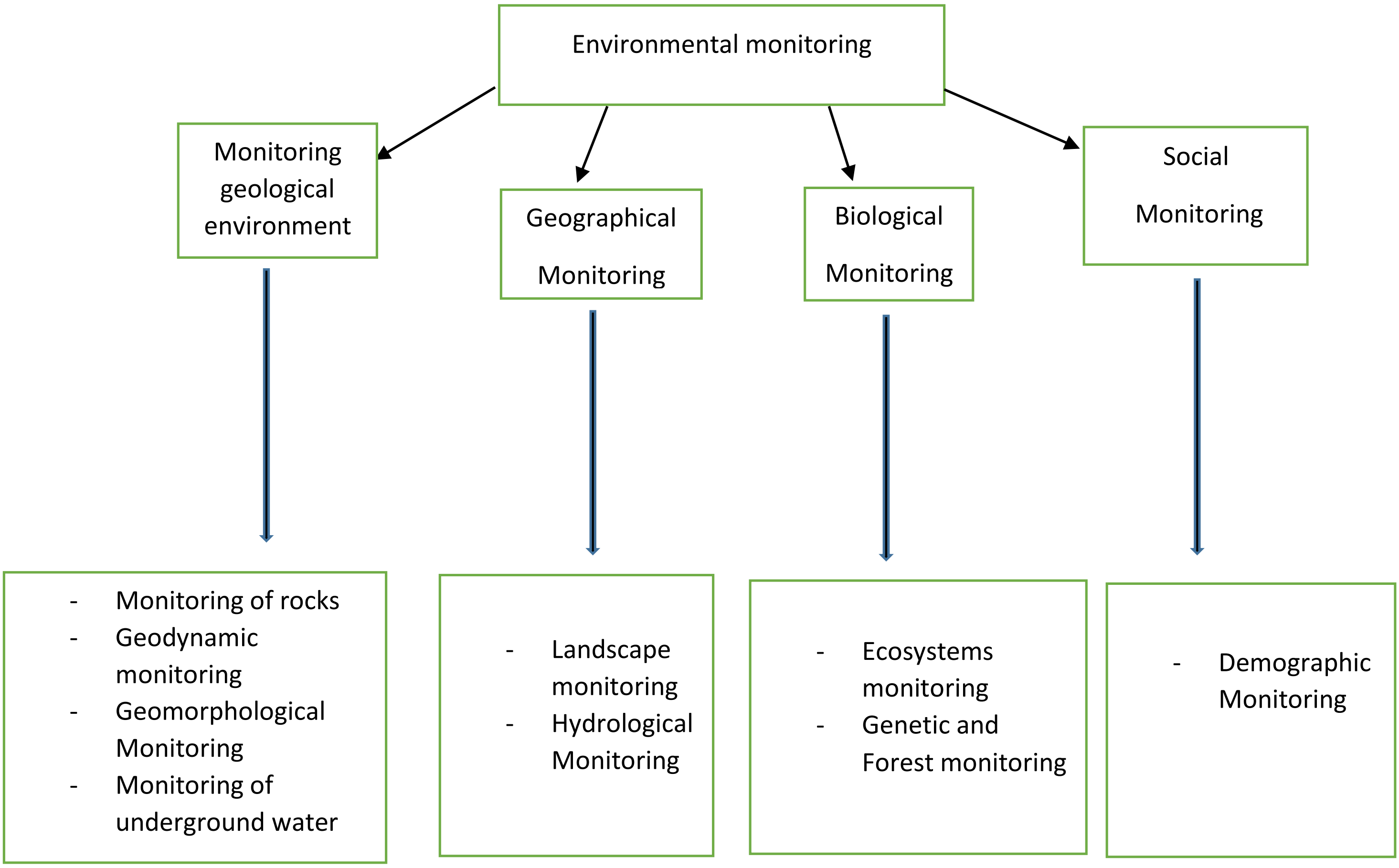


Diagram 1: Shows the structure of the environmental monitoring system

Environmental monitoring is now one of the most important parts of mining operations. According to the definition of E. M. Sergeeva, "the concept of monitoring the geological environment is a multi-component dynamic system that is affected by human engineering and economic activities the direction of which it largely determines". Conducting research on the effects of human activities to the natural environmental resources ensures environmental conditions that control human activities. For example implementing rules and regulations the help control sustainable utilisation of resources.

To date, the main modern methods for observing the earth's surface deformations in open-pit mining areas include:

- Technologies of global navigation satellite systems (GNSS technologies). Global Navigation Satellite System encompasses all global satellite-positioning systems. This includes constellations of satellites orbiting over the earth's surface and continuously transmitting signals that enable users to determine their position. The following global systems are currently in operation: GPS (USA), GLONASS (Russia), Galileo (EU), and BeiDou (China).
- Aerial photography, technique of photographing the Earth's surface or features of its atmosphere or hydrosphere with cameras mounted on aircraft, rockets, or Earth-orbiting satellites and other spacecraft.
- Ground-based radar survey is a geophysical method that uses radar pulses to image the subsurface. This method uses electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum, and detects the reflected signals from subsurface structures.
- Space-based radar sensing is space-borne radar systems that may have any of a variety of purposes. A number of earth-observing radar satellites, such as RADARSAT, have employed synthetic aperture radar (InSAR) to obtain terrain and land-cover information about the Earth.
- Visual observations, which involves gathering data through visual or technological means. For example, by sitting and watching and taking notes, or filming, or photography, or through a computer that records behaviour when collecting data about people, natural environments or transport.
- Land surveying instrumental observations of deformations such as (electronic theodolites, levelers).

Remote data sensing is the ideal technique for environmental impact assessment due to its broad spectral range, affordable cost, and rapid coverage of large areas. Besides that, there are several significant uses of remote sensing data that make it suitable for environmental impact assessment purposes. Firstly, remote sensing data enables the identification, delineating, and monitoring of degradation and affected areas, including derelict land, and changes in surface land use and to water bodies Charou et al. (2010). Moreover, remote sensing data can provide information on changes to surface water and land cover over time, which is essential for environmental monitoring in mining areas. Collective use of remote sensing data can be used to create a GIS database, which can be used to store, process, and retrieve the environmental data.

Underground coal mining is the largest driver of subsidence evident in reports to coal mining from almost all parts of the world. For example, India, being a major coal producer has been facing very severe problems of subsidence in some of its coal fields R. Singh et al.(1995). Analyses have been carried out to predict subsidence due to underground coal mining. Efforts to predict subsidence due to coal mining in India were made using a visco-elastic model.

Environmental problems such as land subsidence occur everywhere in the world and require excess research efforts. Many theoretical studies have been carried out; recent efforts include the use of finite element methods (Reddish, 1984; Jones & Kohli, 1985; Siriwardne & Amanat, 1985, 1988) and distinct element method (Calthard & Dutton, 1988) in the prediction of subsidence. Scientists have made various efforts from the UK, USA, China, Australia and other countries to predict the subsidence of coal mines using numerous methods such as the profile function methods (Kumar et al., 1983).

Interestingly, most recent research used the application of InSAR interferometry techniques have been used. For example In Lisbon, Portugal when an assessment and interpretation of a localized subsidence phenomenon was performed, the research used application of an advanced synthetic aperture radar (InSAR) interferometry technique and the application of the finite-element method. The analysis covered different time intervals in the period of 1995–2010 and processed by means of the persistent scatterers (PSs) technique. Results clearly reveal a localized subsidence, limited to an area 2 km×1.5 km wide, which has been confirmed by the levelling performed in1976, 1996, and 2010. G. Nico et al. (2016).

In Russia, studies have been carried out for the prediction and monitoring land surface subsidence due to human activities, such as the study on earth surface subsidence caused by manmade and natural seismic activity (A. I. Zakharov *et al*. 2013). In their study they used space borne radar interferometry technique application for land subsidence observations in Kuzbass, Russia. Earth surface subsidence in the Kuznetsk Basin, near Polysayevo city, was detected by means of satellite radar interferometry. Linear size of subsiding surface spots was about 300–500 m and amplitude of the vertical displacements was of the order of 12–15 cm.

From an analysis of scientific works and literary sources, it can be stated that the issue of creating environmental protection, low-waste technology for the conditions of the land subsidence due to mining activities remains insufficiently unresolved, although some work in this direction has been carried out. There has been various research on land surface subsidence, these clearly explain the impacts of human activities on the environment, hence there is need to do further research on land surface subsidence due to mining activities highlighting the effects of mining activities and how they have led to land subsidence. However, the current needs of the mining industry put forward new tasks that require improvement of scientific and methodological studies complex deformation monitoring areas of mining enterprises with the use of InSAR analysis.

CHAPTER 2. WORLD EXPERIENCE IN MONITORING LAND SUBSIDENCE TYPES AND CAUSES OF SUBSIDENCE OF THE EARTH'S SURFACE IN THE MINING AREAS

Studies have shown that land subsidence is of global concern to most scientist such as geologists, surveyors, urban planners etc. The rate at which displacements develop, is influenced by the following; physical loading of sediments, natural joints and faults, machinery and soil structure. Observation of the deformation involve considering the state of the rock mass, soil compaction and other objects, subject to deformation.

Some mining methods result in subsidence whereas, with others, subsidence may occur long after the mine workings have been abandoned. Mining methods such as longwall mining, mining of metallic ores, short wall mining, etc. In the latter instance, it is more or less impossible to predict the effects or timing of subsidence. Bell, F et al. (2000). Underground coal mining produces large amounts of coal, generates underground openings and discharges coal gangue. The larger the number of underground openings the higher probability they will cause surface subsidence.

Land subsidence due to coal seam gas extraction

Coal seam gas extraction is the construction of production wells in coal seams. It is also the extraction of groundwater from the coal seams at rates sufficient to lower the water pressure within them and enable gas to be released. This gas is then pumped to the surface along with the groundwater shown in *Figure 1*. Coal seam gas (CSG), also known as coal bed methane, is a form of natural gas typically extracted from coal seams at depths of 300-1,000 metres. The extraction process of ground water and gas from coal seams involves reduction of water pressure, which results in compaction of the geological units, layers above and below, where the depressurisation would have occurred. From coal seams, the liberation of the gas may also result in compaction of the coal. When the water is removed from pores of saturated and high porosity layers such as clay and silts, compaction occurs. Subsidence of the land surface then occurs due to compaction of layers, as the layers cannot maintain the vertical stress that will be increased as water pressure reduces. This type of land subsidence can also be measured using the satellite-based InSAR (Interferometric Synthetic Aperture Radar); using images from different time series, which will then be compared to detect elevation changes with an accuracy of 5-10 millimetres over large areas.

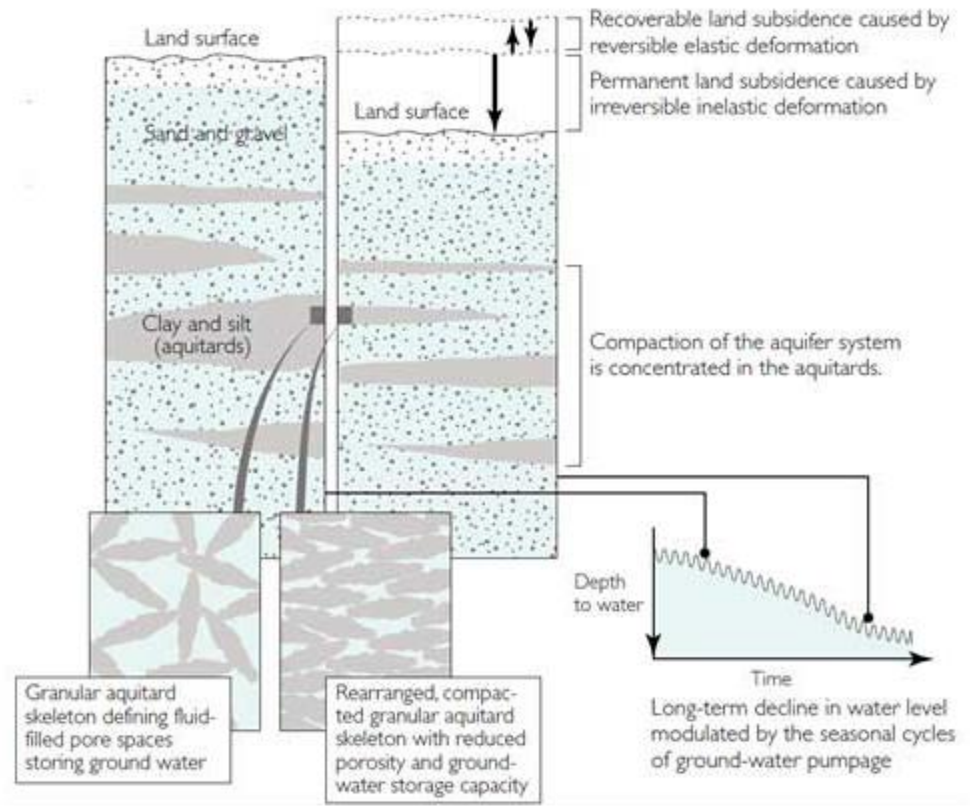


Figure 1: Subsidence from groundwater withdrawal and depressurisation. Source: USGS, 1999.

Land subsidence due to Longwall mining

Longwall mining is a form of underground coal mining where a long wall of coal is mined in a single slice .The longwall panel is the block of coal that is being mined; it is typically 3–4 km long and 250–400 m wide.

Longwall mining usually results in vertical openings shown on *figure 2* or underground void into which the roof and overlying rock might collapse, horizontal and vertical movement occur at the land surface due changes in the behavior of the rock mass which can extend beyond the mine footprint and can impact on natural and built environments. Subsidence, tilt, horizontal displacement, curvature and strain are the parameters normally used to define the extent of the surface movement but however the presence of massive sandstone and conglomerate beds in the overburden can reduce subsidence.

Each method can be characterised by reference to the size of the excavation and of the pillars between them. The magnitude and extent of subsidence is dictated by the extent of coal extraction, the depth of the coal seam and the thickness of the excavated material (the height of the void).

In longwall mining, large rectangular panels of coal are extracted at depth. Strips of coal, typically 3 meters thick, are shaved from the longwall face using a shearer, under the protection of hydraulic supports, until the panel is fully extracted. longwall mining, which is a process to extract large blocks of coal from between chains of pillars. Eventually the void becomes too wide to support itself, causing its roof to sag and finally, the roof and overlying rock collapse into the void. This typically results in horizontal and vertical movement at the land surface, which can extend beyond the mine footprint.

Subsidence, tilt, horizontal displacement, curvature and strain are the parameters normally used to define the extent of the surface movement. They generally form the basis for assessing the effects of subsidence on surface infrastructure. Longwall mining can result in a shallow flat-bottomed rectangular trough at the surface, sometimes accompanied by cracking, heaving, buckling, humping and stepping. These effects can impact built environments such as roads and buildings as well as cause disturbances to river courses and other surface water features. Generally, vertical movement does not cause surface damage. Instead, the damage is caused by tilting and horizontal displacement of the overburden, which accompanies the lowering of the land surface. The magnitude and extent of subsidence is dictated by the extent of coal extraction, the depth of the coal seam and the thickness of the excavated material (the height of the void).

Subsidence of the ground surface above the bord and pillar first workings results from the compression of the coal pillars and the strata above and below the seam from the weight of overburden. Where the pillars have been designed to be stable, the vertical subsidence is typically less than 20 mm. Natural or seasonal variations in the surface levels, due to the wetting and drying of soils, are approximately 20 mm. The vertical subsidence of less than 20 mm can be considered as no more than the variations that occur from natural processes and should have negligible impact on surface infrastructure (MSEC 2007).

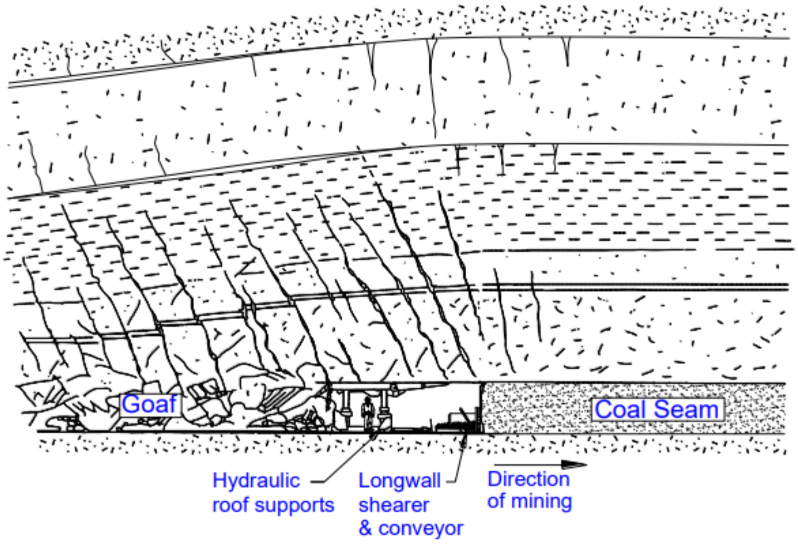


Figure 2: Cross section along the length of a typical longwall at the coal face (© Copyright, MSEC 2007)

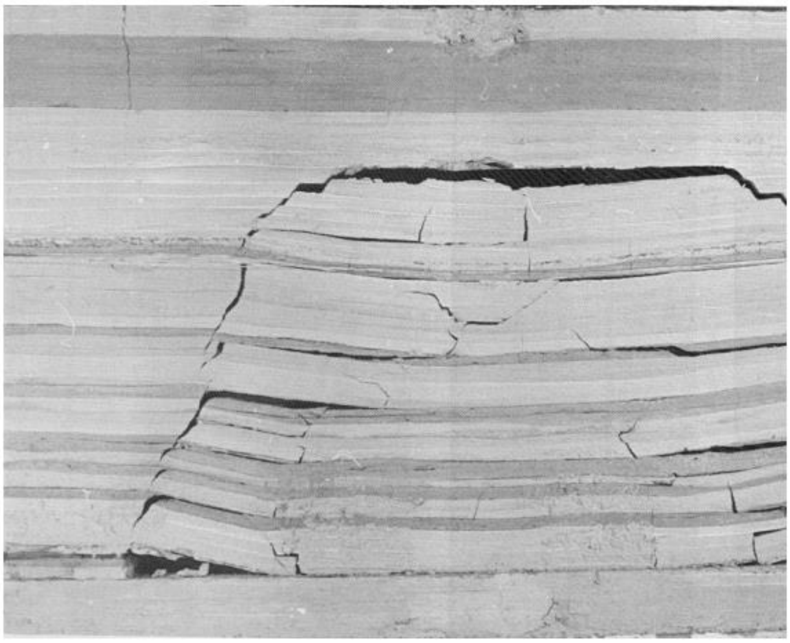


Figure 3: Physical model of subsided longwall panel being extracted from right to left (© Copyright, Whittaker & Reddish 1989).

Coal extraction, whether by longwall or pillar methods, removes support from the overlying earth and generates an arch-shaped or trapezoidal mass of broken and sheared rock above the seam cavity, as illustrated on *figure 3*.

Underground mechanisms causing subsidence

Underground mining activities results in mining subsidence, roadway stability is important which also depend on the strength of the surrounding rock strata and coal seams. During underground mining activities, when a single roadway or tunnel is driven into a coal seam, the pressures or loads originally carried by the coal in the newly extracted area are transferred to the solid coal sides. As a mine develops with an expanding number of roadways, the coal that is left between every territory of extraction frames a load-bearing column. Hence, the pillar loads will increment as the amount of coal extracted on the region increments.

Extra load results in compression of the coal seam and the immediate roof and floor strata of the coal seam around the perimeter of the excavation. The roof strata collapses into the void and separate along bedding planes. The surface motion results from a combination of sag of the roof strata into an excavation and compression of the strata that contain the abutments of the excavation. The surface movement extends past the footprint of the mine excavation.

Subsidence profile

We usually identify a subsidence profile with a tilt surface, horizontal displacement, strain and curvature. These parameters form the basis for assessment and they are normally used to define the extent of the surface movements that occur as mining proceeds .The diagram on *figure 4* illustrates an example of a subsidence profile drawn to an exaggerated vertical scale with a longwall panel that has a long axis or centre line that is perpendicular. Mining-induced subsidence can also be identified through a rectangular shallow baking dish; this dish should be curved at the top bottom ends of each side. Once mining starts, the dish becomes wider and one of the short sides starts acting as longwall face moves forward as the subsidence wave.

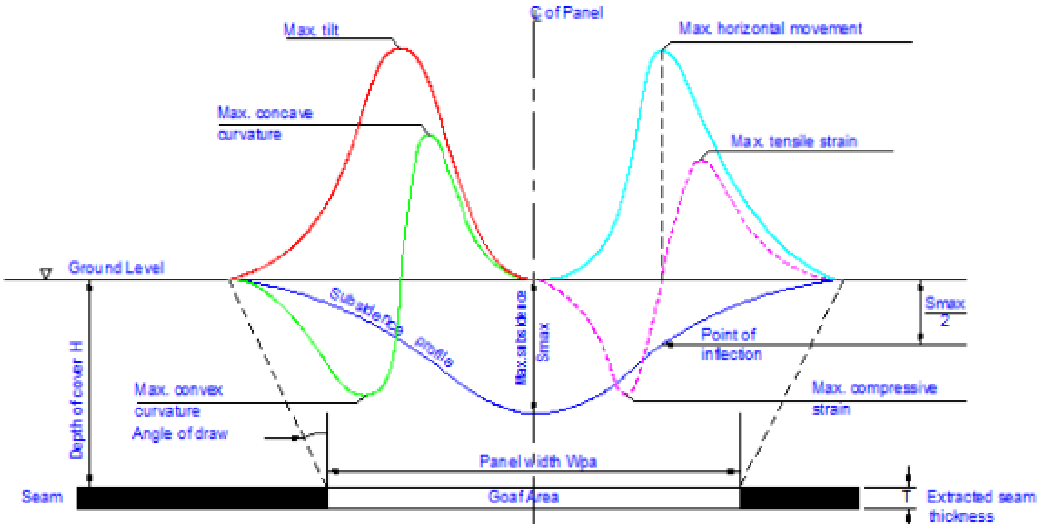


Figure 4: Development of subsidence parameters in relation to the mining void geometry (not to scale) (© Copyright, NSW Department of Planning 2008).

The term subsidence from coal mining activities usually refer to the moving wave shown above, in this case the sign (℄) will be representing the centre line of a panel, (Smax) is the maximum subsidence, and (Wpa)is the width of panel. Maximum tilt is developed and it represents the stress point of the subsidence.

The subsidence profile extends longitudinally and transversely down the length of a mining panel and across the width of the panel respectively. Therefore, points on the surface can be subjected to displacement in three dimensions within subsidence. The vertical component of displacement can also be identified as subsidence. The horizontal component of displacement across the width of the panel is referred to as the transverse component of horizontal displacement. The horizontal component of displacement in the direction the panel is running is referred to as the longitudinal component of horizontal displacement.

A sudden sinking or vertical displacement of a point being undermined is usually refers to as a subsidence. The movement of the ground actually includes vertical and horizontal components.

- Maximum subsidence – vertical movement of the ground surface with little horizontal movement, maximum subsidence values of vertical movements are usually identified as Smax even if sometimes smaller subsidence values will be recorded. Maximum subsidence is also expressed in millimetres.

• Horizontal displacement – is similarly distance moved in the horizontal direction, it can also refer to horizontal component of subsidence. It is identified at the peak point of maximum tilt. Horizontal displacement is usually expressed in millimetres.

• Vertical displacement is distance moved in a vertical direction. The point of maximum vertical subsidence is at the leading edge of the subsidence wave and at its trailing edge. Vertical displacement is also usually expressed in millimetres

• Subsidence factor - this is the ratio of the maximum subsidence measured at the surface to the mined thickness and expressed as Smax/T. It depends on the extraction widths of panels. In areas that contain weak rocks the subsidence factor increases.

• Tilt - tilt is calculated as the change in subsidence between two points divided by the distance between those points. Tilt is therefore the first derivative of the subsidence profile. The sign of tilt is not important, but the convention usually adopted is for a positive tilt to indicate the ground increasing in subsidence in the direction of measurement. The maximum tilt, or the steepest portion of the subsidence profile, occurs at the point of inflection in the subsidence trough, where the subsidence is roughly equal to one-half of the maximum subsidence. Tilt is usually recorded in millimetres per metre and is a key parameter to be assessed for structural damage resulting from mining.

• Curvature – the rate of change of tilt or rather expressed as the second derivative of subsidence. It is calculated as the change in tilt between two adjacent sections of the tilt profile divided by the average length of those sections. Curvature is usually expressed as the inverse of the radius of curvature with the units of 1/km, or km-1. The value of curvature can be inverted, if required, to obtain the radius of curvature, which is usually expressed in kilometres. Curvature is convex over the edges and concave toward the bottom of the subsidence trough. The convention usually adopted is for convex curvature to be positive and concave curvature to be negative.

• Strain - caused by bending and differential horizontal movements in the near-surface strata. It can be thought of as localised ground stretching called tensile strain or shortening called compressive strain. It is determined by dividing the change in length between pegs on a survey line by the initial horizontal length of that section. If the peg spacing has lengthened, the ground is in tension and the resulting strain is positive (+E). If the section has shortened, the ground is in compression and the resulting strain is negative (-E). The unit of measurement adopted for strain is millimetres per metre. The maximum strains coincide with the maximum curvature. Hence, the maximum tensile strains occur towards the sides of the panel, whilst the maximum compressive strains occur towards the bottom of the subsidence trough. Strain is also a key parameter for assessment of structural damage resulting from mining activities.

• Point of flexure (inflection) - On the subsidence profile the point of flexure marks the transition from the tensile to the compressive phase of the subsidence cycle. It is also the approximate point of half-subsidence, symbolised as 0.5 Smax, on the profile.

• Angle of draw (AoD) - it is a term used to define the observed, estimated or modelled limits of the subsidence trough. This is the angle between two lines drawn from the edge of the mine workings, one a vertical and the other a line to the limit of vertical displacement on the surface. Natural phenomenon such as seasonal swelling or shrinkage of soil due to moisture changes can cause small surface movements, where mining induced vertical movements cease can be very difficult to identify. It has been found that in situ horizontal stresses in the bedrock also affect the magnitude of the observed angles of draw. This is because small horizontal displacements and vertical relaxation can occur beyond mined areas. The vertical movement is also affected by seasonal moisture changes.

AoD varies with geology and depth of cover and typically ranges from a few degrees, such as the case of a near-vertical step at the panel edge, up to 60 degrees. Most commonly, AoD is in the range of 10 to 35 degrees (MSEC 2007); Ren and Li (2008) report a range of values for AoD varying between 19 and 50 degrees based on limited data from the Newcastle coalfield.

For wide extraction panels, the stronger the overburden rocks or the shallower the mining, the smaller the AoD. With weak and thinly bedded strata and where deep soils are present at the surface, the AoD may increase beyond 35 degrees. AoD concept is only a measurement of the limit of observed vertical subsidence movements.

Significant impacts on surface infrastructure are associated with maximum ground movements, occurring during the advance of the subsidence trough. As the subsidence wave approaches a point on the surface, the ground starts to settle, displacing horizontally towards the void and is subjected to tensile strains. These strains build from zero to a maximum over the length of convex or hogging curvature, as shown in *figure 5*.

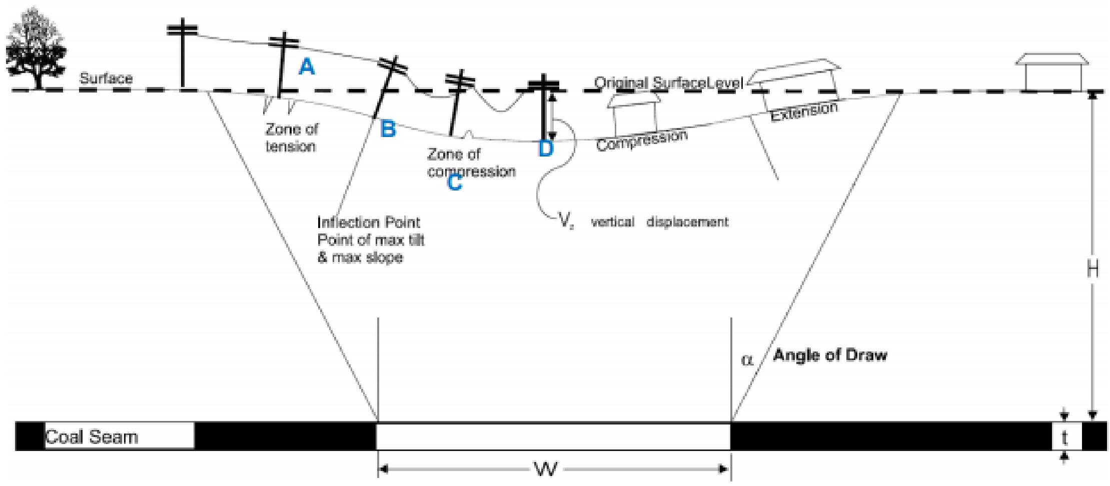


Figure 5: Development of a Subsidence Trough (to an exaggerated vertical scale) (© Copyright, NSW Department of Planning 2008), where W is the panel width, t is the seam thickness, H is the overburden thickness (or depth of cover), α is the angle of draw and Vz is the maximum vertical subsidence (or Smax).

Point A shows the maximum tensile strain. When vertical subsidence is approximately half of the maximum, as the face passes under the surface point, the ground reaches its maximum horizontal displacement and the strain reduces to zero (Point B). As the longwall face moves further away from the surface point, horizontal displacement reduces and the ground is subjected to compressive strains. Compressive strains build from zero to a maximum over the length of concave or sagging curvature (Point C). They decline to zero as maximum subsidence is reached (Point D on the A B C D). The inflection point is also shown on Point B, which is the point at which maximum tilt and horizontal displacement occurs. It is also the point at which the subsidence is approximately equal to half the maximum subsidence.

The impact of subsidence on surface infrastructure is therefore dependent upon its position in relation to the subsidence trough. The above sequence of ground movements, along the length of a panel, only applies to surface structures or features located at a point where the maximum subsidence is likely to occur. Elsewhere, the impacts in both the transverse and longitudinal direction are reduced. Location influences the occurrence of subsidence. If a structure is located on the perimeter of the subsidence trough it will be less affected and have little settlement, residual tilt or strain. A structure or surface feature on the side of the trough between the tension and compression zones will have subsidence. It will be left with residual horizontal displacement and tilt, but will be subjected to lower curvatures and strains. Structures or surface features located at the positions of maximum curvature and strain will generally be most impacted.

Mining-induced subsidence can cause fresh fracturing in the overlying bedrock and also buckling of the near-surface beds during the compressive phase of the subsidence wave. As a subsidence trough develops, surface cracks will generally appear in the tensile zone, typically a horizontal distance equivalent to 0.1 to 0.4 times the depth of cover inwards from directly above the panel edges and aligned parallel to these. Surface cracks develop above and parallel to the moving extraction face, this occurs a the shallow depths of cover. The cracking will be short term since the tensile phase of the travelling wave is generally followed by a compressive phase that closes them.

Shearing also occurs and the surface cracks may not fully close, generating compressive ridges. The depth of surface cracking appears to be in the order of 5 to 20 m, but can be deeper above shallow workings where more shearing occurs. Open fractures and heaving can also occur due to the buckling of surface beds that are subject to compressive strains.

Factors influencing mine subsidence.

Maximum subsidence varies and is directly dependent on a number of factors, including:

- Depth of cover;
- Panel width;
- Pillar width;
- Panel width to depth ratio;
- Seam thickness extracted;
- Proximity of adjacent previously mined panels in current seam;
- Proximity of adjacent previously mined panels in other seams under multi-seam conditions.

The following factors also influence maximum subsidence:

• Geological properties of overburden, including bulking factor, strength and elastic modulus of rock masses and thickness of layers;

• Coal properties including strength and dip of seam;

• Presence of natural joints;

• Presence of faults;

• Presence of thick massive conglomerate, sandstone or igneous sills;

• Presence of intrusive dykes;

• Seam floor conditions, presence of soft and/or water-sensitive floor;

• Strength of immediate roof of seam;

• Surface topography, with particular reference to steep topography, escarpments and gorges.

Subsidence from coal mining activities A critical extraction is one that results in maximum subsidence at a point directly above the centre of the panel. It can be predicted by the ratio of the panel extraction width (W) to the thickness of the overburden or cover rocks (H) – W/H. Extractions where W/H is smaller than the critical range are termed sub-critical, and those where it is larger are termed supercritical; the latter causing maximum subsidence over a larger area (Holla & Barclay 2000). The range in the W/H ratio for critical extraction will vary between coalfields.

One can not quantify the geological factors influencing subsidence overburden, therefore geological explanations of subsidence phenomena are sought only when empirical or numerical modelling predictions fail to match actual measurements. While geology may have little effect on vertical movement, the most commonly recorded subsidence parameter is that it can have a great influence on the structure damaging areas which are lateral movements, horizontal strains, ground curvature and tilt.

According to McNally et al. (1996) .The, geological factors influencing ground response to mining induced caving include:

• Gross lithology, the presence or absence of massive sandstone or conglomerate beds, and hence the overall stiffness and tensile strength of the overburden in its un-subsided state

- Geological structure of the overlying and underlying rock mass; primarily the bulking capacity, the intensity of joints and bedding, and their geo-mechanical properties such as shearing resistance, persistence and spacing

- Faults and dykes have a specific influence on the character of surface subsidence, as they concentrate strain and differential movement along their line of outcrop

- The depth and type of soils overlying the coal measures strata. These influence the surface movements, ground strains and the spread of the subsidence trough

- Surface topography and seam dip. Steep surface topography may cause tensile strains to increase along ridgelines and close to cliffs, and cause compressive strains to increase in valleys. Steep topography and seam dips can distort the subsidence profile. Steep topography may even cause valley floor uplift (upsidence) and closure near the mining panel.

- The proportion of massive sandstone and conglomerate beds in the overburden is the main geological factor influencing surface movements. Geologically, 'massive' means thickly bedded, sometimes 60 to 90 m in a single layer without bedding breaks. They transfer abutment loads to permanent pillars, reduce the angle of draw, and may concentrate ground strains along a few widely spaced joints. In subcritical and partial extraction layouts, especially those shallower than 200 m, the bridging effect of these massive strata reduces surface subsidence and strains.

- The stiffness of the pillar coal and of the immediate roof and floor has a substantial influence on subsidence.

- High tensile strains, linear compression mounds, stepped subsidence and steep ground tilts are associated with longwall mining through, or close to, faults and dykes. Faults and dykes may also provide conduits for gas and groundwater to enter mine workings. Widely spaced master joints create similar effects, though of lesser magnitude, while closely spaced joints may increase vertical movement.

- Large tensile strains are developed along ridgelines, behind cliff faces and on steep slopes, particularly where the slope faces in the direction of panel advance. High compressive strains and reduced vertical movement are experienced in adjacent valley floors, due to large horizontal displacements and the 'piling-up' effect of the regolith.

• Thick residual soils and weathering profiles have little effect on vertical movement due to mining, but cause ground strains to be diminished. Soft and/or saturated soils extend the subsidence trough laterally, reducing surface strain and maximum subsidence, but greatly increase the limit angle (i.e. angle of draw).

• One can outline that effects of topography on subsidence parameters are severe but have not been sufficiently considered. Recent researches supplement levelling with three-dimensional survey that monitoring is a solution to this situation. In this research, it can be noted that horizontal movements can exceed vertical movements on moderate slopes, and very large ground strains can occur on slopes steeper than about 30 degrees. Horizontal movement vectors reveal a definite tendency for overburden 'flow' towards lower or less confined ground.

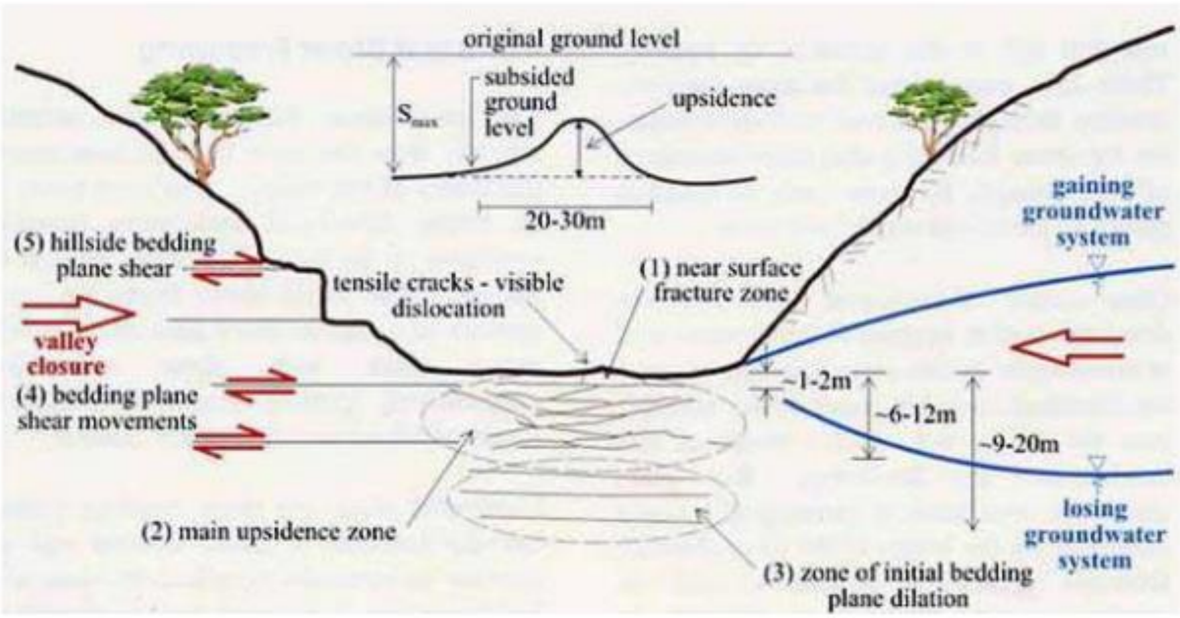


Figure 6: Mechanisms of valley closure and upsidence caused by coal mining-induced subsidence (© Copyright, Mills 2008).

The illustration on *figure 6*, serves to show the conceptual model of movement that develops where mining occurs on steep topography. Mining induces inward displacement of valley sides and compression in valley floors, which will later cause a difference on slip of bedding planes along the valley sides and buckling in the floor. This may result in valley bulging or upsidence. The magnitude of displacements can be modelled using computer programs.

Anomalous ground movements are spikes or other departures from systematically or conventionally smooth subsidence profiles. Apart from variations in overburden geology and topographic effects, profile anomalies may be due to:

- Gravitational movement of subsidence overburden towards old mine workings, which may be either in the same seam or below.

- Shuffling and jostling of near-surface joint blocks or rock slabs, causing small but potentially damaging steps and mounding. Stress relief at shallow depth in such rocks, where the horizontal stress may be up to ten times the vertical stress, may cause localised upwards bulging, buckling and release of slabs

- Survey errors, displaced or replaced pegs, or simply changes in peg spacing. Movement of pegs by clay soil shrink and swell, or by down slope creep, may also contribute to these non-systematic movements.

Predicting subsidence due to coal mining

Methods for predicting surface subsidence effects fall into three categories:

- Empirical, which is primarily based analysis of the field performance.

- Analytical or numerical, which is based on making use of mathematical solutions derived from first concepts to calculate how the rock mass will behave while an excavation is made.

- Hybrid or aggregate techniques, which involve diverse combinations of back-analysis of field information and the implementation of analytical and numerical strategies. A fourth category, physical modelling, provides a visible and qualitative approach of showing subsidence processes, however has little predictive value.

Most strategies are able to generating reasonably accurate predictions of the most vertical displacements, commonly within 150 mm, relying on the complexity of the conditions and the calibration of the method. The accuracy of subsidence prediction techniques should in no way be taken for granted. Subsidence magnitude relies upon to a degree on input parameters represented of the specific site conditions.

Analytical or numerical prediction methods and empirical approaches predict subsidence based on parameter relationships evolved from survey experience. While analytical or numerical modelling strategies predict subsidence utilising theories of rock mechanics, mathematics and physics. These mathematical processes are also on occasion termed ‘mechanistic’, as they rely on an understanding of the fundamental physical behaviour of rocks when disturbed. Mechanistic modelling involves situations of rock deformation mechanisms decreased to definable and quantifiable components. The interaction of these components may be described and for model construction, that reflects behaviour of in situ observations. The modelling approaches are becoming more common due to available processing power. There has been considerable research effort to develop numerical algorithms to simulate observed strata behaviour and predict subsidence accurately, for instance, Keilich et al. (2006).

All mechanistic models require values for in situ rock mass parameters. Although subsidence commonly involves rock disintegration, bed separation, block sliding and rotation, it is not possible to quantify or to incorporate the mechanisms all of them in numerical models. Hence, most models define the actual conditions and the amount of approximations determine the amount of uncertainty in the predictions. Element programs are appointed for modelling and much work is undertaken to modify them and predict surface subsidence.

The constraints that a successful model must overcome include:

- In many instances, the models need are made work through manipulating certain parameters until the results of the model show the measured surface survey profile;
- Stress situations inside the version should combine excessive lateral confinement at depth with unconfined or semi-confined conditions near the ground;
- Element mesh cells, that are removed to create the deformation, are at maximum from the cells within the surface layers where maximum accuracy is required;
- The strata of the model may also behave as soils, vulnerable rocks, elastically deforming rock, plastic deforming shale, or discontinuous blocky loads and mixtures of these. Their deformation may be similarly changed to varying degrees by using unknown or poorly recognized geological structures;
- The model input properties are based on trying out small samples whose size may be less than one per cent than that of the finite element cells. Many of the input properties are untestable and ought to be estimated.

Assessing potential impacts of subsidence due to coal mining

The potential impacts of predicted ground movements are further assessed for each significant natural and built surface feature above or near the proposed mine layout. The potential impacts are determined by:

- Site-specific and regional subsidence-induced changes in vertical position, horizontal position, tilt, strain and curvature
- The nature of the relationship between the ground and the feature activity of interest;
- The nature of construction of the feature activities of interest;
- Other site-specific characteristics, such as permeability of the surface and subsurface rocks;
- The type and effectiveness of mitigation and remediation measures employed.

Given the variable and interactive nature of these factors, impacts and consequences must be assessed on a site-particular basis. Because subsidence impacts rely on the site, each feature that can be affected by subsidence ultimately needs to be subjected to its own risk/impact assessment. Each significant land surface feature located within a study area should be identified in a mine subsidence assessment study. Risks associated with subsidence can be managed using measures including restricting mining in certain areas, changing the mine layout and implementing mitigation measures that support surface stabilisation. The process of impact assessment requires detailed baseline data and specific information from the study area; this improves the accuracy of every assessment.

Subsidence impacts can be managed by the following:

- Considering and paying more attention to resultant impacts, combined with natural processes of remediation;
- Measures of avoiding the development of risks; for example, modification of the mining system or geometry, barriers or buffers between panel extraction, reduce subsurface stress and partial mining;
- Mitigation measures; for example, smaller buffers designed to reduce but not eliminate subsidence impacts, mine layout changes and use of slots to isolate ground movement from features or structures;

• Remediation or rehabilitation measures; for example, filling of surface and subsurface cracks, drainage of ponded areas and re-vegetation of eroding areas.

Mine subsidence impact assessments are multidisciplinary and require skills beyond one individual or company.Mining and geological conditions are difficult. The rocks that contain coal seams are characterized by low mechanical strength, a tendency to soak, delaminate and swell. To this view, subsidence of the earth's surface as a result of coal seams mining is above 90% of their removable capacity.

Land surface displacements can also be monitored using the subsystem geodynamic / geomechanical monitoring. In this case, when a strain is observed it is considered at different level systems of thematic monitoring. Considering the monitoring system in terms of scale observations made, have identified a number of hierarchical levels. In particular, geodynamic monitoring, depends on the scale observed and it can be divided into 3 types:

1. Regional monitoring performed for the study

2. Zonal monitored within a specific zone for example monitored within specific earthquake zones, regional fault zones, possible occurrence are anthropogenic-induced seismicity and deformations.

3. Local monitoring is carried out in local areas - in the source areas on site. Strain monitoring results; depend on the methods of observation of their scale and the final examined data.

Russian federal laws and regulations on deformation monitoring

According to GOST P 55535-2013, the term "deformation monitoring "is considered more general global concept. Deformation monitoring as a study of the change in shapes of objects, which occurs over a certain period, it is required to ensure safety of life and monitoring on the operational territory. The regulation promotes environmental security to industrial safety of buildings and structures. Deformation monitoring, requires integration of monitoring systems of different orientations such as (geodynamic, geomechanical, surveying et al.), providing spatial data for the dynamics changes during the processes.

The need to implement the displacement monitoring and its requirements for organizations is regulated by a number of legal documents. In accordance with Federal Law №116 (On industrial safety of hazardous production facilities objects), controls organizations which carry open pit mining activities and are among the hazardous production facilities. One of the conditions to maintain safe operation is to perform special monitoring observations.

Article 24 of the Russian Federation law ‘on Subsoil’ requires to ensure safe operations related to subsoil use. Land subsidence monitoring requires implement of such documents that help control mining operations and utilization of resources. One of the main requirements to ensure safe operations, related to subsoil use, is having complex of geological, surveying and other observations sufficient to ensure the normal process of works and prediction future risks, identifying on time and application to mining plan.

In paragraph 537 of federal rules and regulations in the field of industrial security "safety rules during mining and processing solid minerals " indicates the need to monitor the status of the boards, trenches, ledges, slopes, and dumps, as well as areas with possible falls or subsidence due to the presence of underground workings.

In accordance with paragraph 3 of the Russian Law Regulations "On Licensing of production Surveying work "mine surveys. It promotes observation of the state of mining leases and justification of their boundaries, and define hazardous mining areas, as well as measures to protect the mining development activities, buildings, constructions activities and natural objects from the effects of the works, related to subsoil use and design surveying works.

In general, we can conclude that, mining activities in Russia function under the regulations that provide security for all activities that might result in land deformation. This is to decrease economic costs and eliminate the impact of destructive manifestations deformations.

Monitoring land subsidence due to open-pit mining depends on the type of minerals extracted. The features are usually composed of the following objects: the mountain zone (open and underground) wells, facilities dump management, processing raw materials, transport and ancillary structures and waterworks. The natural conditions of the field are geological-structural, hydrogeological, geomorphological, geodynamic, physic-Geographical components of the geological environment. Underground and borehole methods also entail violations landscape elements, but to a lesser degree, since the open method is usually characterized by a significant areal coverage of reference works.

Open pit mining also changes rock mass and is associated with collapsing of the surface. Collapse represents the greatest danger for people and mountain equipment in the quarries. Landslides and rock falls are gravitational deformations of the rock mass, sometimes covering the area beyond the upper edge of the excavation. During the mine exploitation period, numerous landslides of various sizes are usually recorded on the open-pit slopes.

Significant impact of physical and geographical factors on the territory

Open pit mining activities are also affected with physical and geographical factors .The nature and amount of precipitation, snow cover, melting effects of snow, affect the conditions of rocks, pits and dump stability. The changing temperatures and freezing of rocks lead to destruction of rocks on the slope surface. Alternate freezing and water frost weathering causes actively destruction of surface rocks. Another factors stimulating destruction of mining surfaces, are the winds, their strength, duration and direction.

CHAPTER 3. THE KUZBASS -KUZNETSK COAL BASIN, SATELLITE OBSERVATIONS

The Study Area

The Kemerovo Region was formed on January 26, 1943 by the Decree of the Presidium of the Supreme Soviet of the USSR by separation from the Novosibirsk Region . It consist of the greater part of the territory of the Kuzbass - Kuznetsk coal basin shown on *figure 7* .The area of the region is 95 725 km² ,mountainous and the region is located in the south-east of Western Siberia. It lies between Tomsk and Novokuznetsk in the basin of the Tom River. From the south, it borders the Abakan Range, from the west, it borders the Salair Ridge, and from the east, it borders Kuznetsky Alatau. It produces some of the most extensive coal deposits anywhere in the world; coal-bearing seams extend over an area of 10,309 square miles (26,700 km^2) and reach to a depth of 5,905 feet (1,800 m). Overall coal deposits are estimated at 725 billion tonnes. The region's other industries, such as machine construction, chemicals and metallurgy, are based on coal mining.

Kemerovo is an industrial city and the administrative centre of Kemerovo Oblast is located at the intersection of the Iskitim and Tom Rivers at the major coal mining region of the Kuznetsk Basin. Russia is the third biggest exporter of coal. The reserves in the Kuzbass nestles roughly North of Mongolia and Kazakhstan. About 76 per cent of Russia’s coal exports come from this region. Coal is one of the largest sources of energy in Russia, accounting for 14.4% of the country's electricity consumption. The Central-Siberian basin has the most significant reserves of open-pit mined brown coal.

The Kuzbass has several favourable factors, which include:

- Competing large Russian coal deposits are mainly located in remote regions such as Kemerovo region, which has continental permafrost climate conditions.
- The coal seams in Kuzbass lay close to the ground level, allowing for open-pit mining which reduces the production costs as compared to underground mining operations.
- The underground mines that are active usually do not exceed 500 metres in depth. Unlike most of the other coal basins, the Kuzbass coal deposits are very well connected to the country’s railroad infrastructure. Gleb Cherdantsev et al. (2017).

When conducting open pit mining there is a high probability to undergo major technological changes in the landscape *figure 8b*, changing of the rock mass and displacement processes can be activated. Underground activities and borehole methods also lead to deformations, but they show land subsidence to a lesser extent, since the open pit mining method as usually is characterized by a significant visible areal coverage for reference.

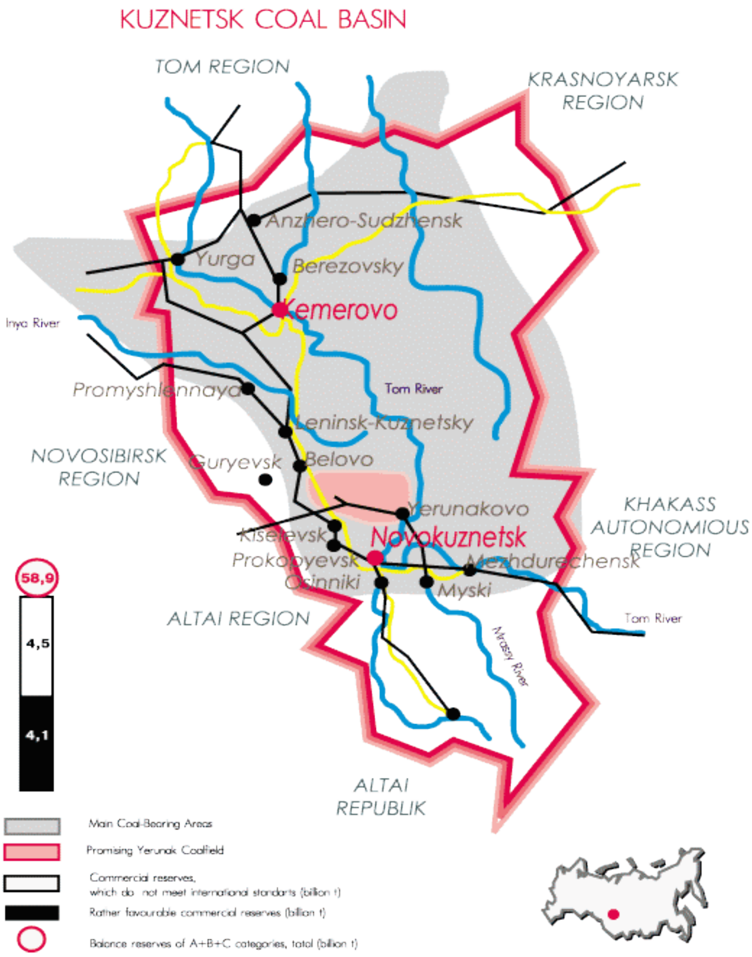


Figure 7: The diagram above show the Kuznetsk coal basin and the main coal bearing areas.
Source: [*Kuznetsk Basin Wikipedia*] alchetron.com Kuznetsk-Basin

Image address:https://alchetron.com/cdn/kuznetsk-basin-3059f313-4df9-4244-95c7-7858fb8dd55-resize-750.jpg

Figure 8 a: (Coal mining in the Kuzbass Region. Photo: Fern)

Figure 8 b: Kuzbass opencast mining basin - Source: Indigenous Defenders Movement

The study area is Kuznetsk Basin, the area where there is strong human impact onto the environment. Active economic activities in the form of pit and underground coal mining affects the stress state of rocks and they can lead to earthquakes. However, this area has also been seismically active long before activities such as coal mining started.

According to research, the mining activities have led to environmental impacts in Kuznetsk coal mining region. The mining activities have destroyed the forests, blackened rivers, contaminated the air with dust, and created waste mounds. People who live near the site say that the region has become a moonscape from which many are desperate to escape. The bulk of the deposits produced when mining are at Kuznetsk Coal Basin *figure 8a*. Mining activities involves utilisation of heavy industry machines that have affected almost every part of the landscape. From the mines themselves to transport infrastructure, electricity wires and water pipes, waste mounds and contaminated waters almost all villages have disappeared. The mines have brought deforestation to the environment since all the forests have been cut down. The coal-bearing stratum at Kuzbass contain approximately 350 coal seams of various types and thicknesses, which are unevenly distributed throughout the site. Kolchuginskaya and Balakhonskaya suites contain 237 layers. The Tarbagan Suite is only 19; therefore, it is much behind the previous ones. Barzasskaya contains only 3 layers.

The maximum thickness of the coal seam layers is 370 m. On average, coal seams with a thickness of 1.3 or more are widespread, with a maximum of about 4.0 m. The depths of coalmines averages about 200 m and the maximum depth reaches a mark of 500 m.

Kuznetsk Coal Basin has large-scale production, which has probabilities to negatively affect the environment. On the territory of inactive mines, where open pits were not reclaimed there are deep sags which sometimes form failures of land surface. When there is windy weather, dust from dumps spreads over a long distance and settles on the territory of settlements. During coal mining and its processing, chemicals are released into the air and water. In most areas, their concentration is higher than permissible.

General information on CA Sentinel 1 and InSAR technique

The principles of radar interferometry

Synthetic aperture radar interferometry is an imaging technique for measuring the topography of a surface, its changes over time and other variations in the detailed characteristics of the surface. The remote sensing InSAR technique is the synthesis of conventional SAR techniques and interferometry techniques that have been developed over several decades in radio astronomy.

Interferometry using data from spaceborne SAR instruments has seen widespread use, largely because of the availability of suitable globally acquired SAR data from the ERS-1, ERS-2, JERS-1, RadarSAT-1 and SIR-C/X-SAR satellites operated by the United States, German, and Italian space agencies.

Basic Measurement Principles:

Interferometry can be understood conceptually by considering the signal return of elemental scatterers comprising each resolution element in an SAR image. A resolution element can be characterized as a complex phasor of the systematic backscatter from the scattering elements on the ground and the propagation phase delay. Conventional SAR system determines targets in the range direction by measuring the time it takes a radar pulse to propagate to the target and return to the radar. For this to take place, three-dimensional positioning information, including additional measurement of elevation angle is needed. Interferometry using two or more SAR images provides a means of determining this angle.

Radar images observed from two nearby antenna locations have resolution elements with nearly the same complex phasor return, but with a different propagation phase delay. In interferometry, the complex phasor information of one image is multiplied by the complex conjugate phasor information of the second image to form an “interferogram,” effectively cancelling the common backscatter phase in each resolution element, but leaving a phase term proportional to the differential path delay. If the slight difference is ignored each resolution is treated as a point scatter.

The Phase in Interferometry

There are approaches to phase unwrapping. There are algorithms based on the integration and based on a Least-Squares (*LS*) phase unwrapping method to the gradients of the wrapped phase. It is assumed that the interferometric return is due to a point scatter. For most situations, this will not be the case:

- Scattering from natural terrain is generally considered as the coherent sum of returns from many individual scatterers within any given resolution cell.

This concept applies in cases where the surface is rough compared to the radar wavelength. The relationship between the scattered fields at the interferometric receivers after image formation is then determined by the statistics at each individual receiver, and by the complex correlation function.

Space borne and Airborne Systems include:

1) Coverage: Spaceborne platforms have the advantage of global and rapid coverage and accessibility. The difference in velocity between airborne systems (200 m/s) and spaceborne platforms (7000 m/s) is roughly a factor of 30.A spaceborne interferometric map product that takes on the order of a month to derive would take several years in an aircraft with comparable swath. Airspace restrictions can also make aircraft operation difficult in certain parts of the world. In addition, for mapping of changes, where revisitation of globally distributed sites is crucial to understanding dynamic processes such as ice motion or volcanic deformation, regularly repeating satellite acquisitions are in general more effective. The role of airborne sensors lies in regional mapping at fine resolution for a host of applications such as earth sciences, urban planning, and military maneuver planning. The flexibility in scheduling airborne acquisitions in

acquiring data from a variety of orientations and in configuring a variety of radar modes are key assets of airborne systems that will ensure their usefulness well into the future.

2) Repeat Observation Flexibility: To construct useful temporal separation in interferometry, it is desirable to have control over the interval between repeat coverage of a site. An observing scenario may involve monitoring an area monthly until it becomes necessary to track a rapidly evolving phenomenon such as a landslide or flood. Suddenly, an intensive campaign of observations may be needed twice a day for an extended period. This kind of flexibility in the repeat period of a platform is quite difficult to obtain with a spaceborne platform. As the satellite ground tracks become more widely spaced it becomes more and more difficult to target all areas between tracks.

3) Track Repeatability: While aircraft do not suffer as much from temporal observation constraints, most airborne platforms are limited in their ability to repeat their flight track spatially with sufficient control. For a given image resolution and wavelength, the critical baseline for spaceborne platforms is longer than airborne platforms by the ratio of their target ranges, typically a factor in the range of 20–100. For example, a radar operating at C-band at 40-MHz range bandwidth looking at 35 from an airborne altitude of 10 km has a critical baseline of 65 m. Thus, the aircraft must repeat this flight track with a separation distance of fewer than about 30 m to maintain adequate interferometric correlation. The ability to repeat the flight track depends on both flight track knowledge and track control. GPS technology allows real-time measurement of platform positions at the meter level, but few aircraft can use this accurate information for track control automatically. The only system known to control the flight track directly with inputs from an onboard GPS unit is the Danish EMISAR.

   Despite the typically longer critical baseline from space, spaceborne orbit control is complicated by several factors such as the limitation of correction maneuvers due to mission constraints and the incorrect computation due to drag and gravitational forces, which alter the orbital elements dynamically. The ERS satellite orbits for example, are maintained to better that 1-km.GPS receivers on spaceborne platforms are allowing kinematic orbit solutions accurate to several tens of meters in real time. With this knowledge, rapid accurate trajectory corrections will become available, either on the ground or onboard.

4) Motion Compensation: Motion compensation is needed in InSAR processing when the platform motion deviates from the prescribed, idealized path assumed. The two processes involved in the compensation make use of:

4.1 Resampling data that is regularly spaced in time with reference grid information such as along-track distance or simply corrects for timing and velocity differences between antennas.

4.2 The second stage of motion compensation amounts to a pulse-by-pulse range-dependent range resampling and phase correction to align pulses over a synthetic aperture in the cross-track dimension as though they were collected on an idealized flight track .In repeat track systems, the propagation effects can be more severe. The refractive indexes of the atmosphere and ionosphere are not homogeneous in space or time. For a spaceborne SAR, the path delays can be very large, depending on the frequency of the radar (e.g., greater than 50-m ionospheric path delay at L-band) and can be quite substantial in the differenced phase that comprises the interferogram (many centimetres differential tropospheric delay, and meter-level ionospheric contributions at low frequencies). These effects in repeat-track interferograms were first identified by Massonnet et al.

Ionospheric delays are dispersive, so recurrence assorted estimations can conceivably help moderate the impact, likewise with two-recurrence GPS frameworks. Tropospheric delays are non-dispersive and mimic topographic or surface displacement effects. There is no means of removing them without supplementary data

5) Frequency Selection for Interferometry: The choice of frequency of an InSAR is usually determined by the electromagnetic phenomena of interest. Electromagnetic energy scatters most strongly from objects matched roughly to the size of the wavelength. Therefore, for the varied terrain characteristics on Earth, including leaves high above the soil surface, woody vegetation, very rough lava surfaces, smooth lakes with capillary waves, etc., and no single wavelength is able to satisfy all observing desires.

International regulations on frequency allocations also can restrict the choice of frequency. If a particularly wide bandwidth is needed for fine resolution mapping, certain frequency bands may be difficult to use. Other practical matters also determine the frequency, including available transmitter power, allowable antenna size, and cost. For topographic mapping, where temporal decorrelation is negligible, frequencies can be chosen to image the topography near a desired canopy height. Generally, higher frequencies interact with the leafy crowns and smaller branches strongly, so the inferred interferometric height is near the top of the vegetation canopy.

SAR processing concepts for interferometry

The precise definition of interferometric baseline and phase depends on how the SAR data comprising the interferometer are processed. Consequently, a brief overview of the salient aspects of InSAR processing is in order. Processed data from SAR systems are sampled images. Each sample, or pixel, represents some aspect of the physical process of radar backscatter. A resolution element of the imagery is defined by the spectral content of the SAR system. Fine resolution in the range direction is achieved typically by transmitting pulses of either short time duration with high peak power or of a longer time duration with a wide, coded signal bandwidth at lower peak transmit power. Resolution in range is inversely proportional to this bandwidth. In both cases, the received echo for each pulse is sampled at the required radar signal bandwidth.

For ultra-narrow pulsing schemes, the pulse width is chosen at the desired range resolution and no further data manipulation is required. For coded pulses, the received echoes are typically processed with a matched filter technique to achieve the desired range resolution. Most spaceborne platforms use chirp encoding to attain the desired bandwidth and consequent range resolution, where the frequency is linearly changed across the pulse.

Resolution in the azimuth, or along-track, direction, parallel to the direction of motion, is achieved by synthesizing a large antenna from the echoes received from the sequence of pulses illuminating a target. The pulses in the synthetic aperture contain an unfocussed record of the target's amplitude and phase history. To focus the image in azimuth, a digital "lens" that mimics the imaging process is constructed and is applied by matched filtering. Azimuth resolution is limited by the size of the synthetic aperture, which is governed by the amount of time a target remains in the radar beam.

To generate an SAR image, a unique range or angle must be selected from the family of ranges and angles to use as a reference for focusing the image. Once selected, the target's azimuth and range position in the processed image is uniquely established. Specifying an angle for processing is equivalent to choosing a reference frequency.

Atmospheric effects

For interferometric SAR systems that obtain measurements at two apertures nearly simultaneously, propagation through the atmosphere has two effects that influence interferometric height recovery: 1) delay of the radar signal and 2) bending of the propagation path away from a straight line. In practice, for medium resolution InSAR systems, the first effect dominates.

CA sentinel 1 and sensors

Figure 9: Artist's view of the deployed Sentinel-1 spacecraft (image credit: ESA, TAS-I)

Sentinel-1 *figure 9* is the European Radar Observatory, representing the GMES (Global Monitoring for Environment and Security) satellite family, designed and developed by ESA and funded by the EC (European Commission). The Copernicus missions (Sentinel-1, -2, and -3) are Europe’s subscription to GEOSS (Global Earth Observation System of Systems).

The Sentinel-1 mission is expected to allow the development of new applications and meet the needs of GMES, such as in the area of climate change.

Table 1: sentinel.esa.int/ web sentinel missions international-cooperation

Copernicus Mission	**Launch**	**Sensor complement**	**Objective**
Sentinel-1	2014	C-SAR (C-band SAR)	ERS/ENVISAT SAR data continuity for Land and Ocean surveillance; interferometry
Sentinel-2	2014	MSI (Multispectral Instrument)	Deliver high resolution optical information of all land-masses of the Earth, complementing e.g. Landsat & SPOT series.
Sentinel-3	2014	OLCI (Ocean and Land Color Instrument) SLSTR (Sea and Land Surface Temp. Radiometer) SRAL (Ku/C-band Radar Altimeter) MWR (Micro-Wave Radiometer)	Global daily land and sea parameter observation POD (Precise Orbit Determination)
Sentinel-4 (on MTG in GEO)	2019	UVN (UV-VIS-NIR) instrument	Monitoring of air quality, stratospheric ozone, solar radiation, and climate monitoring.
Sentinel-5 (on MetOp SG in LEO)	2020	UVNS (UV-VIS-NIR-SWIR) instrument	Atmospheric composition, cloud and aerosol for air quality and climate applications
Sentinel-5P (Precursor)	2016	TROPOMI (Tropospheric Monitoring Instrument)	Atmospheric composition, cloud and aerosol for air quality and climate applications

The Sentinel-1 mission represents a completely new approach to SAR mission, in direct response to the operational needs for SAR data, expressed under the EU-ESA GMES (Global Monitoring for Environment and Security) program. The program ensures continuous flow of C-band SAR information to applications and expands on ESA's involvement in the ERS and Envisat SAR instruments, eminently in keeping up key instrument attributes, for example, steadiness and accurate data products. Marine Core Services, Land Monitoring and Emergency Services are three services of the mission that were identified by user consultation working groups *table 1*.

The fast-track services cover applications such as:

• Monitoring sea ice zones and the arctic environment

• Surveillance of marine environment

• Monitoring deformations and movements

• Mapping of land surfaces: forest, water and soil, agriculture

• Mapping in support of humanitarian aid in crisis situations

SENTINEL-1 carries a single C-band synthetic aperture radar instrument operating at a centre frequency of 5.405 GHz. It includes a right-looking active phased array antenna providing fast scanning in elevation and azimuth, with a data storage capacity of 1 410 Gb and 520 Mbit/s X-band downlink capacity. The C-SAR instrument supports operation in dual polarisation (HH+HV, VV+VH) *table2b* implemented through one transmit chain (switchable to H or V) and two parallel receive chains for H and V polarisation. Dual polarisation data is useful for land cover classification and sea-ice applications.

SENTINEL-1 operates in four exclusive acquisition modes shown in *figure 10*:

- Stripmap (SM)
- Interferometric Wide swath (IW)
- Extra-Wide swath (EW)
- Wave mode (WV).

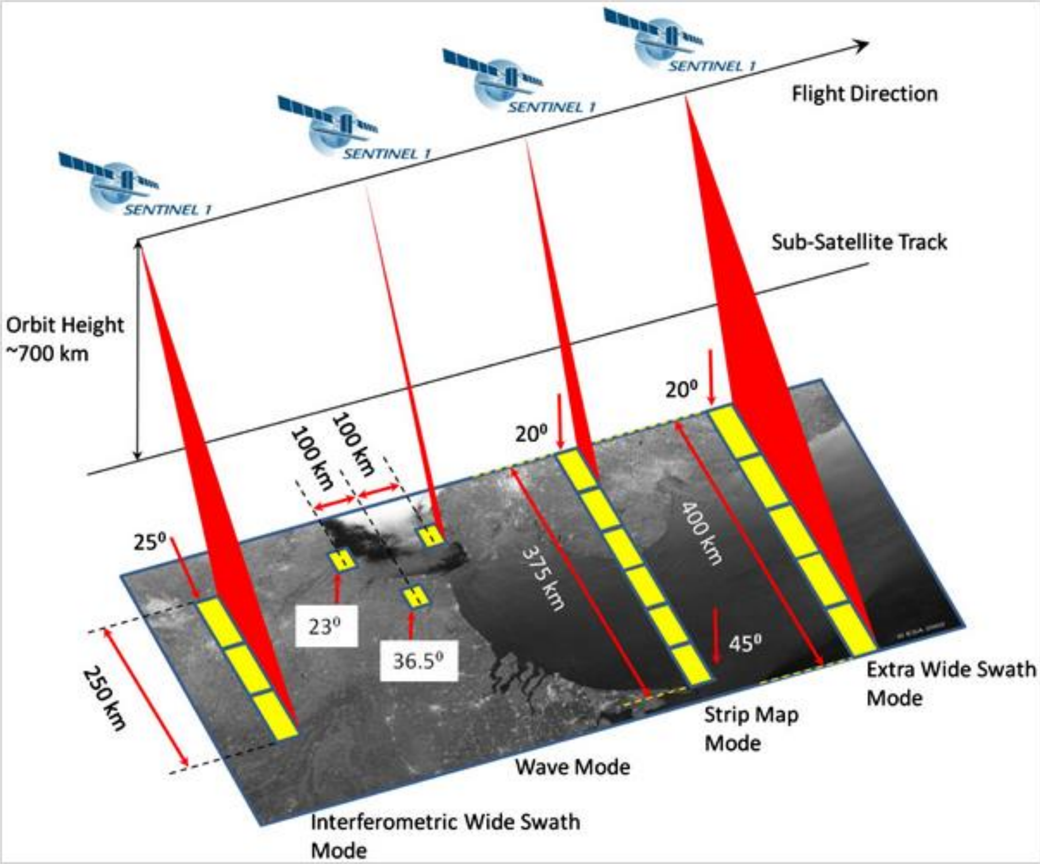


Figure 10: (Sentinel-1 User Handbook, 2016) .SENTINEL-1 operates in four exclusive acquisition modes

Sentinel-1 Modes

SENTINEL-1 satellites convey a solitary payload comprising of a C-band Synthetic Aperture Radar (SAR) instrument. The instrument is made out of two significant subsystems:

- SAR Electronics Subsystem (SES) - The SES gives all radar control, IF/RF signal generation and get information handling capacities involving the following: radar command and control, time control, and excess control, generation frequency, up/down conversion, filtering digitisation, data compression and formatting.

• SAR Antenna Subsystem (SAS)- The SAS is responsible for: signal radiation and reception, distributed transmit signal high power amplification, distributed receive signal low noise amplification with LNA protection, signal and power distribution (corporate feed, power converter),phase and amplitude control, including temperature compensation, internal calibration loop, deployment mechanisms, including hold down and release antenna mechanical structure.

Sentinel-1 operational products:

• Level-0 products: Compressed, unprocessed instrument source packets, with additional annotations and auxiliary information to support the processing *table 2a*.

• Level-1 products: Level-1 Slant-Range Single-Look Complex Products (SLC): Focused data in slant-range geometry, single look, containing phase and amplitude information.Level-1 Ground Range Detected Geo-referenced Products (GRD): Focused data projected to ground range, detected and multi-looked. Data is projected to ground range using an Earth ellipsoid model, maintaining the original satellite path direction and including complete geo-reference information.

• Level-2 Ocean products: Ocean wind field, swell wave spectra and surface currents information as derived from SAR data.

Table 2a: Sentinel-1 Operational products access policy

Source: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar/sar-instrument

Product generation policy	Product type	Access mode	Timeliness
Systematic Global (for all acquired data)	L0 L1 GRD L2 Ocean	Subscription	3 hours from observation (NRT data) 24 hours from observation (standard)
		Free online access from archive	> 24 hours from observation
Systematic Regional (for a subset of acquired data)	L1 SLC (Single-Look Complex)	Subscription	3 hours from observation (NRT data) 24 hours from observation (standard)
		Free online access from archive	> 24 hours from observation
Systematic Local (for a subset of data acquired over ocean in the visibility of a Core Ground Station)	L0	Subscription	< 1 hour from observation

Table 2b: The key parameters of the SENTINEL-1 C-SAR instrument include

Source: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-1-sar/sar-instrument

Centre frequency	5.405 GHz (corresponding to a wavelength of ~5.5465763cm cm)
Bandwidth	0-100 MHz (programmable)
Polarisation	HH+HV, VV+VH, VV, HH
Incidence angle range	20°- 46°
Look direction	right
Antenna type	Slotted waveguide radiators
Antenna size	12.3 m x 0.821 m
Antenna mass	880 kg (representing 40% of the total launch mass)
Azimuth beam width	0.23°
Azimuth beam steering range	-0.9° to +0.9°
Elevation beam width	3.43°
Elevation beam steering range	-13.0° to +12.3°
RF Peak power	- 4.368 kW, - 4.075 kW (IW, dual polarisations)
Pulse width	5-100 µs (programmable)
Transmit duty cycle	Max 12%, SM 8.5%, IW 9%, EW 5%, WV 0.8%
Receiver noise figure at module input	3 dB
Maximum range bandwidth	100 MHz
PRF (Pulse Repetition Frequency)	1 000 - 3 000 Hz (programmable)
Data compression	FDBAQ (Flexible Dynamic Block Adaptive Quantization)
ADC sampling frequency	300 MHz (real sampling)
Data quantisation	10 bit
Total instrument mass (including antenna)	945 kg
Attitude steering	Zero-Doppler steering and roll steering

CHAPTER 4: METHOD FOR MONITORING LAND SUBSIDENCE OF THE EARTH SURFACE DUE TO MINING ACTIVITIES

This chapter presents the method for monitoring land subsidence of the earth surface due to mining activities. In this thesis, results are produced through the application of an advanced synthetic aperture radar (InSAR) interferometry technique; study area is a coal mining area in Kuzbass, Russia. InSAR techniques allow generating of large-scale maps of the line-of-sight (LOS) component of terrain displacement with a cm-to-mm precision. Such techniques have been widely used to measure displacement field or terrain motions in an observed scene. However, such an approach presents several limitations when applied to long-term displacements.

This approach partially overcomes problems such as those due to propagation in atmosphere. It allows to generate time-series of displacements related to the monitored phenomenon.The analysis is based on the determination of ground deformation and identify the dynamics changes in the results after processing radar images obtained by shooting with Sentinel-1 band C.

Other physical phenomena contribute to the interferometric phase, the most important being phase artefacts due to troposphere and ionosphere in homogeneities between two radar passages over the illuminated area. These error sources, together with potential errors in phase-unwrapping process can lead to consistent misinterpretation of deformation phase. That is why advanced InSAR methods was proposed and it considers several differential interferograms of the same area belonging to different temporal acquisitions also identifying characteristics of the earth surface. If there are, identified changes on the characteristics of the earth's surface these might be due to mining activities experienced in Kuzbass Region.

Interferograms generation and selection of pixels to extract displacement information is done using different criteria also through the comparison of single pixel intensities, we can determine displacement. In fact, in order to obtain significant results, decorrelation phenomena is considered. The larger the perpendicular baseline values are, the more significant the phase decorrelation will be. To deal with this crucial point, two different paths are followed: selecting interferograms with relatively small perpendicular baseline values and discard the others or properly selecting point targets that exhibit sufficiently high coherence values and analysing only their behaviour. These different approaches lead to two of advanced InSAR multipass algorithms: the former is known as small baseline subset (SBAS), whereas the latter is called permanent scatterers InSAR (PSInSAR). The family of PSInSAR techniques aims to identify coherent radar targets, known as persistent scatterers (PSs), exhibiting high phase stability over the whole period of observation. Targets such as man-made structures, characterized by high reflectivity values, can give rise to PS. However, coherence can be underestimated in case of PS depending on the size on the estimation window and this can lead to neglect a certain percentage of stable targets. To evaluate coherence in any available interferogram and detect coherence values higher than a certain threshold (usually 0.6) in every interferometric pair.

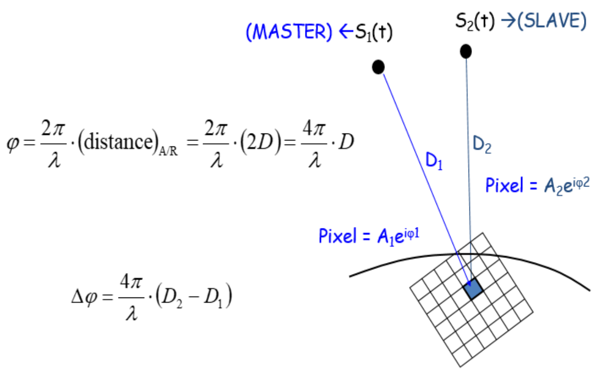
In case of more than 30 images, it is possible to use the time series of the amplitude values of each pixel in the area of interest, with the advantage of certain statistical properties. The selection of PS is based on the amplitude dispersion index Dp defined as the ratio of standard deviation to the mean value of time series of amplitude values at that pixel. When the dispersion index is lower than 0.25, it provides also a good index of ph pixels where to estimate the displacement evolution. The phase stability of each candidate PS is further analysed by iteratively removing the spatially correlated phase contributions due to terrain displacement, look angle error, and orbit inaccuracies to estimate the noise phase term.

For the interferometric technique to be applicable, the data sets are obtained when the sensor is in repeat orbit, such that the scene is viewed from almost the same aspect angle for each of the passes. Each pixel of a SAR image contains information on both the intensity and phase of the received signal. The pixel intensity is related to the radar scattering properties of the surface, and the pixel phase to the satellite to ground path length, or distance. Intensity images are the form of SAR data that is more frequently presented and probably most familiar to the public. However, it is the phase information only (and not the image intensity) that is exploited by interferometric techniques; it contains information about heights orthogonal to the SAR image plane, i.e. the plane formed by the SAR LOS and the orbit direction. An interferometer is a device that superimposes or mixes wave phenomena from two coherent sources. First, the two SAR images are registered to each other to identify pixels corresponding to the same area of the Earth's surface. Then, for each pixel, the phase values are subtracted to produce the phase difference image known as an interferogramme. This phase difference is a measure of the difference in path length from a given pixel to each antenna of the SAR interferometer.

This research is about determining ground deformation and identifying the dynamics changes in the results after processing of radar images obtained from Sentinel-1 band C. Synthetic Aperture Radar (SAR) has the advantage of operating at wavelengths not impeded by cloud cover or a lack of illumination and can acquire data over a site during day or night time under all weather conditions. SENTINEL-1, with its C-SAR instrument, can offer reliable, repeated wide area monitoring. Imaging radars equipped with C-band are generally not hindered by atmospheric effects and are capable of imaging through tropical clouds and rain showers. Its penetration capability with regard to vegetation canopies or soils is limited and is restricted to the top layers.

An interferometer is a device that superimposes or mixes wave phenomena from two coherent sources. First, the two SAR images are registered to each other to identify pixels corresponding to the same area of the Earth's surface. Then, for each pixel, the phase values are subtracted to produce the phase difference image known as an interferogramme. This phase difference is a measure of the difference in path length from a given pixel to each antenna of the SAR interferometer. In order to exploit the phase information of a series of complex SAR images covering the same area, it is necessary to accurately co-register all images over the same master image, arbitrarily chosen as geometric reference. After the co-registration, each interferogram can be chosen by taking a master image M and any of the co-registered SAR images.

The interferometric SAR (InSAR) technique used to exploit the information contained in the phase of two complex SAR images (hereafter referred to as the master, M, and slave, S, images) is shown *figure 11a*. In particular, InSAR technique exploits the phase difference (interferometric phase) of S and M.



Where

$A_2 e^{i\varphi 2}$

A = Amplitude

e=Exponential function

t=Time

λ= wavelength

ΔΦ =change in signal phase

Figure 11a: SAR Interferometry (INSAR)

$$\gamma = \frac{\left|\sum_i M_i \cdot S_i^*\right|}{\sqrt{\sum_i |M_i|^2 \cdot \sum_i |S_i|^2}}$$

γ =INSAR coherence

M_i = MASTER image

S_i = SLAVE image

$0 < \gamma < 1$

Figure 11b : INSAR Coherence

The equations on *figure 11 a,b* ,were implemented to observe the signal phase change between two images from period 12.03.2019 - 13.12.2019 (master image 2019-07-22). Considering the phase shift due to different atmospheric conditions at the time of two radar acquisitions.When a point on the ground moves ,distance between the sensor and the point changes therefore the recorded phase value that is recorded by the sensor is affected too.

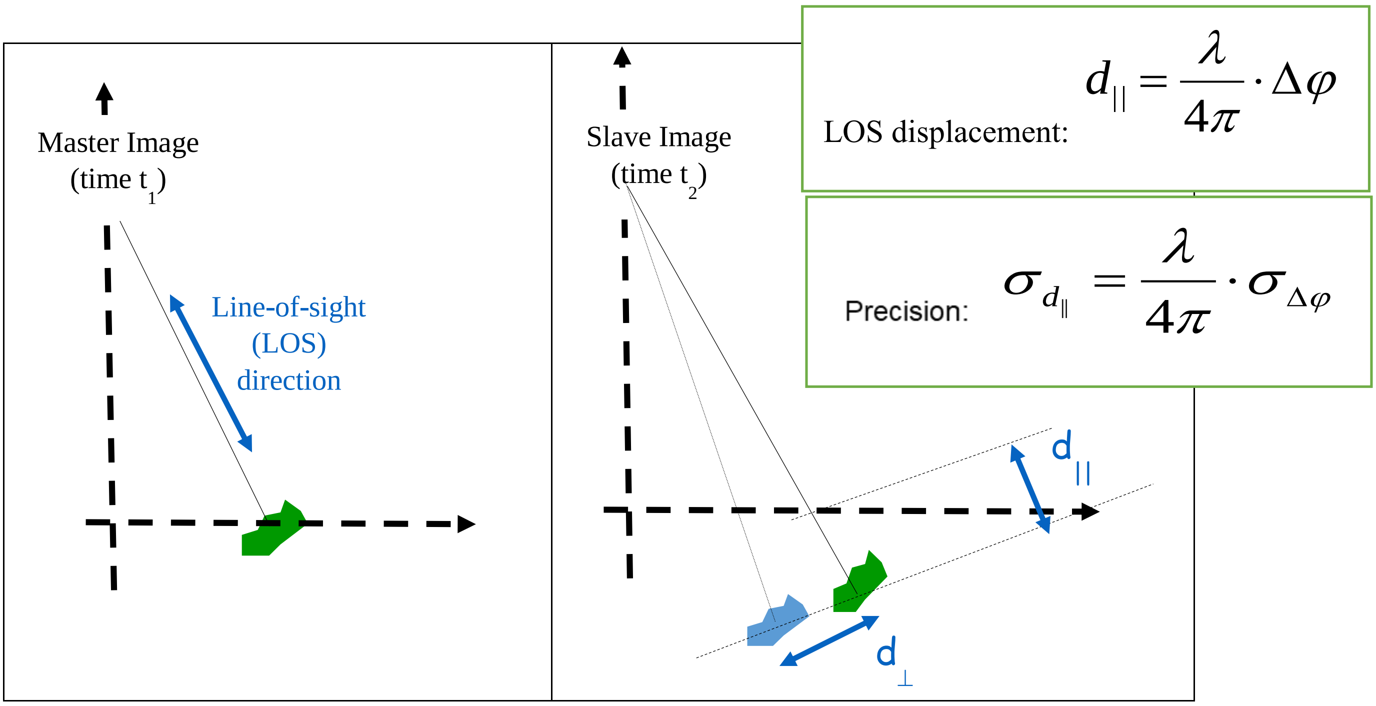


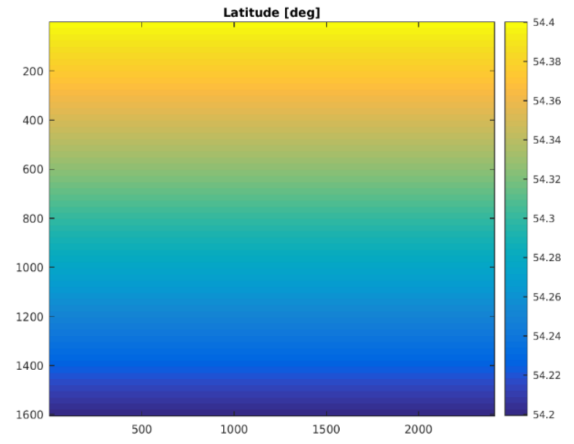
Figure 12 : Differential INSAR

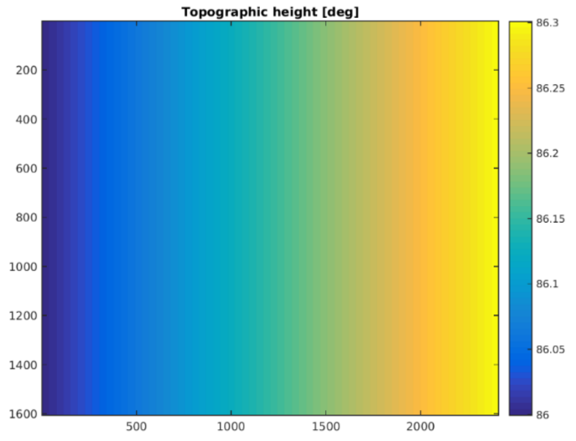
The equation illustrated on *figure 12* explains that each phase difference in interferograms is proportional to terrain displacements in this case which is landsurface subsidence.A slight change in postion of point scatters on the ground in the time interval between two SAR observations in subsidence cases a phase appears.The interferogram phase will contain motion and altitude contributions.If there is a digital elevation model DEM the altitude contribution is subtracted from the interferometric phase creating a differential interferogram and a terrain motion is measured with wavelength and assuming a perpendicular baseline of 100m.Through this the sensitivity of SAR interferometry to surface deformation or displacements is identified.

Verification of the mine location

As part of the analysis, the first task was to identify the location of the coal-mining region of the Kuznetsk Basin (Kemerovo), identify how large the area is and visualize the landscape of the study area. To do this the whole area topographic map and coherence map were geocoded to identify the main landmarks of the region (river, fields, etc.) and detailed (subsets) images of mines. In particular, the images on *table 3 a, b, c* show coherence, latitude, longitude and topographic height) of images from the following acquisition dates 26/10/19(slave image) - 07/11/19(master image). Coherence is providing the information about the capability of the technic to see the mine location.

Table 3a: Latitude and topographic height (degrees)





Location of the mine is between 54.24 and 54.36 in latitude and between 86.00 and 86.25 in longitude.

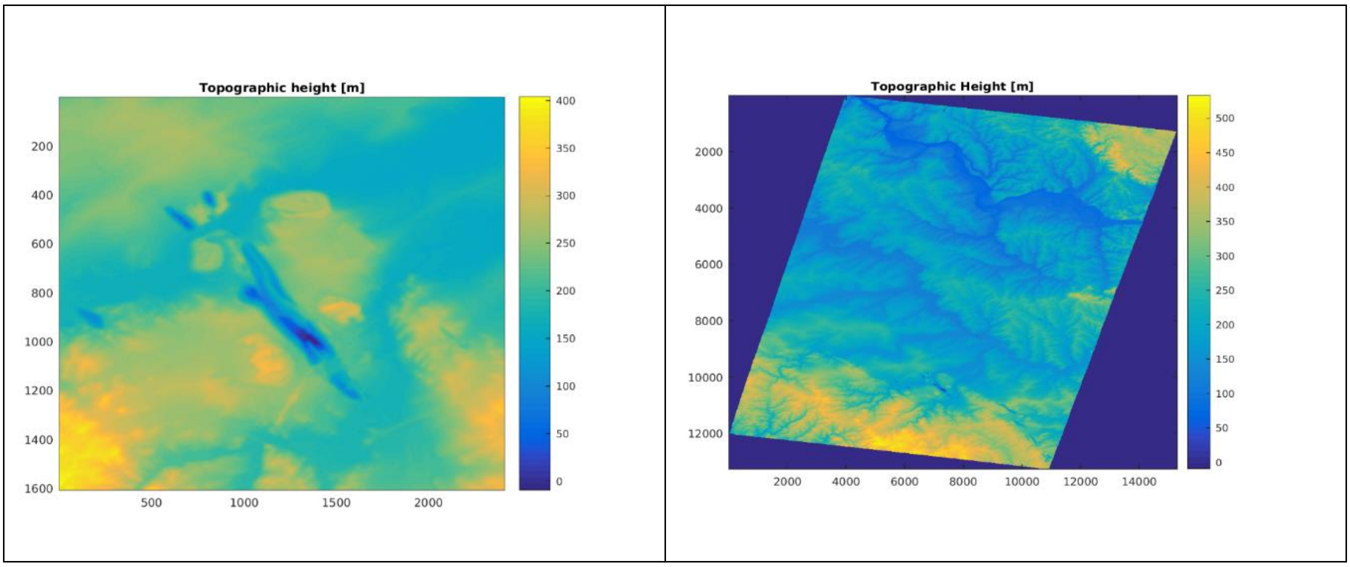


Table 3 b: Topographic height in (m)

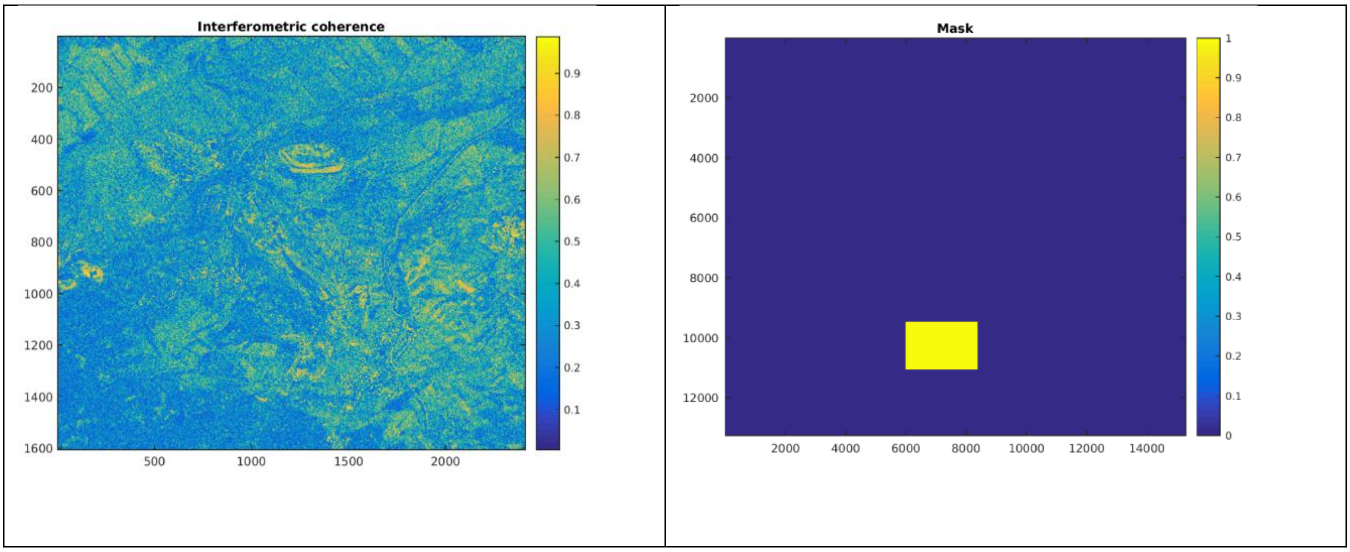


Table 3c: Interferometric coherence and mask

The images in *table 3* show the localisation of the study area's topography: coherence, latitude, longitude and topographic height. The mask shows the whole area that was zoomed to produce topographic height. This process helps to identify the location of mine and the area with high estimation of displacements, which are areas with high coherence values.

Since Google Earth has limitations such as that, the data displayed in Google Earth will never be 100% accurate, after identifying the locating of the coal-mining region of the Kuznetsk

Basin (Kemerovo), there was need to check for accuracy. Confirming whether the location of the mine is between 54.24 and 54.36 in latitude and between 86.00 and 86.25 in longitude.

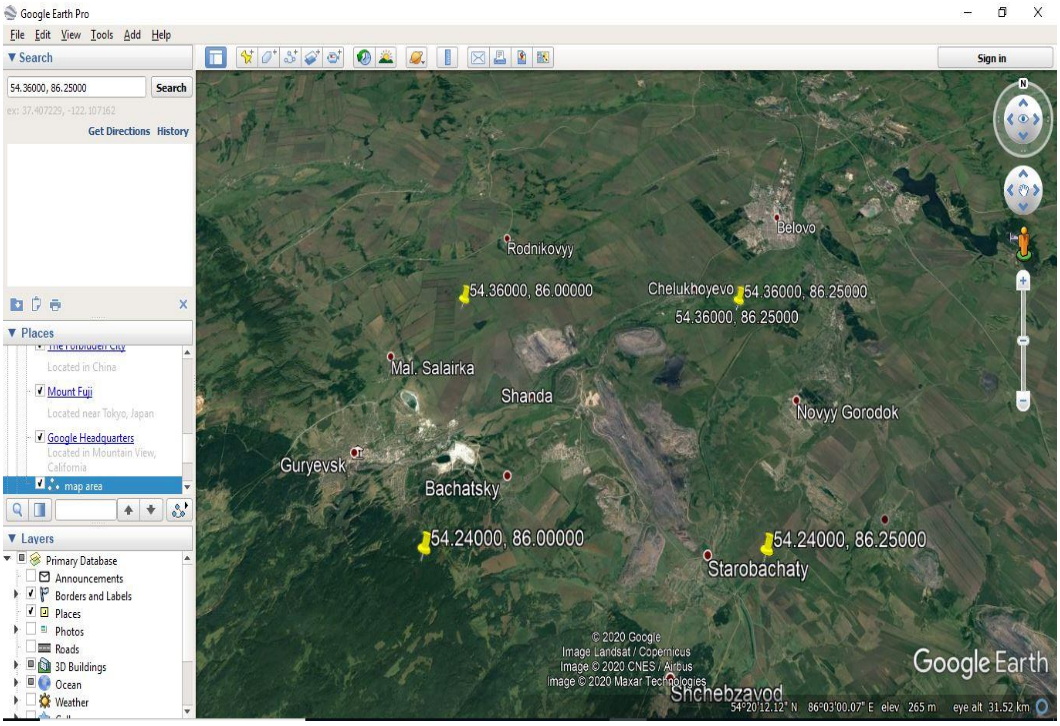


Figure 13: The place marks to verify if the coordinates correspond to Kuznetsk coal basin (Kemerovo) area displayed in latitude and longitude.

The diagram shown on *figure 13* shows the process of geo-location using Google Earth Pro.To start processing the images there is need to check or verify if the images correspond to the location of the mine and process series of images in order to track the properties of the mine along the different time and period.

Representing the area within the marked coordinates in a KMZ file for verification *figure 14*. KMZ is the file extension for the tag file used by Google Earth. The KMZ (Keyhole Markup language Zipped). It is a compressed version of a KML (Keyhole Markup Language) file. KMZ files can contain place marks featuring a custom name; the latitudinal and longitudinal coordinates for the location, and 3D model data. KMZ files can be opened by Google Earth, or unzipped with a compression utility, such as WinZip on Windows, MacZip for Macintosh users, and Zip and UnZip for UNIX systems.

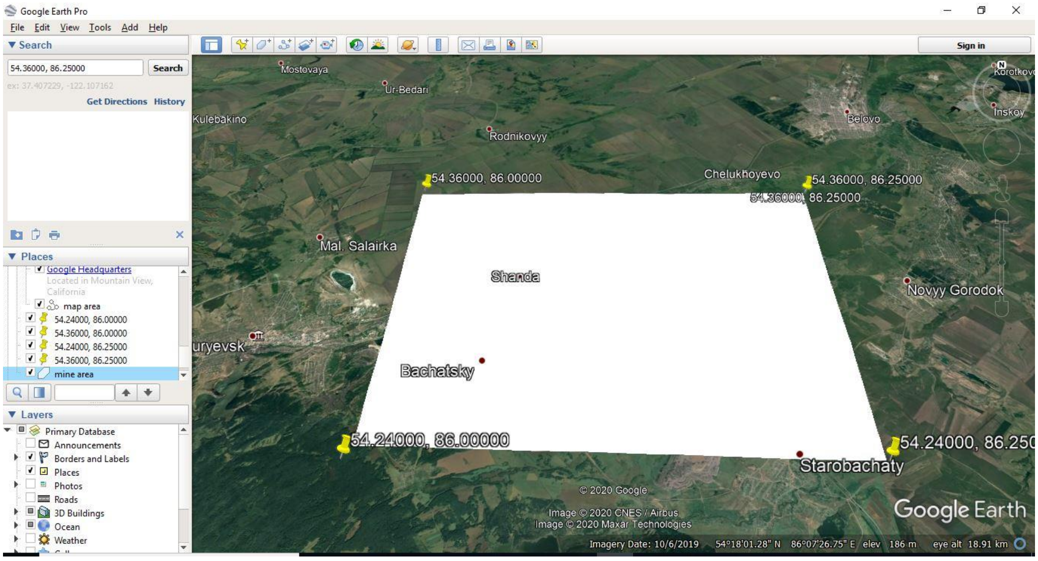


Figure 14: KMZ files opened by Google Earth

For downloading images in this research, the Copernicus Open Access Hub was used to download Sentinel 1band C images of the study area with same footprint *figure 15*. The advantage of using Copernicus Open Access Hub (previously known as Sentinels Scientific Data Hub) to download images is because it provides complete, free and open access to Sentinel-1, Sentinel-2, Sentinel-3 and Sentinel-5P user products, starting from the In-Orbit Commissioning Review (IOCR). The SENTINEL-1 mission includes C-band imaging operating in four exclusive imaging modes with different resolution (down to 5 m) and coverage (up to 400 km). It provides dual polarisation capability, very short revisit times and rapid product delivery. For each observation, precise measurements of spacecraft position and attitude are available.

Data source: https://scihub.copernicus.eu/dhus/#/home

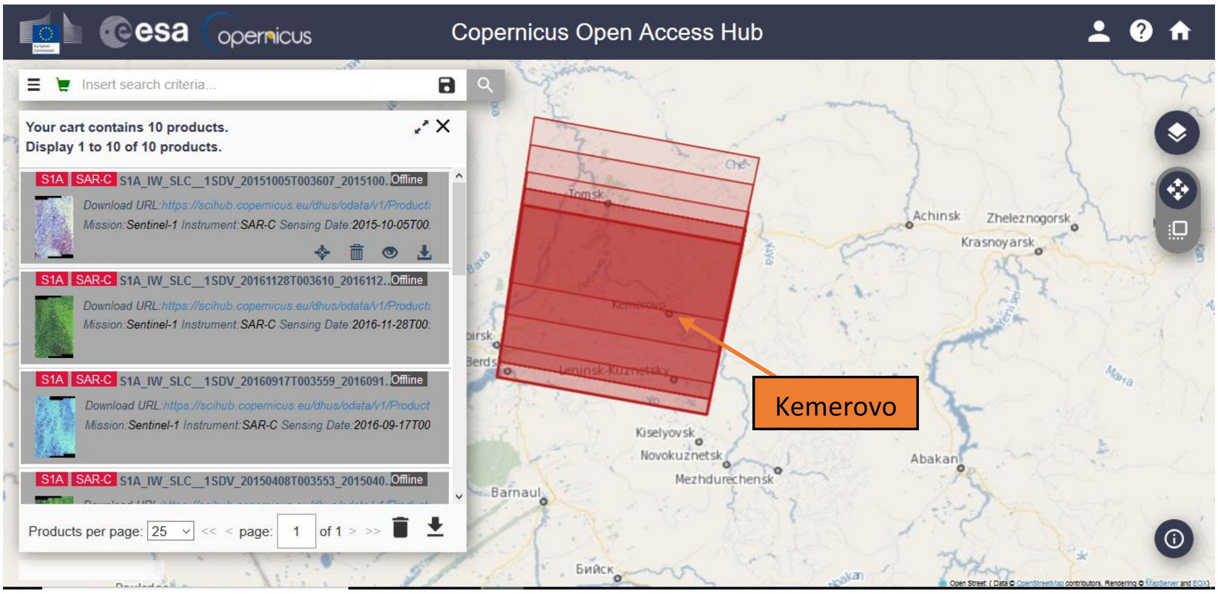


Figure 15: Sentinel 1 footprint Open Access Hub

Characteristics of data used

Kuznetsk Coal Basin has an area of around 10,000 square miles (26,000 km^2); the area was chosen because there is exploitation of coal conducted on a large scale. The process of selecting acquisition dates should consider the seasonal changes of the study area. Weather related surface conditions during winter season in Russia, of low air temperatures that cause development of ice on rivers and reservoirs can cause disturbing effects on Sentinel 1 images. Therefore, the following acquisition dates of radar images were used:

12.03.2019- 13.12.2019 relative orbit 165,S1 band C using WGS84 coordinates,19 images were downloaded and used for processing with the (Master date = 2019-07-22 @ 00:36). Processing parameters:

- (Subswath=IW1),(Polarization=VV),(CohWinAz=4+),(CohWinRg=10),(Dem=SRTM 1Sec)
- The image is in pixels and the parameter of the coherence window is 15x15.The filter window is 9x9 with the Phase unit in radiance (rad).

Radar images were used to obtain a differential interferogram to estimate surface deformations that occurred between the acquisition period 12.03.2019- 13.12.2019 (APPENDIX 2). The main parameter that can be used to estimate the quality of the interferogram is coherence. Coherence is determined by the degree of compliance of the SAR signals phase – the higher the value, the more accurate the interpretation of the interferogram will be. In the case of low coherence, interpretation is practically impossible. Coherence varies in the interval 0 ⩽ (range) ⩽ 1. If range = 1 it means that the signals are perfectly correlated or linearly related and if range = 0 they are totally uncorrelated. Evaluating coherence in available interferograms and detect coherence values higher than a certain threshold (usually 0.5) in some of the interferometric pair. A highly accurate azimuth alignment can help to avoid phase bias in the interferometric phase.

Coherence is the quality of being logical and consistent. The coherence between two SAR images expresses the similarity of the radar reflection between them. Any changes in the complex reflectivity function of the scene are presented as a decorrelation in the phase of the appropriate pixels between the two images. The phase difference between two beams results in a change in the intensity of the light on the detector. It is proportional to the surface deformation that occurred in the direction of satellite line of sight (LOS).The resulting intensity of the light after mixing of these two beams is measured, or the pattern of interference fringes is viewed or recorded. The phase observation in a SAR image contains the superposition of a number of effects. The signal propagation is a second effect that influences the phase: a delay or acceleration of the velocity of the signal yields a bias in the phase observation. Propagation through the atmosphere has two effects that influence interferometric height recovery: 1) delay of the radar signal and 2) bending of the propagation path away from a straight line.

(SNAP) data processing

Interferometric processing is performed, of a couple of Sentinel-1 images over the assumed location of mine, for this research 19 images are processed.To process images without problems there is need to download new versions of modules since the software is designed to work with plugin updates. The processing requires a lot of memory and time

Pre-processing

The extraction of Sentinel-1 TOPS bursts is made per acquisition and per sub-swath. This process will reduce the processing time in the following processing steps and it is recommended when the analysis is focused only over a specific area and not the complete scene.

For this analysis, in the Processing Parameters tab, these parameters were used for InSAR processing.

SWI soil water index, which does not take much time when processing

Subswath=IW1

Polarization=VV

CohWinAz=15

CohWinRg=10

Dem=SRTM 1Sec

To filter interferograms (Win Rg=9), (Win Az=9) and windows must always have an odd number of pixels. Using filter is good for interferometric processing because there will be less noise.

Co-registration

The first processing step is to apply the orbit files in Sentinel-1 products in order to provide accurate satellite position and velocity information.

Interferometric Processing

An Interferogram between the interferometric pair (master and slave) was processed step by step *figure 16 a, b* while a coherence image estimation from the stack of the coregistered complex images is included.

Continue the processing steps with Sentinel-1 TOPSAR Deburst. The final step in this processing part is to export the data for SNAPHU processing in order to apply phase unwrapping APPENDIX 1.Phase Unwrapping – Displacement Map are proceeded via SNAPHU.

Data Download-ESA SciHUB

SNAP-open and explore data

Pre-processing

Graph Builder

Co-registration

Interferometric Processing

Phase Unwrapping-Displacement Map

Geocoding

Fig 16 a: SENTINEL-1 data processing step by step using SNAP

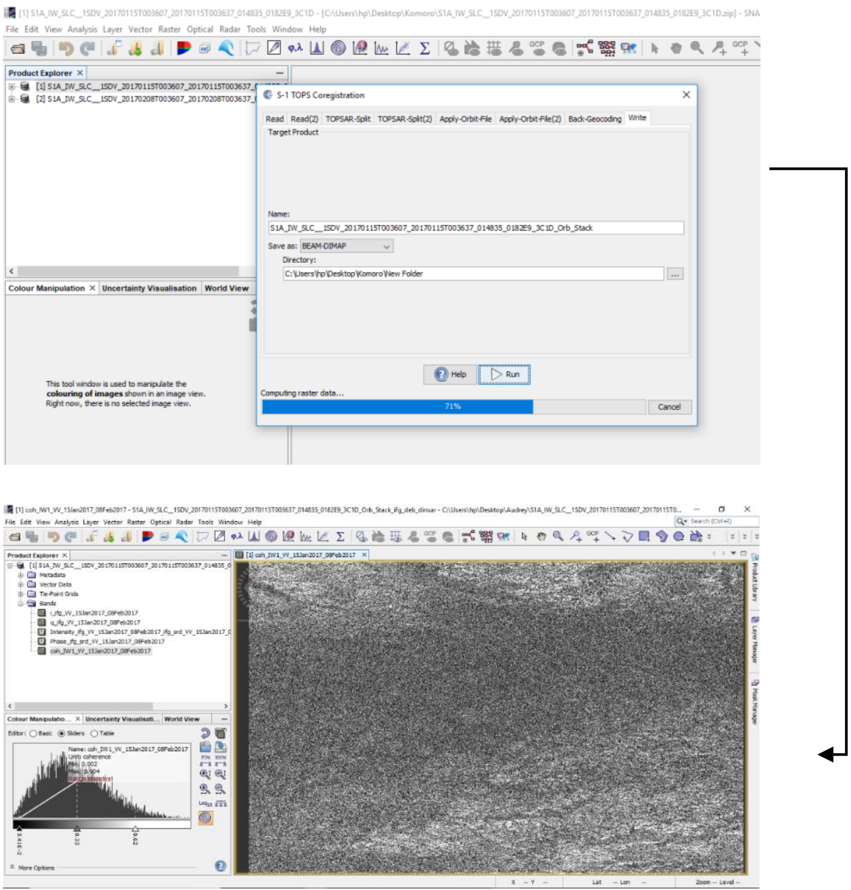


Fig 16 b: SENTINEL-1 data processing using SNAP

To view the products in Google Earth we have to export to KMZ format, readable by Google Earth and then download results to our local PC for visualization. Readable KMZ format by Google Earth is WGS 84 Lat/Lon coordinate system (EPSG 4326). If you have used different coordinates system during geocoding, you need to reproject the final product in SNAP accordingly by going to Raster → Geometric Operations → Reprojection. If results are already in WGS 84, proceed to the export of KMZ layer. After completing Interferogram processing, using Matlab create the Tiff images. The final stage is to do the interpretation of the PS (mean displacement/velocity) map.

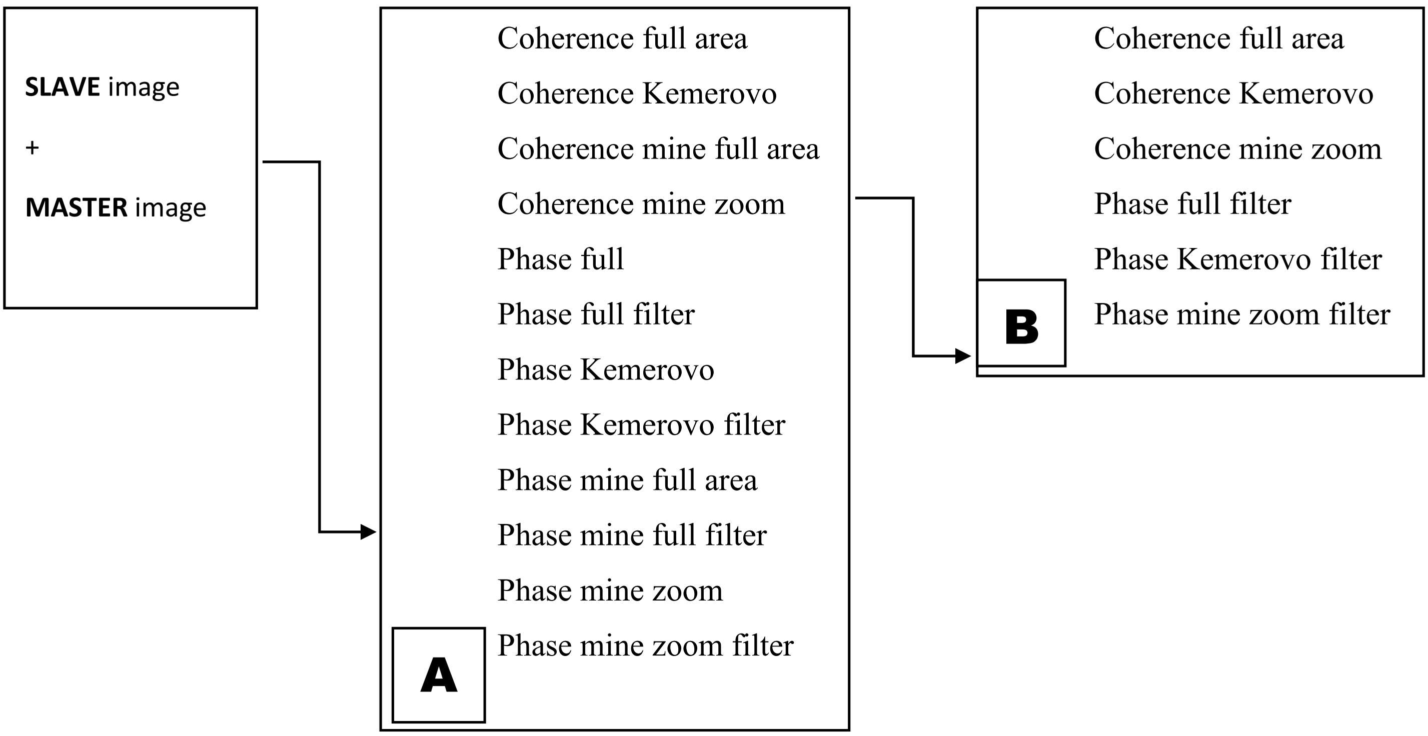


Diagram 2: Outcome interferograms after processing

For one acquisition date in each day, twelve (**A**) sets of interferograms were produced from the InSAR processing and only six (**B**) were used for the analysis *diagram 2*. The same process is repeated for all 19 data acquisitions of the period (12.03.2019- 13.12.2019).

Visualization

Within the framework of cartographic visualization, it is possible to create a series of subsidence maps. Visualization can be done in any software that supports it. Processed interferograms have visualization elements of producing maps that show the characteristics of the site. Raster data in GeoTIF format also reflect zones of subsidence of the earth's surface.

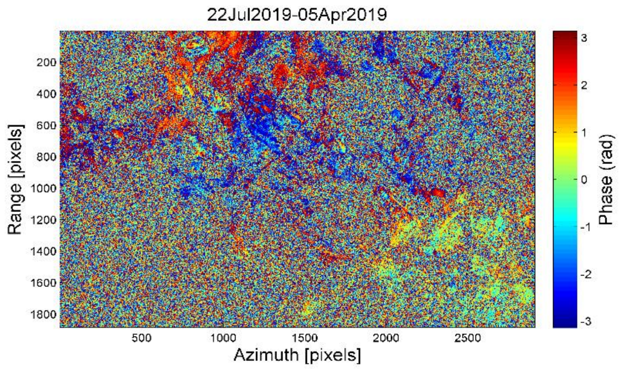
Analysis of the results of processing radar data

The results in (APPENDIX 3) are obtained from coherence and interferogram-processed images showing the characteristics of the land surface of the coal-mining region of the Kuznetsk Basin (Kemerovo).19 interferograms were processed. Area of interest: the mining area and Kemerovo will help us to identify the changes in the characteristics of the land surface, therefore detecting areas of subsidence.

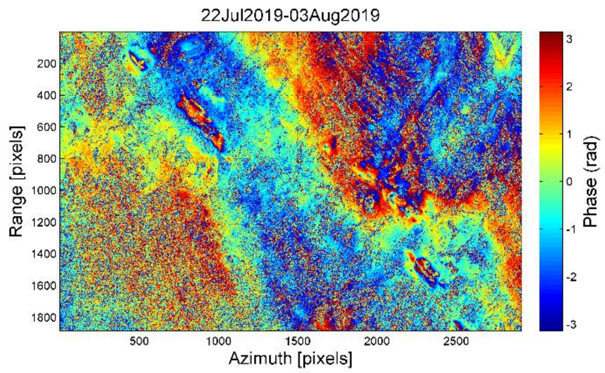
The best results on APPENDIX 3 show fringes where coherent values are greater than 0, 5. High coherence values shown in Kemerovo region (zoom) are at central part where there are probably large urban clusters. The low coherence areas on coherent interferograms probably resulted due to lakes or vegetated areas that have branches and leaves that lead to changes on the position and order of wavelengths; these show that scattering is the most important factor, which causes de-coherence. The decorrelation happens due to backscattering received from targets with different elevation within resolution cell.

The visible spot on the coherence (mine zoom) corresponds with respect to Kuznetsk Basin indicated as (mine).The changes on phase values observed between 12.03.2019- 13.12.2019 (Phase mine zoom filter) are related to displacements and terrain deformation on the land surface. The phase change might also result from displacements only or from both displacements and change in topography of SRTM (shuttle radar topography mission) used for propagation of the terrain. Remote sensing data comprised digital elevation model (DEM) acquired by the Shuttle Radar Topographic Mission (*SRTM*).

The other reason why the site proved to have possible subsidence is that Kemerovo oblast is prone to seismic events for example in 2013 there was an earthquake incident that occurred. Large mining areas can extremely subside during an earthquake because of the offset along fault lines. After all most minerals that are mined are located along faults. Coal mining causes much stress to the environment that triggers earthquakes to occur. Each change on the interferogram fringes is related to displacements. The high coherence (mine zoom filter) is from data acquired in August and September showing coherence values of (0.6-0.8) and Phase between (0 and 2.5) rad *table 4a,b*. Around month of November there was loss of coherence. This might be caused by temporal decorrelation due to temporal baseline of slave image with respect to master image and most important the snow during the cold season as this induces a coherence loss. It is also due to the fact of the terrain surface with and without snow; they have different scattering properties and so resulting in low interferometric coherence.

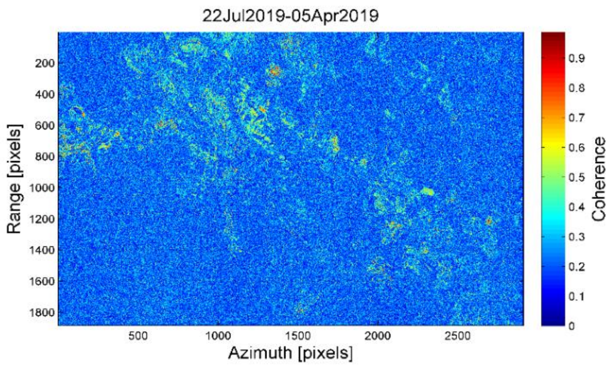


Phase mine zoom filter 05/04/19

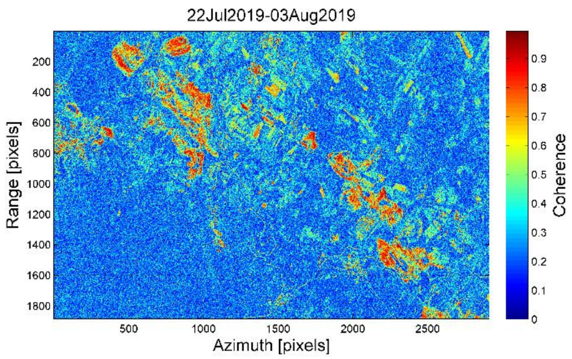


Phase mine zoom filter 03/08/19

Table 4a: showing phase change



Coherence mine zoom (05-04-2019)



Coherence mine zoom (03-08-2019)

Table 4b: Showing Coherence change

InSAR limitations

InSAR technique requires considering seasonal and weather conditions of the study area, during and before data acquisition. Wet weather and vegetation cover affect the quality of interferograms (atmospheric disturbance). It was noted that some of the dataset are totally "green" after processing, i.e. due to the problems of the sentinel-1 satellite that did not contain data. The area with no data *figure 17* gave no results after processing as the interferograms only show a green colour. This limitation decreased the number of successfully processed interferograms thus affecting the procedure to conduct a PS analysis, which requires more than 20 interferograms.

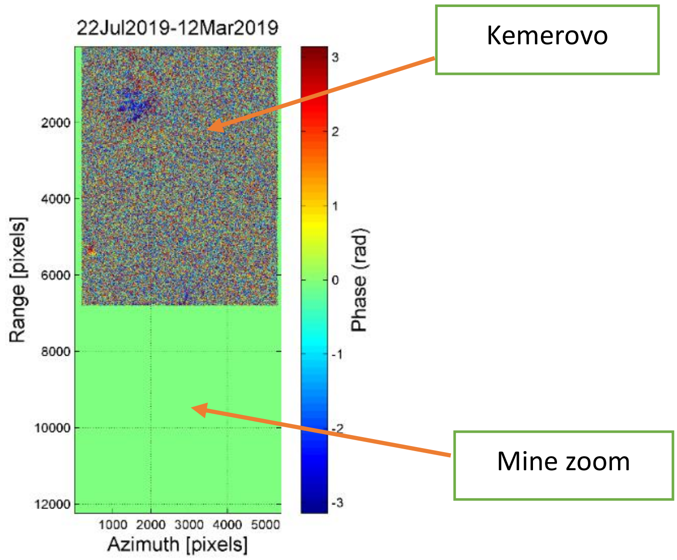


Figure 17: Showing areas with no data

CONCLUSION

The work offers a methodology (presented in fourth chapter of the thesis) of monitoring based on the use of an advanced synthetic aperture radar (InSAR) interferometry technique. Despite the limitations, the InSAR technique proved its high potential in this application to detect displacements on the Earth’s surface. However, long-time monitoring of land subsidence covering mine area Kuznetsk coal basin is lacking. Subsidence of the earth's surface due to mining activities is one of the biggest problems in monitoring land surfaces. It needs prompt and constant monitoring to prevent possible consequences. Basing on our experience, we may recommend that to improve the interferograms there is need to consider seasonal variability, i.e. the best interferograms presents data acquired during autumn season or summer season with limited effects of wet surface, humid and snow.

In general, the following practical results were obtained:

- The causes of subsidence of the earth's surface is determined.
- Methods of monitoring land surface subsidence were considered
- The general theory of radar satellite interferometry is explained
- The use of an advanced synthetic aperture radar (InSAR) interferometry technique detected displacements related to phase and coherence changes.
- Evaluate coherence values and detect values higher than the threshold (usually 0.5).
- Interferometric phase comparison of data obtained from the period 12.03.2019 and 03.08.2019.

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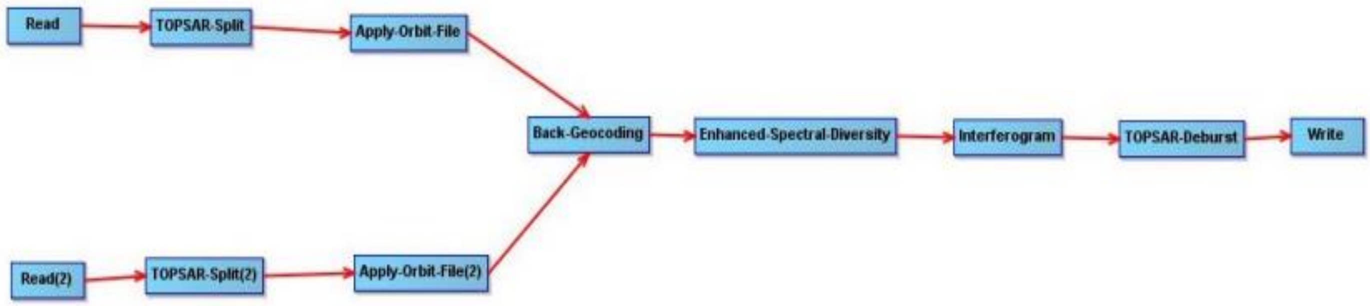
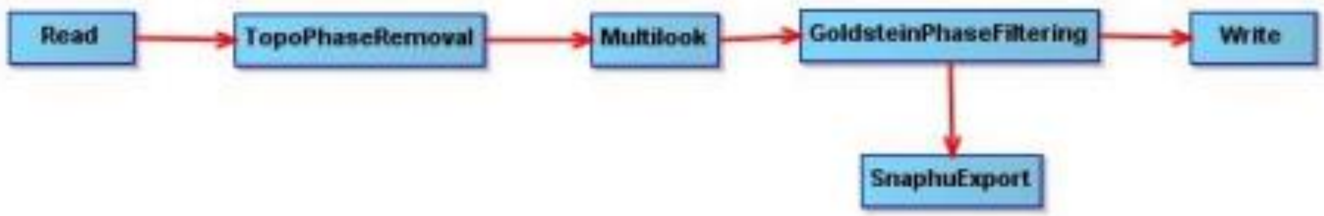
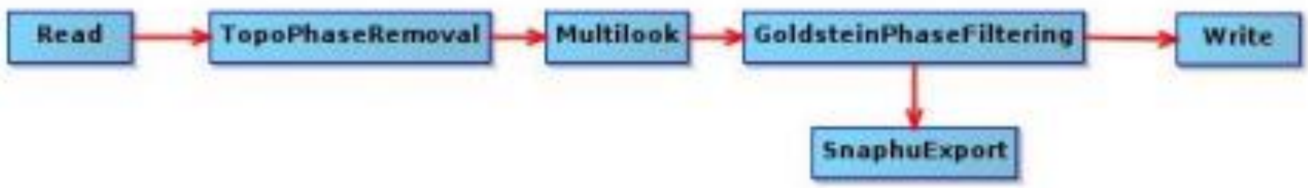
APPENDIX 1: SENTINEL-1 INSAR PROCESSING





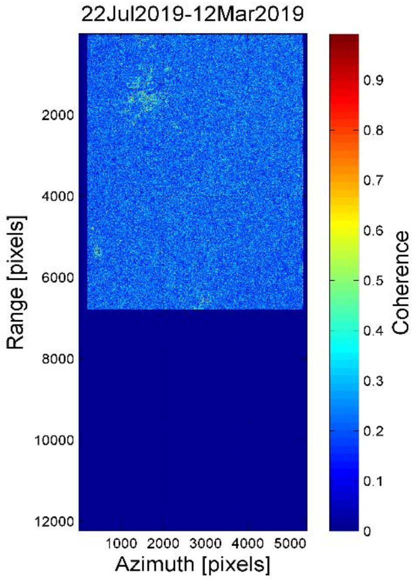


APPENDIX 2: A SERIES OF ACQUISITION DATES

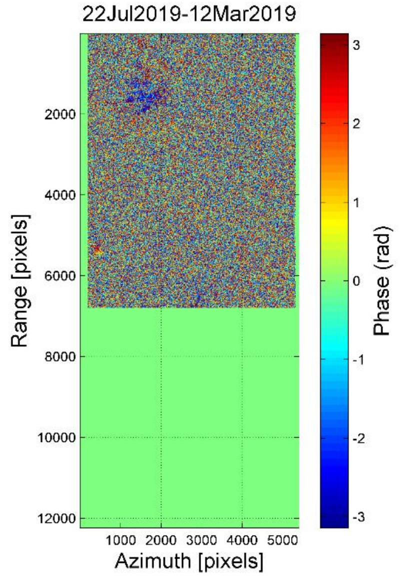
SENSOR	RELATIVE ORBIT	DATE	TIME
S1	165 descending	2019-12-13	00:36
S1	165 descending	2019-12-01	00:36
S1	165 descending	2019-11-19	00:36
S1	165 descending	2019-11-07	00:36
S1	165 descending	2019-10-26	00:36
S1	165 descending	2019-10-14	00:36
S1	165 descending	2019-10-02	00:36
S1	165 descending	2019-09-20	00:36
S1	165 descending	2019-08-03	00:36
S1	165 descending	2019-07-22	00:36
S1	165 descending	2019-06-28	00:36
S1	165 descending	2019-06-16	00:36
S1	165 descending	2019-06-04	00:36
S1	165 descending	2019-05-23	00:36
S1	165 descending	2019-05-11	00:36
S1	165 descending	2019-04-29	00:36
S1	165 descending	2019-04-17	00:36
S1	165 descending	2019-04-05	00:36
S1	165 descending	2019-03-24	00:36
S1	165 descending	2019-03-12	00:36

APPENDIX 3

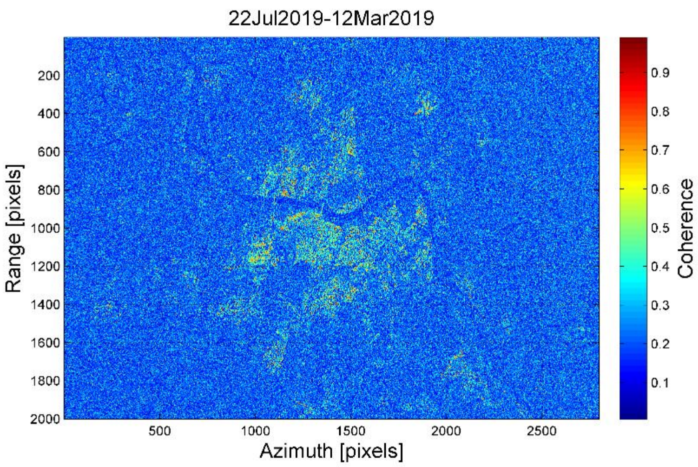
22.07.2019 – 12.03.2019(Coherence of full area)



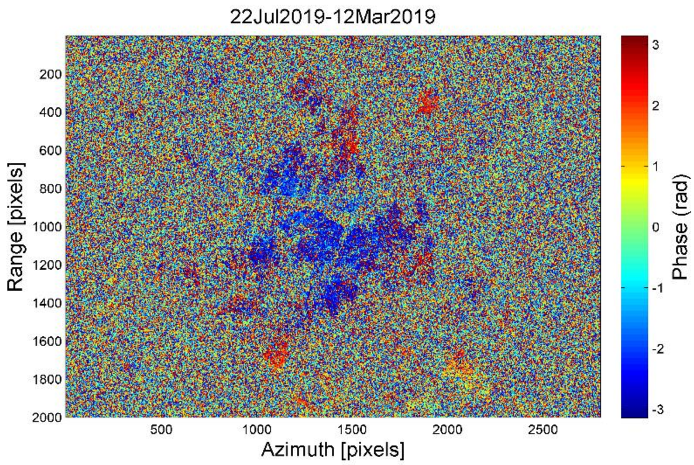
22.07. 2019 – 12.03.2019(Phase full area filter)

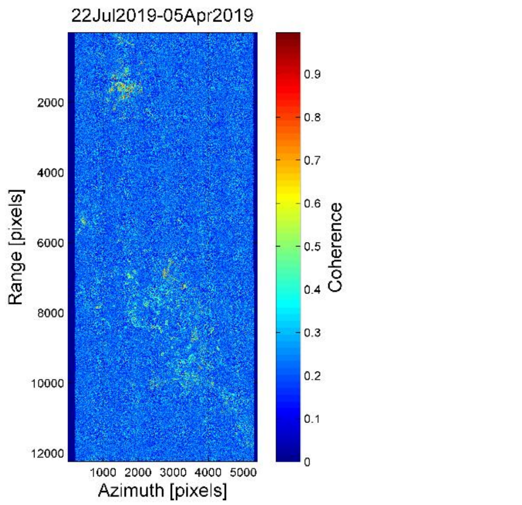
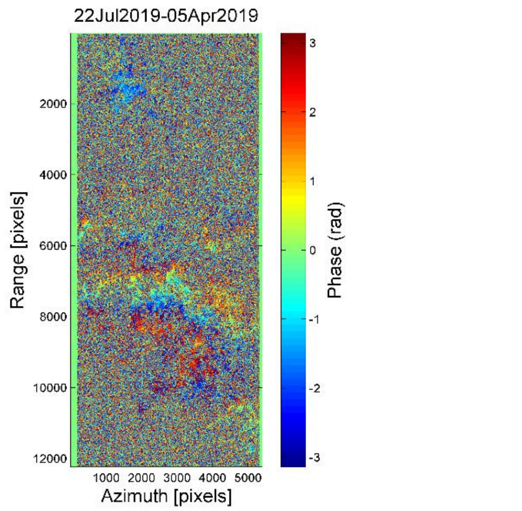


22.07.2019 – 12.03.2019(Coherence Kemerovo)



22.07. 2019 – 12.03.2019(Phase Kemerovo filter)



22.07.2019 – 05.04.2019(Coherence full area)	22.07. 2019 – 05.04.2019(Phase full area filter)
	

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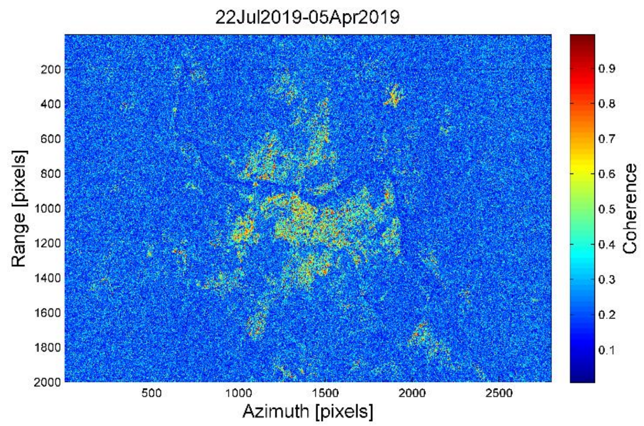
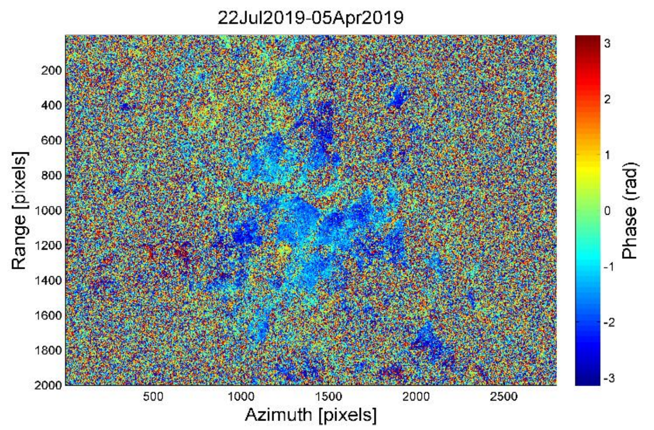
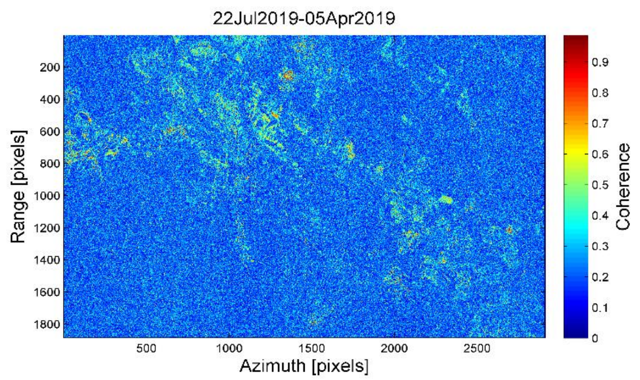
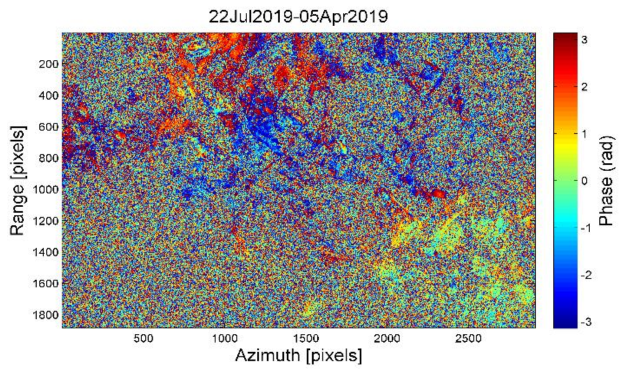
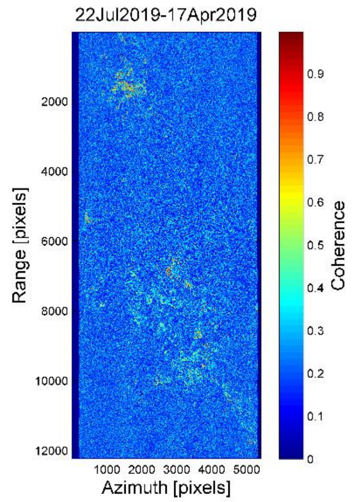
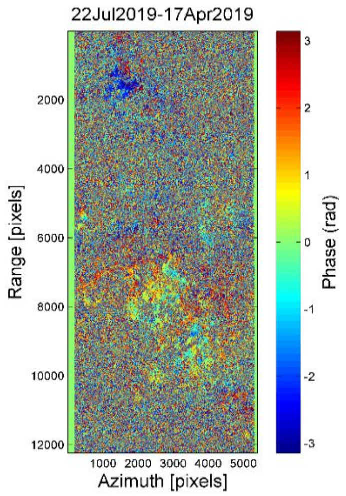
	

22.07.2019 – 05.04.2019(Coherence mine zoom)	22.07. 2019 – 05.04.2019(Phase mine zoom filter)
	

22.07.2019 – 17.04.2019 (Coherence full area)	22.07. 2019 – 17.04.2019(Phase full filter)
	

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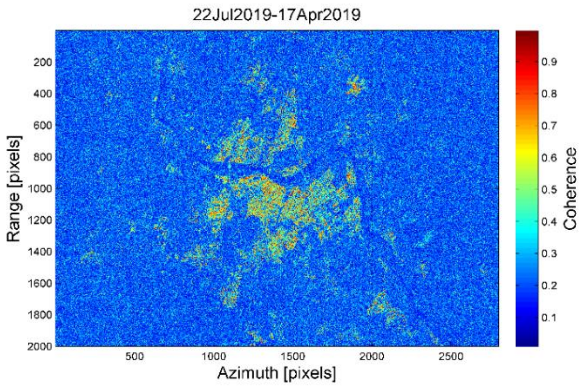
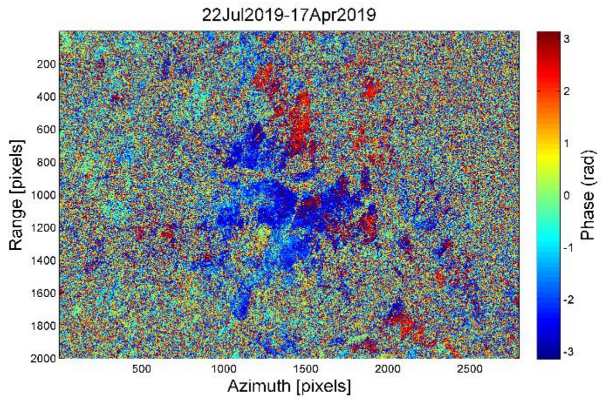
<tr><td>
</td><td>
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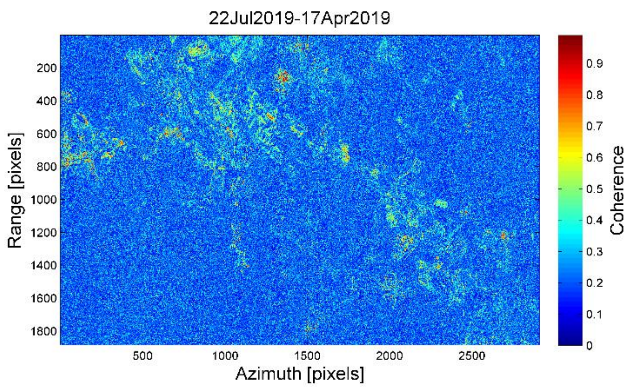
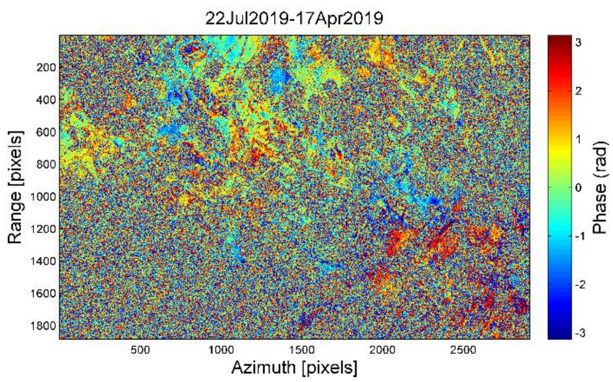
<tr><td>
</td><td>
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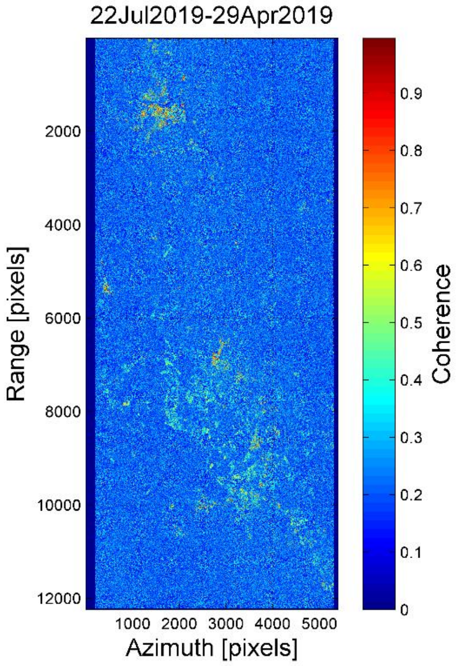
22.07.19–29.04.2019 (Coherence area full)



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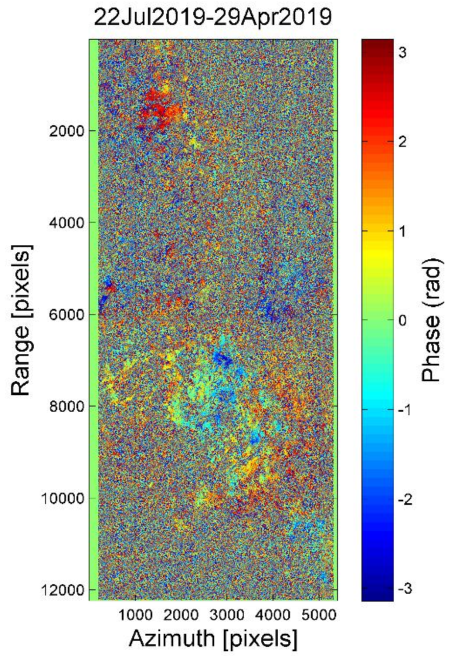

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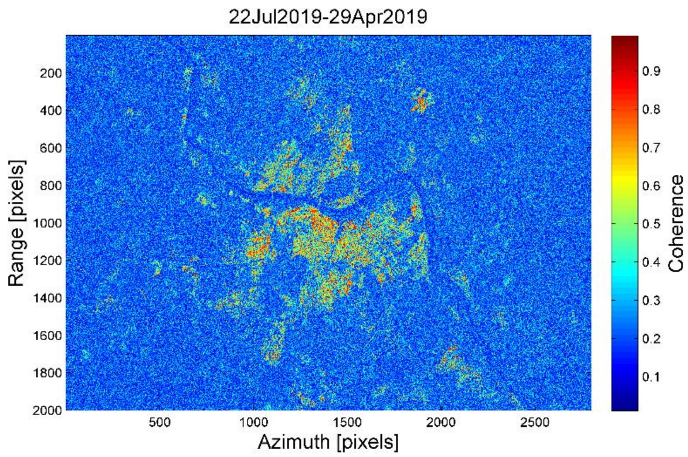

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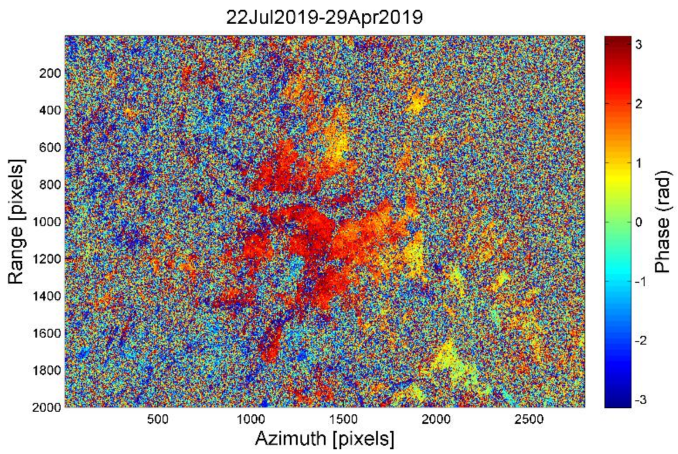

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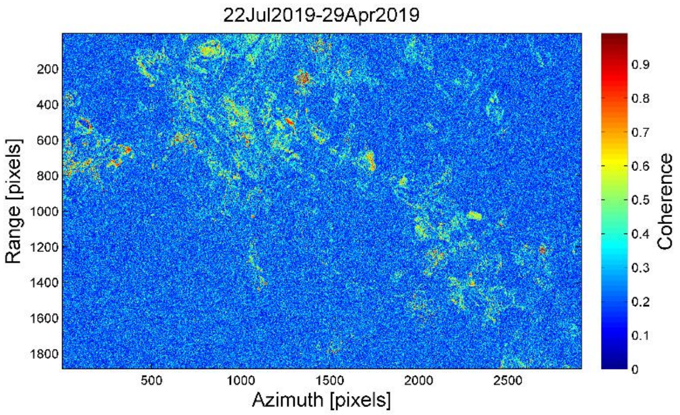	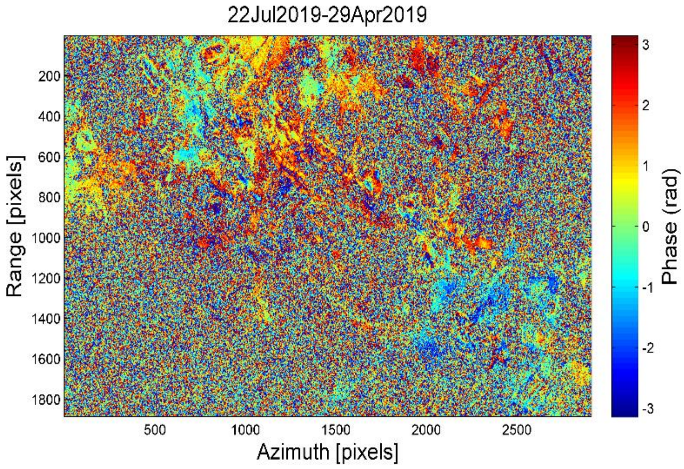

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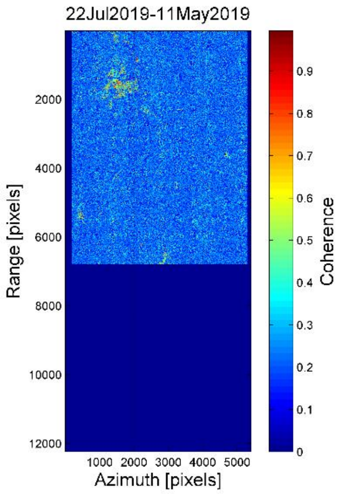

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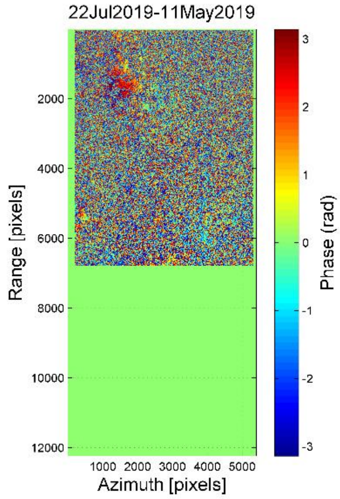

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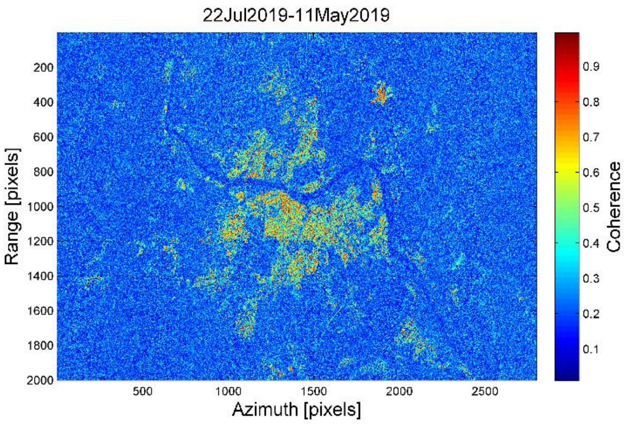

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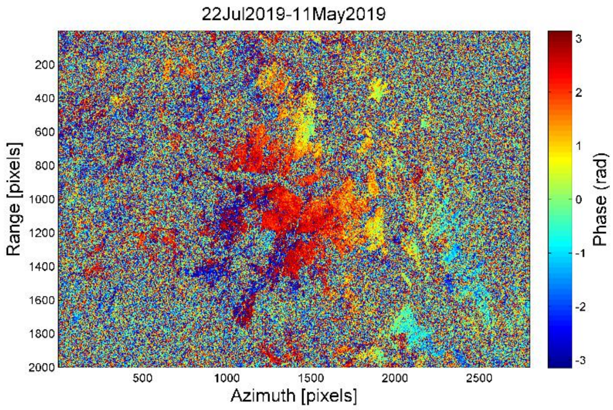

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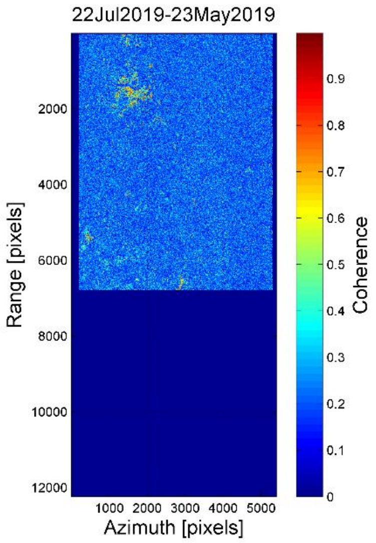

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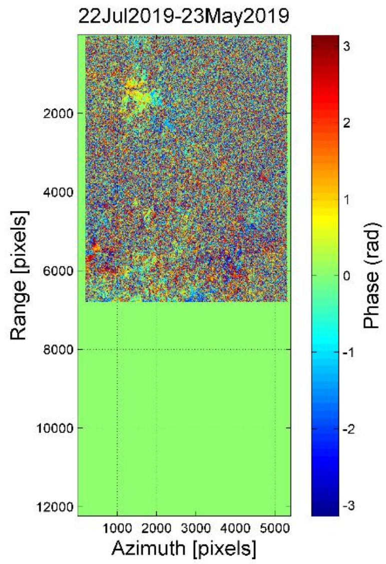

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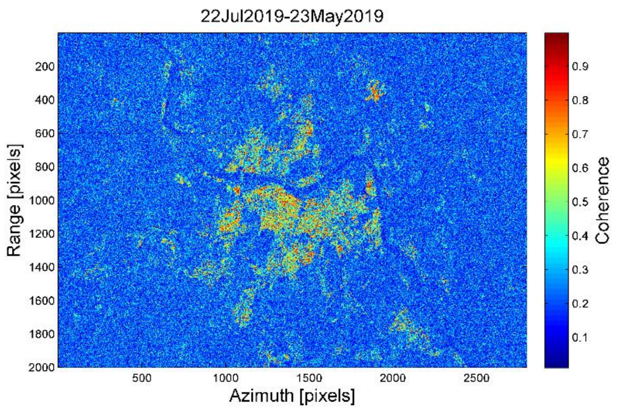

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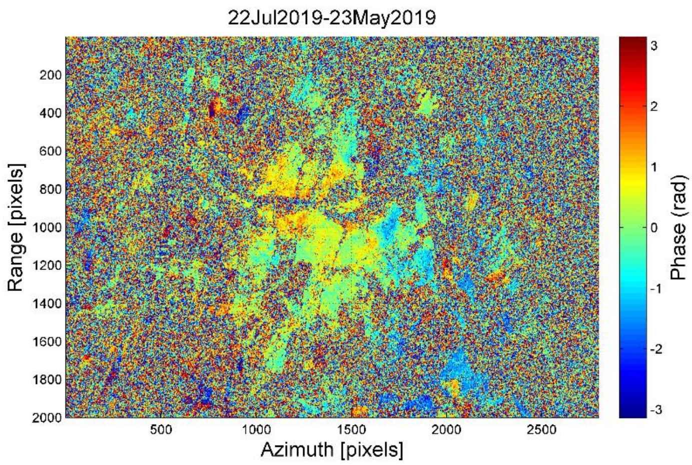

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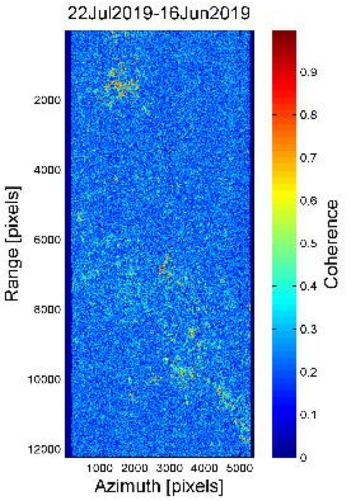

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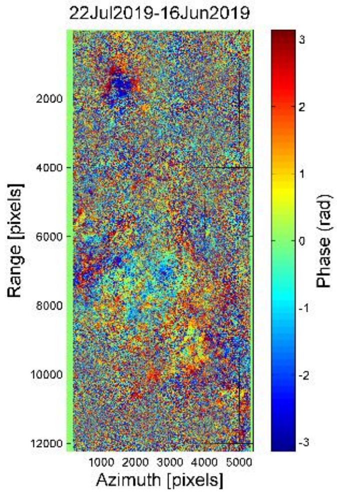

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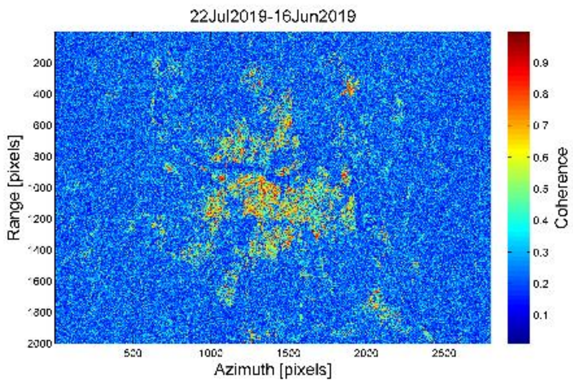

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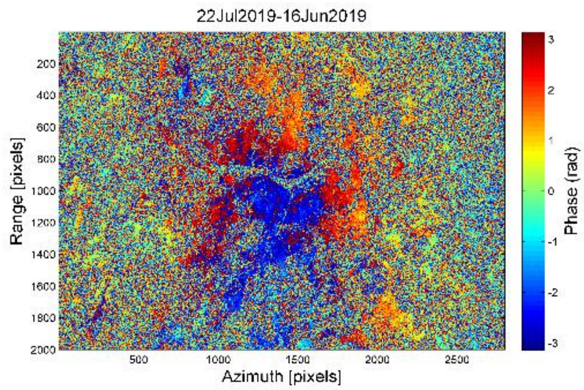
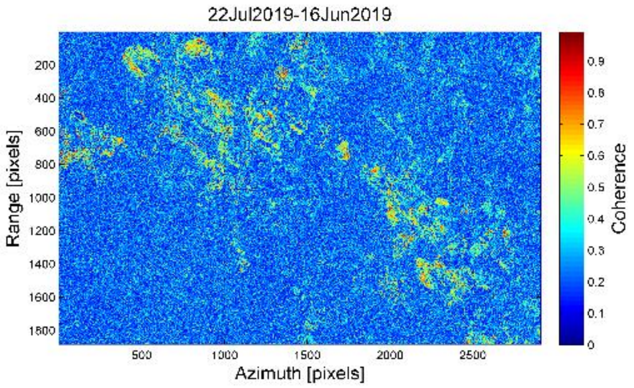
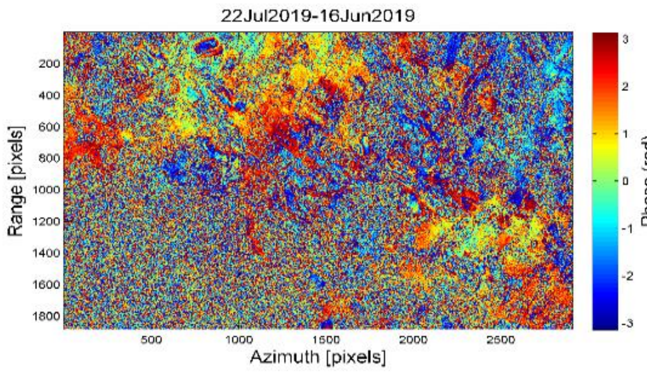
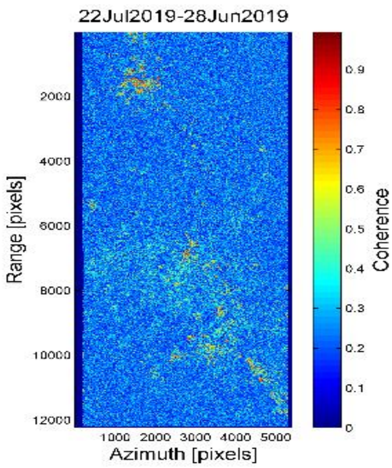
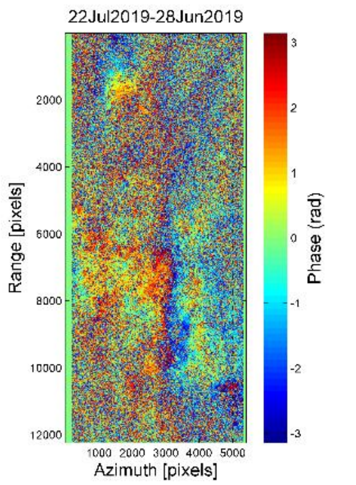


22.07.2019 – 16.06.2019 (Coherence mine zoom)	22.07. 2019 – 16.06.2019(Phase mine zoom filter)
	

22.07.2019 – 28.06.2019 (Coherence full area)	22.07. 2019 – 28.06.2019(Phase full area filter)
	

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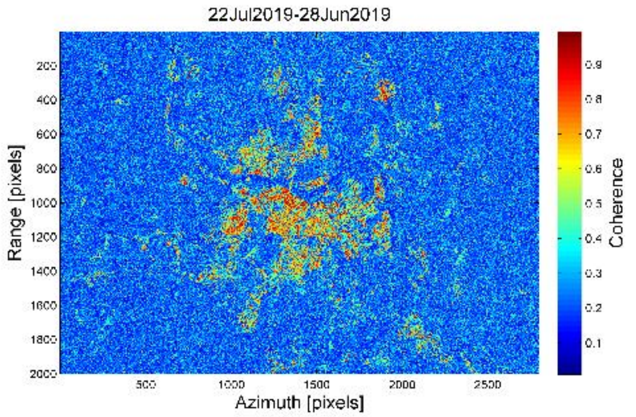

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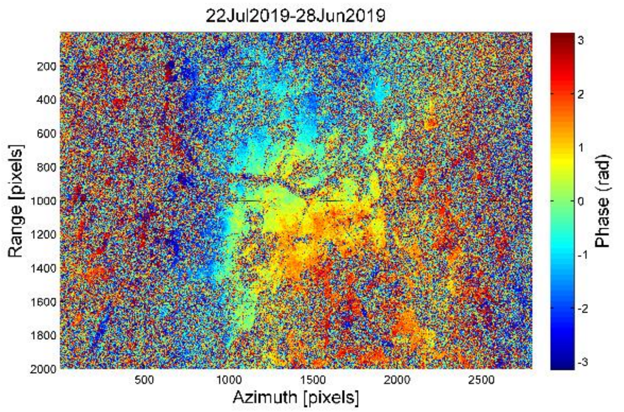

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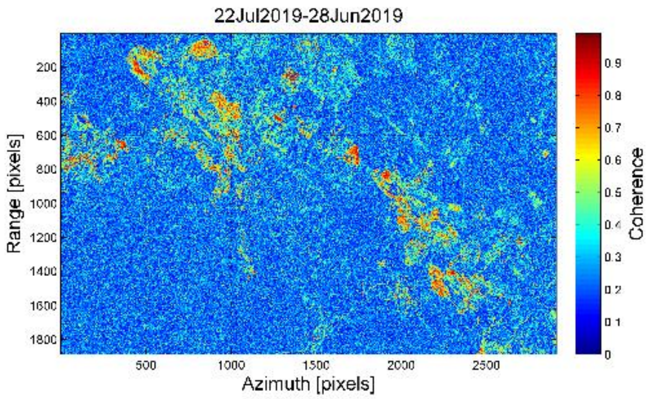

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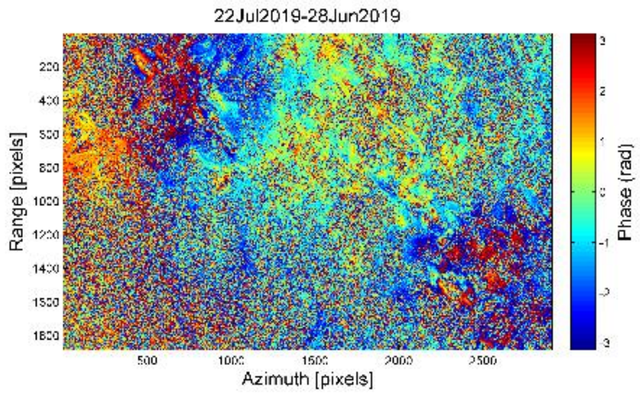

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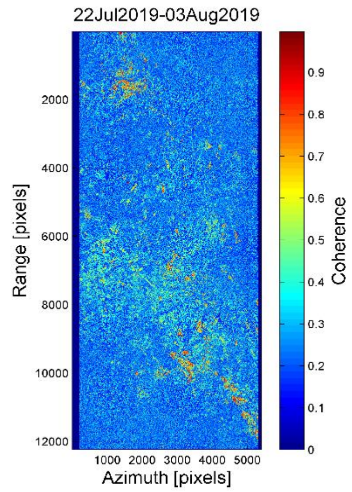
22.07.2019 – 03.08.2019 (Coherence full area)



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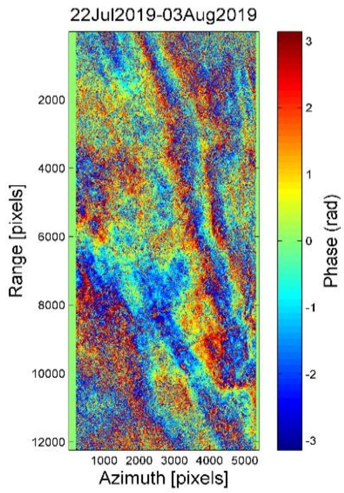

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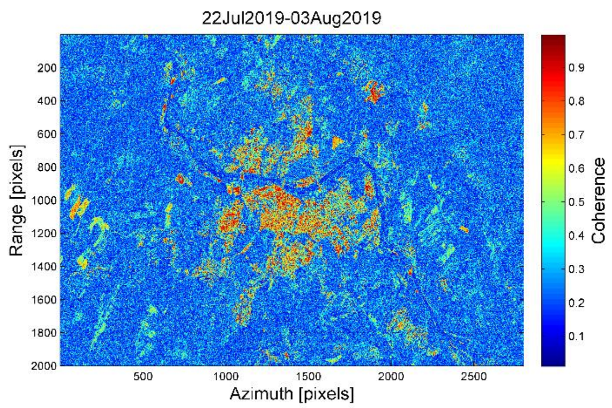

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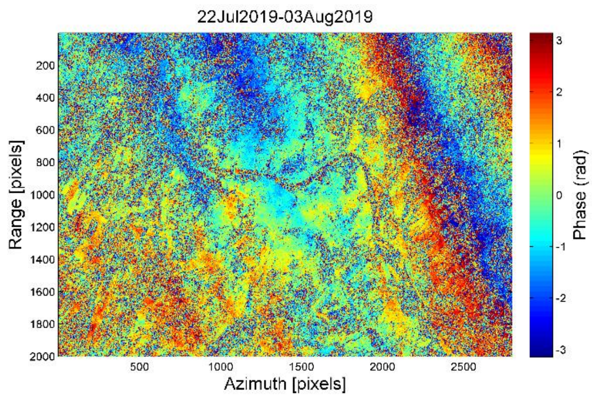

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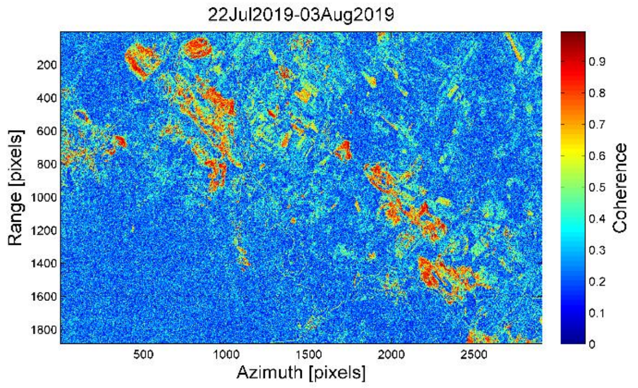

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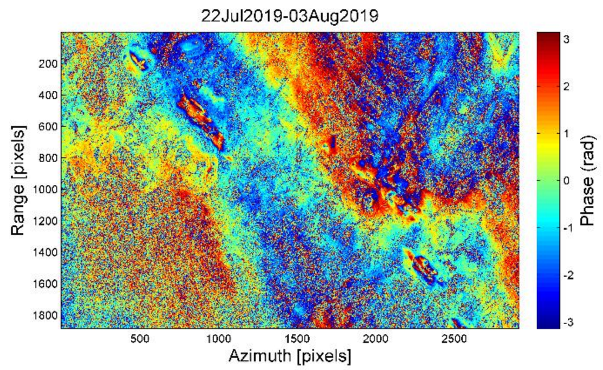

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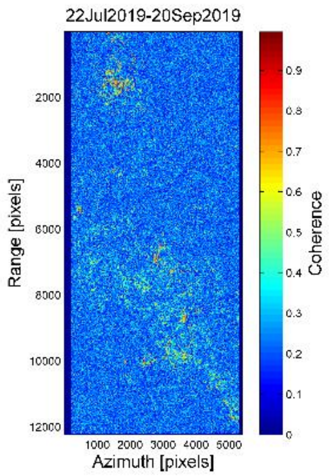

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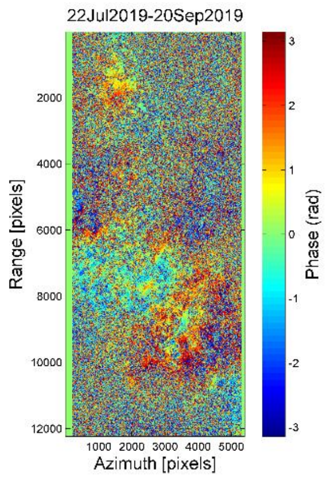

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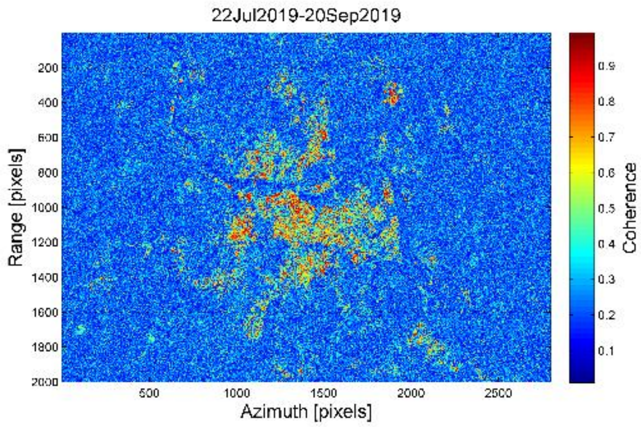

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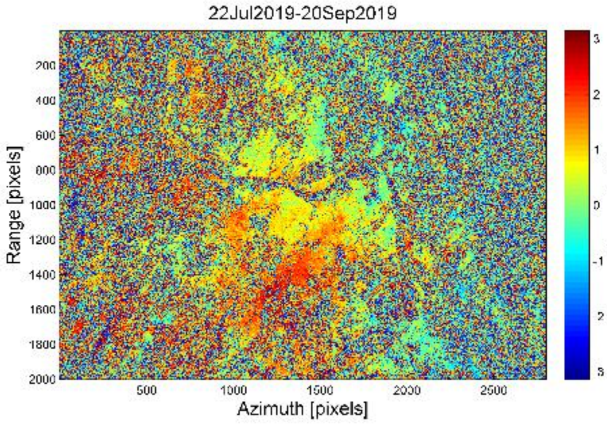

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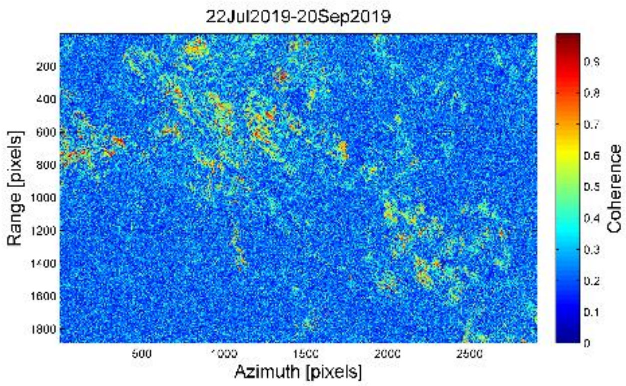

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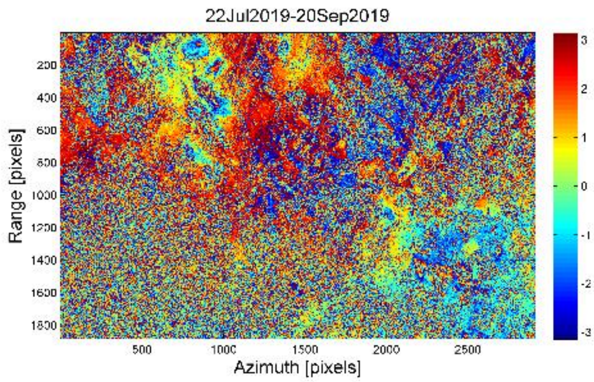

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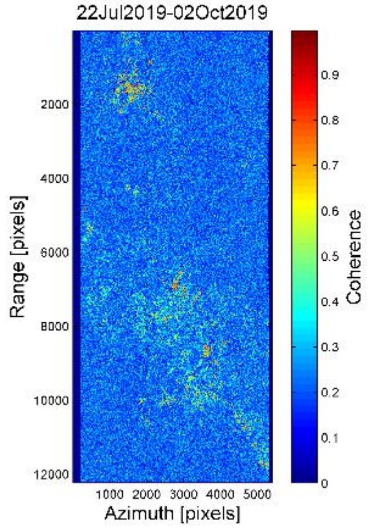	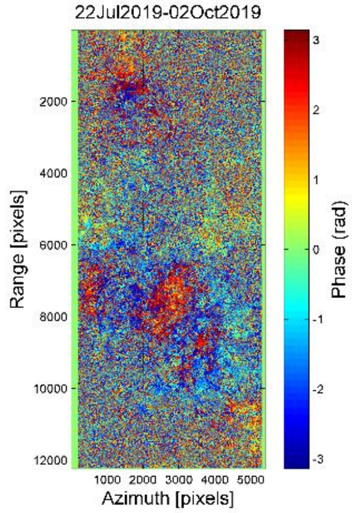

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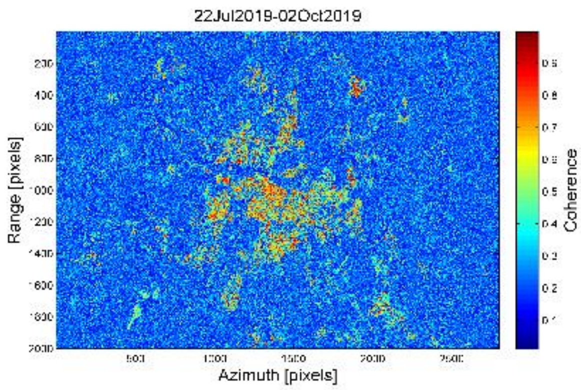	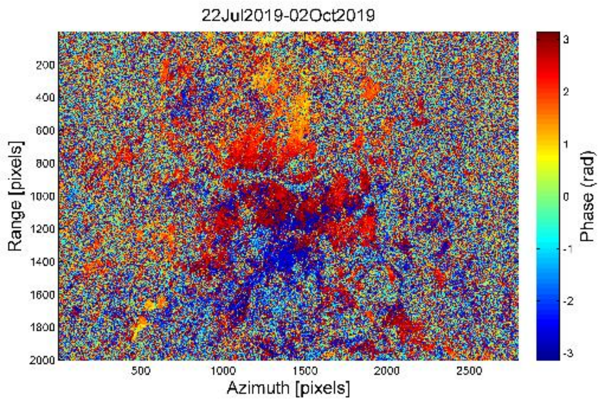

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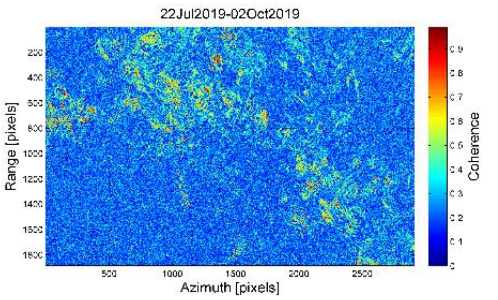

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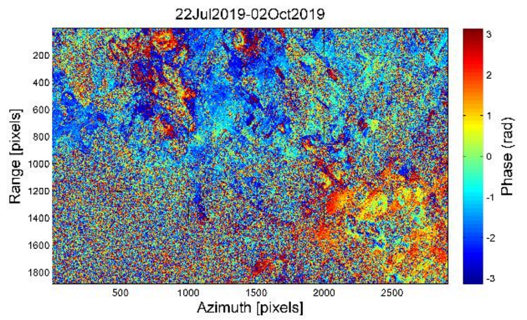

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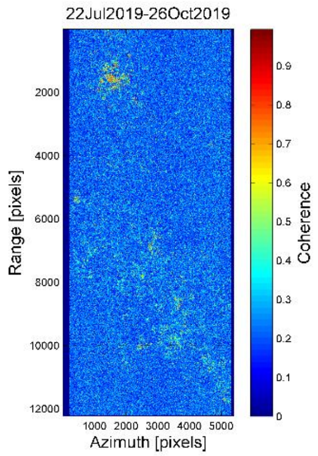

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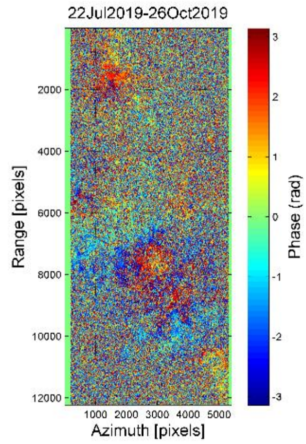

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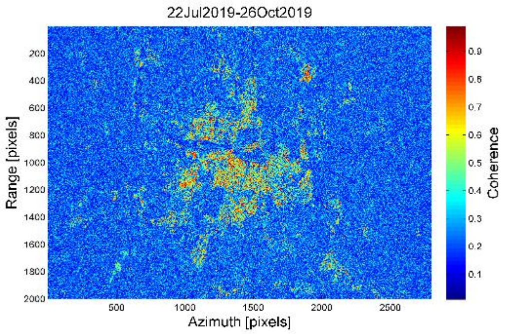

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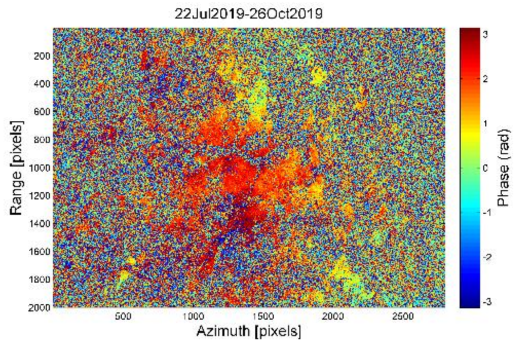

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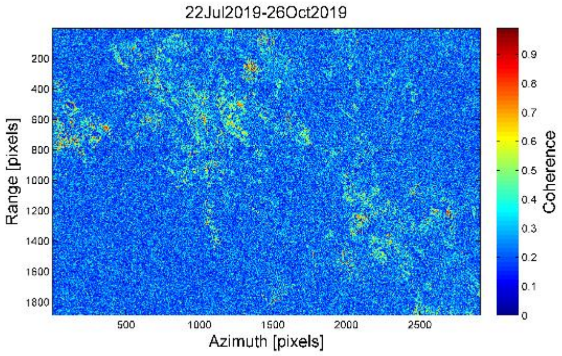

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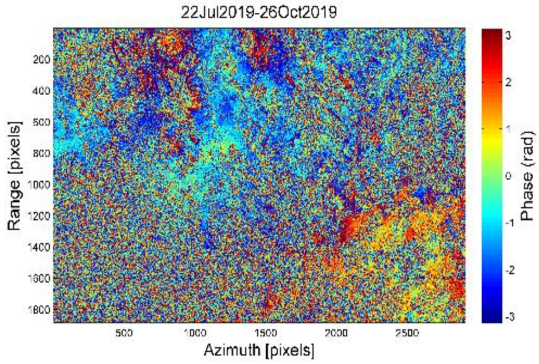

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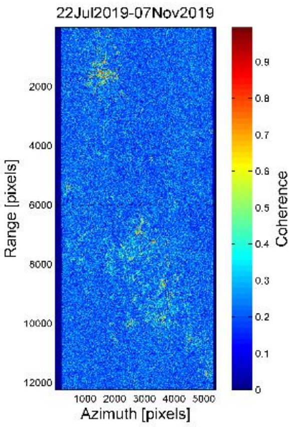

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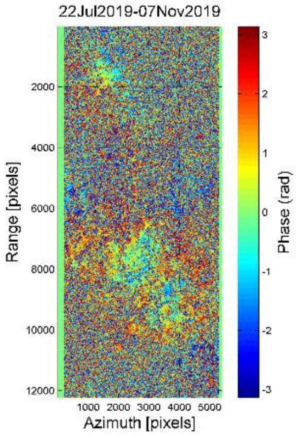

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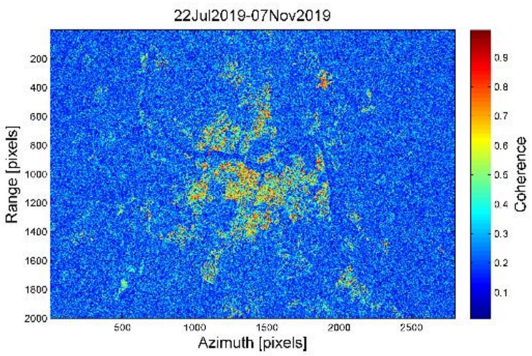

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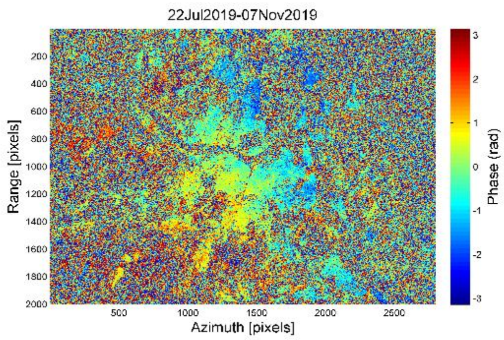

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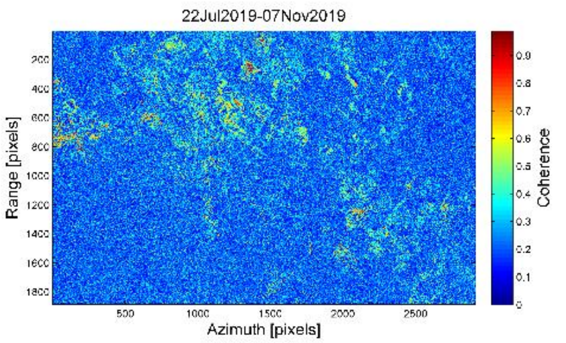
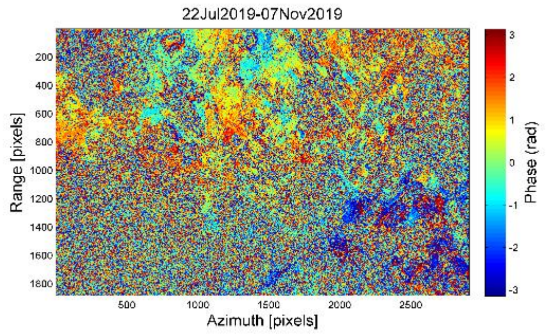
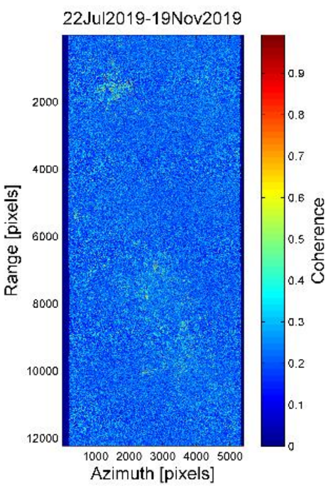
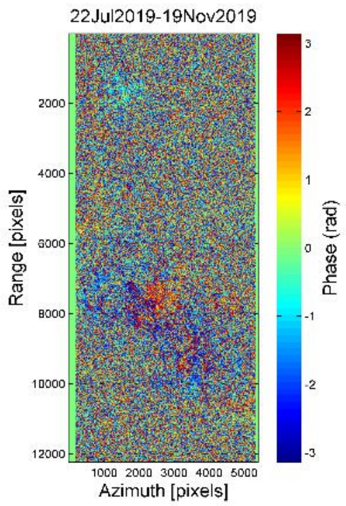
	

22.07.2019 – 19.11.2019 (Coherence full area)	22.07. 2019 – 19.11.2019 (Phase full area filter)
	

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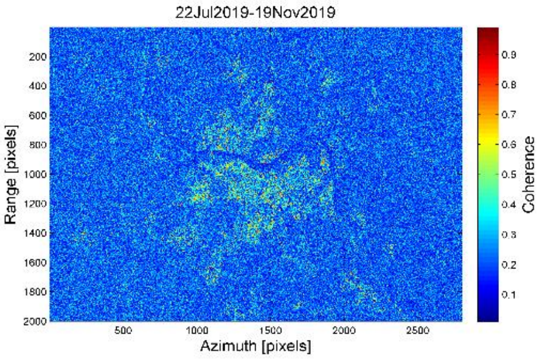	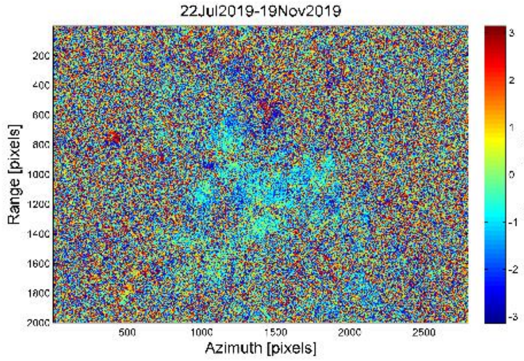

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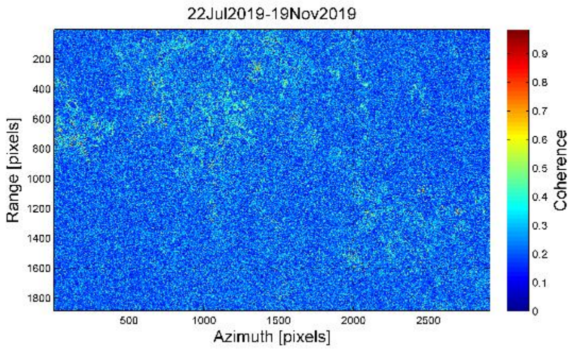	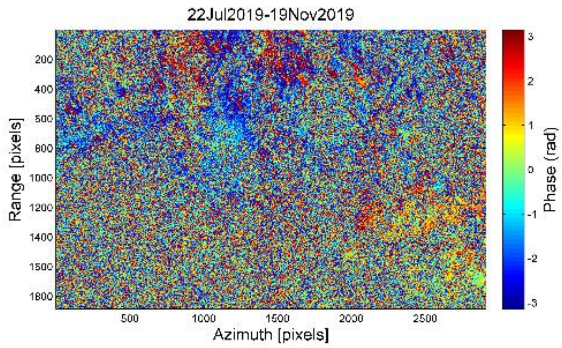

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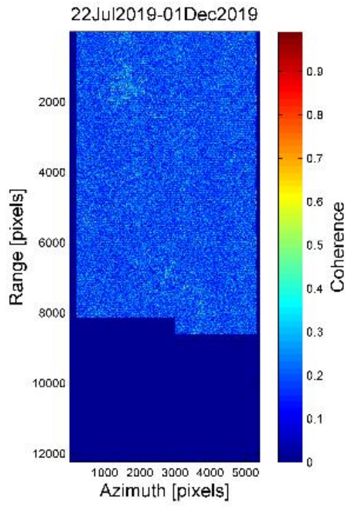
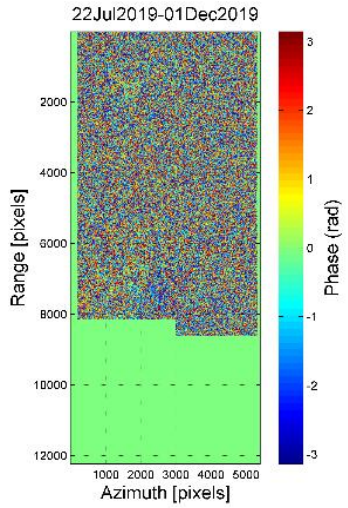
<tr><td>
</td><td>
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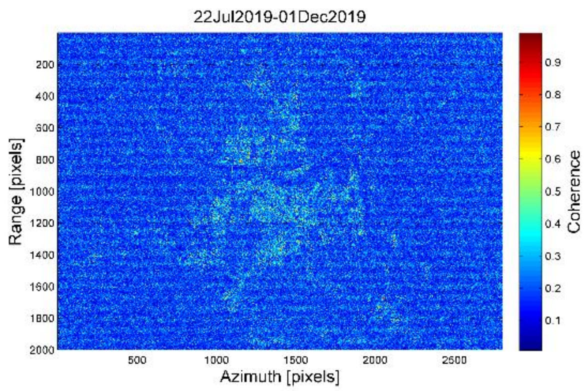
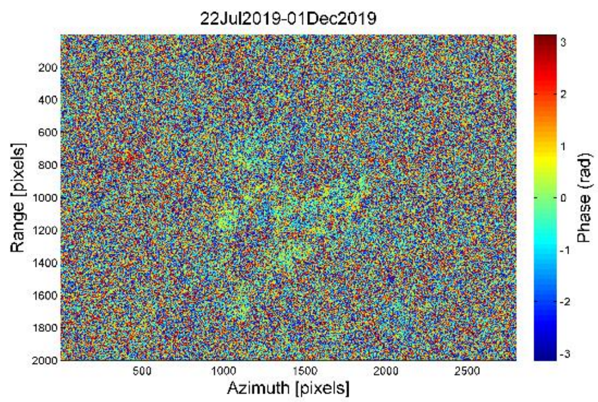
<tr><td>
</td><td>
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